THEME: Environment (including climate change)

TOPIC: ENV.2011.2.1.2-1 Hydromorphology and ecological objectives of WFD

Collaborative project (large-scale integrating project)

Grant Agreement 282656

Duration: November 1, 2011 – October 31, 2015

REstoring rivers FOR effective catchment Management

Deliverable D2.1 Part 3

Title Catchment Case Studies: Full Applications of the Hierarchical Multi-scale Framework

Author(s) (authors of Part 3 in alphabetical order*) B. Blamauer[1], B. Belletti [2], D. García De Jalón[3], M. González Del Tánago[3], R. Grabowski[4], A.M. Gurnell[4], H. Habersack[1], Mario Klösch[1], Paweł Marcinkowski[5], V. Martínez-Fernández[3], L. Nardi[2], T. Okruszko[5], M. Rinaldi[2]

[1]BOKU, [2]UNIFI, [3]UPM, [3]ISPRA, [4]QMUL, [5]WULS

Due date to deliverable: 1 November 2014
Actual submission date: 30 October 2014

Project funded by the European Commission within the 7th Framework Programme (2007 – 2013)

Dissemination Level

PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

* Please cite the whole of Deliverable 2.1 as follows:

A.M. Gurnell, B. Belletti, S. Bizzi, B. Blamauer, G. Braca, T.Buijse, M. Bussettini, B. Camenen, F. Comiti, L. Demarchi, D. García De Jalón, M. González Del Tánago, R.C. Grabowski, I.D.M. Gunn, H. Habersack, D. Hendriks, A. Henshaw, M. Klösch, B. Lastoria, A. Latapie, P. Marcinkowski, V. Martínez-Fernández, E . Mosselman, J.O. Mountford, L. Nardi, T. Okruszko, M.T. O'Hare, M. Palma, C. Percopo, M. Rinaldi, N. Surian, C. Weissteiner and L. Ziliani (2014) A hierarchical multi-scale framework and indicators of hydromorphological processes and forms. Deliverable 2.1, a report in four parts of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Please use the following citation for Deliverable 2.1 part 3

B. Blamauer, B. Belletti , D. García De Jalón, M. González Del Tánago, R.C. Grabowski, A.M. Gurnell, H. Habersack, M. Klösch, P. Marcinkowski, V. Martínez-Fernández, L. Nardi, T. Okruszko and M. Rinaldi (2014) Catchment Case Studies: Full Applications of the Hierarchical Multi-scale Framework. Deliverable 2.1, Part 3, of REFORM (REstoring rivers FOR effective catchment Management), a Collaborative project (large-scale integrating project) funded by the European Commission within the 7th Framework Programme under Grant Agreement 282656.

Summary

Background and Introduction to Deliverable 2.1.

Work Package 2 of REFORM focuses on hydromorphological and ecological processes and interactions within river systems with a particular emphasis on naturally functioning systems. It provides a context for research on the impacts of hydromorphological changes in Work Package 3 and for assessments of the effects of river restoration in Work Package 4.

Deliverable 2.1 of Work Package 2 proposes a hierarchical framework to support river managers in exploring the causes of hydromorphological management problems and devising sustainable solutions. The deliverable has four parts. Part 1 provides a full description of the hierarchical framework and describes ways in which each element of it can be applied to European rivers and their catchments. Part 2 includes thematic annexes which provide more detailed information on some specific aspects of the framework described in Part 1. Part 3 (this volume) includes catchment case studies which present the application of the entire framework described in Part 1 to a set of European catchments located in different biogeographical zones. Part 4 includes catchment case studies which present a partial application of the framework described in Part 1 to a further set of European catchments.

Summary of Deliverable 2.1 Part 2.

Part 3 of Deliverable 2.1 provides a set of full case study applications of the framework described in Part 1 that are designed to guide users of the framework through the various stages of its application. The five case studies are set within different biogeographical regions of Europe.

Case Study 1 is a fully worked example which applies the entire framework to the catchment of the River Frome, UK. The aim of this case study is to fully illustrate every stage and aspect of the framework, including discussion of how surrogate data and indices were developed when the preferred data types were not available, and a description (in chapter 9) of how analyses were conducted in ArcGIS.

Case studies 2 to 5 are also fully developed examples of the framework of the Upper Esla River (Duero basin, NW Spain), the River Narew (Poland), the Magra and Cecina rivers (Italy) and the River Drau (Austria). They provide examples of its application to different European biogeographical environments, often using different, locally-available data sets, models and methods.

Applications of the hierarchical framework to other regions of Europe are provided in Deliverable 2.1 Part 4. These case studies provide partial applications of the framework, mainly covering the delineation and characterisation phases.

Acknowledgements

REFORM receives funding from the European Union's Seventh Programme for research, technological development and demonstration under Grant Agreement No. 282656. We gratefully acknowledge the following for their constructive reviews: Gary Brierley, Judy England, Ángel Garcia Canton, Fernando Magdaleno Mas, María Isabel Berga Cano.

Table of Contents

Catchment Case Study 1

Hydromorphological assessment of the River Frome (UK): a lowland Northern European river

Robert Grabowski, Angela Gurnell
Queen Mary University of London

1. Introduction

In this document, we demonstrate how the hierarchical hydromorphological assessment framework can be applied to an entire river catchment. We use the guidelines outlined in the D2.1 main report to:

- Delineate the river and its catchment into spatial units (Section 3)
- Characterise the current hydromorphological condition of the spatial units (Section 4)
- Characterise past temporal change in hydromorphology in the spatial units (Section 5)
- Assign a river typology to the river reaches (Section 6)
- Quantify indicators of current hydromorphological condition (Section 7)
- Interpret hydromorphological condition and predict trajectories of change (Section 8)

To support these key stages in applying the methodology described in the D2.1 main report, we also introduce the River Frome catchment (Section 1.1), and provide a brief technical summary of the data sources and methods used in the delineation and characterisation stages (Section 2). Full details on these methods and their implementation are provided at the end of this case study in section 9.

1.1 The River Frome

The River Frome is a lowland, gravel bed, chalk river in Dorset, southern England. It is protected under multiple UK and EU statutes for its species-rich aquatic plant communities and important river and floodplain habitats. The River Frome is designated as a Site of Special Scientific Interest under the Wildlife and Countryside Act 1981, a priority habitat under UK Biodiversity Action Plans, and was protected under the EU Freshwater Fish, Nitrates, and Shellfish Directives, which are now superseded by the Water Framework Directive (WFD).

Whilst the River Frome has historically supported diverse ecological communities and productive fisheries, concerns have been raised about ecological degradation in the system. In fact, the ecological status was classified as poor for most of the main river in the first WFD assessment cycle (Figure 1.1). Of the 4 WFD waterbodies on the main stem of the River Frome, three are rated as poor and the fourth is classified as heavily-modified (Table 1.1). The majority of the tributaries are classified as having good ecological status (6), though 2 are in poor condition and 1 is heavily-modified (Figure 1.1).

In this report, we use the hierarchical assessment framework to investigate the hydromorphological condition of the River Frome. Whilst intended as a demonstration of the application of the hierarchical framework, the outcomes of this assessment could be used for a variety of purposes, for example to identify significant hydromorphological pressures in the catchment, to support and interpret ecological surveys, or to inform catchment management decisions or restoration options.

Figure 1.1 Current ecological status of waterbodies in the River Frome catchment. Yellow: poor ecological status, green: good ecological status. (What's in your backyard? Online mapping tool, maps.environment-agency.gov.uk. Environment Agency copyright and database rights 2012 and Ordnance Survey Crown copyright).

Table 1.1 Waterbodies defined for the River Frome and its tributaries for the WFD.

Name	Length (km)	Heavily Modified Water Body	Ecological Status	Predicted Eco. Status (2015)	Waterbody ID
River Frome					
Frome - Headwaters	5.12	No	Poor	Good	GB108044009620
Frome - Upper	3.81	Yes	Good Potential.	Good Potential	GB108044009780
Frome - Lower & Furzebrook Stream	76.58	No	Poor	Good	GB108044009690
Frome - Bifurcation (North Stream)	5.22	No	Poor	Good	GB108044009670
Tributaries					
Compton Valence Stream	4.17	No	Good	Good	GB108044009680
Wraxall Brook	6.59	No	Poor	Good	GB108044009610
Hooke	10.46	No	Good	Good	GB108044009800
Sydling Water	8.63	Yes	Good Potential	Good Potential	GB108044009700
Cerne	17.36	No	Poor	Good	GB108044009710
Tadnoll Brook	14.92	No	Good	Good	GB108044009660
River Win	6.31	No	Good	Good	GB108044009650
Luckford Lake	3.55	No	Good	Good	GB108044009640
South Winterbourne	10.86	No	Good	Good	GB108044010060

2. Materials and Methods

2.1 Datasets

A selection of remotely sensed and national datasets was used in the delineation and characterisation processes (Table 2.1).

2.1.1 Mapping

Ordnance Survey (OS) maps for the River Frome catchment were obtained from the Digimap service[1]. The MasterMap Topography Layer is a high resolution digital map series that contains layers for 9 different themes of objects, such as buildings, roads, vegetation type and water features (updated 2012). Position accuracy depends on the location of the feature; urban data has a horizontal accuracy of 1.0 m and rural data 2.5 m (equivalent to the OS 1:2500 maps). It is provided in GML format and was converted to ArcGIS shapefile using the InterpOSe software from Dotted Eyes[2].

Two large-scale (1:2500) historical OS maps were used in the temporal analysis, the first dating from 1889, and the second from 1960 / 1975.

2.1.2 Aerial Imagery

Delineation and characterisation of the reach and geomorphic units were supported by satellite imagery from Google Earth. Images from 20/09/2008 were the primary source of data, as they were the most recent images to cover the entire catchment (Copyright © 2013 Infoterra and Bluesky).

2.1.3 Elevation

The Profile DTM is a 10m resolution Digital Terrain Model generated from the OS Land-Form Profile contour data (5m contours, 10m in mountainous areas), which is based on 1:10,000 scale mapping (updated 2009). DTM height accuracy is less than or equal to half of the contour interval (2.5 m), absolute accuracy of contours is on the order of +-1.0 m root mean square error. Tiles (5 km x 5 km) were obtained from Digimap[1] in a GeoTIFF format and mosaicked in ArcGIS 10.0. Licence permits academic use for UK researchers only.

High resolution digital elevation models (DEMs) based on LiDAR surveys were obtained from the Environment Agency (EA) for the majority of the main stem of the River Frome. LiDAR, or light detecting and ranging survey, uses a laser scanner to obtain data point clouds of the topography of the land surface. An airborne LiDAR survey was conducted in

[1] Digimap. http://edina.digimap.ac.um, accessed on 15-March-2013)

[2] InterpOSe software by Dotted Eyes. http://misoportal.com/data/interpose-for-digimap/

2006 (9 and 11 November) using the Environment Agency ALTM 3100 LiDAR instrument. The original point cloud data, or digital surface model (DSM), was processed to remove surface elements such as houses and trees, producing a DTM. Both the original and processed DEMs were converted to ASCII GRID format, and the resulting DSM and DTM have a horizontal resolution of 1 m and a vertical accuracy of better than 0.1 m (RMSE = 0.050).

2.1.4 Geology

A digital map (1:625,000 scale) of the bedrock and surficial geology of the UK was obtained from the British Geological Survey. The geology is generalised from a larger 1:50,000 'poster' map of UK geology (version 1, 1977 and 1979). Accuracy is 1 mm on the poster, which equates to 625 m on the ground. The data is freely available from the BGS website[3].

2.1.5 Soil

The soil dataset was obtained from the European Soil Portal run by the European Commission's Joint Research Centre (JRC)[4]. The vector dataset of the European Soil Database (ESDB) (version 2) was downloaded in a joined shapefile that contains the attributes from the Soil Geographical Database of Eurasia (SGDE) (scale 1:1,000,000), Pedotransfer Rules Database (PTRDB), Soil Profile Analytical Database of Europa (SPADBE) and the Database of Hydraulic Properties of European Soils (HYPRES). Soil Typological Units (STU) are grouped into Soil Mapping Units (SMU) to display attributes. Three derived PTRDB attributes were used in the analysis: soil erodibility, soil hydrology and water regime.

The Pan-European Soil Erosion Risk Assessment map (PESERA) was used to estimate fine sediment input into the river. PESERA is a process-based model that quantifies soil erosion by water based on rainfall, topography, soil characteristics and land cover (based on CORINE from 1989, see below for more details). The soil loss estimates (t ha^{-1} yr^{-1}) are freely available in GeoTIFF format from the JRC[5].

---

[3] British Geological Survey. http://www.bgs.ac.uk/products/digitalmaps/digmapgb_625.html, accessed on 15-March-2013.

[4] European Soil Portal. http://eusoils.jrc.ec.europa.eu/, accessed on 15-March-2013.

[5] PESERA. Joint Research Centre. http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_data.html, accessed on –March-2013.

2.1.6 Aquifers

Groundwater data were downloaded as shapefiles from JRC's European Soil Portal[6]. The datasets are based on maps produced in a 1982 study by the European commission (1:500,000 scale). Theme 1 relates to aquifer coverage, and is the only theme included in these analyses.

[6] Digital Dataset of European Groundwater Resources - version 1.0, European Soil Portal http://eusoils.jrc.ec.europa.eu/ESDB_Archive/groundwater/gw.html, accessed on 15-March-2013.

Table 2.1 Primary datasets used in the delineation and characterisation of the River Frome.

Property	Dataset	Format	Resolution	Version	Source
Mapping	MasterMap	GLM	1:12500	2012	Ordnance Survey (UK)
Aerial Imagery	Satellite	Online	variable	2000-2012	Google Earth
Elevation	Profile DTM LiDAR	GeoTIFF ASCII GRID	10 m 1 m	2009 2006	Ordnance Survey (UK) Environment Agency (UK)
Geology	Bedrock & Superficial	Shapefile	1:625,000	v. 5	British Geological Survey
Soils & Aquifers	European Soil Database	Shapefile	1:1,000,000	2006	Joint Research Centre (EC)
Soil erosion	PESERA	GeoTIFF	1 km		Joint Research Centre (EC)
Land Cover	CORINE Countryside Survey	GeoTIFF GeoTiff	100 m	2006 2000	European Environment Agency
River flows	Mean Daily 15-minute	Discharge Discharge	5 stations 3 stations		Environment Agency (UK) Environment Agency (UK)
Vegetation & sediment	River Habitat Survey Mean Trophic Rank	Survey Survey	199 sites 59 sites		Environment Agency (UK) Centre for Ecology and Hydrology (UK)

2.1.7 Land cover and land use

The CORINE Land Cover (CLC) dataset was produced by the European Topic Centre on Spatial Information and Analysis and is made freely available as raster and vector datasets on the European Environment Agency website[7]. It is a pan-European dataset collected in 2006 by the SPOT-4/5 and IRS P6 LISS III satellites. Geometric accuracy of the satellite imagery is less than 25 m, and of the CLC data is less than 100 m. Thematic accuracy of the land cover theme is greater than 85%. The first and second levels of land classification were used in this spatial characterisation section.

The temporal analysis of land cover used historical land cover maps and county agricultural statistics. Recent changes in land cover were examined using the UK Countryside Survey digital land cover maps for 1990, 2000 and 2007. The freely-available 1-km resolution GeoTiffs were used[8], and thematic classes were aggregated to match those used in the Corinne land cover dataset and recommended in Section 5 of the D2.1 main report. Scanned maps from the First Land Utilisation Survey of Britain (1:63,360 scale, 2 maps dated 1936 and 1943) were obtained from the University of Portsmouth[9]. The maps were georeferenced in ArcGIS and land cover was classified using maximum likelihood classification. Finally, agricultural statistics were obtained for the county of Dorset from the Department of Environment and Rural Affairs (DEFRA)[10].

2.1.8 Hydrology – Rainfall and Discharge

A map of average annual rainfall for the catchment was obtained from the Centre for Ecology and Hydrology's (CEH) National River Flow Archive (NRFA)[11]. Historic rainfall gauging station data were downloaded from the Met Office[12]. There were no rainfall monitoring stations situated within the River Frome catchment on the website, and records were used from the nearby Wyke Regis, Swanage, Yeovilton and Hurn gauging stations.

The Environment Agency has a network of 7 river gauging stations distributed around the River Frome catchment. Of these, 5 stations have discharge data for which at least part

---

[7] Corine Land Cover v. 2006. http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2, accessed on 15-March-2013.

[8] Countryside Survey, Information Gateway, Centre for Ecology and Hydrology. http://gateway.ceh.ac.uk/, accessed on 1-Dec-2013.

[9] First Land Utilisation Survey of Britain, A vision of Britain through time, University of Portsmouth. http://vision.port.ac.uk/maps/, accessed on 1- Dec-2013.

[10] Structure of the agricultural industry in England and the UK at June, DEFRA. https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june, accessed on 8-Dec-2013.

[11] National River Flow Archive. Centre for Ecology and Hydrology. http://www.ceh.ac.uk/data/nrfa/, accessed on 15-March-2013.

[12] UK climate – Historic station data. Met Office. http://www.metoffice.gov.uk/public/weather/climate-historic/. Accessed on 12-July-2013

of the time-series has been checked and verified for quality (Table 2.2). Two of these 5 stations are located on the main stem of the River Frome, in the middle and lower catchment. Mean daily flows were obtained from the NRFA, and 15 minute flow data were obtained directly from the Environment Agency.

Table 2.2 Gauging stations in the River Frome catchment.

Gauge	River - Site	Data type	Period of Record	Catchment Area	Grid Reference
44004	Frome - Dorchester	Mean daily	1970 - 2011	205.54	370920, 90550
		15 min flow	1992 - 2012		
44001	Frome - East Stoke	Mean daily	1966 - 2011	413.46	386760, 86860
		15 min flow	1992 - 2012		
445210	Hooke	15 min flow	1992 - 2012	11.60	353748, 100032
44006	Sydling Water	Mean daily	1970 - 2011	12.06	363270, 99640
445930	Win	15 min flow	1999 - 2012	18.18	380640, 84880

2.1.9 Field survey datasets

Two sources of field survey data were used to quantify various segment- and reach-level characteristics, including channel dimensions, bed and bank material/modifications, riparian and aquatic emergent vegetation, and geomorphic features.

The River Habitat Survey (RHS) is a standardised survey used by the Environment Agency to assess the physical structure of rivers and streams. The survey is based around a 500 m long reach, and involves a combination of general site characterisation, regularly spaced spot-checks (10 per reach) and a final sweep-up survey. A broad array of features are recorded during the survey, including valley form, channel dimensions (e.g. bankfull width and depth), bed and bank material, river flow types, geomorphic features (e.g. vegetated and unvegetated bars), land-use, riparian and aquatic vegetation, and artificial features. A total of 119 surveys are available for the River Frome.

The Mean Trophic Rank Survey (MTR) was designed to assess the trophic status and eutrophication impact of rivers according to the aquatic vegetation (i.e. aquatic macrophytes) growing within the channel. The species and percentage cover of the macrophytes are recorded along 100 m stretches of river. Physical data on channel width, depth, bed substrate, shading by riparian trees and flow types (referred to as habitats in this method) are recorded. This information is then used to calculate a mean trophic rank for each survey; however, for the purpose of this hydromorphological characterisation, the use of the MTR data is limited to plant species, percent cover and bed substrate. A total of 59 MTR surveys were conducted by CEH, of which 40 include a complete physical survey.

2.2 Delineation and characterisation

The methods for delineation and characterisation are based on the guidelines described in the D2.1 main report (Sections 4 and 5). Delineation and characterisation are presented as separate phases of the framework, but many aspects of the characterisation are actually conducted within the delineation phase because of the need to characterise the river system in order to delineate it into internally consistent spatial units. Furthermore, the delineation process is principally a top-down approach, but we found it advantageous to conduct the initial characterisation of the smaller spatial unit prior to deciding upon the delineation of a larger-scale unit. Delineation boundaries are carried down through the delineation process, and we found that a larger-scale delineation boundary often needed to be adjusted slightly to produce a more parsimonious delineation of the smaller-scale units.

General methods for delineation and characterisation for each spatial scale are included below. For the complete guidelines, please refer to the delineation and characterisation sections in the D2.1 main report (Sections 4 and 5). For detailed step-by-step methodologies for analysis of spatial datasets in ArcGIS, please see Section 9.

2.2.1 Region

The region was identified from online maps and publications of biogeographic regions in Europe (www.globalbioclimatics.org; EEA 2002).

2.2.2 Catchment

The catchment was delineated based on topographic divide using the watershed delineation procedure in ArcGIS and the Profile DTM (10 m resolution) (See Section 9.1.1 for detailed steps in ArcGIS).

Catchment characteristics were summarised from the relevant ArcGIS layers, including elevation, geology and land cover (See Section 9.1.2 for more details). Elevation and geology raster files were reclassified to be consistent with the WFD river typology.

2.2.3 Landscape unit

General patterns in elevation, topography, geology and land cover were examined in ArcGIS. Landscape units were delineated such that the dominant characteristics were broadly consistent internally.

Landscape unit characteristics were calculated from the ArcGIS layers used in the catchment and landscape unit delineation stages (See Section 9.2.1 for more details).Potential fine sediment availability was estimated using the PESERA raster dataset and a 500m wide buffer around the river (See Section 9.2.3 for more details). Sources of coarse sediment delivery were assessed visually using satellite imagery (Google Earth).

2.2.4 Segment

A long-profile of elevation and catchment area was extracted from the DTM and flow accumulation layer (an output of the ArcGIS watershed delineation process) (See Section 9.3.1 for more details). The DTM was a mosaic of the 2006 LiDAR DTM and the Profile DTM. The mosaic ensured that elevation data had complete coverage over the river network (Profile DTM) but that it utilised the most accurate and highest spatial resolution data where available (LiDAR). Segment delineation was based on discontinuities in gradient and catchment area. Increases in catchment area were deemed significant when the sub-catchment area drained by the tributary was greater than 20% of the main stem catchment area immediately upstream of the confluence.

Valley confinement was determined by overlaying the channel layer, which was obtained from the water theme in the OS MasterMap dataset, onto a map of the floodplain. The floodplain was delineated from the DTM based on elevation using the Thiessen polygons method of Alber and Piégay (2011) (See Section 9.3.2 for more details). A flood depth of 1.85 m was used to initially define the width of the floodplain. This flood depth was selected based on the level of the 1 in 100 year flood obtained from online flood extent maps published on the Environment Agency's website[13]. The floodplain edges were then adjusted based on a break in slope using a countour map derived from the mosaic DTM.

Flow regime characteristics were calculated from mean daily flow using the IARI software developed by ISPRA (Annex C) and the Indicators of Hydrologic Alteration software (version 7.1, The Nature Conservancy). Discharge was estimated at the outlet of segments and reaches using the relationship between catchment area and discharge for the 3 river gauging stations (second-order polynomial). Geomorphologically-relevant discharge (QP_{median}, Qp_2, Qp_{10}) was calculated for three different flood return period (median annual, 2-year, and 10-year return period flood) using maximum annual flow derived. Two different datasets were used: the mean daily flow record was used to ensure consistency with the flow regime analysis and the instantaneous flow (15-min flow) to better characterise the high flow events in smaller streams, where flood peaks are more likely to last less than a full day.

The dominant calibre of the river bed material was obtained from RHS data. Presence, width and structure of the riparian vegetation were extracted from the OS MasterMap (1:2500) layer (See Section 9.3.3 for more details). The accuracy of the riparian vegetation data, including its location and vegetation classification, was verified visually using satellite imagery (Google Earth). An inventory of structures within the river was obtained from the Environment Agency and used to assess physical pressures. The level of impact of the structures was evaluated using satellite imagery (Google Earth), and was supported for Segments 5 and 6 by an assessment of impoundment impacts of weirs (Environment Agency, 2011).

[13] Flood maps, http://www.environment-agency.gov.uk/homeandleisure/37793.aspx, accessed on 5 June 2013

2.2.5 Reach

River sinuosity, braiding and anabranching were quantified using aerial imagery and large-scale maps (MasterMap, 1:2500). Sinuosity was measured based on the axis of the overall planimetric river course (See Section 9.4.1 for more details). The multi-thread attributes were quantified at cross sections spaced 0.5 – 1 times the maximum width of the outer wetted channels, and for all channels (artificial or natural) that regularly carry water and are connected to another channel at both their upstream and downstream ends. Multi-thread attributes were assessed at the floodplain cross-sections that were created in the segment characterisation process (See Section 9.3.2 for more details). Reach delineation was based on confinement, planform and the presence of major weir structures.

Total stream power and specific stream power were calculated at Qp_{median}, Qp_2, and Qp_{10}. Information on bed and bank material was obtained from RHS spot-check results (10 spot-checks per survey). Lateral sediment delivery was calculated using the PESERA model data and a 500 m buffer, as stated above and explained in further detail in Section 9.2.3. A preliminary sediment budget was conducted in SIAM: details of the analysis are provided as Thematic Annex I.1. Riparian vegetation was analysed as described above in section 2.2.4 (methodological details: Sections 9.3.3 and 9.4.3), and emergent aquatic vegetation data was obtained from RHS and MTR surveys. Physical pressures were assessed using a combination of RHS data, land cover data from the OS MasterMap dataset and the EA's inventory of structures. Infrastructure within 0.5 channel width was calculated using the riverbank point method developed for riparian vegetation (Section 9.3.3). Major weirs located at reach divisions are included in the upstream reach.

3. Delineation of the Spatial Units

3.1 Region

The region is a large geographic area that contains characteristic assemblages of natural ecological communities that reflect broad climate patterns. This scale is important because it is these climate patterns and natural land covers that are the primary controls on all spatial scales of hydromorphological processes.

The River Frome is located in southern England, which lies within the Atlantic European biogeographic region (Figure 3.1). The climate is characteristically mild and humid and strongly influenced by the Atlantic Ocean

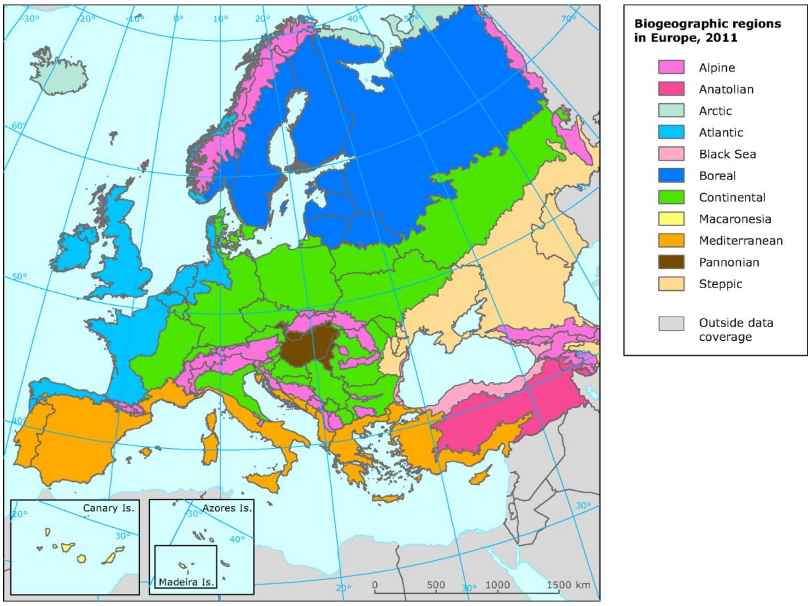


Figure 3.1 The biogeographic regions of Europe. ***European Environment Agency 2012, http://www.eea.europa.eu/data-and-maps, accessed on 10 May 2013.***

3.2 Catchment

A catchment is an area of land that is drained by a river and its tributaries. The River Frome catchment is a medium-sized, lowland, calcareous catchment according to the Water Framework Directive typology (catchment area = 459 km^2, mean elevation = 108 m) (Figures 3.2 and 3.3).

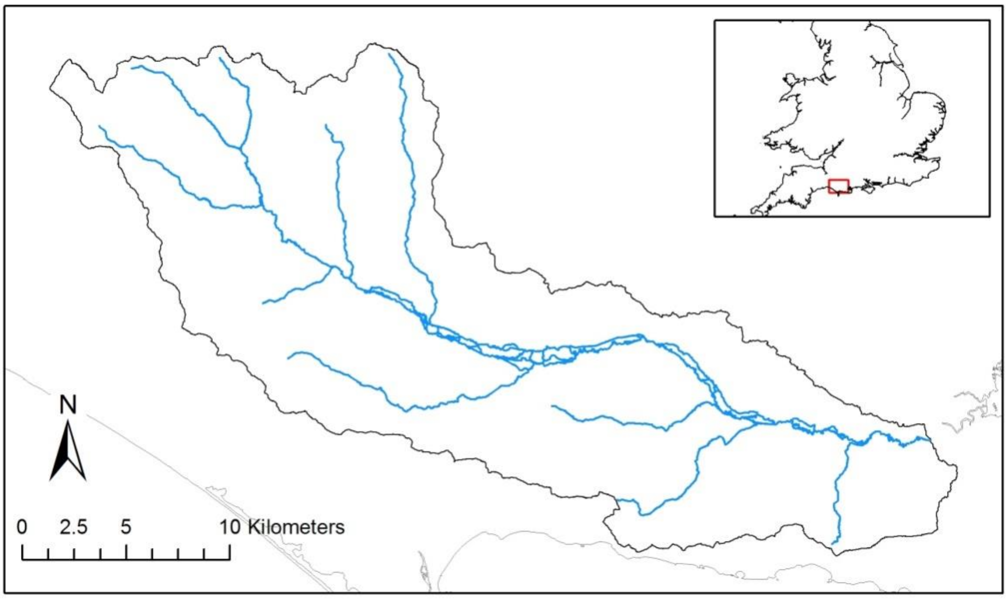


Figure 3.2 The River Frome catchment located in southern England. Profile DTM: © Crown Copyright/database right 2012.

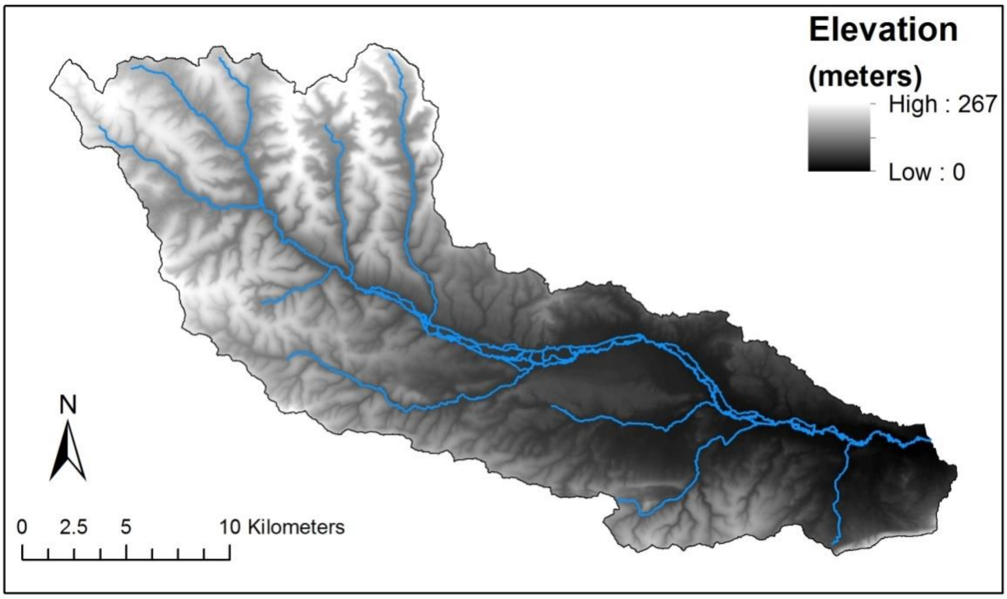


Figure 3.3 The River Frome catchment is classified as lowland according to the WFD typology (elevation: minimum = 0 m, maximum = 267 m, median = 104 m)

3.3 Landscape units

Landscape units are portions of the catchment with similar morphological characteristics. The catchment is divided into landscape units that are broadly consistent in terms of their topography, geology and land cover, as these factors determine the hydrological responsiveness of a catchment and the source and delivery of sediment to the river system.

The Frome catchment was delineated into 3 landscape units (Figure 3.4; Table 3.1). Landscape Unit 1 is the highest elevation unit, and is characterised by low rolling hills of mixed geology, composed of Cretaceous chalk, Cretaceous sandstone, Jurassic limestone, and Jurassic mudstone (Figures 3.5 and 3.6). The mixed geology impacts the local hydrology; permeability in the soil substratum is reduced relative to Landscape Unit 2. Land cover is predominantly pasture, and estimated erosion rates are low (Figure 3.7).

Landscape Unit 2 is characterised by low rolling hills, but geology is exclusively Cretaceous chalk (Table 3.1; Figure 3.6). The chalk provides an extensive aquifer that supports stable baseflows in the river. Land cover is predominantly arable agriculture and estimated soil erosion rates are 3 times greater than in Landscape Unit 1 (Table 3.1; Figure 3.7).

Landscape unit 3 is a low-gradient coastal plain formed by siliceous marine sediments during the Cainozoic era (Figure 3.6). The impermeable geology produces a more complex surface hydrology and aquifer structure, and as a result river flows are more similar to clay than chalk rivers (Natural England, 1991). Land cover is predominantly arable agriculture and estimated soil erosion rates are intermediate of Landscape Units 1 and 2 (Table 3.1; Figure 3.7).

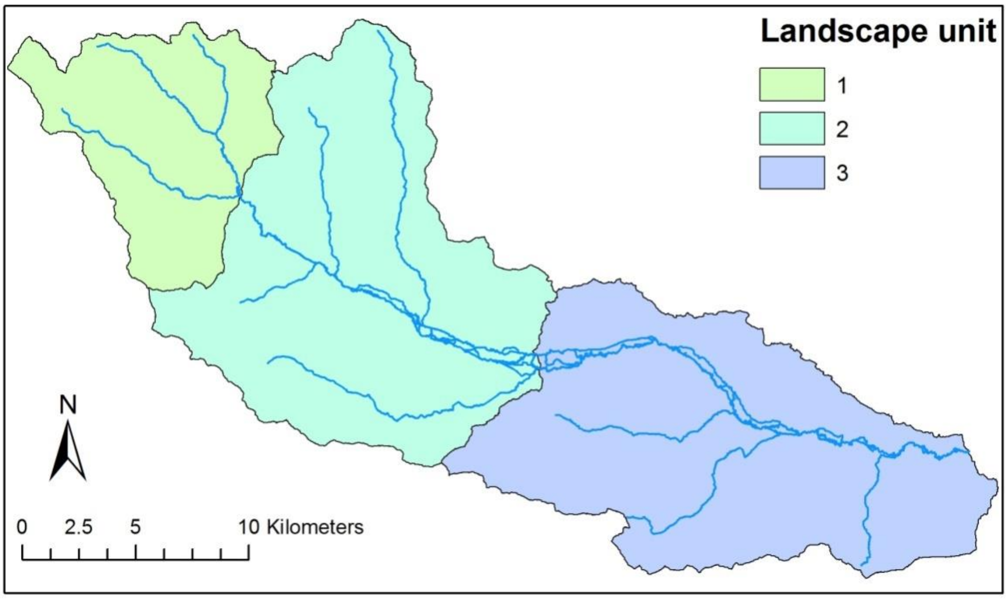


Figure 3.4 The River Frome was delineated into 3 landscape units based on elevation, geology and land cover. Profile DTM: © Crown database right 2012.

Table 3.1 Preliminary characterisation of the elevation, geology and land cover of the landscape units in the River Frome.

	Landscape Units		
	1	**2**	**3**
Area (km^2)	82	190	187
Mean Elevation (m)	170	131	56
Dominant Geology	Calcareous / Siliceous	Calcareous	Siliceous
Land Cover	Pasture	Arable Land	Arable Land
Mean soil erosion rate (tons/ha/year)	0.09	0.28	0.17

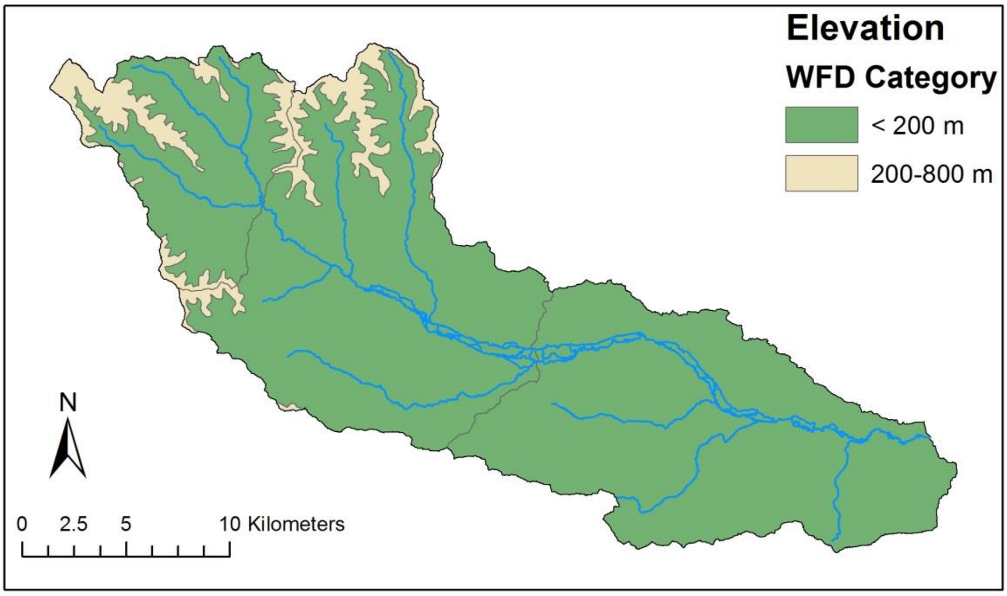


Figure 3.5 The River Frome catchment is classified as lowland according to the WFD typology with 92% of the catchment area less than 200 m in elevation.

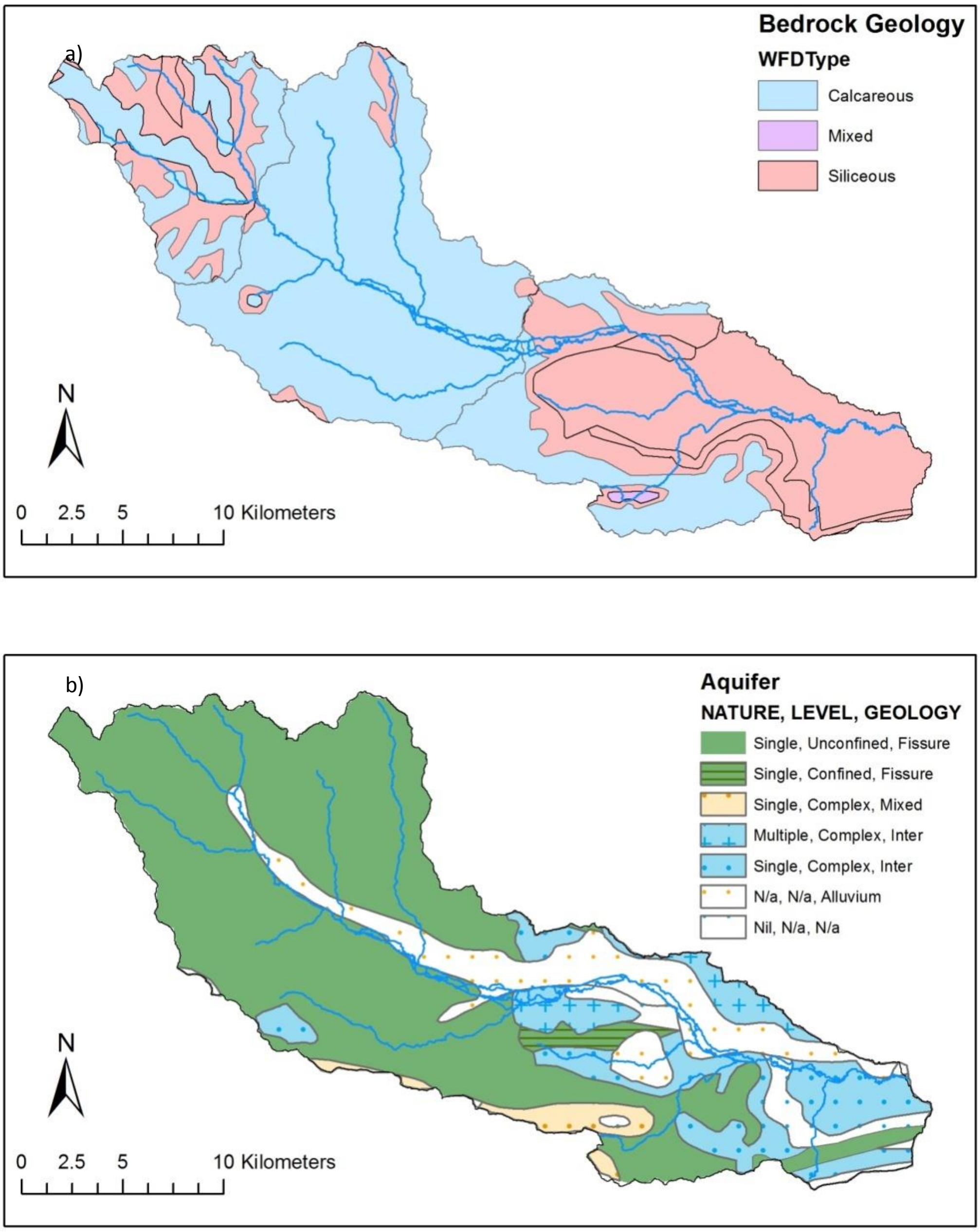
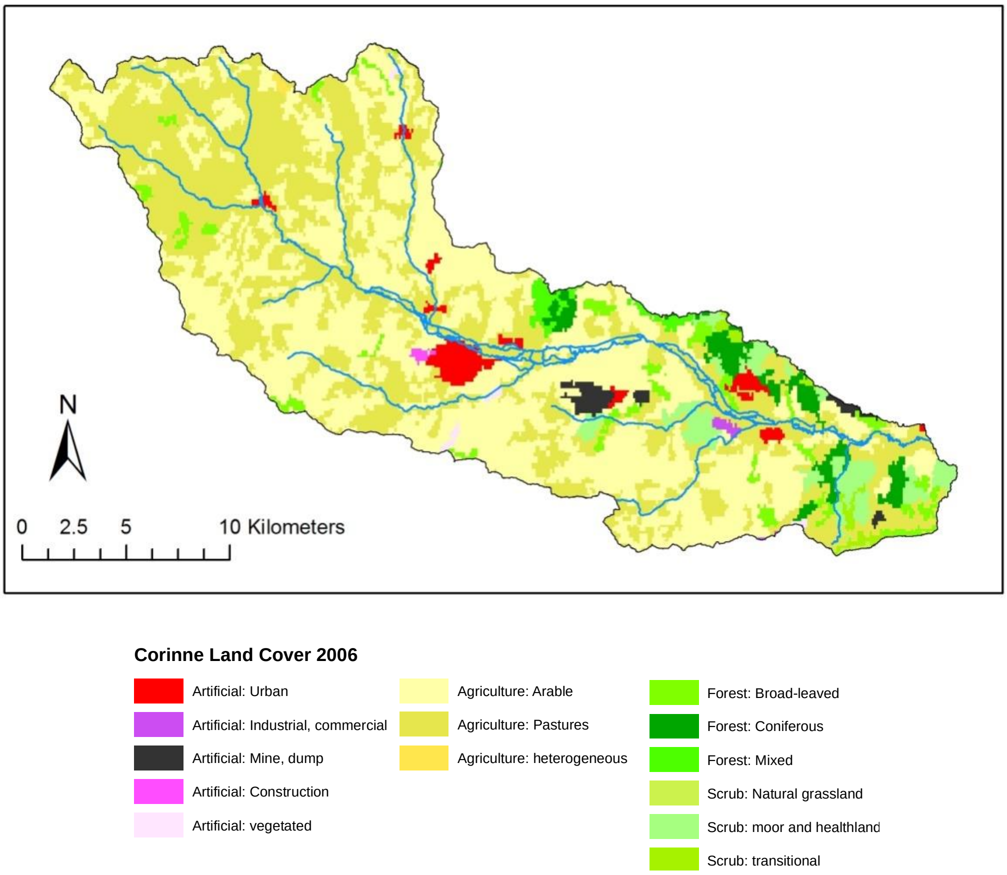


Figure 3.6 (a) Bedrock geology and (b) aquifer type for the River Frome catchment.

a)



b)

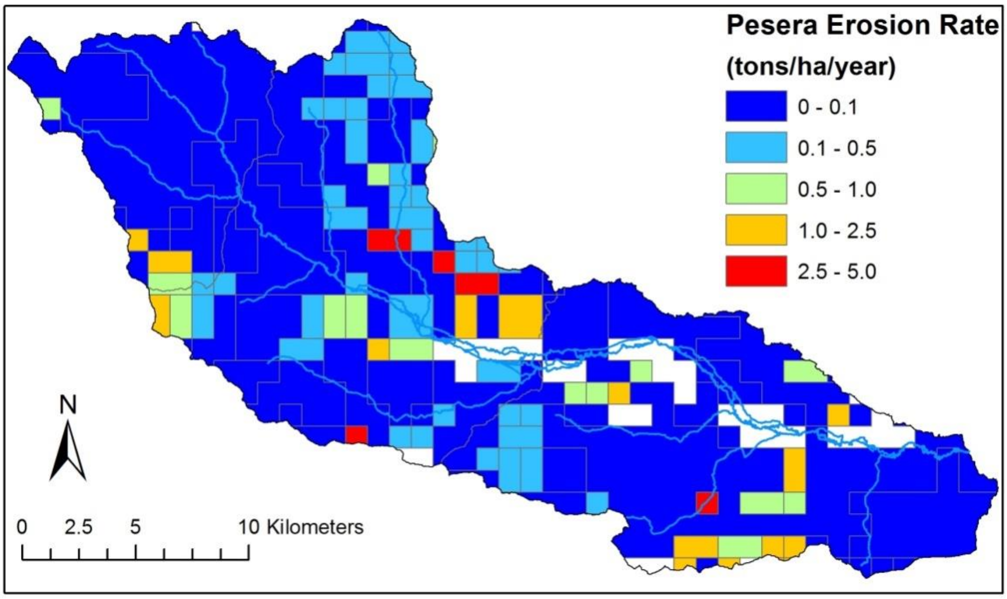


Figure 3.7 (a) CORINE land cover (2006) and (b) soil erosion rates (PESERA) for the River Frome catchment

3.4 River segments

River segments are sections of the river network that are subjected to similar valley-scale influences and energy conditions. Delineation is based on major changes in valley gradient, major tributary confluences and valley confinement.

The River Frome is delineated into 6 river segments (Figure 3.8, Table 3.2). These divisions are primarily associated with significant increases in catchment area due to major tributary confluences and align with the landscape unit divisions (Figure 3.9). A confluence was deemed significant when the sub-catchment area drained by the tributary was greater than 20% of the main stem catchment area immediately upstream of the junction. The River Frome is laterally unconfined over the majority of its length. There are pockets of partial valley confinement, particularly in Segments 2 and 3, but they account for less than 10% of the river length. Consequently all segments are classified as unconfined.

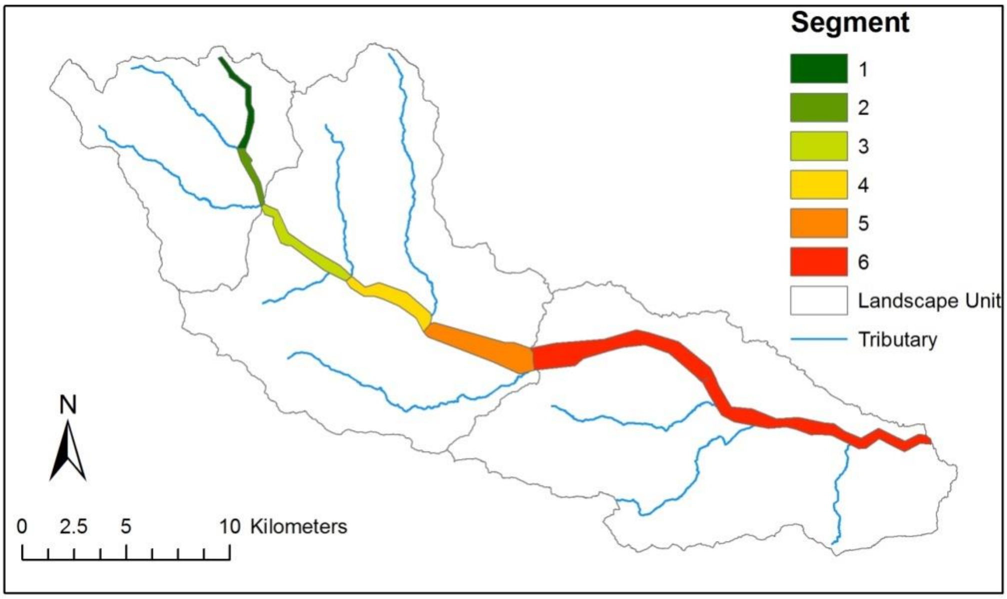


Figure 3.8 The River Frome is delineated into 6 segments based on major changes in valley gradient, major confluences and valley confinement.

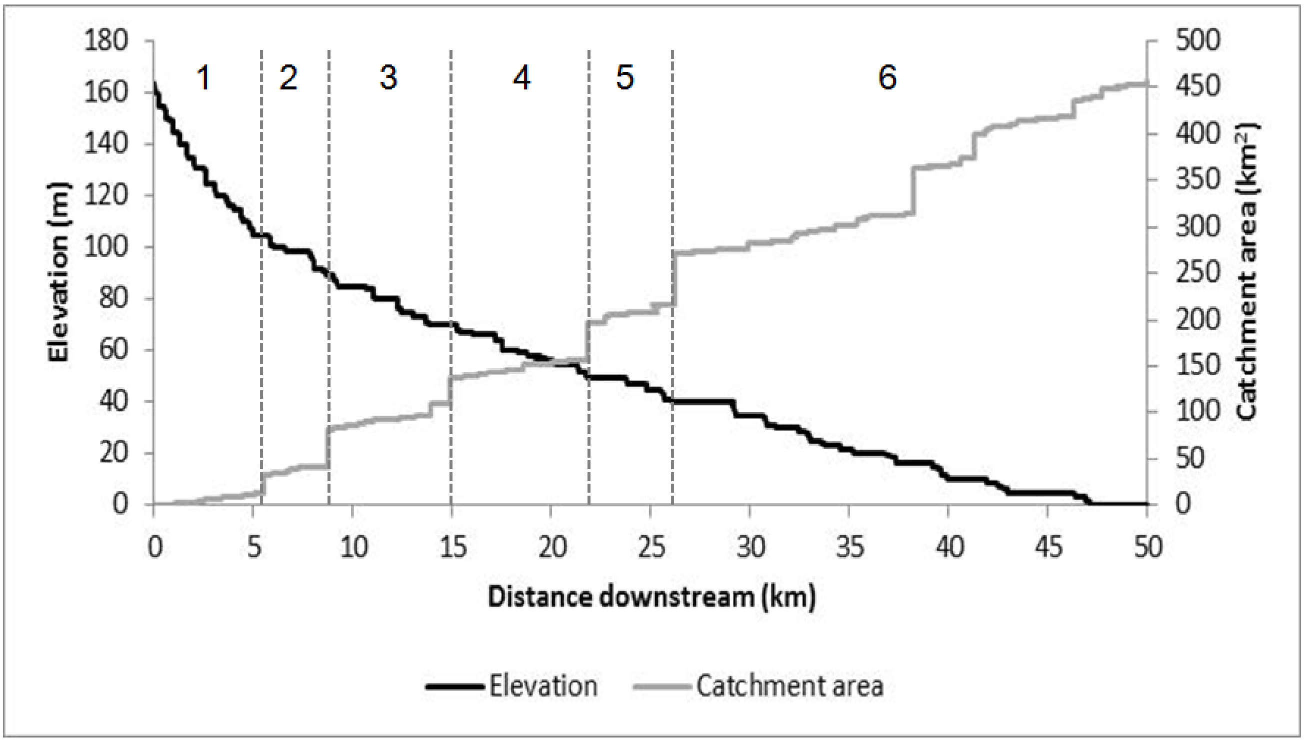


Figure 3.9 The River Frome was delineated into 6 river segments based primarily on increases in catchment area caused by major confluences.

Table 3.2 Characteristics used in the segment delineation process.

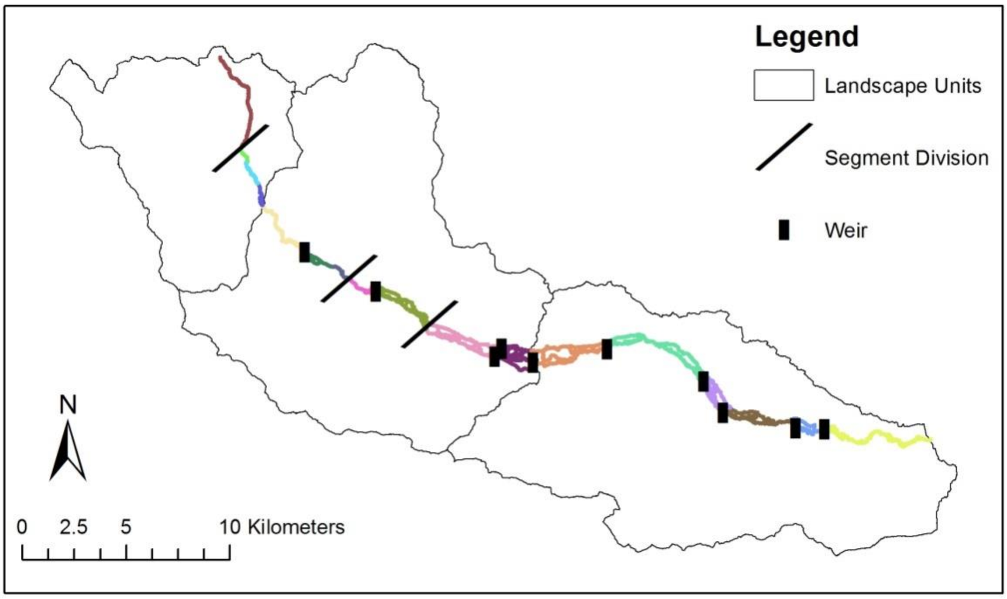
Segment	Increase in catchment area due to tributary		Gradient	Valley Confinement
	Area (km^2)	% increase		
1			0.011	Unconfined
2	19.57	144%	0.005	Unconfined
3	40.00	96%	0.003	Unconfined
4	26.77	24%	0.003	Unconfined
5	39.55	25%	0.002	Unconfined
6	55.48	26%	0.002	Unconfined

3.5 River reaches

The reach is the scale at which most people view and interact with the river, and the scale at which most restoration projects are focused. Hydromorphologically speaking, it is a section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent set of process-form interactions. In other words, the controlling factors that we identified in the earlier delineation steps produce characteristic patterns and landforms in the channel and floodplain, like river meanders and gravel bars. Delineation is based primarily on channel planform but also the presence of flow control structures, resulting in a discrimination of river reaches according to a set of simple types.

The River Frome was delineated into 17 river reaches (Figure 3.10; Table 3.3). The reaches are predominantly sinuous in the upper catchment and anabranching in the middle and lower. The river channel is unconfined in all reaches.

a)



b)

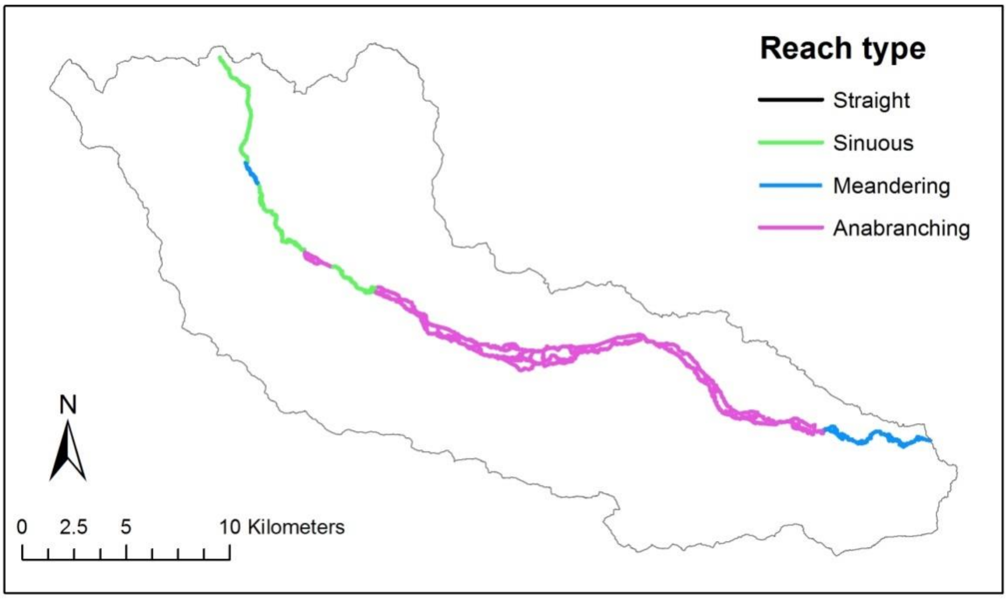


Figure 3.10 The River Frome was delineated into 17 reaches. Reach divisions align first with the landscape unit and segment divisions, and are then delineated based on (a) the presence of major weirs and (b) changes in river planform.

Table 3.3 Characteristics used in the reach delineation process.

Land-scape Unit	Segment	Reach	River Confinement	Threads	Planform	Structure at downstream end
1	1	1	Unconfined	Single thread	Sinuous	
	2	2	Unconfined	Single thread	Sinuous	
		3	Unconfined	Single thread	Meandering	
		4	Unconfined	Single thread	Sinuous	
2	3	5	Unconfined	Single thread	Sinuous	Weir
		6	Unconfined	Multi-thread	Anabranching	
		7	Unconfined	Single thread	Sinuous	
	4	8	Unconfined	Single thread	Sinuous	Weir
		9	Unconfined	Multi-thread	Anabranching	
	5	10	Unconfined	Multi-thread	Anabranching	Weir
		11	Unconfined	Multi-thread	Anabranching	Weir
3	6	12	Unconfined	Multi-thread	Anabranching	Weir
		13	Unconfined	Multi-thread	Anabranching	Weir
		14	Unconfined	Multi-thread	Anabranching	Weir
		15	Unconfined	Multi-thread	Anabranching	Weir
		16	Unconfined	Multi-thread	Anabranching	Weir
		17	Unconfined	Single thread	Meandering	

4. Characterising the Spatial Units

The aim of spatial characterisation is to build an understanding of the catchment. Therefore, throughout we indicate where we have estimated the characteristics listed in the D2.1 main report or why these have not been estimated. However, we also present additional characteristics that were assembled during the characterisation phase.

4.1 Region

The River Frome is located in southern England, which lies within the Atlantic European biogeographic region (Figure 3.1), and the South West River Basin District for WFD.

4.2 Catchment

4.2.1 Size, Morphology, Hydrological Balance

Table 4.1 lists the main characteristics described in D2.1 main report, section 5.2.1. The average annual rainfall of 968 mm is for the period 1961-1990 (standard period average annual rainfall, CEH) and for the catchment down to the East Stoke gauging station (catchment area 414.4 km^2). The average annual streamflow over the 1966-1990 period at this gauge was 6.66 m^3/s, leading to an annual average runoff (i.e. water yield) of 507 mm and an annual runoff ratio is 0.52.

Table 4.1 Characteristics of the size, morphology and hydrology of the catchment.

Attribute	Value
Catchment area (km^2)	458.78
Elevation (m)	
Mean	108
Minimum	0
Maximum	267
Elevation – WFD Classes	
<200 m	92%
200 – 800 m	8%
> 800 m	0%
Relative Relief (m)	267
Relative Relief / Longest distance	0.0044
Hydrology	
Average annual rainfall (mm)	968
Average annual runoff (mm)	507
Runoff ratio	1.91

4.2.2 Geology and Soils

The main characteristics listed in the D2.1 main report, section 5.2.2 are emboldened in Table 4.2. The River Frome catchment is composed predominantly of calcareous bedrock, but siliceous bedrock is dominant in the lower catchment (Figure 3.6; Table 4.2). The calcareous bedrock produces a highly productive, unconfined aquifer over the majority of the catchment area, in which groundwater flows are primarily through fractures (Figures 3.6 and 4.1; Table 4.2). Soils lie largely over a free-draining substratum (76%) except for the headwaters and lower catchment, which may be waterlogged seasonally or permanently as a result of a near-surface water table (Figures 4.2 and 4.3; Table 4.2).

Table 4.2 Characteristics of the geology and soil of the Frome catchment.

Attribute	Value
Geology	
Calcareous	**60%**
Siliceous	**40%**
Bedrock hydrogeology	
Flow through fractures	63%
Intergranular flow	26%
Rocks with no groundwater	12%
Aquifers	
Unconfined	**65%**
Confined	1%
Complex	18%
N/a – Alluvium	13%
None	4%
Hydrology of soil substratum	
Permeable (Free-draining)	**76%**
Affected by high water tables	**23%**

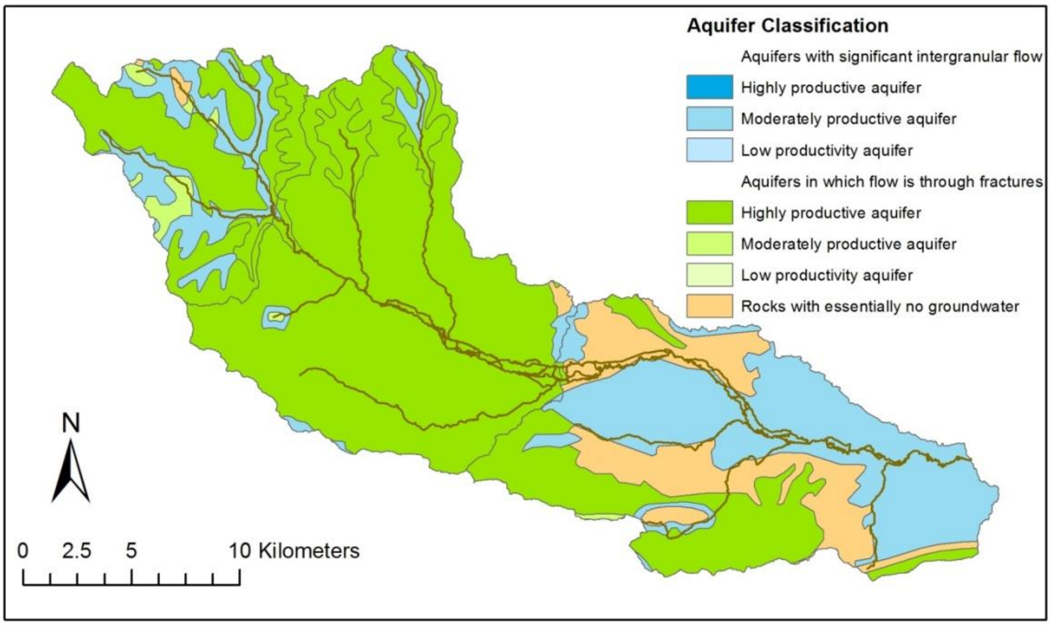


Figure 4.1 Classification of aquifers within the Frome catchment. (© NERC. All rights Reserved. Reproduced with the permission of the British Geological Survey).

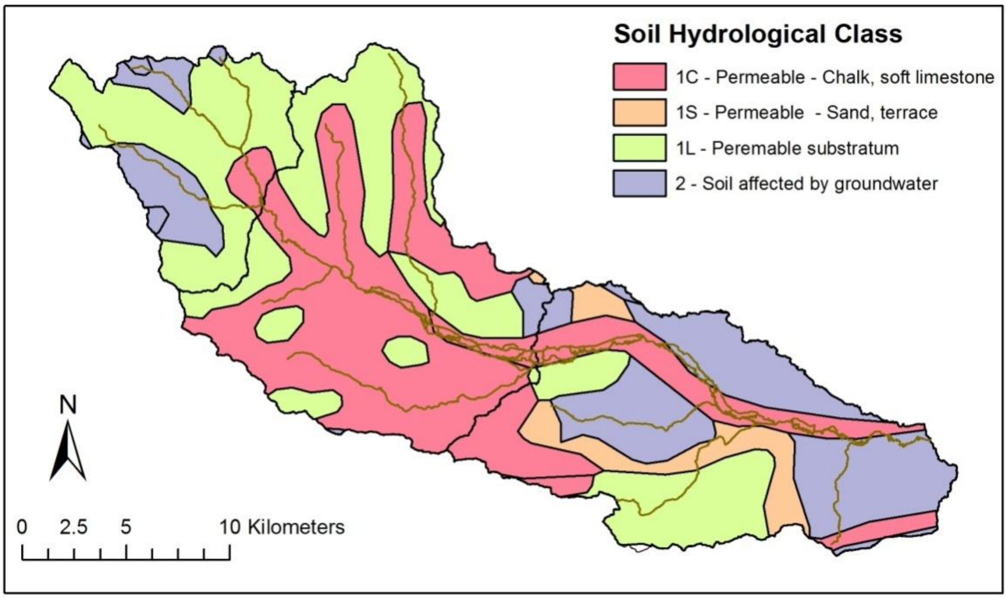


Figure 4.2 Hydrological class for soil in the River Frome catchment. Soils are classified as: (1) soil with a permeable substratum or (2) lowland soil affected by groundwater. Data from the European Soil Portal JRC.

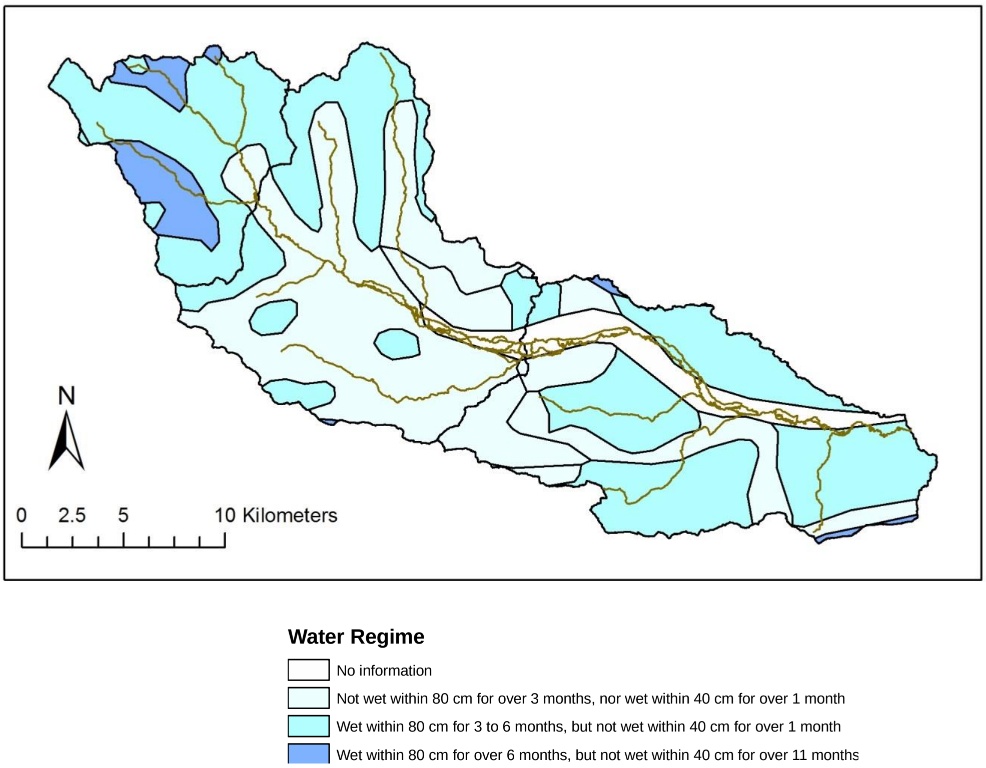


Figure 4.3 Dominant annual average soil water regime class for the River Frome catchment. Data from the European Soil Portal JRC.

4.2.3 Land cover

The main characteristics mentioned in the D2.1 main report, section 5.2.3 are listed in Table 4.3. The land cover in the Frome catchment is predominantly agriculture (86%), of which arable land and pastures are present in approximately equal proportion (Figure 3.7 and Table 4.3).

Table 4.3: Land cover for the Frome catchment from the CORINE land cover database (European Environment Agency).

Land Cover Class	% Cover
Artificial	3.5%
Agricultural	86.0%
Forest	10.5%
Wetlands	0%

4.3 Landscape Units

4.3.1 Water Production

(i) Rainfall

No long term rainfall data is available on-line for rainfall gauges within the River Frome catchment and thus it was not possible to assemble any rain gauges with more than 10 years of records in any of the landscape units. Therefore, the required summary information (D2.1 main report section 5.3.1 (i)) is presented in Table 4.4 for several nearby gauges along with their distances from the Frome catchment boundary. A more detailed analysis is presented for the Yeovilton gauge (Table 4.5) for the period (1981-2010). The freely available rainfall data on the Met Office and CEH websites does not have a fine enough temporal resolution (e.g. daily or storm) for intensity-duration-frequency analysis.

On average, April is the driest month and December the wettest. Average annual rainfall for the catchment ranges from 850 to 1200 mm (1961-1990) according to estimations by CEH (Figure 4.4). Rainfall is greatest in the western headwaters and lowest in the east near the river outlet. Rainfall in Landscape Unit 1 ranges from 950 to 1100 mm yr^{-1}, Unit 2 from 900 to 1200 mm yr^{-1}, and Unit 3 from 800 to 1100 mm yr^{-1}. The average annual rainfall for the subcatchment down to the East Stoke river gauging station is 968 mm yr^{-1}.

(ii) Relief/Topography

Of the three characteristics listed in the D2.1 main report section 5.3.1 (ii), the drainage density was estimated for a derived network extracted from a DEM, yielding values of 0.4, 0.45 and 0.51 km km^{-2} for Landscape Units 1, 2 and 3, respectively. The minimum drainage area threshold was set at 2.5 ha, which produced a river network that approximates the perennial network.

The remaining two characteristics are illustrated in Figure 4.5 (Hypsometric curves) and Figure 4.6 (Land surface slope elevation-frequency distribution). From the hypsometric curves (Figure 4.5), Landscape Unit 1 has the highest elevation with 23% of the area greater than 200 m, Landscape Unit 3 has the lowest elevation with 100% of the area below 200 m, and Landscape Unit 2 is intermediate with the greatest range in elevations (Figure 4.5; Table 4.6). The greatest slopes are found between 100 and 200 m of elevation, with a peak in mean slope at 160 m (Figure 4.6).

Table 4.4 Average monthly rainfall (mm) and average annual rainfall at nearby rainfall gauging stations (1981 – 2010). Distance and direction from catchment boundary are included.

Month	Wyke Regis	Swanage	Yeovilton	Hurn
	9 km S	*10.5 km ESE*	*14 km N*	*23 km ENE*
Jan	78.5	87.2	67.6	86.9
Feb	58.3	64.6	48.5	62.5
Mar	58.0	65.2	49.6	64.7
Apr	49.4	51.9	50.2	53.9
May	44.7	48.2	48.5	49.5
Jun	40.2	45.9	50.3	51.6
Jul	35.9	46.5	53.3	47.8
Aug	50.0	46.2	55.0	51.8
Sep	55.8	63.9	54.9	65.3
Oct	85.3	105.8	78.3	100.7
Nov	88.7	104.7	74.2	100.5
Dec	85.5	99.4	78.1	100.0
Annual	730.3	829.4	708.5	835.2

Table 4.5 Monthly and annual rainfall (mm) for the Yeovilton gauging station (1965-2012).

	Minimum	Mean	Maximum
Jan	8.6	70.2	132.3
Feb	2.1	53.9	137.6
Mar	19.3	52.0	113.5
Apr	1.6	47.8	136.6
May	5.7	52.4	171.3
Jun	4.9	53.9	139.8
Jul	10.0	57.7	155.2
Aug	11.6	60.4	151.0
Sep	5.0	57.7	160.6
Oct	5.8	70.9	188.4
Nov	19.7	72.8	192.4
Dec	14.4	78.5	166.1
Annual	542.9	727.0	542.9

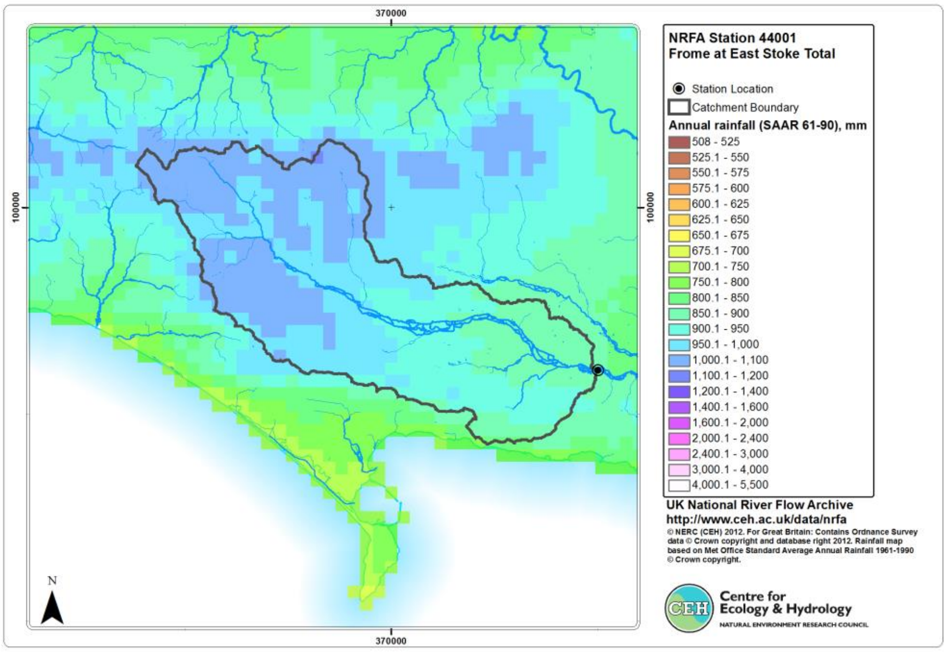


Figure 4.4 Annual rainfall (mm) for the Frome catchment. The black line indicates the sub-catchment area for the gauging station at East Stoke. Image: CEH National Flow Archive.

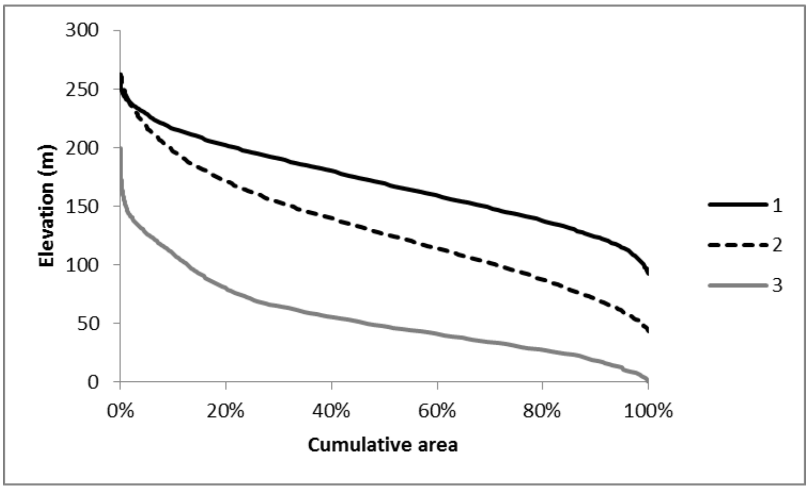


Figure 4.5 Hypsometric curve for the landscape units (1-3) of the River Frome.

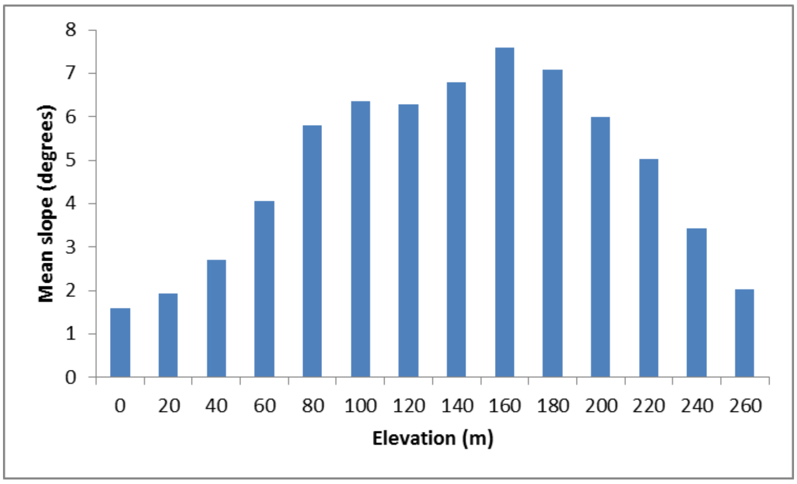


Figure 4.6 Mean land surface slope for the catchment by 20 m elevation bins.

(iii) Surface:Groundwater

Table 4.6 summarises elevation, geology, and bedrock/soil hydrogeology characteristics of the Frome catchment with the characteristics listed in the D2.1 main report, section 5.3.1(iii), emboldened. The landscape units differ in their geology, which impacts on how water flows within and across the land surface (Table 4.6; Figures 3.6, 4.1 and 4.2). Landscape Unit 1 is composed of a mixture of calcareous and siliceous rock. The underlying chalk geology supports an extensive unconfined aquifer over the entire landscape unit, but the overlying siliceous geology in some areas creates a less permeable substratum for the soil (Table 4.6). Landscape Unit 2 is almost entirely underlain by chalk geology, in which groundwater flows primarily through bedrock fractures. The aquifer is predominantly unconfined and is responsible for the stable river flows in the landscape unit. Landscape Unit 3 has a more complex geology and hydrology. The chalk is overlain by the Thames Group of bedrock, which are less permeable or impermeable to groundwater flow, producing a less permeable soil substratum and a more variable aquifer structure.

(iv) Land cover

Table 4.6 summarises the characteristics listed in the D2.1 main report, section 5.3.1(iv). Land cover is predominantly agricultural with pastures dominant in Landscape Unit 1, and arable land in 2 and 3 (Table 4.7). Landscape Unit 3 also has substantially more forest and scrub than the other landscape units (23% compared to 2%).

Table 4.6 Characteristics of the elevation, geology, bedrock hydrogeology, aquifers and soil substratum hydrology of the River Frome catchment.

	Landscape unit		
Attribute	1	2	3
Elevation classes			
< 200 m	77%	90%	100%
200 – 800 m	23%	10%	0%
Geology			
Calcareous	**53%**	**95%**	**26%**
Siliceous	**47%**	**5%**	**73%**
Mixed	**0%**	**0%**	**1%**
Bedrock hydrogeology			
Flow through fractures	68%	96%	27%
Intergranular flow	31%	3%	46%
Rocks with no groundwater	1%	1%	27%
Aquifers			
Unconfined	**98%**	**85%**	**26%**
Confined	0%	0%	3%
Complex	0%	4%	41%
N/a - Alluvium	2%	10%	21%
None	0%	0%	9%
Hydrology of soil substratum			
Permeable	**73%**	**98%**	**77%**
Affected by high water tables	**27%**	**2%**	**23%**

Table 4.7 Land cover by landscape unit for the River Frome catchment from the CORINE land cover database (European Environment Agency).

		Landscape unit		
Class	**Type**	**1**	**2**	**3**
Artificial	Urban fabric	0%	3%	2%
	Industrial, commercial, transport	0%	0%	2%
	Open spaces	0%	1%	0%
Agricultural	Arable land	26%	55%	44%
	Pastures	72%	39%	29%
Forest	Forests	2%	2%	13%
	Scrub and/or herbaceous vegetation	0%	0%	10%

4.3.2 Sediment Production

(i) Potential fine sediment availability

Table 4.8 summarises potential fine sediment production characteristics (as listed in the D2.1 main report, section 5.3.2(i)) and an extract of the PESERA map (Figure 3.7) on which they are based. Fine sediment erosion rates are low to moderate for all landscape units in the catchment, as compared to the range across Europe (0 to >50 tons ha^{-1} year^{-}

[1], PESERA). The highest erosion rates are predicted for Landscape Unit 2 (Figure 3.7; Table 4.8)

Table 4.8 Estimated soil loss by landscape unit (tons ha^{-1} year^{-1}) (Pan-European Soil Erosion Risk Assessment-PESERA, European Commission, Joint Research Centre).

	Landscape unit		
	1	**2**	**3**
Minimum	0	0	0
Mean	0.09	0.28	0.17
Maximum	1.87	3.79	3.73

(ii) Potential coarse sediment availability

No coarse sediment sources were visible in aerial imagery of the catchment and so no characteristics could be estimated. Bank erosion is the only likely source of bed material for the river, and this is estimated from an analysis of channel margin position changes identified from historical sources in section 5.3.

4.4 Segment

4.4.1 Flow Regime

The gauging station network on the River Frome catchment does not have a fine enough spatial resolution to calculate the flow regime for every segment. Therefore this analysis is limited to the landscape unit scale. The river does not have any significant water diversions or storage structures that would alter the volume or timing of water flows. River flows are potentially impacted by surface and groundwater abstraction, though computer modelling has indicated that current abstraction rates have minimal impacts on river flows at most discharges (Punchard, 2013). Abstraction would depress river flows in dry years, but a catchment abstraction management plan enforces limit or bans on water abstraction at low flows (Environment Agency, 2012). Consequently, flow records from the catchment are considered to be essentially natural. Furthermore, the flow records analysed do not extend back far enough to pick up any changes that may reflect the impact of groundwater abstractions, and so 'altered' flow regime characteristics are not be presented.

(i) Flow regime classification

Table 4.9 illustrates the various components of the flow regime analysis described in the D2.1 main report section 5.4.1(i), applied to the three gauging stations within the Landscape Units of the Frome catchment. The River Frome is classified as a perennial stable or super-stable river. Flow records show that it has a very high baseflow index (BFI ~ 50) and low CV in its daily flows (DAYCV ≤ 100) at all three gauging stations.

Table 4.9 Hydrological indicators for the 3 gauging stations within the River Frome catchment.

	LU 1 River Hooke	LU 2 - Segment 5 Dorchester	LU 3 - Segment 6 East Stoke
BFI – Baseflow index *Annual mean of the monthly ratio between min month discharge and mean monthly discharge*	53.64	49.69	55.74
ZERODAYS *Number of days with no channel flow per year*	0	0	0
FLDFREQ *Average number of flood 'events' per year*	0.45	0.82	0.71
FLDPRED *Maximum proportion of floods that falls in one of six 60-day seasonal windows*	0.70	0.61	0.47
FLDTIME *First Julian day within the seasonal window when FLDPRED is highest*	335	335	1
DAYCV *Standard deviation of daily discharge divided by annual mean discharge (x 100)*	49.07	67.23	58.76
Regime	Perennial superstable	Perennial stable	Perennial superstable

(ii) Flow characteristics

Morphologically representative discharges (described in the D2.1 main report section 5.4.1(ii)) were calculated for each gauging station using two datasets. The first analysis used annual maximum 1-day flows from the mean daily flow record, which was used to maintain comparability with the previous flow regime analysis (Table 4.10). The second analysis used annual instantaneous peak flows derived from the 20 year-long, 15-min flow records, which gives a more accurate representation of peak flows. Three morphologically representative discharges (Qp_{median}, Qp_2 and Qp_{10}) were estimated at the outlet of each segment based on a relationship between discharge and catchment area estimated for the gauging station records (Table 4.11).

Extreme flow conditions (described in the D2.1 main report section 5.4.1(ii)) were calculated using the mean daily flow record and were analysed using the Indicators of Hydrologic Alteration software (v. 7) (Table 4.12). Minimum flows in the catchment most commonly occur in early autumn (September) and maximum flows in winter (January) (Table 4.13).

The annual hydrographs for the 3 gauging stations (constructed for the calendar year) demonstrate the characteristic temporal patterns in flow for UK chalk rivers (Figure 4.7). Discharge is lowest in August (month 8) and September (month 9) at the end of the drier summer months. Flows begin to increase in the autumn as heavy rains recharge the chalk aquifer, reaching their peak in January (month 1).

The River Frome does not have any large flow control structures that produce 'abrupt, anthropogenically-controlled flow fluctuations (described in the D2.1 main report section 5.4.1(ii)).

Table 4.10 Morphologically representative discharges by landscape unit based on annual maximum 1-day flows from the mean daily flow records used in the flow regime analysis, and annual maximum instantaneous flow from the 15-min flow records. Qp_{median} – median annual flood, Qp_2 – 2-year return period flood, Qp_{10} – 10-year return period flood.

Landscape unit	River Location	Catchment Area (km^2)	Discharge (m^3s^{-1}) *based on max 1-day flow			Discharge (m^3s^{-1}) *based on max instant. flow		
			Qp_{median}	Qp_2	Qp_{10}	Qp_{median}	Qp_2	Qp_{10}
1	Hooke Hooke Bridge	11.60	0.62	0.65	1.12	1.38	1.04	2.07
2	Frome Dorchester	205.54	11.71	11.41	15.14	16.61	15.42	20.45
3	Frome East Stoke	413.46	20.72	20.00	24.25	23.49	22.32	28.00

Table 4.11 Estimated morphologically representative discharges at the outlet of each segment.

Landscape unit	Segment	Catchment Area (km^2)	Discharge (m^3s^{-1}) *based on max 1-day flow			Discharge (m^3s^{-1}) *based on max instant. flow		
			Qp_{median}	Qp_2	Qp_{10}	Qp_{median}	Qp_2	Qp_{10}
1	1	13.55	0.85	0.84	1.19	1.40	1.28	1.75
	2	43.50	2.59	2.54	3.56	4.15	3.81	5.21
2	3	96.64	6.56	6.41	8.82	10.06	9.25	12.59
	4	109.22	9.13	8.91	12.08	13.53	12.48	16.88
	5	194.62	12.17	11.84	15.73	17.18	15.91	21.36
3	6	457.41	22.24	21.32	25.46	23.76	22.63	28.86

Table 4.12: Discharge (m^3 s^{-1}) for the short term (1 day) and prolonged extreme flow conditions (30 day) for the gauging stations in the River Frome catchment. LU – Landscape unit, 1Q – Lower quartile (25%), Median (50%), 3Q – Upper quartile (75%).

	LU 1 River Hooke			LU 2 - Segment 5 Frome (Dorchester)			LU 3 - Segment 6 Frome (East Stoke)		
	1Q	Median	3Q	1Q	Median	3Q	1Q	Median	3Q
Min									
1-day	0.07	0.08	0.08	0.74	0.90	1.09	2.22	2.57	2.89
30-day	0.08	0.09	0.10	10.11	12.40	14.36	2.39	2.84	3.14
Max									
1-day	0.49	0.62	0.81	0.85	1.08	1.24	19.26	20.72	22.64
30-day	0.28	0.36	0.45	6.25	7.30	9.09	12.71	14.07	16.22

Table 4.13: Month of occurrence of short term and prolonged extreme flow conditions (median) for the gauging stations in the River Frome Catchment.

	LU 1 River Hooke	LU 2 - Segment 5 Frome (Dorchester)	LU 3 - Segment 6 Frome (East Stoke)
Min			
1-day	Sep	Sep	Sep
30-day	Sep	Sep	Aug
Max			
1-day	Dec	Jan	Jan
30-day	Jan	Jan	Jan

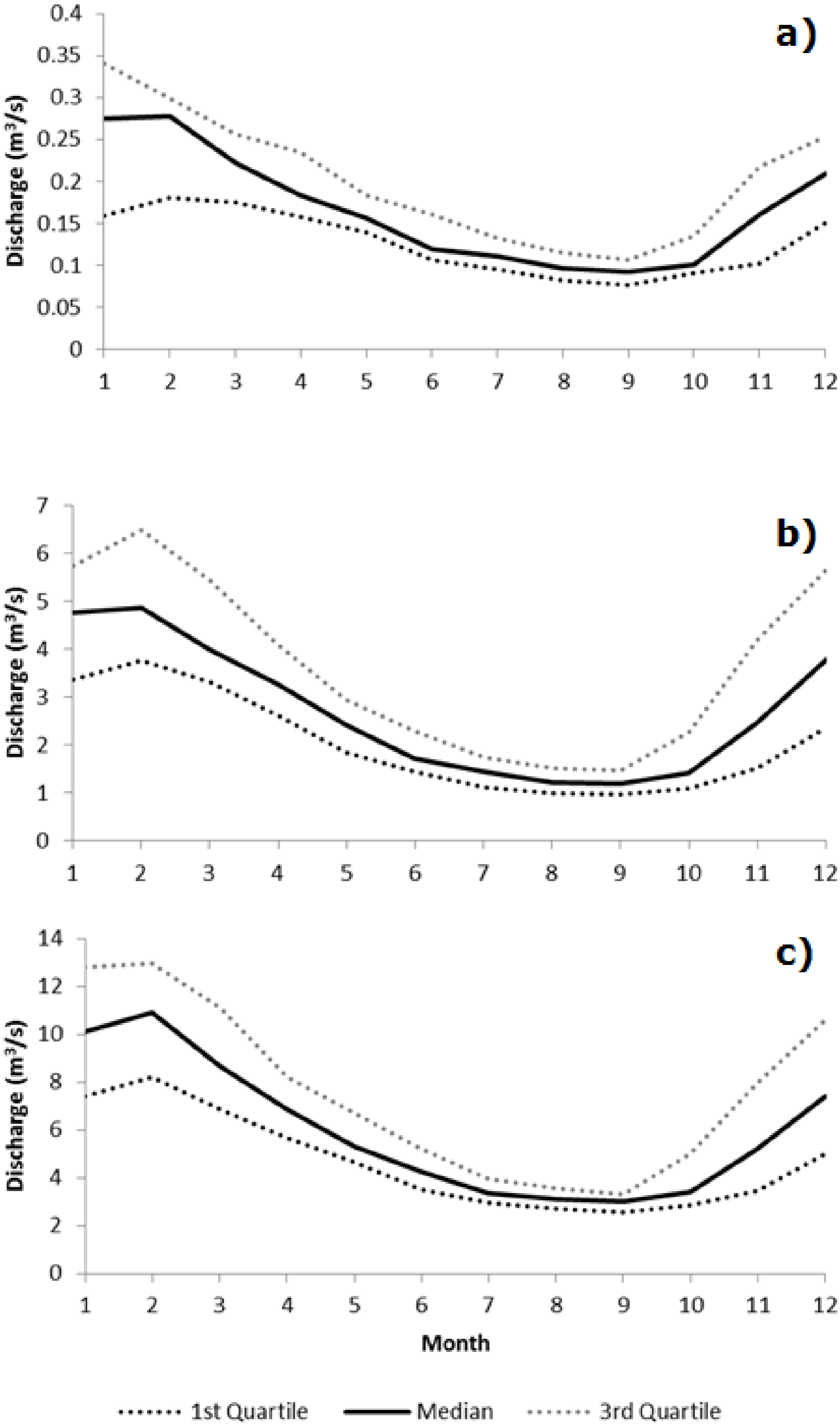


Figure 4.7: Annual hydrograph (by calendar month) for (a) the River Hooke, a tributary of the River Frome located in Landscape Unit 1; (b) River Frome at Dorchester located in Landscape Unit 2, Segment 5; and (c) River Frome at East Stoke located in Landscape Unit 3, Segment 6.

4.4.2 Valley characteristics

Table 4.14 lists the valley characteristics described in the D2.1 main report section 5.4.2. The River Frome is a low gradient, unconfined river. Valley gradient is greatest in Segment 1, intermediate in Segment 2 and very low for the remaining segments. There are pockets where the valley is partly confined in Segments 2 and 3, however they account for less than 10% of the channel length, and consequently all segments are classified as unconfined. Thus, the river is unconfined along its entire length and the valley width is 14-28 times greater than the channel width.

Table 4.14 Valley characteristics for the segments of the River Frome. River confinement index was calculated using the channel width (sum of all channels widths in a cross section).

Segment	Gradient	Valley Confinement	River Confinement Index
1	0.011	Unconfined	25.06
2	0.005	Unconfined	13.77
3	0.003	Unconfined	20.07
4	0.003	Unconfined	20.08
5	0.002	Unconfined	27.81
6	0.002	Unconfined	28.07

4.4.3 Sediment

(i) Sediment size.

Dominant bed material calibre (D2.1 main report section 5.4.3(i)) was estimated using RHS surveys of the River Frome. From the spot checks recorded in these surveys, the dominant bed material is gravel-pebble (2 – 64 mm) for all segments. On average 91% of RHS survey spot-checks identified gravel and /or pebble as the dominant bed sediment size class, of which 26% were gravel, 52% gravel-pebble and 13% pebble. However, MTR surveys, which estimate the percent cover of different sediment types across the entire bed, rarely indicate more than a 50% cover of gravel and coarser sediments (Table 4.21), suggesting that gravel-sand or sand-gravel might be a more appropriate description of the dominant bed material. This theme will be revisited at the reach scale. Furthermore, neither dataset provide evidence of a longitudinal change in dominant bed material size (i.e. no apparent downstream sediment fining).

(ii) Sediment supplied to the channel

This characteristic is listed in the D2.1 main report section 5.4.3(ii). For the Frome, this was estimated from the PESERA dataset and a 500m buffer around the river, which predicts 575 tons of fine sediment is delivered to the River Frome per year in total. The average amount of fine sediment delivered per segment was estimated at 96 tons year^{-1}, with values ranging from 0 in Segment 1 to 314 in Segment 5 (Table 4.15). Fine sediment delivery expressed as a function of river length shows a similar pattern.

Sediment delivery is substantially greater for the segments in Landscape Unit 2 than in the other segments, and Segment 5 had the highest sediment delivery per km of river, regardless of whether it was calculated using the length of the main channel or of all minor and major channels.

No land surface instabilities connected to the channel were identified and thus bank erosion is the only potential source of coarse sediment to the river, but this is likely to be small, given the predominant composition of the river banks (Figure 4.17, based on RHS data, shows that 'earth' is the dominant bank material size class). Bank erosion also acts as an intermediate source of fine sediment to the river, but the annual rates are generally small because a similar or greater amount is accounted for in bank accretion (see section 5.4.1).

Table 4.15: Estimated fine sediment delivery to the River Frome by segment, expressed as total load and by channel length (main channel length and the length of all channels in a reach).

LU	Segment	Sediment input (tons yr^{-1})	Sediment delivery (tons km^{-1} yr^{-1})	
			Main channel	All channels
1	1	0.0	0.0	0.0
	2	14.0	3.7	3.1
2	3	31.5	4.4	3.5
	4	150.7	26.3	11.2
	5	314.2	39.4	12.6
3	6	65.0	2.0	1.1

(iii) Sediment Transport and Budget

No sediment transport measurements are available for the Frome. Therefore, as described in section 5.4.3(iii) of the D2.1 main report, a preliminary sediment budget analysis was conducted for the River Frome catchment using SIAM (see Thematic Annex I.1 for full details). The base model represents the river as a single thread with a mixed sand/gravel bed (based on combined MTR and RHS surveys), with river discharge based on the flow duration curve, fine sediment input to the channel based on the PESERA buffer and no coarse sediment input. This simplification was adopted because only the very lowest layers of the river banks contain material coarse enough to count as a coarse sediment input and bank erosion as a whole is generally balanced or exceeded by bank aggradation (see section 5.3.2) suggesting that most eroded bank material is retained and reabsorbed into the floodplain locally rather than providing a true addition to sediment load. The analysis found that transport capacity exceeds sediment supply in the tributaries, resulting in a net loss of bed sediment in all tributaries and Segment 1 of the River Frome (Figure 4.8). Conversely, supply exceeds transport capacity for the main stem, resulting in a net gain of bed sediment. The greatest annual loss of sediment was found in the South Winterbourne tributary, whilst Segment 6 immediately downstream of the confluence with South Winterbourne had the greatest annual gain of bed sediment (Figure 4.9).

When the results are viewed by grain size, though, it becomes clear that the majority of the bed sediment transported in the SIAM river network is sand. The only reach that had a sediment transport potential for medium gravel was the South Winterbourne at discharges that occurred for only 1 or 2% of the time, which resulted in 9 tons of gravel being transported to the downstream reach, segment 6 in the Frome, during a short period (7 days) of high flows incorporated within the flow duration curve.

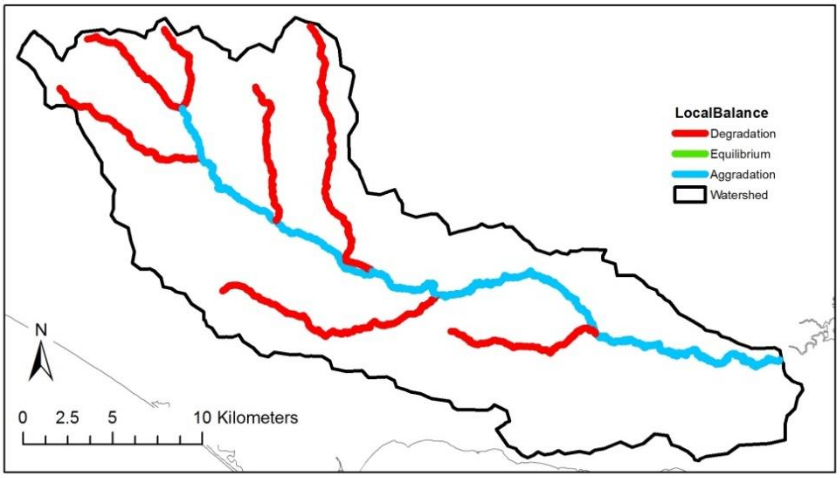


Figure 4.8 Predicted aggradation or degradation of bed material by sediment reach for the base SIAM model (Yang transport equation, wash load maximum diameter = 0.062 mm, Pesera soil erosion source).

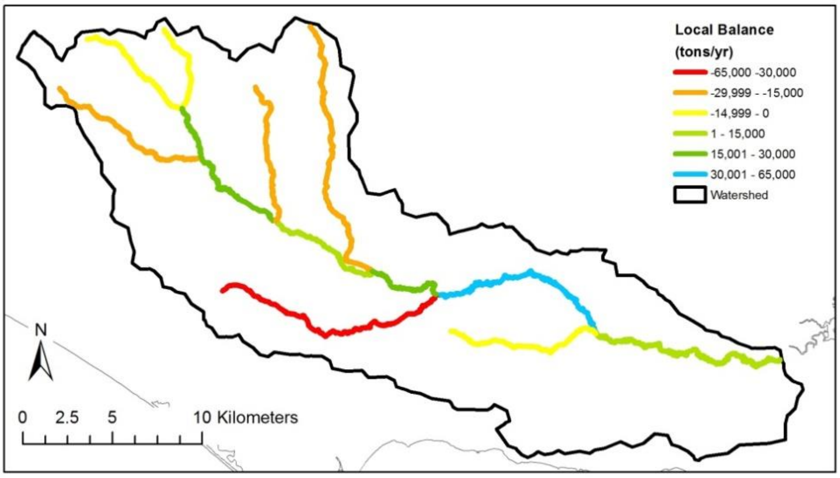


Figure 4.9 Local balance of bed material by sediment reach for the base SIAM model (Yang transport equation, wash load maximum diameter = 0.062 mm, PESERA soil erosion source).

4.4.4 Riparian corridor features

(i) Presence of a riparian corridor

The characteristics required to describe the riparian corridor can be found in section 5.4.4(i) of the D2.1 main report. The River Frome is a low gradient, low energy river in a humid temperate setting. The wide floodplain has minimal topographical variation, high groundwater levels, and receives regular inundation from flood waters. Consequently, riparian vegetation has the potential to grow over the entire floodplain, and the potential riparian corridor is synonymous with the non-developed portions of the floodplain. However, riparian vegetation is sparse, fragmented and heavily influenced by humans, and only 10% of the riparian corridor is covered by functioning riparian vegetation.

Table 4.16 lists the dimensions of the riparian corridor and the areas of functioning riparian vegetation that are found within it. Table 4.17 lists the continuity and wood delivery potential of the functioning riparian vegetation located along the river margins. Segment 2 has the highest proportion of functioning riparian vegetation within the riparian corridor (61% of width and 35% of area), whilst Segment 4 has the lowest (9% of width and 5% of area) (Table 4.16). The riparian corridor in the middle and lower sections of the River Frome is much wider than in the upper segments and functioning riparian vegetation is limited to small, often narrow strips along the river margins. Thus riparian corridor continuity is higher than the proportion of functioning vegetation by corridor width or area in these segments (Table 4.17). The highest continuity is found in Segment 1 and the lowest in Segment 4.

Table 4.16 Characteristics of the riparian corridor: average width, average area, proportion of riparian corridor with vegetation.

	Riparian corridor		Riparian vegetation		Proportion of corridor under riparian vegetation	
Segment	Width (m)	Area (km^2)	Width (m)	Area (km^2)	Width	Area
1	70	0.36	31	0.11	44%	32%
2	122	0.38	74	0.13	61%	35%
3	227	1.41	43	0.15	19%	10%
4	345	1.61	32	0.08	9%	5%
5	603	3.48	59	0.28	10%	8%
6	585	12.96	71	1.27	12%	10%

Table 4.17 Proportion of river length that abuts riparian vegetation (continuity), and proportion of river length that abuts non-coniferous trees and tree/scrub that can contribute to wood delivery (N.B. coniferous stands are excluded because they are managed plantations that do not contribute wood to the river).

Segment	Continuity	Wood delivery potential
1	42%	32%
2	30%	14%
3	27%	24%
4	9%	8%
5	18%	13%
6	21%	13%

(ii) Vegetation cover of the riparian corridor

The characteristics required to describe the riparian vegetation cover can be found in section 5.4.4(ii) of the D2.1 main report. For the River Frome, the vegetation was allocated to dominant classes through analysis of information from the Ordnance Survey MasterMap land theme and the proportions of the corridor under different vegetation patch types is shown in Figure 4.11.

The most abundant vegetation type found in the riparian corridor is non-coniferous tree forest, which occupies 130 hectares and 64% of the total area covered by riparian vegetation. The non-coniferous tree class is defined as having non-coniferous trees dominant and can include other secondary vegetation types, such as scrub. Segment 6 has the greatest area of non-coniferous forests (78 ha) (Figure 4.10). This segment also has the largest potential riparian corridor area, and consequently non-coniferous forests only cover 6% of the riparian corridor in this segment (Figure 4.11). Segment 1 has the greatest proportion of non-coniferous trees relative to the potential riparian corridor (26%). The second most abundant vegetation type is rough grassland, which occupies 37 hectares and 19% of the area covered by riparian vegetation. The greatest area of rough grasslands is found in Segment 6 (12 ha) (Figure 4.10), however the greatest area of grassland relative to riparian corridor area is found in Segment 2 (22%) (Figure 4.11).

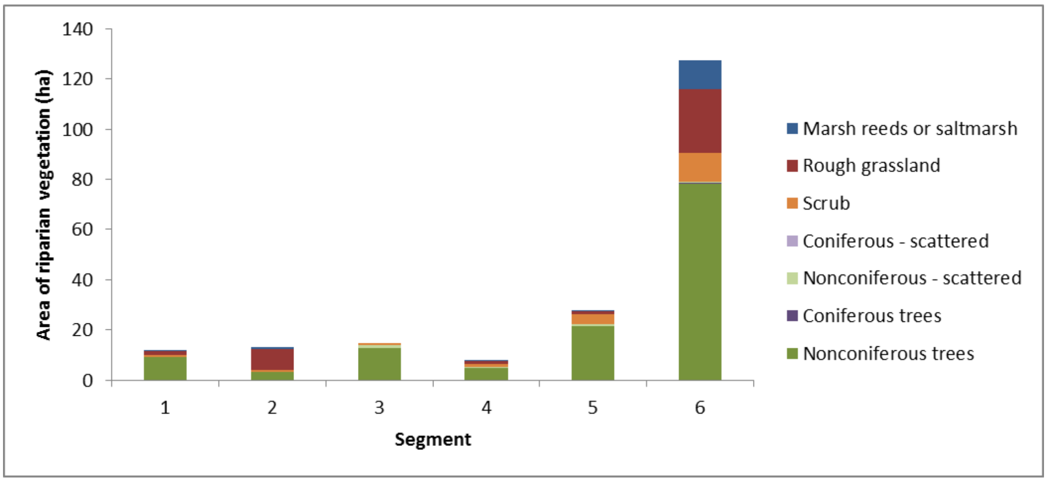


Figure 4.10 Areas of functioning riparian vegetation within the riparian corridor of segments 1 to 6 based on the OS MasterMap classification of dominant vegetation type.

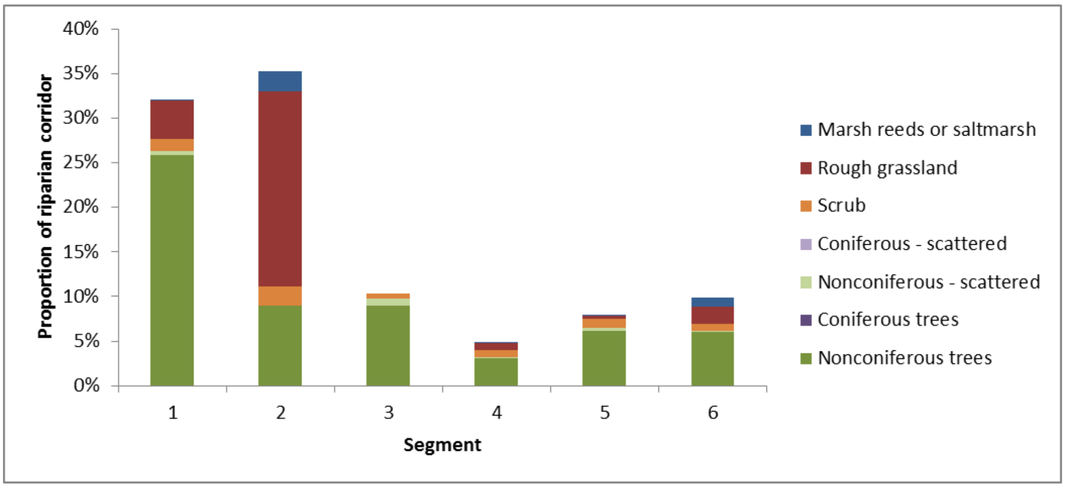


Figure 4.11 Proportion of the potential riparian corridor occupied by functioning riparian vegetation by OS MasterMap classification based on dominant vegetation type.

(iii) Wood delivery potential

Wood delivery potential is characterised by the proportion of the river channel edge covered by mature living or dead trees (D2.1 main report section 5.4.4(iii)). For the River Frome, this was estimated as the proportion of the riverbank with adjacent non-coniferous trees (< 1 m from either riverbank) (Table 4.17). Coniferous trees are typically associated with plantations in this area and therefore are heavily managed and not relevant to wood delivery potential. Segment 1 has the greatest wood delivery potential with 32% of riverbanks covered with non-coniferous trees, followed by segment 3 with 24%. These are conservative estimates that only include intact vegetated areas. The MasterMap dataset used in the riparian vegetation characterisation records the location of intact blocks of trees and not individual ones. From the satellite data, though, it is clear that isolated riparian trees, of various sizes up to those with crowns spanning the river, are found along the entire length of the Frome. These isolated trees have the potential to deliver wood to the river; although it could be argued that they do not represent long-term sources of wood (i.e. an intact forest that would regenerate lost trees).

4.4.5 Physical Pressures

The pressures that should be characterised at the segment scale are listed in section 5.4.5 of the D2.1 main report.

There are no major point interventions where water or sediment is added to or removed from the River Frome

The River Frome has high numbers of blocking and spanning structures reflecting a long history of agriculture, milling, water meadow management and transportation (Figure 4.12). A total of 93 blocking structures were recorded in the Environment Agency's inventory of engineering structures on the river network, 29 of which are rated as intermediate and 63 low. Most of the low impact structures are sluices that control flow into and out of artificial side channels. The medium impact structures are predominantly fixed weirs constructed of concrete. These structures block all coarse sediment transport, but impacts to water and fine sediment transport are minimal. Water appears to be flowing over all weirs in the historical satellite imagery (2005, 2008, and 2009/10). Fine sediment may deposit upstream of these structures during intermediate to low flows but is likely to be flushed out at high flows. Three blocking structures were rated as high (Figure 4.12a). Two are weirs that have a significant impoundment effect (>700 m upstream): Loud's Mill and Nine Hatches (Environment Agency, 2011)), and the third is Stony Weir, which is a stone structure built in the medieval period and associated with Bindon Abbey, near Wool. The weir is currently 0.6 m above the average level of the Frome, and blocks flow and sediment from entering a meandering side channel for most of the year. The side channel normally has a water surface 1.6 m below the weir crest. Most of the anabranch channels in this area appear to be either straightened or artificial, and the meandering nature of the Stony Weir channel may reflect the planform the existed prior to recent human alteration.

A total of 226 spanning structures were recorded in the EA's inventory, of which 21 are rated high, 47 intermediate and 158 low (Figure 4.12b). The high and intermediate impact structures are concrete or masonry bridges for roads or railways that have central piers and/or abutments that extend into the channel, whilst the low impact structures are predominantly simple span pedestrian bridges.

The greatest numbers of blocking and spanning structures are found in Segment 6 and the lowest in Segment 1 (Figure 4.12). Because the length of segments (and reaches) varies considerably in the River Frome, blocking and spanning structures area also presented as the number of structures per kilometre of river. Blocking structures are most abundant in Segments 2-5 and spanning structures in Segment 2 (Figure 4.13). The high value for spanning structures per km in Segment 2 is primarily caused by the large numbers of bridges that cross the multiple channels around the village of Maiden Newton and the short length of the segment's channel network (Figure 4.13b).

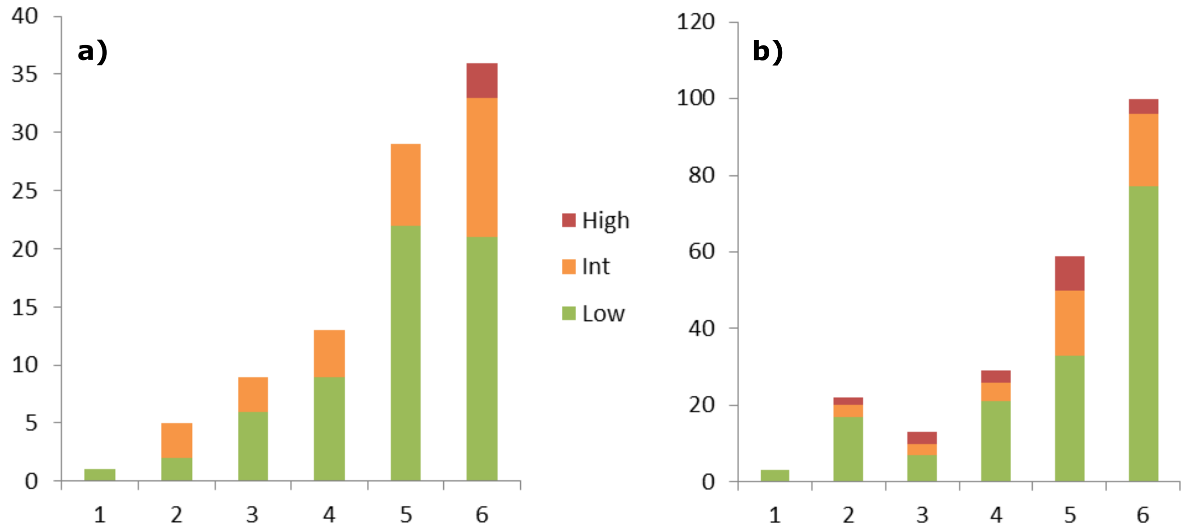


Figure 4.12 Count of (a) blocking and (b) spanning structures on the River Frome by segment.

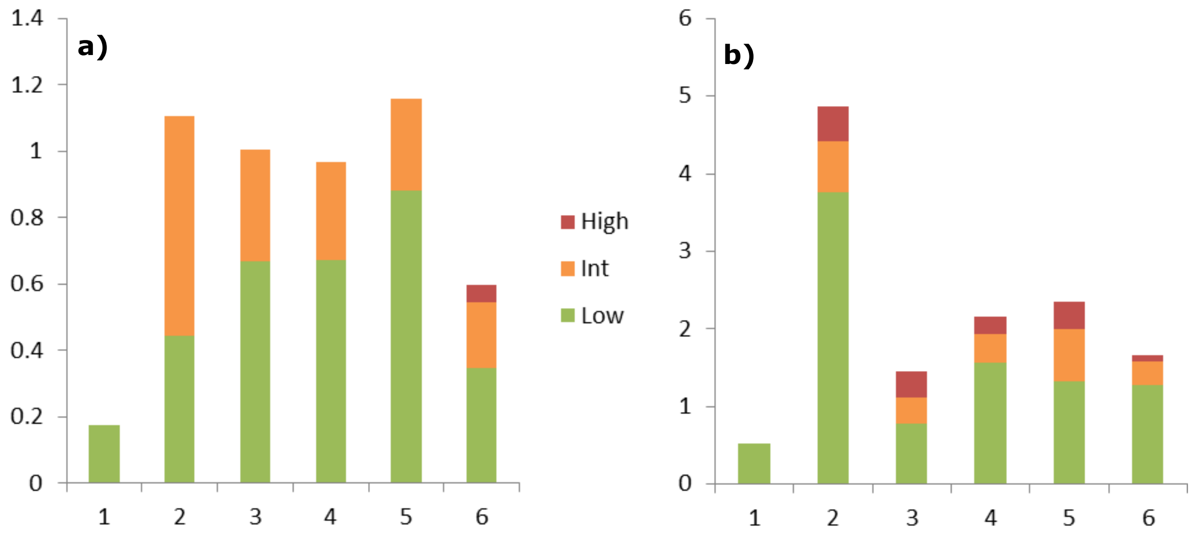


Figure 4.13 The number of (a) blocking and (b) spanning structures per kilometre of river network length by segment.

4.5 Reach

At the reach scale the analysis remains mainly based on information extracted from secondary sources. However, field surveys in parts of reaches 4, 5 and 6 provide additional information on some aspects of reach characteristics.

4.5.1 Channel dimensions (width, planform, gradient)

Section 5.5.1 of the D2.1 main report describes the relevant characteristics required to describe channel dimensions. Those that were calculated for the River Frome are listed in Tables 4.18 and 4.19.

The River Frome is a low gradient river that is predominantly sinuous in its upper reaches and anabranching in its middle and lower reaches. Its high width:depth ratio, low stream power and baseflow-dominated flow regime produce channels with similar baseflow and bankfull channel dimensions (e.g. width and sinuosity). Therefore, a smaller number of channel dimensions are reported below than are listed in Section 5.5.1 of the main D2.1 document.

The narrowest channels and highest gradients are found in the reaches within the headwater region of Landscape Unit 1 (Reaches 1 - 4) (Table 4.18). The river is sinuous to meandering in these reaches.

Landscape Unit 2 has the reaches with the highest width:depth ratio (Table 4.19). Reach 6 flows past the site of an ancient monastery, where the monks are believed to have straightened and widened the river in the medieval period. The main channel is classified as straight, but the presence of several smaller channels in the reach causes it to be classified as anabranching. Channel gradients are low in Landscape Unit 2 (0.002 – 0.004) and decrease to 0.001 in Landscape Unit 3 (Table 4.18).

Extensive anabranching begins in Reach 9 downstream of the confluence with Sydling Water (Table 4.18). A second channel starts as a small artificial channel connected to the main channel by a sluice gate, but grows to become a significant secondary channel that later joins the River Cerne. The river has at least 2 significant channels along most of the rest of its length, and in some sections anabranching indices reach as high as 4.67 due to the presence of multiple, often artificial or straightened, side channels (e.g. Reach 11). The main river is meandering in the last two reaches, but is classified as anabranching in Reach 16 due to the presence of a significant, apparently artificial, side channel.

Channel widths are greatest in the anabranching sections, where the average combined width of the multiple channels can reach 29 meters (Reach 11) (Table 4.19).

Table 4.18 Gradient and planform indices for the River Frome reaches.

LU	Seg	Reach	Gradient		Sinuosity	Braiding Index	Anabranching Index
			Reach	Channel			
1	1	1	0.011	0.010	1.12	1.00	1.00
	2	2	0.004	0.004	1.13	1.00	1.00
		3	0.005	0.003	1.51	1.00	1.04
		4	0.006	0.006	1.06	1.00	1.41
2	3	5	0.003	0.002	1.28	1.00	1.06
		6	0.004	0.004	1.03	1.00	1.75
		7	0.002	0.002	1.20	1.00	1.00
	4	8	0.003	0.002	1.28	1.00	1.43
		9	0.003	0.003	1.21	1.00	2.39
	5	10	0.002	0.002	1.21	1.00	2.93
		11	0.003	0.002	1.30	1.00	4.67
3	6	12	0.002	0.002	1.45	1.00	2.87
		13	0.003	0.002	1.34	1.00	2.00
		14	0.002	0.002	1.18	1.00	3.00
		15	0.002	0.001	1.39	1.00	2.23
		16	0.002	0.001	2.11	1.00	2.00
		17	0.001	0.001	1.59	1.00	1.20

Table 4.19 Average dimensions for bankfull / active channel for the reaches in the River Frome. Total channel width includes all major side channels (measured from OS map data: Profile DTM and MasterMap topography layers. Main channel dimensions are derived from RHS

LU	Seg.	Reach	All channels Width (m)	Main Channel Width (m)	Main Channel Depth (m)	W:D
1	1	1	3.1	3.1	0.95	3.3
	2	2	4.8	4.5	1.38	3.3
		3	5.0	5.5	1.18	4.7
		4	7.7	6.5	1.15	5.6
2	3	5	10.0	9.1	1.45	6.9
		6	14.1	13.9	0.97	14.5
		7	14.7	11.7	1.52	9.7
	4	8	12.6	11.0	1.13	9.7
		9	17.2	9.8	0.87	11.3
	5	10	20.9	12.0	0.87	13.9
		11	29.4	10.3	1.13	9.1
3	6	12	23.7	11.6	1.14	10.2
		13	21.1	13.9	1.12	12.5
		14	23.7	11.8	1.00	11.8
		15	20.1	13.1	1.18	11.1
		16	17.5	12.2	1.36	9.0
		17	15.5	14.2	1.13	12.6

4.5.2 River energy

River energy characteristics are described in section 5.5.2 of the D2.1 main report.

Total stream power is lowest in the upstream reaches (1 - 3) and increases to a maximum in Reach 14 (41 - 43 km downstream, mean = 439 W m^{-1}) (Figure 4.14).

Specific stream power is greatest in Reach 1 (mean = 43.4 W m^{-2}) where the channel is narrowest and steepest. It decreases down through Reach 9 and then fluctuates around a mean of approximately 14 W m^{-2} in the remaining reaches, due to variations in gradient and channel width. The lowest specific stream power is in Reach 11 (25 – 28 km downstream, mean = 10.8 W m^{-2}) (Figure 4.14), where the river has the highest anabranching index and the greatest channel width (Tables 4.18 and 4.19).

Total and specific stream power estimates are greater when calculated using annual maximum instantaneous flows from the 15-min flow record (Figure 4.14b,d) than when calculated with the annual maximum 1-day flows from the mean daily flow record (Figure 4.14b,d).

Average bed shear stress decreases with distance downstream (Figure 4.15), mirroring the longitudinal pattern in channel gradient (Table 4.18).

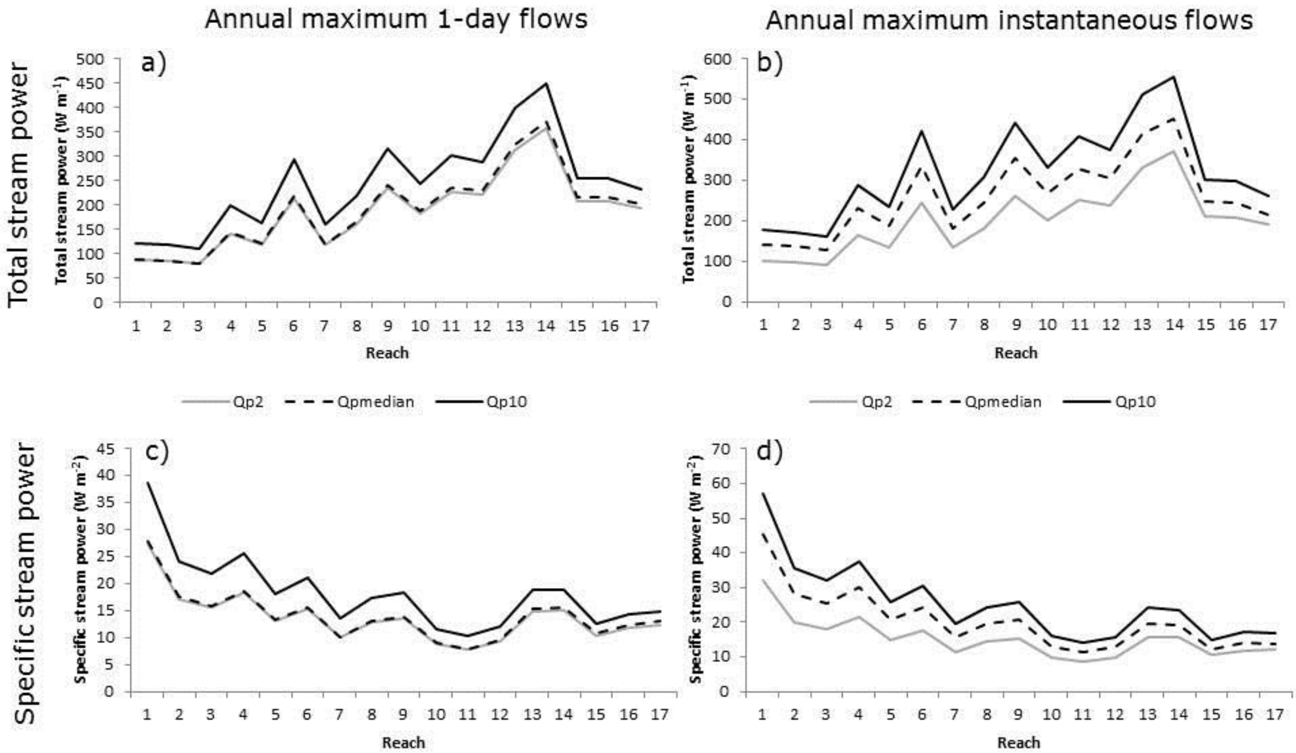


Figure 4.14 (a,b) Average total stream power and (c,d) average specific stream power for Reaches in the River Frome, as calculated based on (a,c) annual maximum 1-day flows from the mean daily flow record and (c,d) annual instantaneous maximum flows from the 15-min flow record. Power estimates based on river flows at reach outlet that are based on relationships between catchment area and flow.

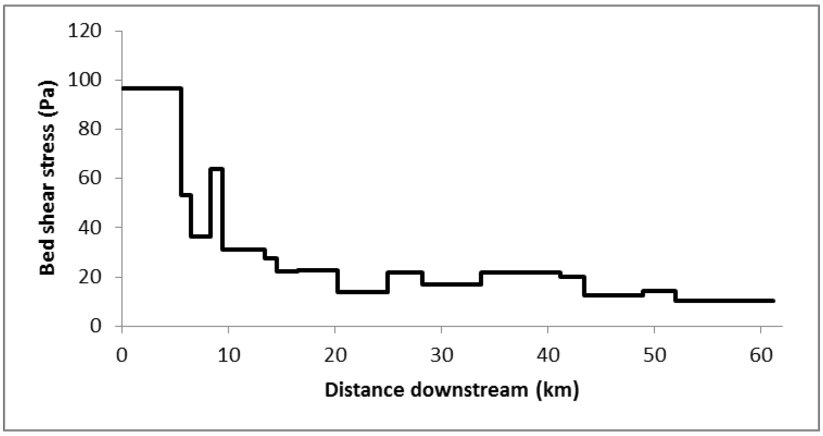


Figure 4.15 Average bed shear stress by distance downstream in the River Frome at bankfull discharge (Qp2). Each plateau in the long profile represents a reach.

4.5.3 Bed and bank sediment

(i) Sediment size

Descriptions of relevant characteristics can be found in the D2.1 main report, section 5.5.3(i). Although gravel was identified as the dominant bed sediment size in 75-100% of the RHS spot-checks conducted on the River Frome (10 spot checks per survey) (Table 4.20), the more accurate percent cover data, estimated during Mean Trophic Rank surveys, show that high percentages of the river bed are covered by sand and silt+clay (Table 4.21). Silt+clay covered between 5 and 25% of the areas surveyed, with the maximum found in Reach 9. Sand covered between 19 and 55% of the areas surveyed, with the maximum found in Reach 8. Field surveys were conducted in parts of reaches 4, 5 and 6, which confirmed the higher percentage of finer sediment indicated by MTR surveys (e.g. Figure 4.16). In general this mix of gravel and finer sediment, which is not picked up in the RHS surveys (possibly because they are conducted in summer from the river bank, at a time when aquatic macrophytes are extensive and cover the areas of the bed most likely to retain finer sediment) indicates that gravel-sand or sand-gravel might be the best descriptors of the river bed in most reaches. MTR surveys are more detailed channel surveys, which require a deeper inspection of the river bed.

'Earth' is the most abundant bank material along the River Frome; 94% of the banks surveyed during RHS spot-checks were classified as earth (defined as crumbly material of mixed particle size, typically < 2mm, and thus containing little potential bed material) (Figure 4.17). These data further confirm the very small contribution bank erosion is likely to make to bedload.

Table 4.20 Dominant channel bed sediment size category, as percentage of RHS spot checks (10 spot-checks per survey , n = number of surveys per reach).

LU	Seg.	Reach	Silt+clay	Sand	Gravel	Cobble	Artificial	Survey *n*
1	1	1		3	**87**		2	15
	2	2	6		**82**		12	1
		3	2	6	**91**			6
		4	14	11	**75**			3
2	3	5	7	12	**81**			13
		6	4		**96**			5
		7		18	**83**			3
	4	8	2	9	**89**			6
		9		5	**95**			7
	5	10	3	9	**88**			9
		11			**100**			9
3	6	12		6	**94**			8
		13		4	**96**			16
		14			**100**			6
		15		2	**98**			9
		16		17	**83**			5
		17			**100**			9

Table 4.21 Percent cover for bed sediment (%) from Mean Trophic Rank surveys (CEH).

LU	Seg.	Reach	Clay+Silt	Sand	Gravel	Cobble	Survey (*n*)
1	1	1	11	19	**62**	8	11
	2	2	15	40	**45**		1
		3	20	38	**42**		3
		4	20	**40**	**40**		1
2	3	5	13	31	**49**	6	7
		6	5	22	**72**	2	3
		7					0
	4	8	8	**55**	33	5	2
		9	25	33	**42**		3
	5	10	14	36	**50**		3
		11					0
3	6	12	10	30	**60**		1
		13	10	**45**	**45**		1
		14	13	**43**	**45**		2
		15					0
		16	14	**43**	**43**		1
		17	15	40	**45**		1

Figure 4.16 Fine sediment deposited on and within the surface layers of the River Frome's gravel bed in Reach 5.

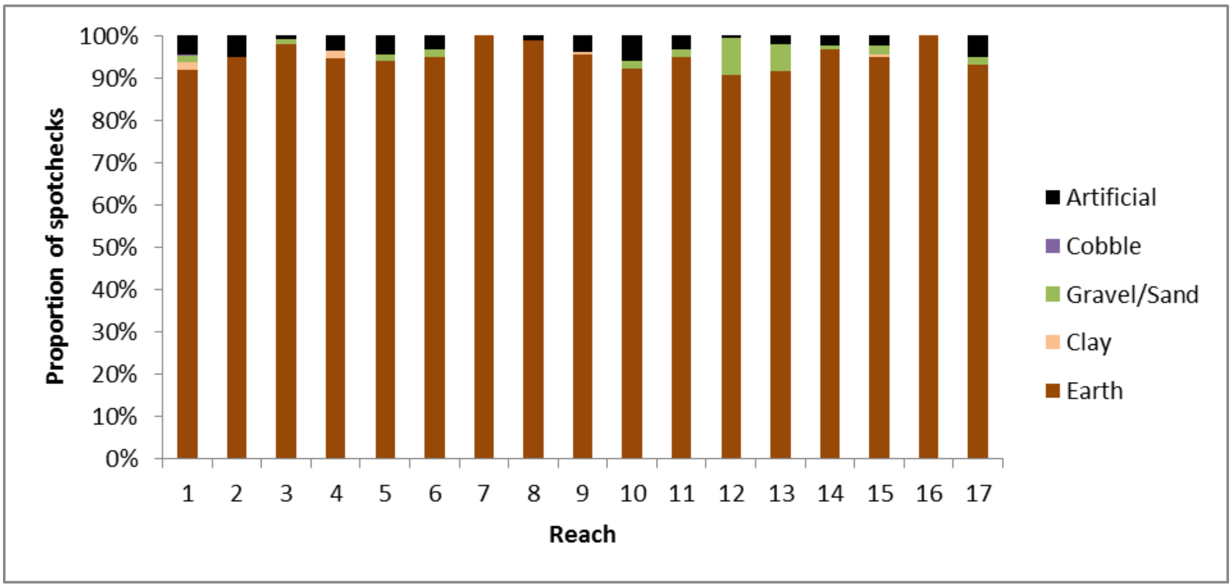


Figure 4.17 Dominant bank material in reaches in the River Frome as proportion of RHS spot-checks.

4.5.4 Riparian and aquatic vegetation

(i) Riparian vegetation

Riparian vegetation characteristics are described in the D2.1 main report section 5.5.4(i). As stated earlier (Section 4.4.4(ii)), the most abundant vegetation type in the riparian corridor is non-coniferous forest (Tree and Tree/Scrub; 65% of vegetated riparian area), followed by rough unimproved grassland (18%). Whilst we do not have information on the species or age of the riparian vegetation, we can infer a measure of maturity from the vegetation classification itself (using dominant and secondary vegetation types) and the principles of forest succession (Table 4.22).

Rough grasslands are areas of unimproved pastures that are composed of herbaceous plants. This vegetation type, along with marshes, would represent the earliest growth vegetation types that would recruit to a newly formed area of the floodplain in this region. Scrub would be the next stage in forest succession, where herbaceous plants are replaced by short to medium height woody plants (i.e. shrubs). Vegetation classified as tree-dominated (non-coniferous, coniferous or non-coniferous/coniferous) would represent the most mature stage of floodplain vegetation succession. Plant community succession is a natural ecological process, but early growth stages may be maintained in a landscape through grazing or other land management practices. Pasture is not normally included in naturally-functioning riparian zones, but rough pasture is included here because it is minimally managed and it has been identified as a habitat that supports a diversity of native wetland species (e.g. East Holme, Natural England 1991). Additionally, the author has seen morphological features within rough grassland areas along the Frome that naturally occur in wetlands (e.g. hummocks in Reach 4).

Table 4.22 Estimated vegetation maturity based on the vegetation classification used in the land theme of the OS MasterMap topography dataset.

Vegetation classification	Maturity
Marsh or reeds	Pioneer
Rough grassland; Marsh or reeds	↓
Rough grassland	Early growth
Scrub; Rough grassland	↓
Scrub	Intermediate / juvenile
Scrub; Tree	↓
Tree; Scrub	↓
Tree	Mature

Figure 4.19 indicates the proportion of the riparian corridor supporting different 'age' classes of riparian vegetation. Reach 1 has the greatest coverage of mature vegetation (i.e. Trees) in the riparian corridor (Figure 4.18). This reach (which is the only reach in Segment 1) had the second largest area of riparian vegetation relative to riparian corridor area (32%) (Figure 4.19; Table 4.16) and longest length of riverbank with adjacent riparian vegetation (42%) (Table 4.17). Mature vegetation is sparse to absent in Reaches 2-8, but becomes more abundant in the middle to lower reaches (9-15). The

largest areas of intermediate growth (Tree/Scrub, Scrub/Tree and Scrub) and early growth (Scrub/Grass, Grass and Grass/Marsh) vegetation types are found in the reaches in Landscape Unit 3 (Reaches 13, 15 and 17). Relative to riparian corridor area, though, Reach 4 has the greatest cover of riparian vegetation proportional to the potential riparian corridor and the greatest proportion of early growth vegetation (42%) (Figure 4.19).

Lateral gradient in riparian vegetation structure was assessed initially based on the network of active channels that was used in the earlier characterisation stages (e.g. anabranching index and river lengths) (Figure 4.20a). Only side channels that were connected to the river at both their upstream and downstream ends and had water visible in the channels in the historical satellite imagery were included. Based on these channels, there is little change in the area of naturally-functioning riparian vegetation up to 250 m from the channel margins, or in the relative proportion of vegetation types up to 500 m (Figure 4.21a,c). However when all channels and drains are included (Figure 4.20b), a pronounced lateral gradient in vegetated area is apparent (Figure 4.21b). Riparian vegetation coverage quickly decreases with distance from the river and drain banks, which aligns with previous observations that the vegetation is limited primarily to narrow strips along the channel margins (Figure 4.21b). However, vegetation structure still shows little variation with distance from the riverbanks. A slight increase in the area of rough grassland and a slight decrease in tree and tree/scrub are noted in the first 50 meters, which is followed by a slight increase in the proportion of tree and tree/scrub area at further distances. These subtle patterns do not suggest that fluvial processes are controlling riparian vegetation structure.

Figures 4.22 to 4.24 characterise lateral gradients in riparian vegetation ‘age’ structure for all 17 reaches of the River Frome. Several reaches show substantial shifts in vegetation with distance from the riverbanks. For example, the proportion of vegetated area covered in marsh increases with distance from the riverbank in Reach 3 (Figure 4.22), whilst tree cover increases in Reach 11 (Figure 4.23). The reach with lateral gradients in vegetation structure that most suggest reworking by riverine processes is Reach 17 (Figure 4.24). This meandering reach shows decreases in the area of marsh and rough grassland, and increases in scrub and trees with distance from the river banks.

The third characteristic suggested in D2.1 main report section 5.5.4 (i) is patchiness within the riparian vegetation. Riparian vegetation is found in small, often isolated pockets on the River Frome, and as a result it is not possible to resolve small-scale variations in structure beyond those reported in the above description of lateral gradients.

In relation to the dominant riparian plant species present, no catchment-wide survey of riparian vegetation was available for the River Frome catchment. Species information was gathered from the MTR survey and scientific studies (Gurnell et al., 2006; Gurnell et al., 2007). Whilst only plant species that are rooted below the water are recorded in MTR surveys, many of the species that were identified are commonly found in wetland, riparian and terrestrial environments (Table 4.23). In a study on channel bed seedbanks, Gurnell et al. (2007) identified the riparian plant species found at two locations along the river, in Reaches 5 and 6. *Salix* was the most abundant woody riparian plant genus, and was represented by the following species, in approximate decreasing order of abundance, *S. viminalis*, *S. cinerea*, *S. fragilis*, *S. alba* and *S. triandra*. Other woody riparian species included *Alnus glutinosa*, *Rubus fruticosus*, *Fraxinus excelsior*, *Acer pseudoplatanus*, *Sambucas nigra* and *Symphoricarpus spp*.

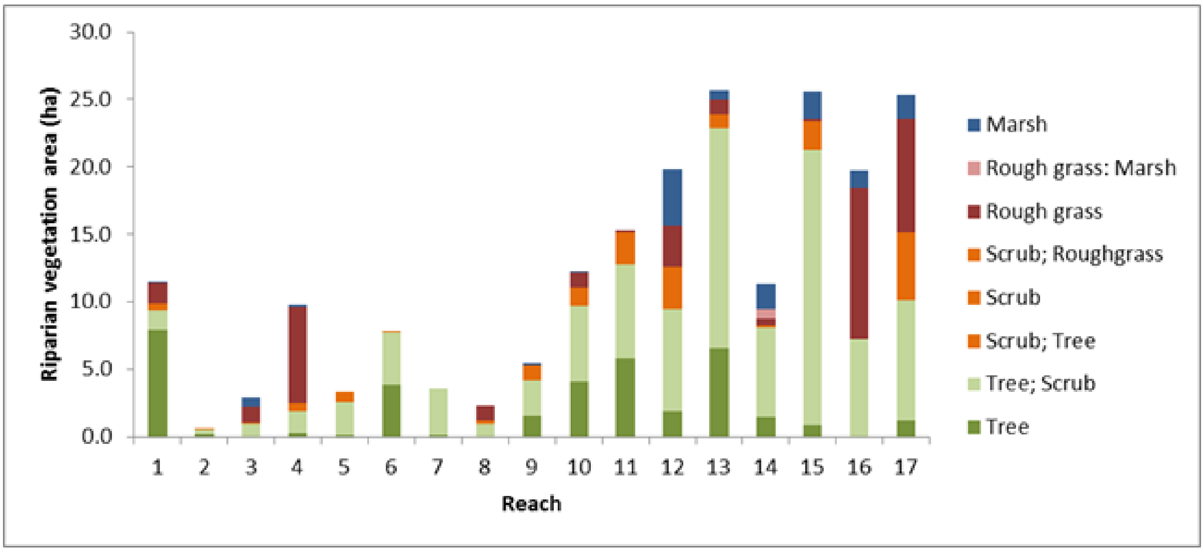


Figure 4.18 Area (ha) covered by different types ('ages') of riparian vegetation. The progression from marsh/grassland to tree cover represents an approximate increasing gradient in the age of the vegetation.

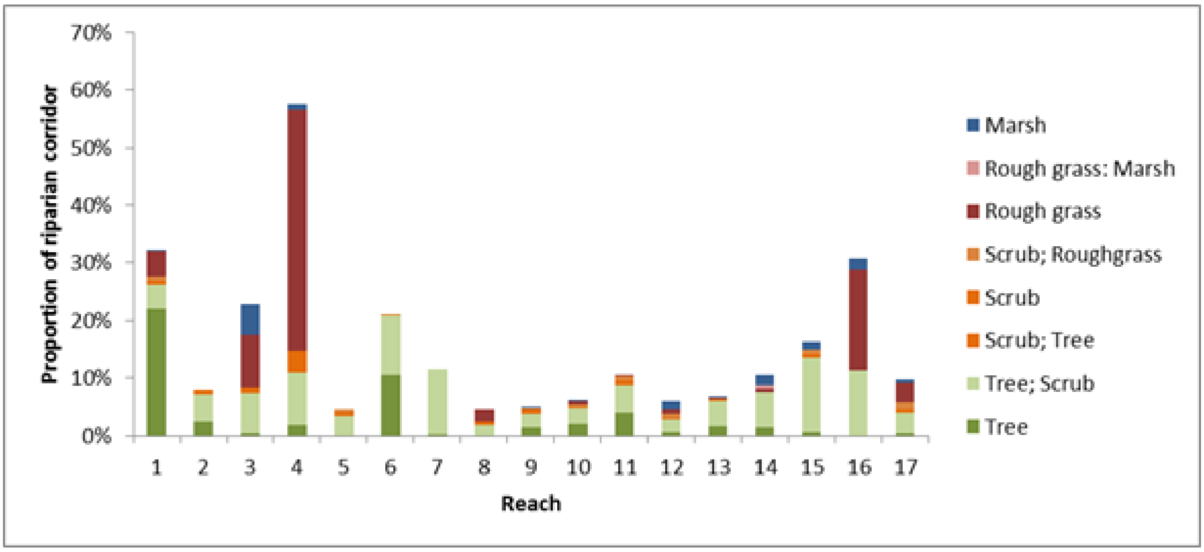
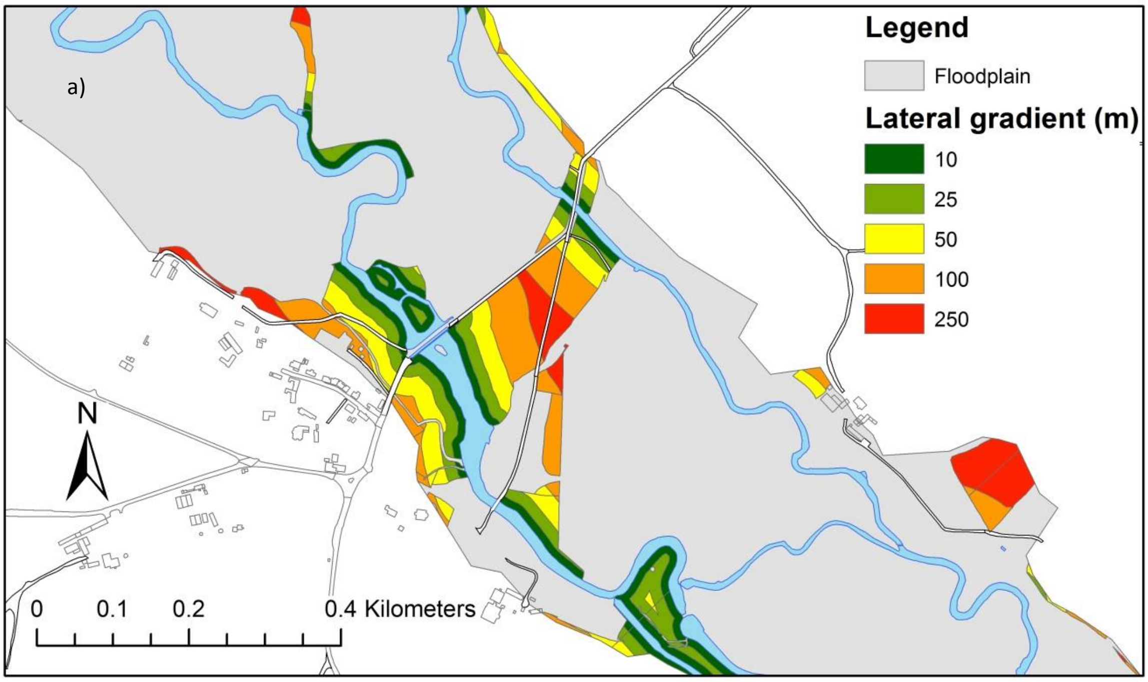


Figure 4.19 Proportion of the riparian corridor covered by different types ('ages') of riparian vegetation. The progression from marsh/grassland to tree cover approximates an increase in vegetation maturity.



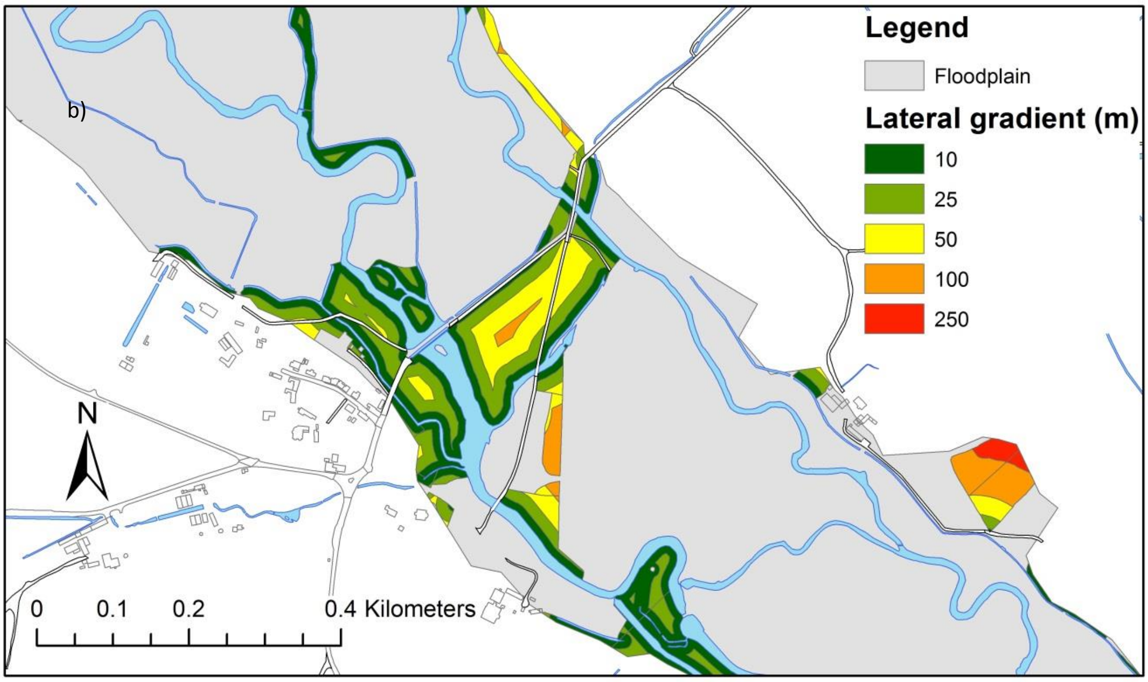


Figure 4.20 Lateral gradient in riparian vegetation structure as calculated from (top) the main channel network and (bottom) the main channel plus all minor channels and drains.

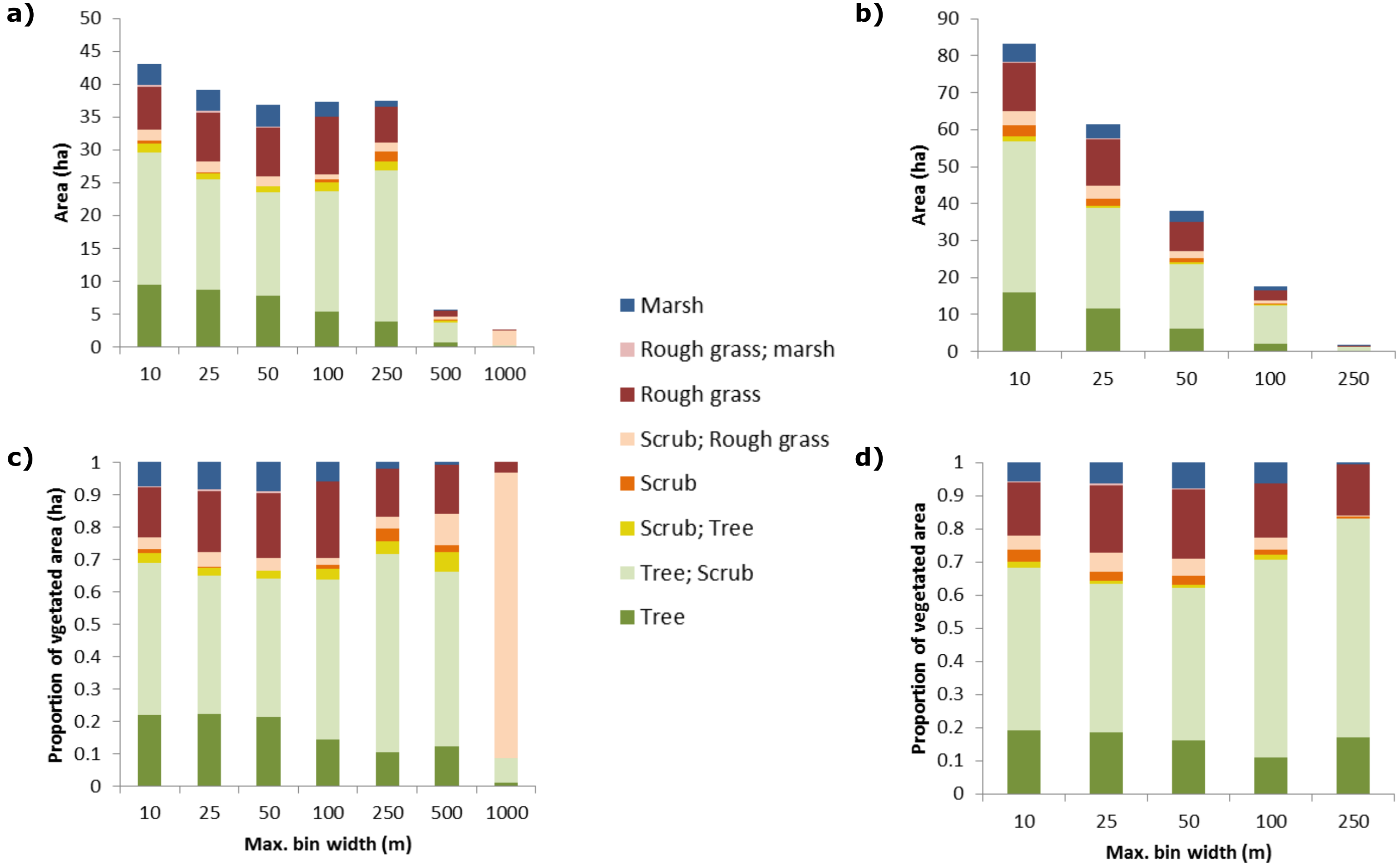


Figure 4.21 Lateral gradient in riparian vegetation structure across the riparian corridor, represented as (a, b) vegetated area within given distances from the channel (width bins) and as (c, d) area relative to the total vegetated area in the bin for the (a, c) main channel network and (b,d) for the network plus all drainage and irrigation channels.

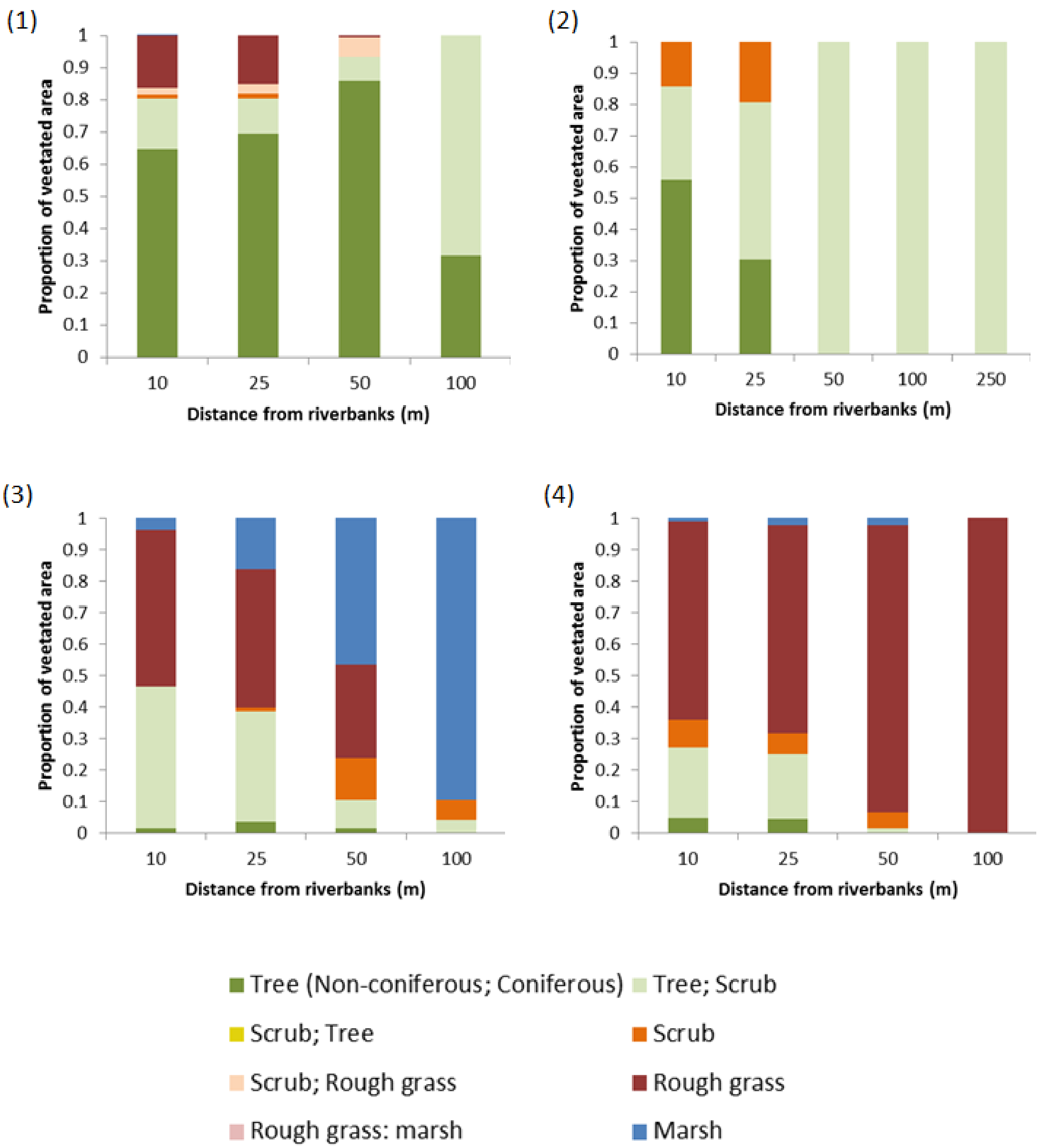


Figure 4.22 Lateral gradient in riparian vegetation structure for Reaches 1 -4 in Landscape Unit 1.

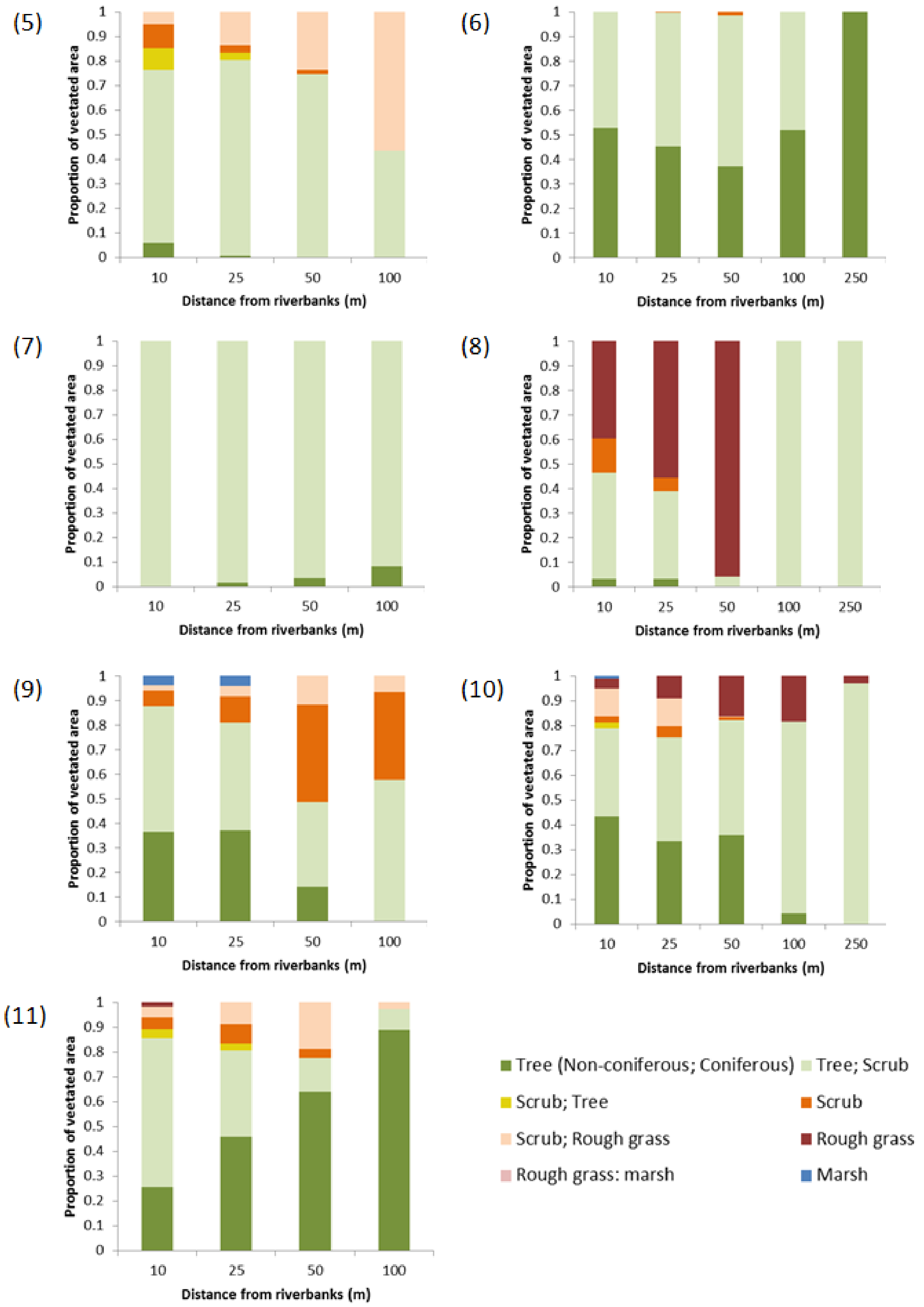


Figure 4.23 Lateral gradient in riparian vegetation structure for Reaches 5-11 in Landscape Unit 2.

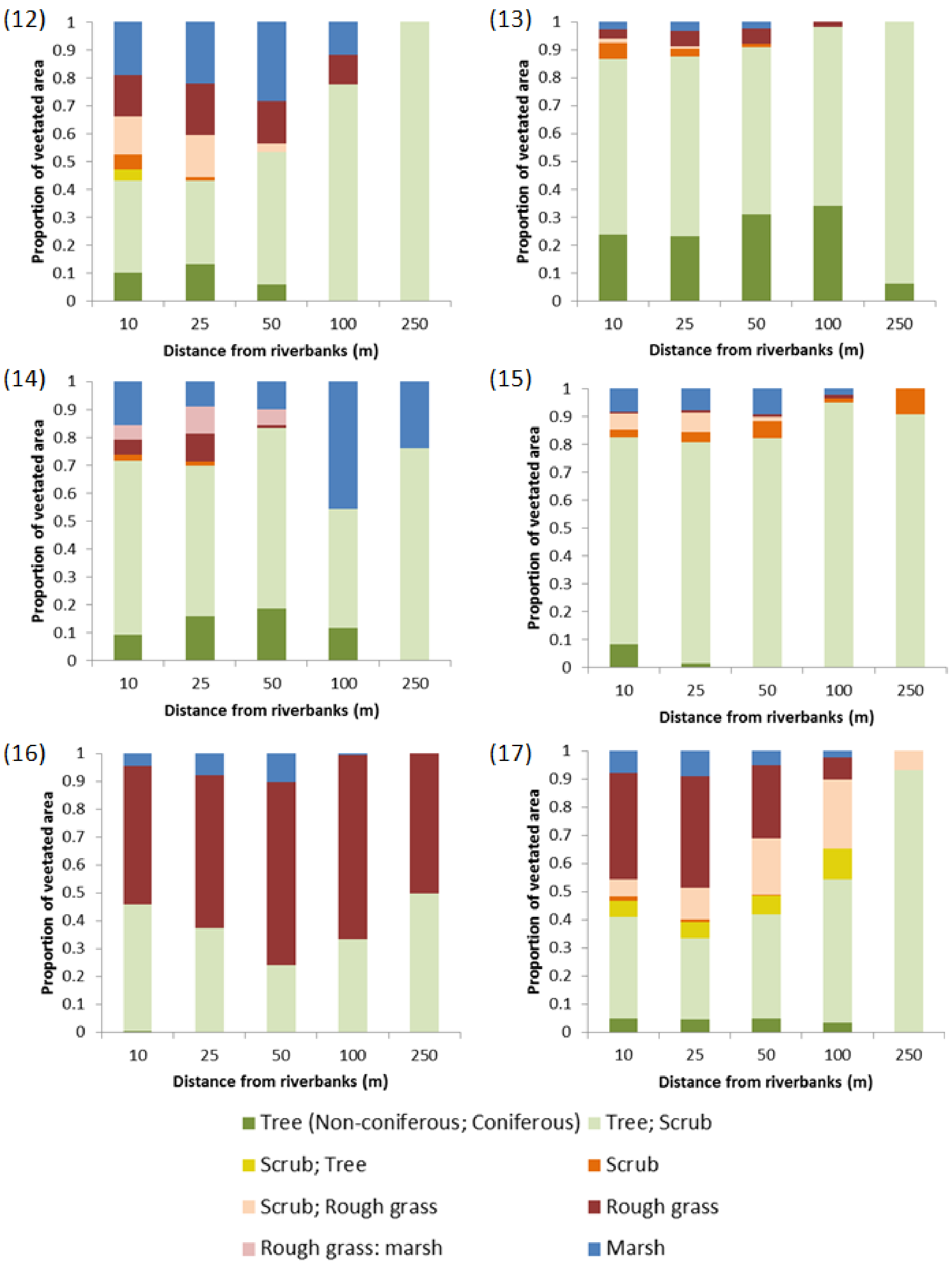


Figure 4.24 Lateral gradient in riparian vegetation structure for Reaches 12 – 17 in Landscape Unit 3.

Table 4.23 Plants identified during Mean Trophic Rank surveys of the River Frome, which are often found in terrestrial or wetland riparian environments.

Species	Type
Agrostis stolonifera	Graminoid
Asplenium spp.	Fern
Cardamine spp.	Herb
Carex acutiformis	Cyperaceae
Carex pendula	Cyperaceae
Carex remota	Cyperaceae
Carex riparia	Cyperaceae
Carex spp.	Cyperaceae
Conocephalum conicum	Liverwort
Epilobium hirsutum	Herb
Epilobium sp.	Herb
Equisetum fluviatile	Herb
Equisetum sp.	Herb
Eupatorium cannabinum	Herb
Fissidens crassipes	Moss
Fissidens sp.	Moss
Fontinalis antipyretica	Moss
Glyceria fluitans	Graminoid
Impatiens glandulifera	Herb
Iris pseudacorus	Aquatic
Juncus acutiflorus	Juncaceae
Juncus effuses	Juncaceae
Juncus inflexus	Juncaceae
Lycopus europaeus	Herb
Lythrum salicaria	Herb
Marchantia spp.	Liverwort
Mentha aquatica	Herb
Mentha spp.	Herb
Mosses	Moss
Myosotis scorpioides	Aquatic
Oenanthe crocata	Aquatic
Pellia epiphylla	Liverwort
Persicaria hydropiper	Herb
Petasites hybridus	Herb
Petasites spp.	Herb
Phalaris arundinacea	Graminoid
Ranunculus acris	Herb
Ranunculus repens	Herb
Riccia spp.	Liverwort
Rumex hydrolapathum	Herb
Rumex spp.	Herb
Salix spp.	Woody
Scrophularia auriculata	Herb
Solanum dulcamara	Herb
Stachys palustris	Herb
Stellaria spp.	Herb
Symphytum officinale	Herb
Thamnobryum alopecurum	Moss
Urtica dioica	Herb
Veronica anagallis-aquatica	Aquatic

Verrucaria spp.	Lichen

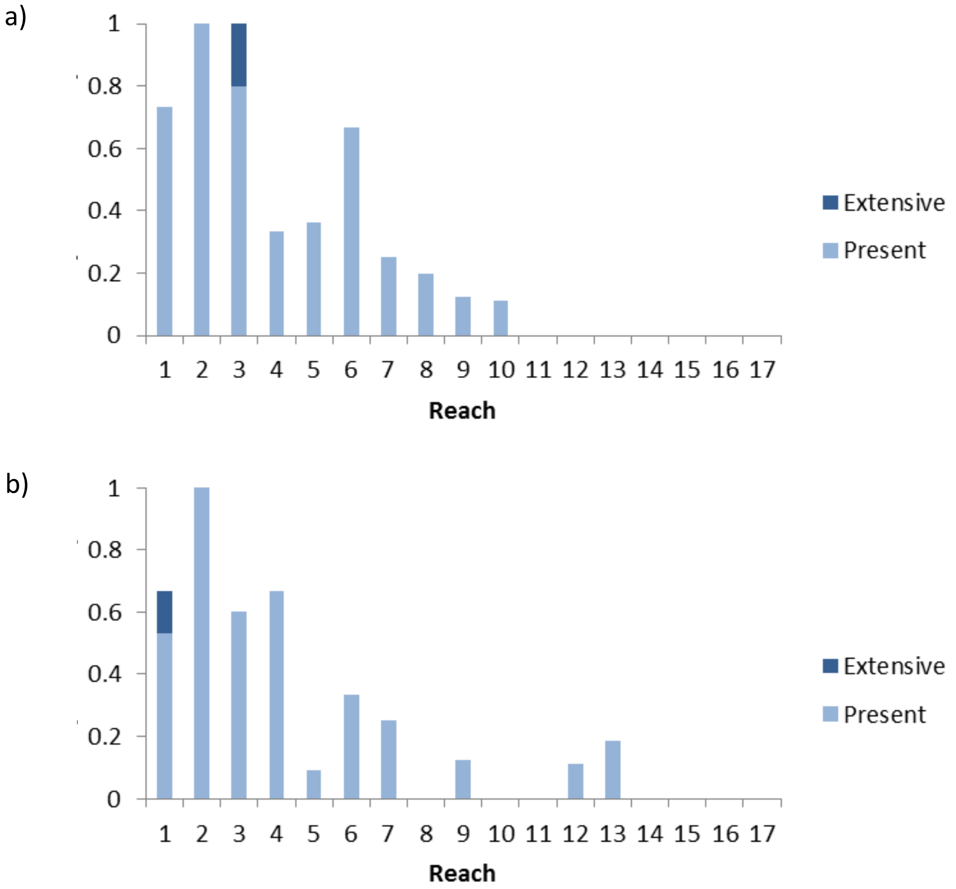


Figure 4.25: The proportion of RHS surveys that reported the presence of (a) large woody debris or (b) fallen trees. Present: cover <33%, Extensive: cover ≥ 33%.

(ii) Large wood

Appropriate characteristics (presence, abundance, distribution) of large wood are described in section 5.5.4(ii) of the D2.1 main report.

RHS surveys report the presence of large wood and fallen trees in the upper and middle reaches of the River Frome (Figure 4.25). RHS defines large wood as 'woody debris that is not attached to the bank and that was transported downstream of where it entered the river'. Fallen trees are defined as trees that are lying in the water, but are still rooted into the bank. Reaches in Landscape Unit 1 had the greatest occurrence of large wood and fallen trees (Figure 4.25). Reach 3 had the greatest proportion of surveys reporting large wood; large wood occurred at all surveys sites (n = 5) and was extensive at one (Figure 4.25a). Fallen trees were observed most frequently in Reach 1; they were present in 53% of surveyed reaches and extensive in 13% (Figure 4.25b). (Note: Reach 2 only had 1 RHS survey, so is not included in this interpretation). No large wood was reported downstream of Reach 10. Fallen trees were rare downstream of reach 7 and none were reported in the most downstream 4 reaches. No large wood was identified in the highest resolution satellite imagery on Google Earth. The narrow width of the channel, the presence of overhanging trees in many sections and the relatively coarse spatial resolution of the images limits the utility of satellite images for this purpose on small rivers such as the Frome.

Field survey is needed to further characterise large wood within the small, channels of the River Frome, which are often overhung by trees. Within the lengths of three reaches investigated in the field, Reach 4 contained fallen trees, large wood jams and also widespread encroachment of woody vegetation (*Salix* spp.) into the channel, whereas in Reaches 5 and 6, large wood and fallen trees were absent, but some riparian trees were growing into the channel and acting as a trap for smaller wood pieces. This variability between the lengths of channel investigated support the spatially variable observations of wood recorded in the RHS surveys.

(iii) Aquatic vegetation

Section 5.5.4(iii) of the D2.1 main report lists characteristics that describe the extent, patchiness and species composition of aquatic vegetation. In this section aquatic vegetation is assessed in its entirety and also in terms of emergent species only.

Aquatic vegetation is found in all reaches in the River Frome according to RHS and MTR surveys (Figures 4.26 and 4.27). The extent of aquatic vegetation within the channel generally increases with distance downstream. Aquatic vegetation is present in the upper reaches, but at low percent cover, and is more abundant in the middle and lower reaches. Submerged morphotypes are more abundant than emergent ones. MTR data has a finer resolution of percent cover and permits an estimation of average coverage per reach. Reaches with the highest total average coverage of aquatic vegetation are 12, 15 and 17 with 78%, 72% and 58% cover, respectively (Figure 4.27). Reaches 1-7 and 14 have the lowest percent cover (≤ 6%).

Patchiness information is not included in the final MTR and RHS results. In the field, both emergent and submerged macrophytes are observed to form a highly patchy mosaic, with the former largely distributed along the channel edges, and the coverage can be extremely high in mid summer (e.g. Reach 6, Figure 4.28).

Table 4.24 lists the plant species identified in the MTR surveys that have an upright habit and are usually found rooted (i) below the water level (aquatic) or (ii) in the shallow margins or above the water level (wetland). *Sparganium erectum* was the most widespread of emergent species (aquatic or wetland) and was found at 66% of sites. The second most widespread aquatic species was *Apium nodiflorum* (49% of sites). *Phalaris arundinacea, Veronica anagallis-aquatica*, *and Myosotis scorpioides* were the most widespread of wetland species and were reported at 49%, 46% and 42% of sites, respectively.

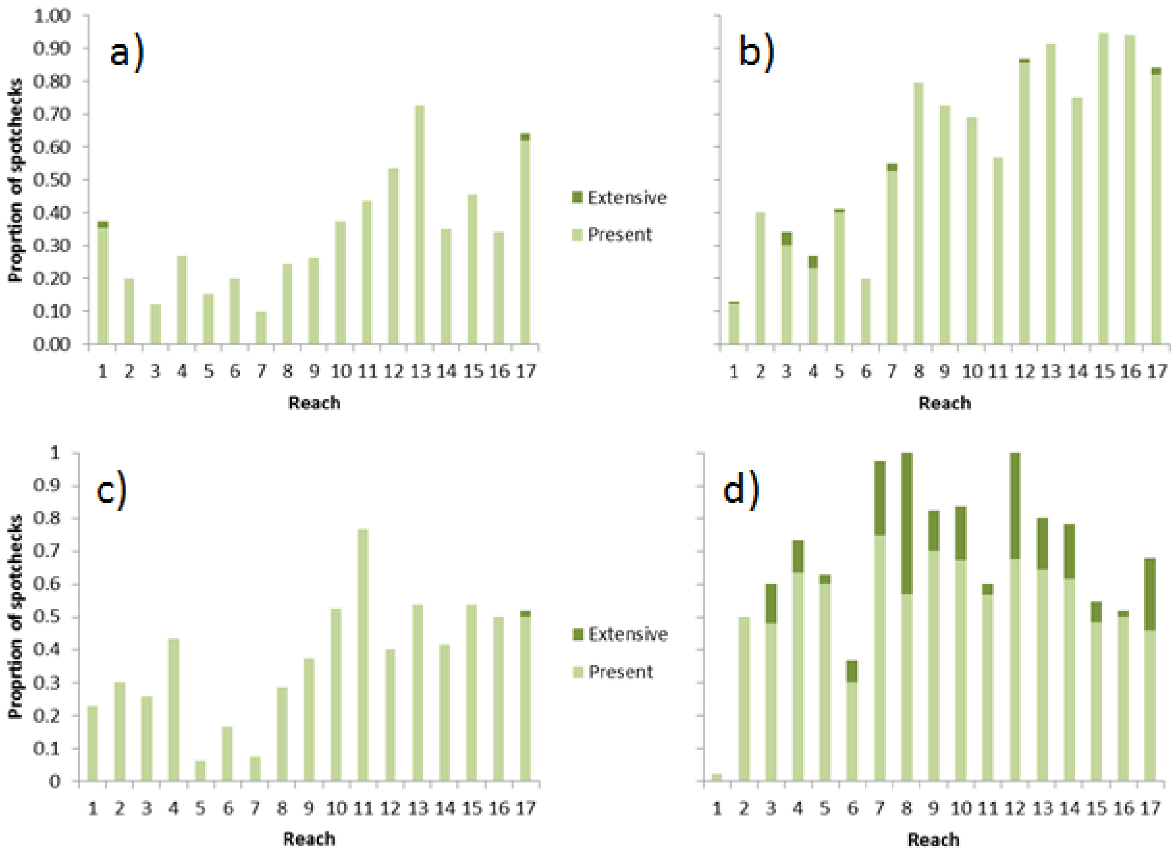


Figure 4.26 Coverage of aquatic vegetation identified in RHS surveys, reported as proportion of spot-checks per reach. (a) Broad-leaved emergent, (b) narrow-leaved emergent (e.g. reeds, sedges, rushes, grasses and horsetails), (c) amphibious (i.e. marginal with trailing shoots / leaves) and (d) submerged macrophytes. Present: macrophyte is present but cover is <33%, Extensive: cover >33%.

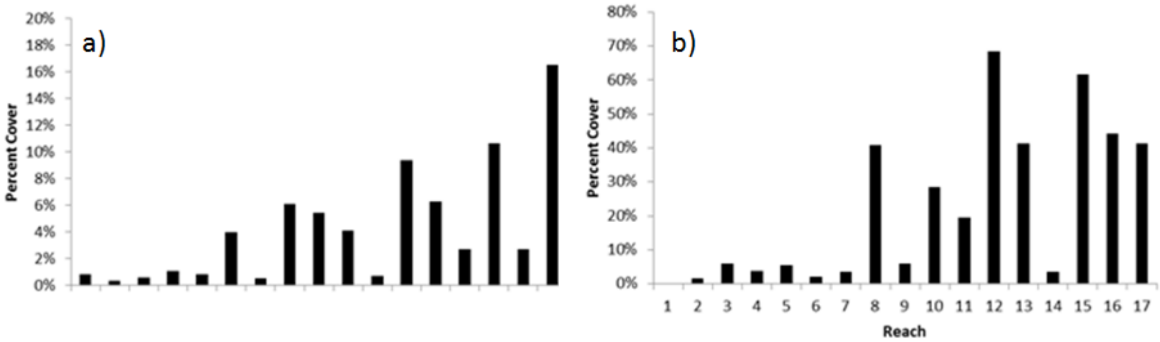


Figure 4.27 Average percent cover of (a) emergent and (b) submerged / floating-leaved aquatic vegetation identified in MTR surveys.

Figure 4.28 Patchy distribution of emergent macrophytes (mainly *Sparganium erectum*) and submerged macrophytes (mainly *Ranunculus penicillatus ssp. Pseudofluitans)* in a part of Reach 6

Table 4.24 Plants identified in the Mean Trophic Rank surveys, which record species growing within the channel. Species are classified by preferred habitat (channel or wetland). Type is the growth form or general taxonomic grouping of the species: Aquatic – rooted below waterline, Cyperacea – Carex species, Graminoid – Grass, Herb – herbaceous plant rooted above the waterline, Juncaceae – Juncus species, Wood – woody perennial, shrub or tree).

Species	Type
Channel	
Apium nodiflorum	Aquatic - Emergent
Callitriche obtusangula	Aquatic - Floating-leaved
Callitriche stagnalis	Aquatic - Submerged
Elodea canadensis	Aquatic - Submerged
Elodea nuttallii	Aquatic - Submerged
Glyceria maxima	Graminoid
Myriophyllum alterniflorum	Aquatic - Submerged
Myriophyllum spicatum	Aquatic - Submerged
Nuphar lutea	Aquatic - Emergent
Oenanthe fluviatilis	Aquatic - Emergent
Persicaria amphibia	Aquatic - Emergent
Potamogeton crispus	Aquatic - Submerged
Potamogeton lucens	Aquatic - Submerged
Potamogeton natans	Aquatic
Potamogeton pectinatus	Aquatic - Submerged
Potamogeton perfoliatus	Aquatic - Submerged
Ranunculus peltatus	Aquatic - Floating-leaved
Ranunculus penicillatus ssp. penicillatus	Aquatic - Submerged
Ranunculus penicillatus ssp. pseudofluitans	Aquatic - Submerged
Phragmites australis	Graminoid
Rorippa nasturtium-aquaticum	Aquatic - Emergent
Sparganium erectum	Aquatic - Emergent
Sparganium emersum	Aquatic - Emergent
Zannichellia palustris	Aquatic - Submerged
Typha latifolia	Aquatic - Emergent
Veronica beccabunga	Aquatic - Emergent
Wetland	
Cardamine sp.	Herb
Carex acutiformis	Cyperaceae
Carex pendula	Cyperaceae
Carex remota	Cyperaceae
Carex riparia	Cyperaceae
Carex sp.	Cyperaceae
Epilobium hirsutum	Herb
Epilobium sp.	Herb
Equisetum fluviatile	Herb
Equisetum sp.	Herb
Eupatorium cannabinum	Herb
Glyceria fluitans	Graminoid
Impatiens glandulifera	Herb
Iris pseudacorus	Aquatic
Juncus acutiflorus	Juncaceae
Juncus effusus	Juncaceae
Juncus inflexus	Juncaceae
Lycopus europaeus	Herb
Lythrum salicaria	Herb
Mentha aquatica	Herb
Myosotis scorpioides	Aquatic - Emergent
Oenanthe crocata	Aquatic - Emergent
Persicaria hydropiper	Herb

Species	Type
Petasites hybridus	Herb
Petasites sp.	Herb
Phalaris arundinacea	Graminoid
Rumex hydrolapathum	Herb
Salix sp.	Woody
Scrophularia auriculata	Herb
Stachys palustris	Herb
Stellaria sp.	Herb
Symphytum officinale	Herb
Veronica anagallis-aquatica	Aquatic - Emergent

4.5.5 Physical Pressures

(i) River Bed condition

How to characterise both armouring and clogging / burial, as well as artificial influences on bed condition, are described in section 5.5.5(i) of the D2.1 main report.

Information on bed armouring is not available for the Frome, but observations in Reaches 4, 5 and 6 revealed a firm gravel bed with individual particles often encrusted with algae. Fresh, apparently mobile gravel was largely restricted to locations where flow became confined by, for example, a wood jam. However, the widespread presence of fine sediment within and on the gravel (e.g. Figure 4.16) indicates that there is no genuine armour layer, rather the presence of largely immobile gravel because of the low energy of the river and thus its inability to mobilise the gravel.

Fine sediment is reported to be a significant problem (Environment Agency, 2011). Collins and Walling (2007) undertook a catchment wide survey of fine sediment storage in the river bed (bed clogging) and other research studies on particular reaches have investigated fine sediment accumulation and its dynamics (Cotton et al., 2006; Gurnell et al., 2006; Heppell et al., 2009). Collins and Walling (2007) took measurements in reaches 4 to 17 and also in the Tadnoll Brook and River Hooke tributaries. They found an average of 918 $g.m^{-2}$ of fine sediment stored within the gravel bed of the Frome, with extremes of 410 and 2630 $g.m^{-2}$. Through the use of sediment fingerprinting techniques, they attributed the fine sediment to the following sources: cultivated land – 70%, pasture – 18%, channel banks and subsurface sources (e.g. field drains) – 10%, woodland – 2% (reported in Punchard, 2013). This links closely with the assessment of land cover presented previously. Gurnell et al. (2006) found average depths of fine sediment deposited across the surface of the gravel bed at study sites in reaches 5 and 6 to vary greatly through time but with minimum and maximum reach average values of 0.2 cm and 4.0 cm. Surface accumulations were particularly high within emergent macrophyte stands where average depths of fine sediment varied from 3 to 4 cm in early spring to over 8 cm in August. Heppell et al. (2009) report that fine sediment storage varied between 11.6 and 66.8 kg m^{-2} at a site in Reach 4 in monthly measurements over a 2 year period. The majority of this sediment was found within submerged macrophytes growing in the middle of the channel, particularly within patches of *Ranunculus* sp.

The proportion of the bed of the River Frome that is artificially reinforced is extremely low. On average only 0.42% of RHS survey spot checks reported artificial bed material (Table 4.20). Reach 2 has the greatest proportion of observations of an artificial bed (12% of spot-check locations) and artificial bed material was only noted in one other reach (Reach 1).

Figure 4.29a indicates numerous blocking structures on the Frome (the greatest number of blocking structures is found on Reach 10, which flows through the town of Dorchester), but they are predominantly low impact sluice gates that control flow into and out of side channels. There are 4 weir structures rated as having an intermediate impact on water and sediment transport. When represented as the number of structures per river length, Reach 4 has the greatest number of blocking structures (6.6 per km) due to the large number of sluice gates and weirs in the village of Maiden Newton (Figure 4.29b).

No quantitative data is available on the removal of sediment, wood or aquatic vegetation from the active river channel. In the past, the Environment Agency operated a policy of aquatic vegetation (i.e. weedcutting) and wood (i.e. obstruction) removal, but their programme of river maintenance works lists only obstruction removal for the 2013-2014 operations year[14].

a)

b)

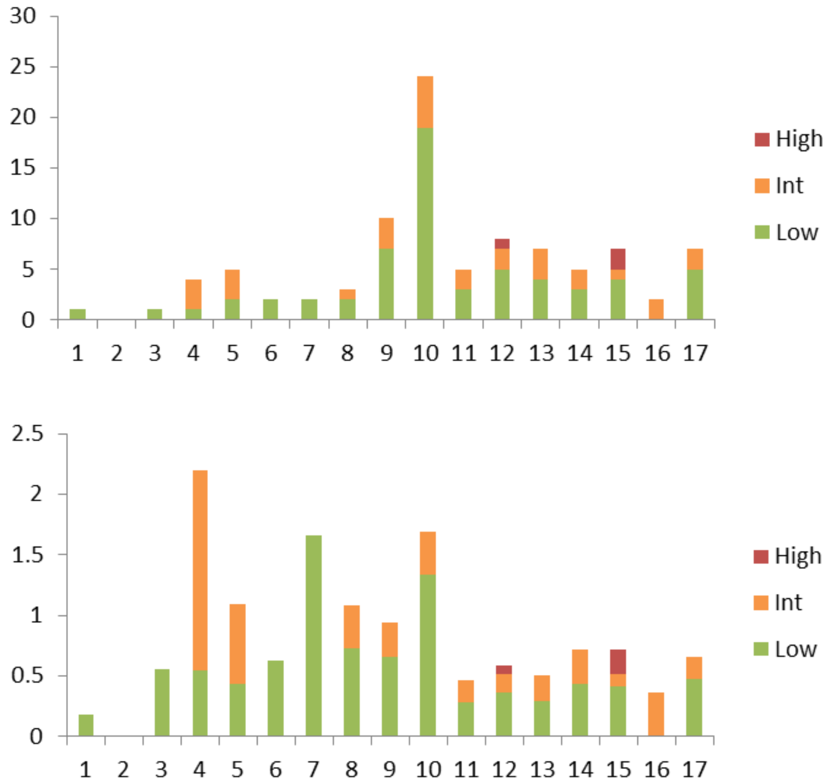


Figure 4.29 (a) The total number of blocking structures and (b) the number per kilometre of river in each reach by level of impact (low, intermediate or high).

(ii) River Bank condition and processes

A variety of characteristics of river bank condition and processes are listed in section 5.5.5(ii) of the D2.1 main report, of which the following were evaluated for the Frome.

The banks of the River Frome are predominantly composed of natural material (Figure 4.17). On average only 3% of RHS survey spot checks reported 'hard'-reinforced banks. Reach 10 has the greatest proportion of reinforced banks (6.15% of spot check locations). Reinforced banks were reported in all except Reaches 7 and 16. Of the banks

[14] River and coastal maintenance programmes 2013-2014. The Environment Agency. http://www.environment-agency.gov.uk/homeandleisure/floods/109548.aspx. Accessed on 8-July-2013.

with 'hard'-reinforcement, the majority were composed of brick (55%) or concrete (24%).

Banks with 'soft' reinforcement (i.e. bioengineered banks) are not recorded in RHS surveys, so this characteristic could not be assessed without conducting field surveys.

Embankments on the banktop were identified at 14 out of a total of 2380 spot-checks (0.6%). All were noted in the mid to lower sections of the Frome, with the greatest number (6) found in Reach 13.

No set-back embankments were noted in the RHS surveys on the River Frome.

On average only 6% of the river has infrastructure within 0.5 bankfull width of the channel. The reaches with the highest occurrence of infrastructure near the channel are located in Landscape Unit 2, particularly within and around the town of Dorchester (i.e. Reach 10) (Figure 4.30).

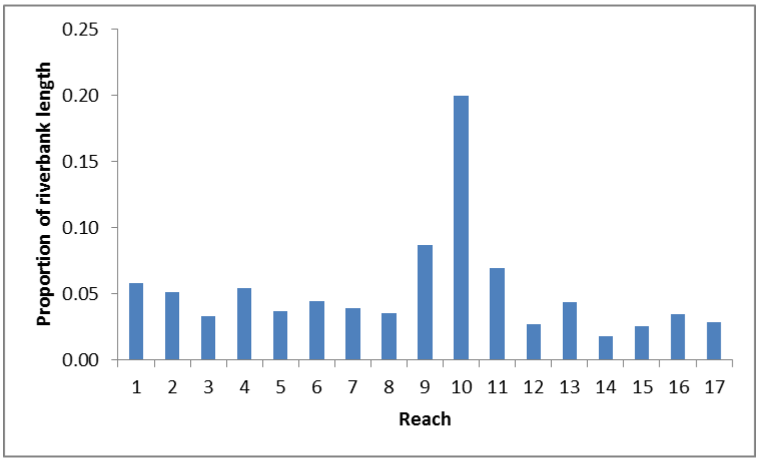


Figure 4.30 Proportion of the riverbank length with infrastructure within 0.5 bankfull width of the channel by reach.

The total proportion of potentially erodible channel margin was calculated by combining the RHS spot-check data on artificial banks and embankments with the ArcGIS analysis of river bank length with nearby infrastructure. Due to the imprecise nature of the RHS spot-check locations (survey start locations are accurate to 100 m, and individual spot-check location and bank data are not recorded), it was difficult to determine which spot-checks corresponded to the river length data (location accurate to 1m). Therefore, a conservative estimate was generated by multiplying the proportion of spot-checks with artificial banks or levees in each survey by the survey length (500 m) and adding it to the river length data (Figure 4.31). The pattern by reach is similar to the inverse of Figure 4.30, except with lower values for several of the reaches (e.g. Reach 1 dropped by 0.057 with the inclusion of the RHS data).

The proportion of actively eroding channel margin is estimated from RHS spot-check data on bank features. The survey records the presence of bank 'cliffs' that are taller than 0.5

meters, and notes whether they are stable or eroding. Eroding bank cliffs were reported at 53 spot-checks and stable cliffs at 154, accounting for 2 and 7% of spot-checks conducted on the River Frome. Eroding banks were rarely reported along the river, and the most numerous were identified on the meandering Reach 5 (5% of spot-checks) (Table . This dataset gives an indication of the proportion of actively eroding margins, however it shows far lower values than were observed during field surveys of three sites within reaches 4, 5 and 6, where field surveys were undertaken. Here, 23, 40, and 0% bank length was eroding in the surveyed parts of Reaches 4, 5 and 6, respectively. Further RHS data shows that vertical and vertical with toe bank profiles are the dominant bank profile and are extensive in all reaches, which are profiles suggestive of active or recent bank erosion.

The width of the erodible corridor is classified as wide for all reaches (> 10 bankfull width) (Figure 4.31b). It is lowest for Reach 3 because of the railway embankment that cuts across the floodplain (10.6 times river width), and is widest in Reach 12 (38). The erodible corridor extent was based initially on the extent of the floodplain and corrected for the presence of infrastructure that would impact the mobility of the river.

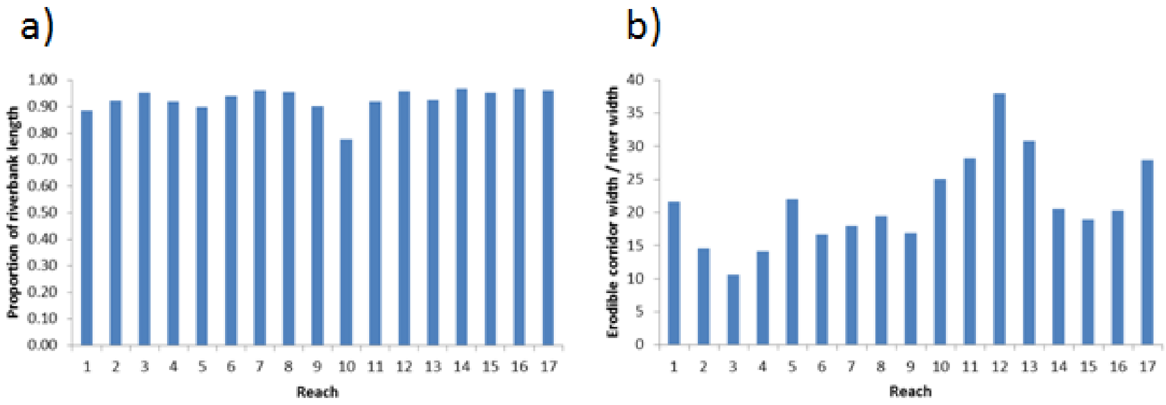


Figure 4.31 (Left) Proportion of potential erodible channel margin and (Right) the width of the erodible corridor as a function of average channel width by reach.

Table 4.25 The proportion of RHS spot-checks with eroding cliffs (eroding banks > 0.5 m high), and the proportion of RHS reaches with extensive vertical or near-vertical bank profiles.

LU	Segment	Reach	Eroding cliffs	Extensive vertical bank profile	Survey (n)
1	1	1	2%	87%	15
	2	2	0%	100%	1
		3	4%	80%	5
		4	4%	67%	3
2	3	5	5%	91%	11
		6	0%	100%	3
		7	3%	75%	4
	4	8	0%	60%	5
		9	1%	94%	8
	5	10	1%	94%	9
		11	2%	100%	3
3	6	12	1%	56%	9
		13	3%	72%	16
		14	0%	83%	6
		15	3%	91%	11
		16	4%	90%	5
		17	3%	100%	5

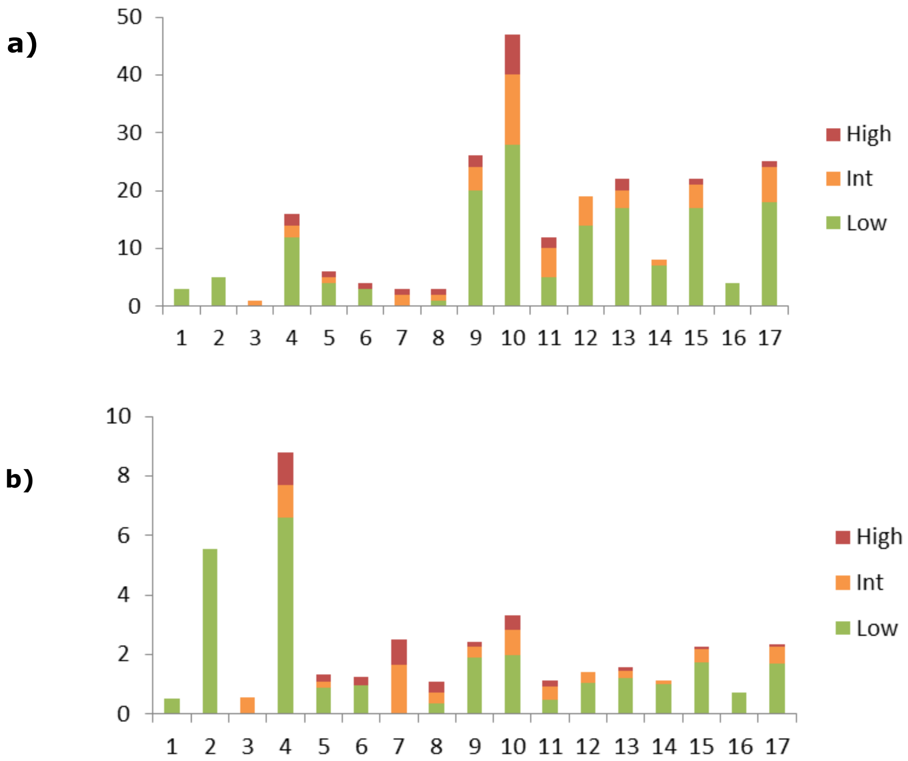


Figure 4.32 (a) The total number of spanning structures and (b) the number per kilometre of river in each reach by level of impact (low, intermediate or high).

(iii) Riparian corridor connectivity and condition

There are numerous spanning structures along the River Frome (Figure 4.32a) but they are mostly low impact pedestrian or rail bridges. There are 12 medium and 7 high impact spanning structures, predominantly road bridges with abutments that extend into the channel and/or have central piers. When represented as the number of structures by river length, Reach 4 has greatest number of spanning structures (8.8 per km) due to the large number of bridges spanning the two channels in the village of Maiden Newton and the short length of the channel (Figure 4.32b).

Characteristics to describe the riparian corridor connectivity and condition are listed in section 5.5.5(iii) of the D2.1 main report.

On the Frome, all areas of the potential riparian corridor are accessible by floodwater. The floodplain was delineated based on the flood extent of the 1 in 100 year flood, which was the only flood extent information available, and incorporated the impacts of rail and road embankments on the lateral extent of the floodplain.

The riparian corridor was defined as the maximum extent of naturally functioning riparian vegetation within this floodable area. Only a small portion of the potential floodplain was excluded due to embankments: 8.0% in Reach 3, 0.76% in Reach 16 and 3.2% in Reach 17. Any vegetation in these excluded areas would have been part of the riparian corridor prior to the construction of the railway line in the 19th century, but these areas are no longer inundated by floodwater. Currently, though, no riparian vegetation is growing in these areas (total area: 10.5 ha, 0.5% of floodplain area).

It is not possible to estimate the proportion of the active channel margin and riparian corridor under riparian vegetation that is subject to management. Woodland patches are generally small and disconnected, and, in the authors' experience, lightly managed. Satellite imagery and LiDAR data could potentially be used to assess this characteristic, however field surveys would be necessary to identify areas of intense woodland management and to calibrate any automated (or semi-automated) analytical processes.

Abundance of alien, invasive plant species can be estimated from RHS survey data, which shows that over half of all surveyed sites have at least one of the three most common invasive species present (55%). The survey records the presence of giant hogweed (*Heracleum mantegazzianum*), Japanese knotweed (*Fallopia japponica*), and Himalayan balsam (*Impatiens glandulifera*), all of which were identified at least once on the River Frome (Figure 4.33). Reaches in Landscape Unit 1 had the lowest occurrence of invasive species, with invasives present at none of the survey sites in Reaches 1-3 and 33% in Reach 4. Invasive species were present at all reaches in Landscape Units 2 and 3 with the exception of Reaches 16 and 17. Himalayan balsam was the most common invasive species, present (<33% bank cover) at 48% of surveys and extensive (≥ 33% bank cover) at 3%.

Impervious surfaces cover a small proportion of the River Frome floodplain area (Figure 4.34). On average, only 2% of the floodplain is covered by buildings, roads or other man made surfaces (e.g. tarmac). The greatest cover of impervious surfaces is found in Reaches 9 and 10, caused largely by transport infrastructure (Reach 9) and the town of Dorchester (Reach 10). The lowest proportion of impervious surfaces was in Reaches 2 and 3 and all reaches within Landscape Unit 3, where less than 1% of the floodplain area is covered by impervious surfaces.

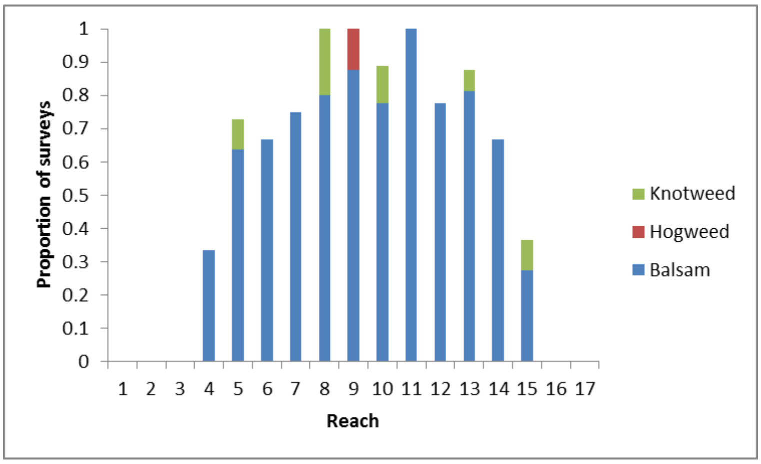


Figure 4.33 The proportion of RHS surveys that reported the presence of 3 of the most problematic invasive plant species: Giant hogweed, Japanese knotweed, and Himalayan balsam.

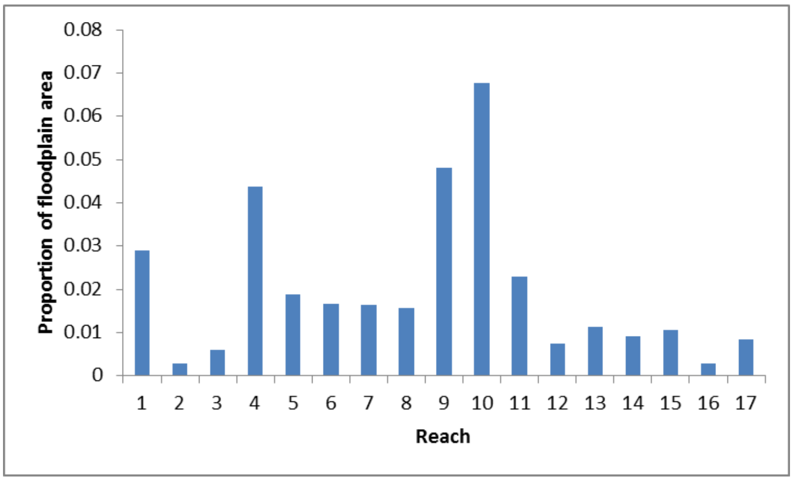


Figure 4.34 Proportion of the floodplain area covered by impervious surfaces, including buildings, roads and other manmade surfaces.

4.6 Channel and floodplain geomorphic units

An assessment of channel and geomorphic units was conducted using a combination of River Habitat Surveys and historical aerial photographs from Google Earth to extract the characteristics listed in section 5.6 of the D2.1 main report.

4.6.1 Geomorphic units within the bankfull channel

(i) The river bed

As inferred from RHS flow types, glides and runs, indicative of a relatively featureless bed, were present at 95% of the RHS spot-checks (Figure 4.35). Glides, which are typically associated with smooth, near-laminar, flow over a relatively featureless bed, accounted for 55% of spot-checks; runs, which are typically associated with a rippled water surface, accounted for 40% (N.B. RHS surveys are undertaken during 'normal' or baseflow conditions). Pools and riffles, as inferred from the flow types 'no perceptible flow' and 'unbroken standing waves' respectively, were observed at only 2% and 4% of the spot-checks on average, showing a much lower frequency than would be expected for a gravel-bed river, although RHS defines these features quite restrictively. There also appears to be little variation in bed configuration between reaches, although there was a slight increase in runs and glides with distance downstream, corresponding with a decrease in riffles. Riffles and pools are also expressed as a reach count within the RHS (Figure 4.36) and, as would be expected, riffles are more common in headwater reaches with a relatively steeper slope, although pools did not show the same pattern.

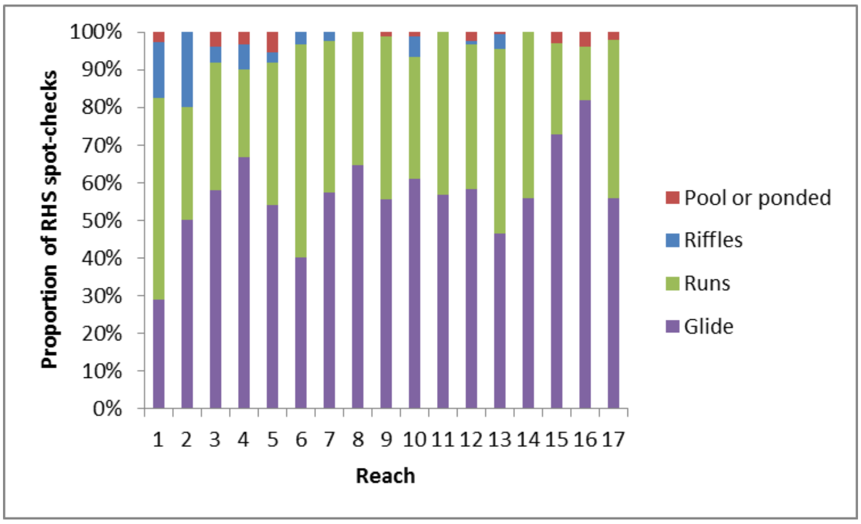


Figure 4.35 RHS flow types reported as the proportion of spot-checks and used to infer bed configuration

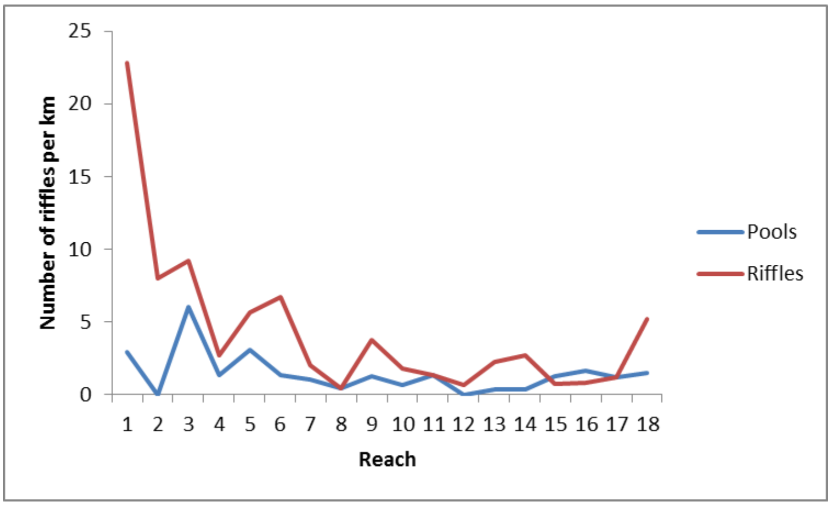


Figure 4.36 Average number of riffles and pools identified in RHS reaches and scaled to kilometre of river. The total number of riffles and pools was visible in each study reach was recorded additionally to flow types.

(ii) Depositional emergent sediment features

The analysis of emergent sediment features was conducted using two data sources, RHS and aerial imagery. RHS reports the number of islands, bars and vegetated bars in a survey. The average numbers were calculated per survey reach and scaled to km to yield the number of features per km. This analysis found the greatest number of channel geomorphic features in Reach 5, and the lowest (0) in Reaches 4, 11, 16 and 17 (Figure 4.37). Reach 1 had the greatest number of unvegetated bars, Reach 9 vegetated bars and Reach 7 islands. Note: only bars composed of coarse-grained sediment are recorded in RHS.

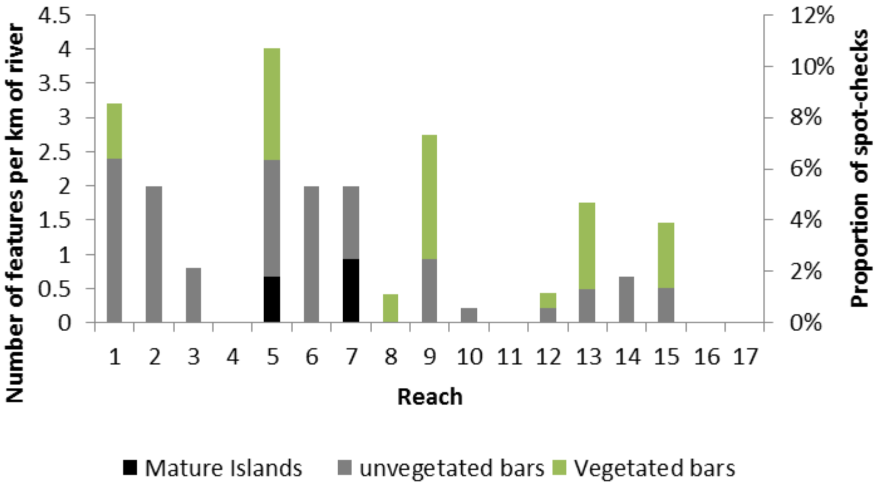


Figure 4.37 The number of vegetated and unvegetated bars (point, side and mid-channel) and mature islands identified in RHS per kilometre of river and as the proportion of spot-checks.

A second analysis using historical Google Earth Imagery (2002, 2005, 2008 and 2009/20) and supported by OS maps found the greatest number of emergent channel features in Reach 13, but the greatest number per km of river in Reach 5 (Figure 4.38). Vegetated sediment features were the most commonly identified and comprised 56% of all features identified on the river. The lower reaches are dominated by vegetated bars, particularly vegetated point/side bars. Reaches in the upper and middle Frome had the highest number of islands and mid-channel vegetated bars. The lack of data for Reaches 1 and 4 is caused by the difficulty observing features due to the narrow channel widths and the presences of riparian vegetation obscuring the channel. Figure 4.39 illustrates how geomorphic features can be identified from successive aerial images, and how they can induce changes in channel width and planform over time

The results from the two data sources show little similarity, with the exception of Reach 5 (Figures 4.37 and 4.38b). Unvegetated bars appear to be under-represented by the aerial imagery analysis as compared to RHS. The most likely reasons for this are the timing of aerial images in relation to river levels (i.e. bars were submerged) or the presence of overarching riparian vegetation.

Not represented in the above results is a general trend of encroachment of the channel by vegetation in the middle reaches. The channel visibly narrowed over the time series of aerial images in Reaches 11-14. Whether this is due to changes in land management (i.e. exclusion of grazing of the riparian zone) or an artefact of the data is not clear. We do not have exact dates for the aerial images, and it is possible that the more recent images were taken at later times in the year and thus would have greater macrophyte cover or lower river levels. For example, Figure 4.40 shows encroachment of the channel by marginal vegetation in a meander bend of Reach 12.

Finally, it is worth pointing out that neither data source identified geomorphic units in Reach 4. This reach has dense riparian vegetation bordering the channel, so aerial imagery was unsuitable. A field survey was conducted in this reach in September 2013 and numerous vegetation- and large wood-induced sedimentary features were found in the channel.

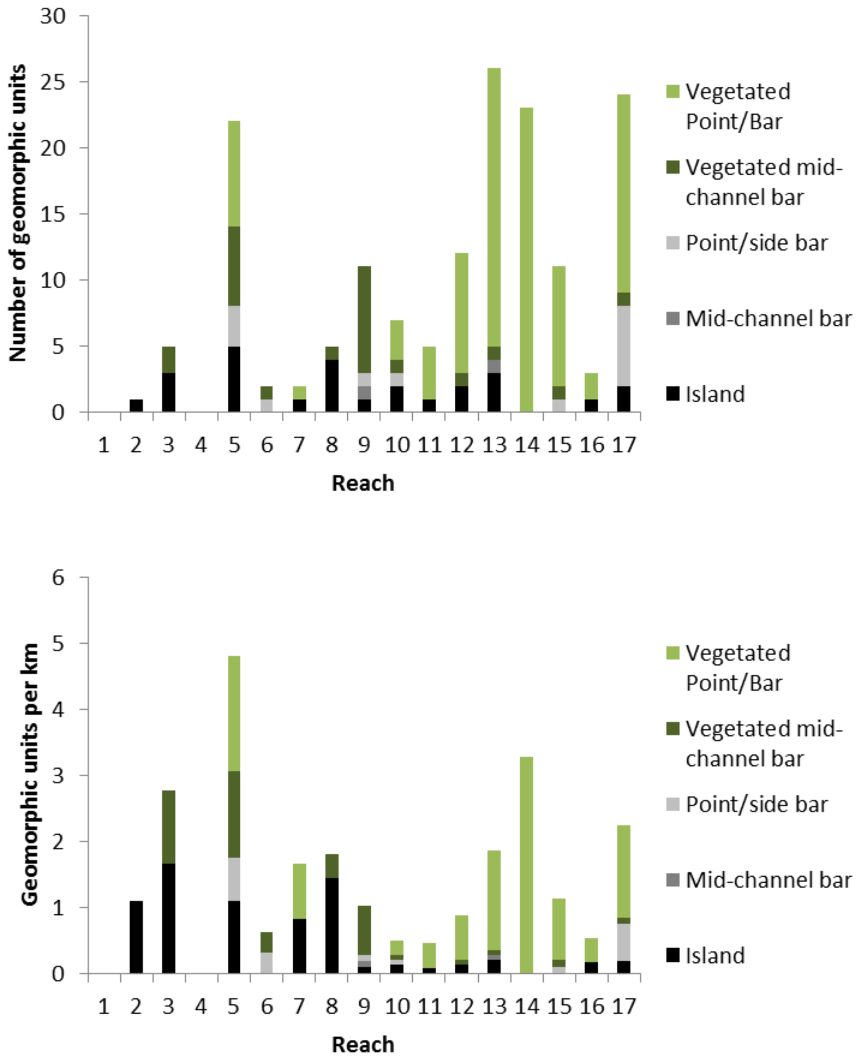


Figure 4.38 Channel geomorphic features identified from Google Earth imagery, (top) total number per reach and (bottom) features per km of river. Note: the lack if geomorphic features in Reaches 1 and 4 is related to the small size of the channel and the presence of riparian vegetation that obscures the channel.

Figure 4.39 Vegetated sedimentary features within the channel in Reach 14 identified from successive aerial images, which have resulted in planform change (© Google Earth, Getmapping, Infoterra and Bluesky).

Figure 4.40 Encroachment of the channel by marginal aquatic vegetation in Reach 12. (© Getmapping, Infoterra and Bluesky).

(iii) Large wood and vegetation induced bars, benches and islands

Field surveys are needed to fully identify large wood and vegetation induced bars, benches and islands, particularly in small river channels that are well-shaded by trees. The RHS data presented earlier on large wood and fallen trees provides some information of the potential for wood-induced geomorphic features (Figure 4.25). Moreover, many of the bars reported in the RHS dataset (Figure 4.37) and probably all of the vegetated bars from the aerial image analysis, which account for over half of all sedimentary features identified (Figure 4.38) are likely related to aquatic or riparian vegetation.

Figures 4.41 – 4.48 show examples of vegetation-induced emergent sedimentary features found in Reach 4. Reach 4 was previously straightened and in some places its banks were reinforced. Riparian vegetation has been left to grow since at least the early 1970s, and has contributed to the formation of abundant and diverse geomorphic features.

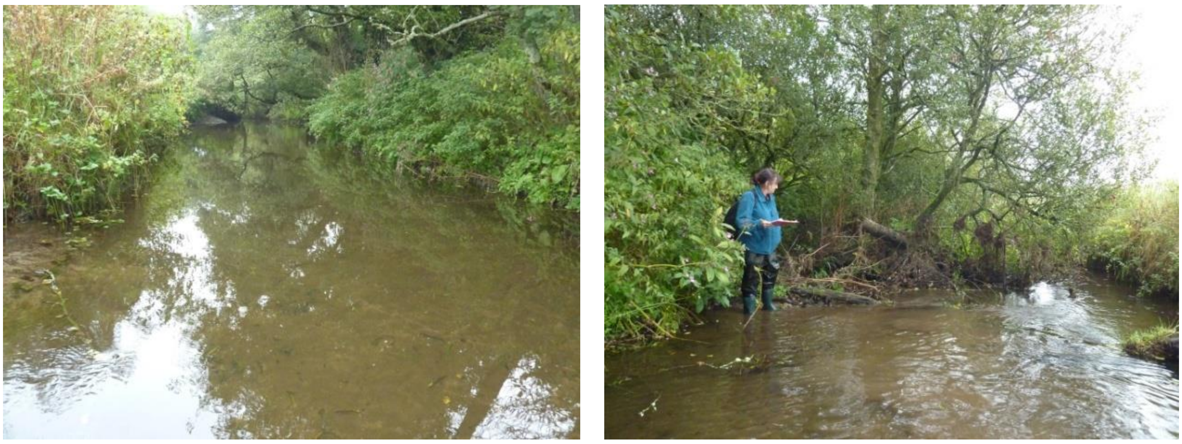


Figure 4.41 The River Frome in Reach 4. Left: Photo facing upstream towards a section of river with limited influence by riparian vegetation and large wood. Note: the channel is shallow and has a thick and uniform covering of fine sediment over the gravel bed (channel is *ca.* 5 m wide). Right: Facing downstream at the same location towards a section with natural riparian vegetation that is interacting with fluvial processes. Note: the large wood and tree jam on the left bank that is narrowing the channel and directing it towards the right bank. A riffle composed of clean gravel/cobbles has formed in the narrowed channel.

Figure 4.42 Left: A large wood jam complex. Note: flow is directed to the left bank producing high flow velocities and scouring a pool. Right: Fine sediment deposition downstream of the wood jam on the right bank.

Figure 4.43 Gravel bar formed downstream of a living tree branch that is in contact with the river bed. Note: the reduced channel width on either side of the bar has increased flows and produced riffles (Photo facing upstream).

Figure 4.44 A vegetated bar (incipient island) that developed as follows: submerged *Ranunculus* sp. patch accumulates fine sediment (sand and silt), other aquatic vegetation colonise the nascent bar and induced further fine sediment accumulation (dark fine sediment layer) (Photo facing downstream).

Figure 4.45 Bench on left bank downstream of large wood and above and lateral to a living riparian tree (Photo facing upstream).

Figure 4.46 Ridged bench structures formed downstream of riparian trees and wood jams. Left: Bench with scroll-like forms on its surface on the left bank of the river. Right: A separate bench further downstream with multiple scroll-like forms on the left bank. The photo is facing upstream and the river is to the left of the picture (Photos facing upstream).

Figure 4.47 Two depositional forms induced or stabilised by vegetation. In the lower portion of the photo, a small vegetated bar is visible within a *Ranaunculus* stand. In the upper portion of the image, a ridged bench has been stabilised by vegetation, and fine sediment behind the ridge has been scoured to form a small vegetated island (Photo facing downstream).

Figure 4.48 a) a log jam accumulated around branches of a tree that have rooted into the river bed and then sprouted to produce a shrub and wood reinforced island in the middle of the river channel; b) a tree growing within the edge of the channel with roots forming an obstruction across the channel bed; c) roots from trees growing in the channel edge stabilising a bar-bench of fine sediment; d) tree trunks and branches rooting into the channel bed and stabilising a bar-bench of fine sediment

4.6.2 Marginal and bank features

RHS data was used to investigate bank profiles. Bank profiles are recorded during the sweep-up phase of the survey, and profile types are recorded as being present (present but <33% of riverbank length) and extensive (>33%) for the left and right bank independently. The data for each bank were combined and are reported as the percentage of surveys reported as present or extensive for each profile type and reach.

A vertical profile was the most commonly identified profile type, and was reported as extensive for 81% of the surveys and present for 12% (Figure 4.49). Steep planar was the second most commonly occurring bank profile, and was reported extensive at 18% of the sites and present at 42% (Figure 4.50). A gradual planar bank profile was present at 51% and extensive at 2% of the sites, and was locally extensive in Reach 7. A vertical with toe bank profile was rarely identified, and was only found to be extensive in surveys within Reaches 5 and 13. Complex bank profiles were present in only 1% of sites. Figure 4.51 shows example of steep bank profiles in Reaches 5 and 6.

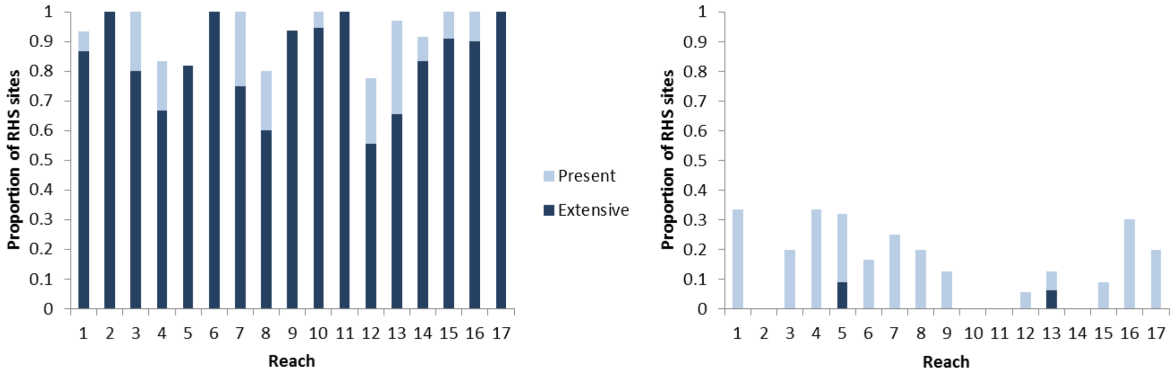


Figure 4.49 The proportion of RHS surveys where a vertical (left) or vertical with toe bank profile (right) was present or extensive by reach.

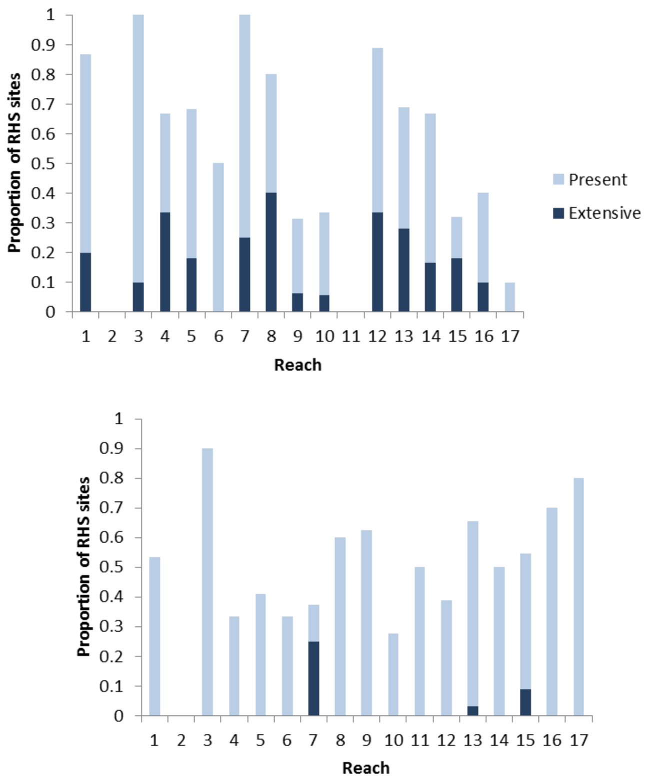


Figure 4.50 The proportion of RHS surveys where a steep planar (left) or gradual planar profile (right) was present or extensive by reach.

Figure 4.51 Examples of steep bank profiles in Reaches 5 and 6

4.6.3 Floodplain units

Floodplain geomorphic units were initially investigated using aerial imagery from Google Earth and historical topographic maps. Features identified in one source (e.g. location of a wetland or oxbow in a historical map) were confirmed in the other source (e.g. difference in vegetation structure between the oxbow and surrounding land). Only features that were confirmed to be induced by fluvial processes were included, with the exception of former land drains that were flooded in aerial imagery creating backwater habitat.

Wetlands associated with abandoned channels were the most common type of floodplain geomorphic unit, and comprised over 50% of features recorded (Figure 4.52). The second most abundant type was wetland associated with oxbows (33% of features). Floodplain geomorphic features were more abundant in the mid to lower Frome, with the greatest number found in the meandering, single-thread Reach 17. Overall, the floodplain contains few geomorphic features other than the anabranches (natural or otherwise) identified in the reach-scale assessment. The geomorphic units that were identified from the aerial imagery were small in size relative to the floodplain area.

To explore whether additional features were present that were not identifiable from maps and colour aerial images, DEMS derived from Lidar surveys were also inspected. These revealed more widespread remnants of old channels, including major channel shifts as well as cutoffs, including ox bows, and scrolls left by channel migration (see Figures 6.1, 6.2 and 6.3). These very subdued features, suggest that the geomorphic features identified from the map and image sources are actually more widespread, but because of their subdued nature they have little effect on floodplain morphology.

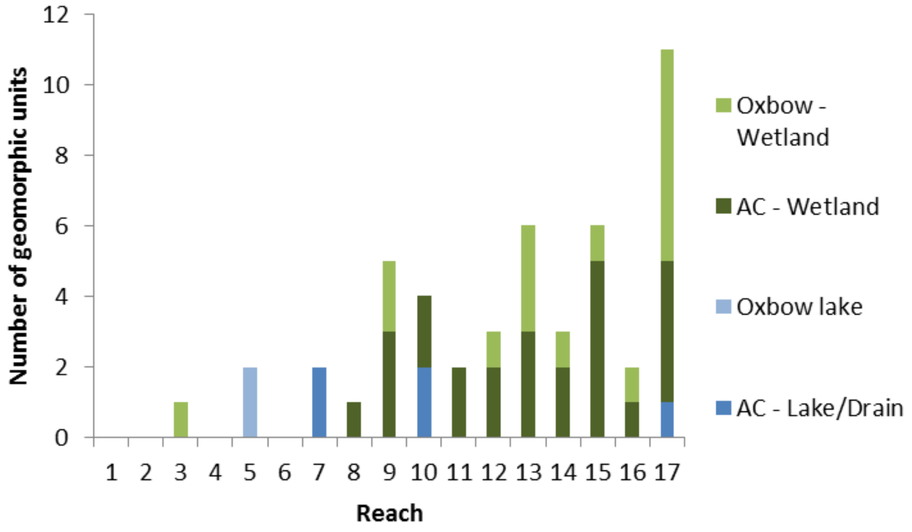


Figure 4.52 The number of floodplain geomorphic features per reach identified using aerial imagery, including abandoned channels (AC) and oxbows that are functioning as wetlands or open water (lakes, backwaters).

5. Characterising temporal change in spatial units

5.1 Introduction

This section provides an overview of changes that have occurred in hydromorphology in the River Frome over approximately the last century. The structure follows that of Section 6 in D2.1, in which similar characteristics are grouped together and presented at their largest relevant spatial scale. The specific indicators that are extracted from this analysis for the assessment of river condition are presented in Section 7.

5.2 Catchment and landscape unit

5.2.1 Topography and coarse sediment production

The River Frome is a lowland catchment with no significant sources of coarse sediment. Coarse sediment production may have changed over time as a result of land cover and land use changes. Palaeo work in other catchments in Britain has shown that sediment production has high in the medieval period because of changes in agricultural practices and deforestation; however evidence does not suggest that this was sediment was delivered to the channel in large quantities in chalk catchments (Lewin, 2010).

5.2.2 Land use

Information on changes in land cover and land use can be obtained from several sources, both cartographic and statistical. Based on a comparison of the 1889 and 2013 Ordnance survey maps, land cover has changed minimally at the catchment scale over the last 100 years; though there has been an expansion of urban areas, particularly the town of Dorchester. The Frome catchment was and remains a rural catchment. According to the 2006 CORINE dataset, land cover is predominantly associated with agriculture (86%). To explore changes in land use that could impact soil and runoff production, the June agricultural census was used to track changes in the amount of arable land, permanent grasslands and rough pastures, as well as the number of livestock in the catchment. Estimates are only available at the county scale, and are used to infer changes within the Frome catchment. This is a reasonable approach as the Frome catchment comprises a substantial portion of the county (18%) and elevation, land cover and land use are similar within the catchment and in the rest of Dorset.

At the county level, total agricultural area has remained unchanged over the past 100 years at approximately 2000 km^2, which encompasses approximately 75% of the area of Dorset (Figure 5.1). Decreases in the area of permanent grassland and rough pasture are evident over the time series. The area of arable land fluctuated in the early 20th century, but increased to account for half of the agricultural area by the 1960s. Figure 5.2 clearly illustrates the switch from low-intensity agriculture (grasslands and pastures) to high-intensity, tilled agriculture that has occurred over the last century. County-level agricultural statistics also provide information on the total area of arable land under cultivation for different crop types. Examples are provided for selected cereals and root crops (Figure 5.3). The area of agricultural land under cultivation for cereals decreased during the early part of the 20th century, increased during WWII, and then increased dramatically in the late 20th century, first with barley production and then wheat (Figure 5.3a). The area under root crops used for fodder decreased to zero over the first half of the 20th century, whereas potato cultivation was historically low, but peaked during WWII (Figure 5.3b).

To complete this picture, crop yields are needed to investigate if the intensity as well as the type of agricultural production has changed over this time period. Unfortunately, crop yields are not available on a county basis. Country-level crop yields, though, demonstrate that the amount of wheat and barley produced per hectare of land increased dramatically from the 1930s (Figure 5.4a). The increase in yields for cereal crops at the national-scale was accompanied by an increase in the area under cultivation (Figure 5.4b) that exhibited similar temporal trends to the Dorset County dataset (Figure 5.3a). Crop yields in the Frome catchment would have likely seen a similar trend in crop yield, as the modernisation of agricultural practices that produced this increase in crop yield would have been adopted over the country, albeit at slightly different times. The statistical data strongly suggest that the Frome catchment would have experienced an increase in the amount of land under tilled agriculture along with an intensification of agricultural production.

Livestock numbers have also changed substantially over time in Dorset (Figure 5.5). Total livestock numbers were high in the early 20th century, declined until the 1950s, then increased to a maximum in 1995 and have since declined. Sheep were the dominant livestock in the early 20th century; however numbers declined markedly and were surpassed by cattle in the 1940s. The cattle numbers reached a high in 1975 and have since declined to a similar level as sheep. Grazing by cattle and sheep influences vegetation cover and biomass and as a result impacts fine sediment production. Cattle accessing the river for drinking water (i.e. poaching) has been identified as a major source of bank degradation, and thus fine sediment input, for chalk rivers such as the Frome. The recent increase in the number of pigs may also be associated with an increase in outdoor breeding, which releases significant quantities of fine sediment.

Recent changes in land use between 1990 and 2007 show a fluctuation in the area occupied by arable crops and pasture, likely reflecting market forces, and little change in other land use types (Figure 5.6).

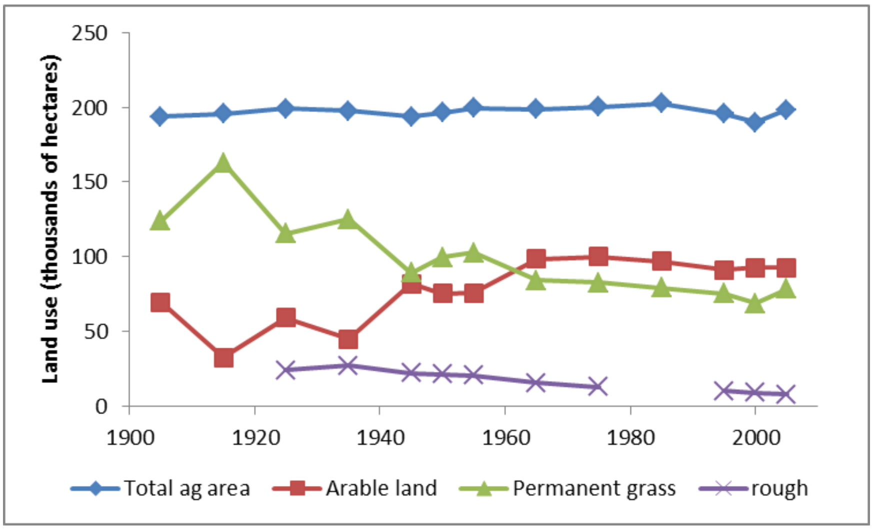


Figure 5.1 Agricultural land use for Dorset obtained from the June agricultural census

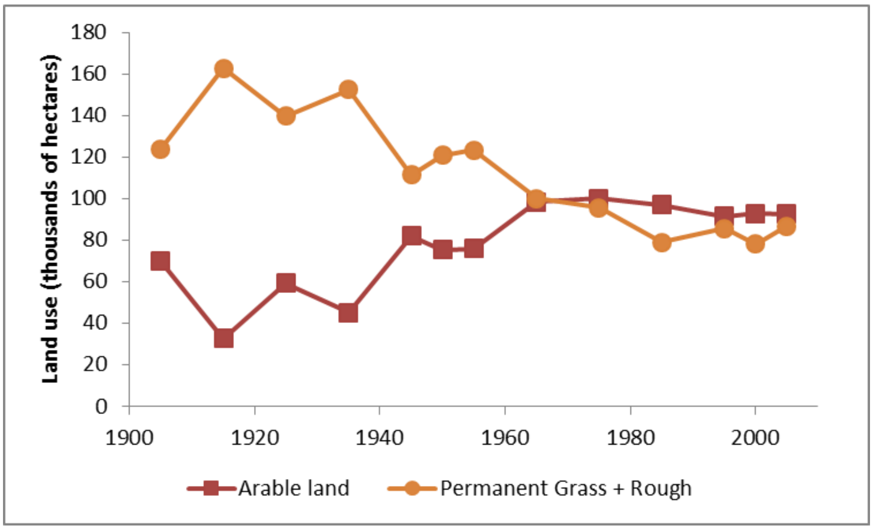
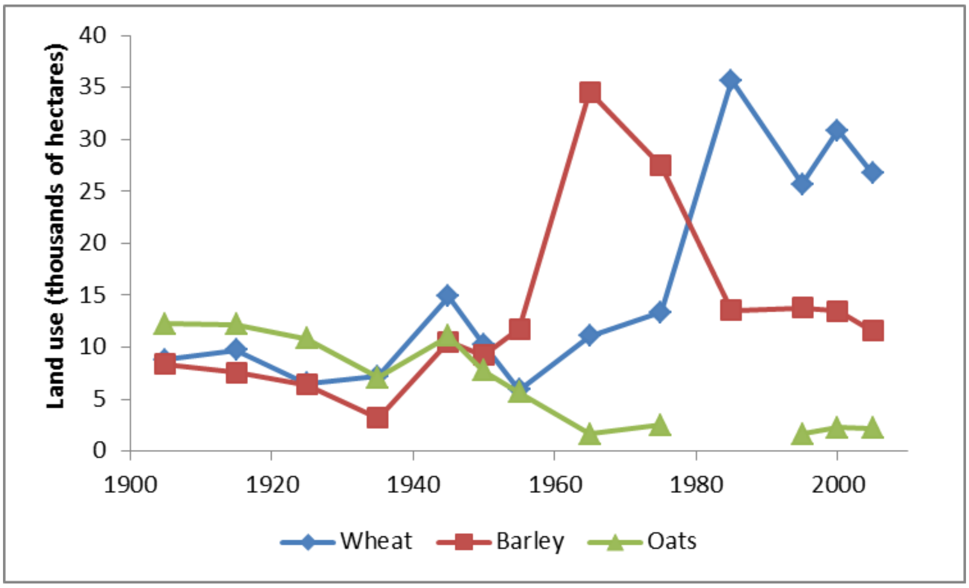


Figure 5.2 Agricultural land use for Dorset, comparing the amount of arable land and grass / pasture

a)



b)

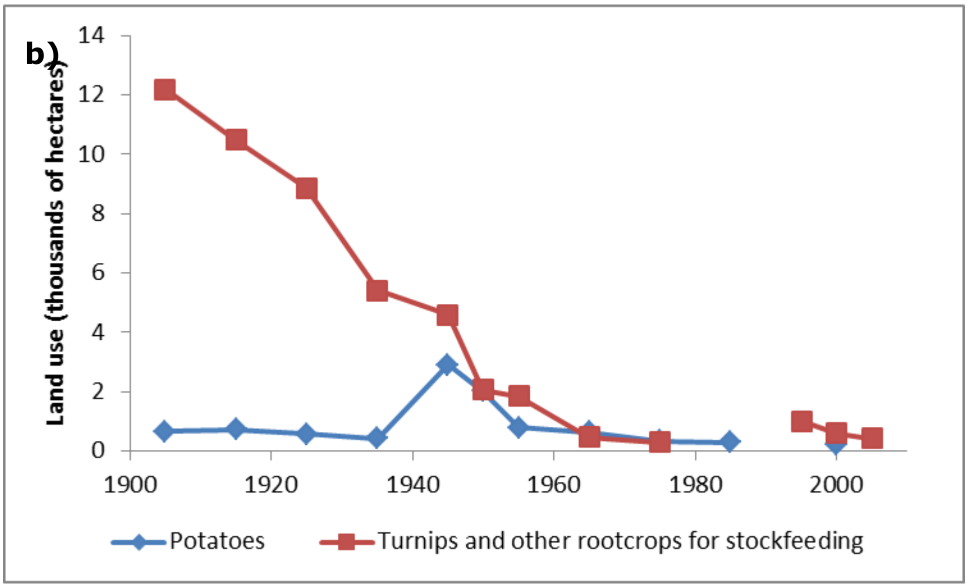


Figure 5.3 Area of agricultural land under cultivation for (a) cereals and (b) root crops for Dorset.

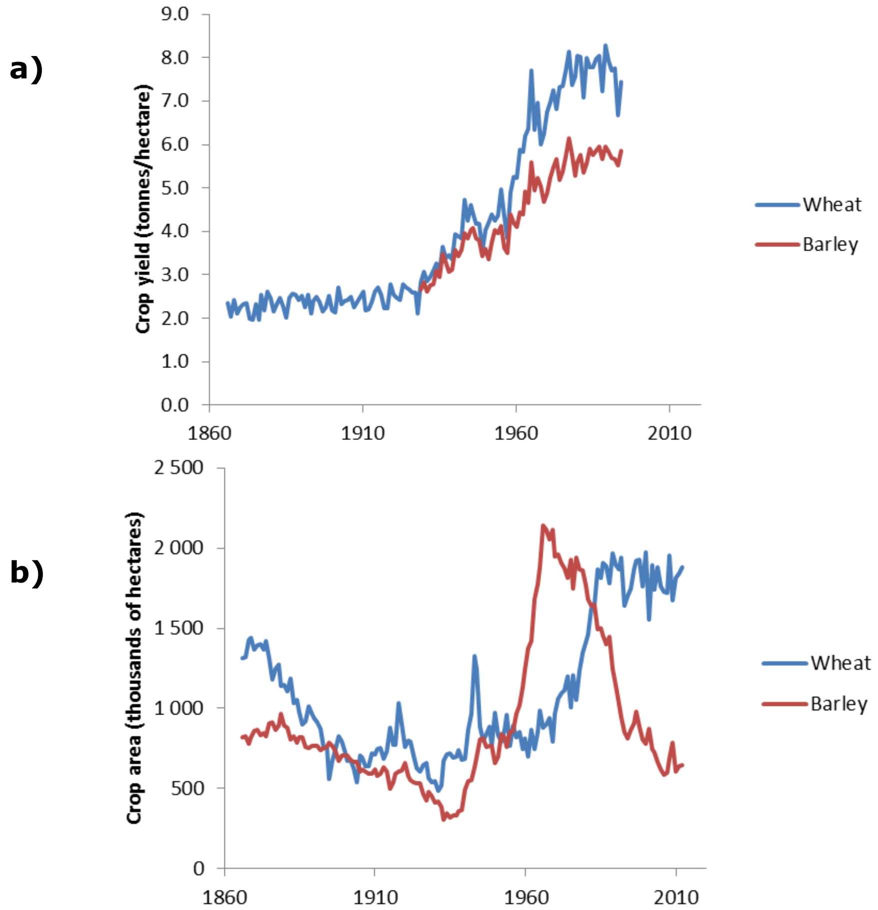


Figure 5.4 (a) Crop yield and (b) crop area and for the two major cereals in England and Wales over the last 150 years.

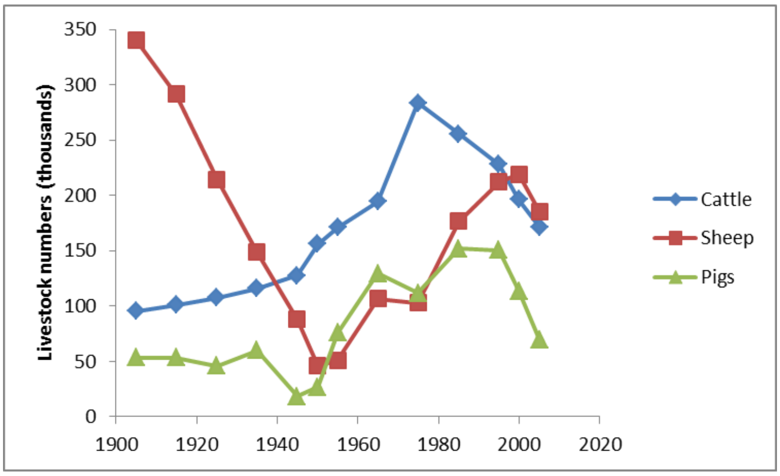


Figure 5.5 Historical livestock numbers for Dorset obtained from the June agricultural census

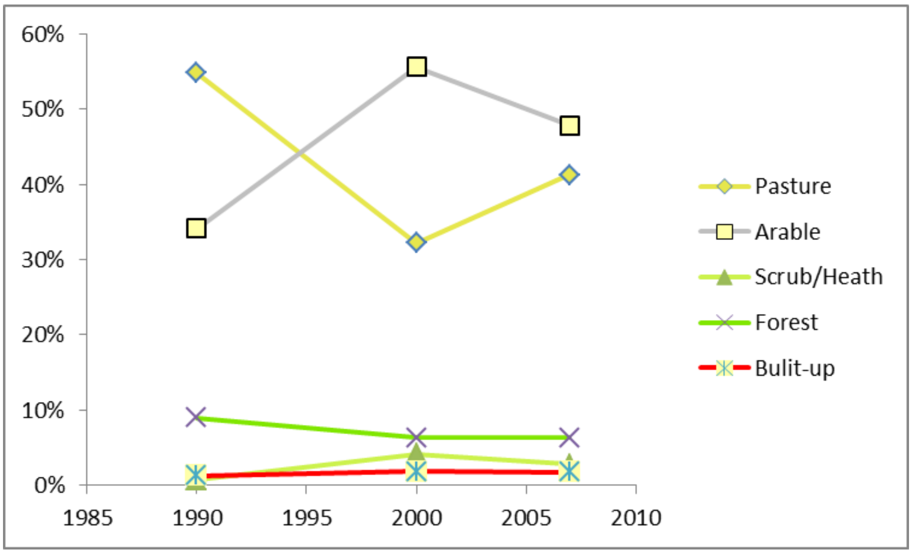


Figure 5.6 Recent changes in land cover according to the UK Countryside Survey for the Frome catchment

5.2.3 Rainfall and groundwater abstraction

No significant change in rainfall is detected in the precipitation gauging station records for either annual or maximum monthly rainfall (Figure 5.7). Similarly there is no significant change in run-off ratio over time, as estimated from the Yeovilton rainfall gauge time series and the East Stoke river gauging station records (Figure 5.8). Runoff ratios in the time series are greater than the estimates provided in Section 4.2.1 because annual average rainfall at Yeovilton, the nearest gauge to the catchment, is lower than the catchment average, although temporal trends would be similar.

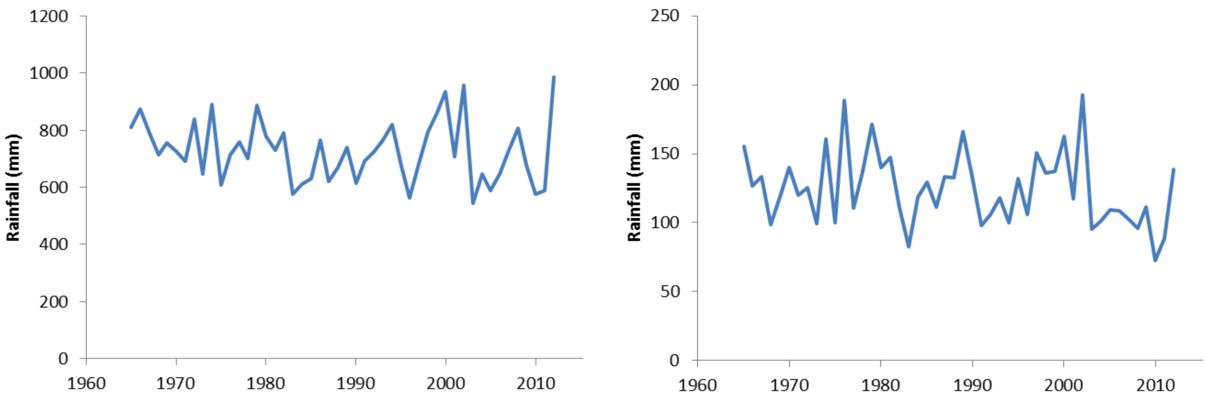


Figure 5.7 (Left) Total annual rainfall and (Right) monthly maximum rainfall based on the Yeovilton rainfall monitoring station.

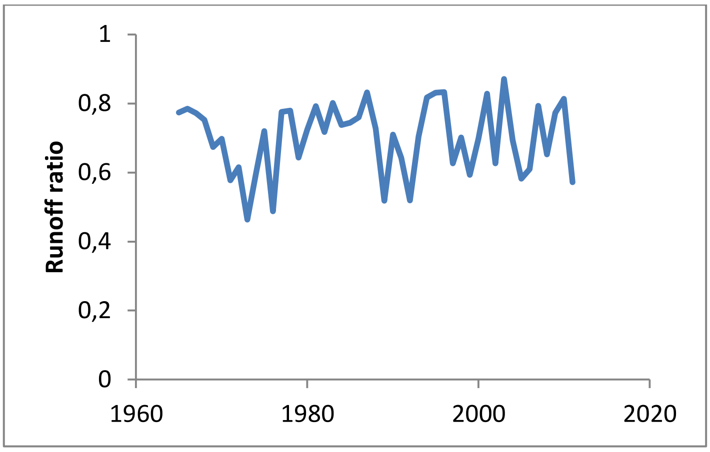


Figure 5.8 The temporal trend in runoff ratio as calculated from the Yeovilton rainfall gauging station data and the East Stoke flow record.

5.3 Segment

5.3.1 Water flow

There is no evidence of long-term changes in river flows, as can be seen in the mean, minimum and maximum daily flows recorded in each year for East Stoke (1966 to present, Figure 5.9). However, a flow regime analysis was conducted on the first and last 20 years of this 46 year record (Table 5.1). This identified a sizeable increase in the baseflow index, a decrease in flood frequency, and an increase in flood predictability between the two time periods, causing the flow regime type to change from perennial stable to perennial superstable.

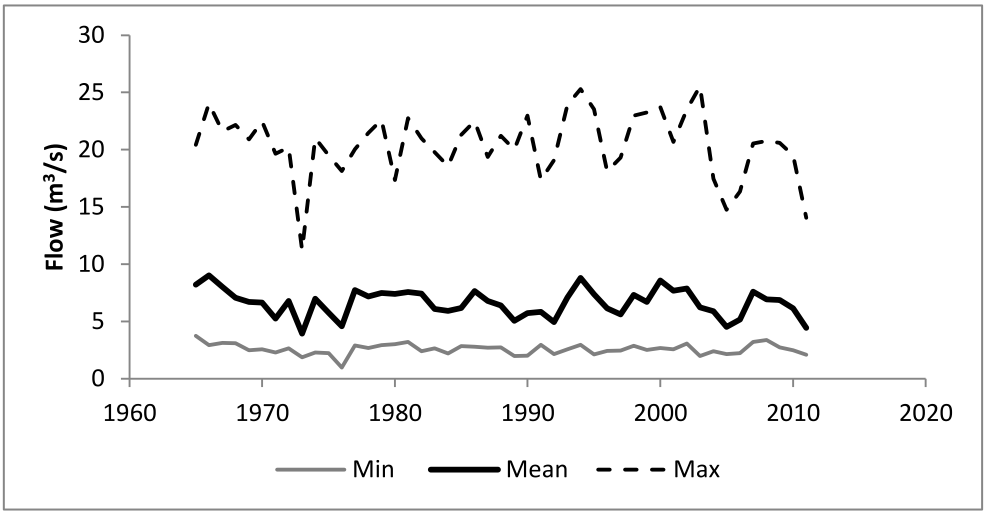


Figure 5.9 Mean, minimum and maximum annual flows from the East Stoke river gauging station.

Table 5.1 Flow regime analysis for the first and last 20 years of the 46 year long East Stoke gauging station mean daily flow record.

Start YEAR	End YEAR	BFI	FLD FREQ	FLD PRED	FLD TIME	ZERO DAYS	DAY CV	FLOW REGIME TYPE
1966	1985	39.86	0.75	0.53	1 (Jan-Feb)	0.00	57.02	PS
1992	2011	58.75	0.65	0.69	335 (Dec-Jan)	0.00	58.90	PSS

5.3.2 Sediment delivery

Long-term sediment monitoring has not been conducted on the River Frome. Potential changes in sediment delivery over time were inferred from land use changes (Section 5.2.2). Increases in the area of arable cropland, higher agricultural yields, and changes in livestock numbers and types suggest fine sediment delivery has likely increased significantly from the mid 20th century. This is supported by research that shows that cultivated land is the primary source of suspended sediment in the River Frome (Collins and Walling, 2007).

The delivery of sediment to the channel via bank erosion was estimated from an historical analysis of planform change conducted at the reach scale (Section 5.4.3) and summarised by segments in Table 5.2. Channel positions from different points in time (1889, 1960/75, 2013) were overlain to quantify the area of floodplain eroded over the time periods. The eroded area was divided by the average riverbank length for the points in time, and divided by the number of years to yield an estimate of average bank retreat rate. Bank sediment is predominately earth (i.e. fine sand, silt and clay), but field observations noted a layer gravel (ca. 5 cm thick) was frequently visible towards the base of the bank profile. To quantify coarse sediment delivery by bank erosion, the area eroded (m^2) was multiplied by 0.05 m for the estimated depth of gravel and by an average bulk density of 1.6 tons m^{-3}, and divided by the number of years. Fine sediment delivery was calculated in the same manner, except that the depth of fine sediment was estimated as the average bank height (RHS) subtracted by 0.05 for the gravel lens and bulk density for dry earth is ca. 1.25 tons m^{-3}.

Bank retreat rates were substantially greater in the last half century (average rate - 0.053 m yr^{-1}, 1960/75 – 2013) than in the first half of the 20th century (average rate - 0.037 m yr^{-1}; 1889 – 1960/75), consequently sediment delivery rates were higher as well (Table 5.2). Sediment delivery from bank erosion was greatest in Segment 6 for both coarse and fine sediment. Whilst these estimates appear large, particularly in comparison to the estimates of fine sediment delivery from PESERA and bed sediment transport from SIAM, they are balanced or exceeded by rates of deposition within the reaches. This is why these figures were not included in the SIAM modelling. Average bank aggradation rate estimated in the historical analysis was 0.042 m yr^{-1} for 1889-960/75 and 0.058 m yr^{-1} for 1960/75 – 2013 (Table 5.2), and, as shown in the following reach-scale analysis, most reaches in the River Frome experienced a distinct and continuous reduction in channel area, i.e. net deposition, since 1889 (Section 5.4.1).

Table 5.2 Estimates of average bank advance, bank retreat and sediment delivery to the channel from bank erosion, based on a historical analysis of channel position at the reach scale. (for methods used to obtain these data, see section 5.4.1)

Segment	Bank advance ($m.yr^{-1}$)		Bank retreat ($m.yr^{-1}$)		Gravel delivery ($t.km^{-1}.yr^{-1}$)		Sand & finer delivery($t.km^{-1}.yr^{-1}$)	
	1889-1960/75	1960/75-2013	1889-1960/75	1960/75-2013	1889-1960/75	1960/75-2013	1889-1960/75	1960/75-2013
1	0.014	0.042	0.017	0.049	1.33	3.96	18.69	55.49
2	0.034	0.048	0.025	0.051	2.01	4.14	37.26	76.74
3	0.041	0.049	0.036	0.037	2.90	3.00	57.13	59.06
4	0.040	0.100	0.048	0.064	3.99	5.23	59.17	77.58
5	0.030	0.063	0.025	0.047	2.06	3.90	30.46	57.74
6	0.069	0.103	0.047	0.094	3.88	7.67	66.87	132.23

5.3.3 Valley setting

There have been no significant changes in the valley gradient or width in the last 100 years. The railway line that was built in the mid-19th century narrowed the effective floodplain width in Segments 2 and 6 (e.g. Figure 5.10).

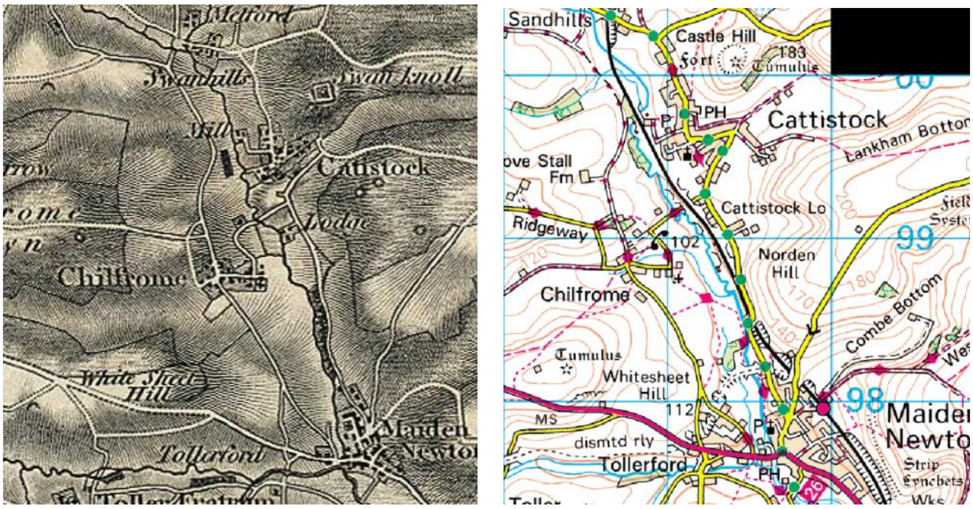


Figure 5.10 Ordnance Survey maps for Segment 2 (left) from 1811 (1:63360) and (right) present-day. Note the railway line (solid black line) that passes diagonally through the valley and has resulted a narrowing of the effective valley width in the segment (© Crown Copyright and British Library)

5.3.4 Channel gradient

Bed levels are not monitored in the River Frome and a sufficient number of historical cross-sections could not be found, so we are unable to provide direct evidence of changes in channel gradients.

The River Frome has a long history of use and modification by humans. The Domesday Book recorded numerous mills along the length of the river, largely in the upper and middle catchment[15]. For example the stretch of river from Cattistock to Frampton (ca. 6.4 km long, Reaches 3 to 5 and part of 6) had 6 mills in 1086. The number of mills would have increased during the medieval period (Lewin, 2010). First edition Ordnance Survey maps from 1889 show that most towns and villages had a mill on either the main stem of the River Frome or on a secondary / mill channel. For example, Dorchester had three mills in the town: the West Mill was for corn and bone, Friary Mills was a saw mill, Fordington Mill was for corn. Moreover, river flows in secondary channels and river levels within the floodplain have been controlled by sluice gates for centuries. Consequently, channel gradients that were already low because of the low valley gradient would have become even lower due to impoundment by the numerous dams, weirs and sluices.

5.3.5 Riparian corridor and wood

There is no evidence of substantial changes in the size, type or location of naturally-functioning riparian vegetation at the segment-scale from the analysis of land cover conducted at the landscape unit scale. No information on historical wood production or delivery to the catchment was found; however given the long history of intensive river management and of wood removal it is unlikely that wood delivery to the channel varied significantly in the last century.

5.4 Reach

5.4.1 Channel planform, migration and features

Despite being a low energy river, the River Frome has adjusted noticeably over time. Overlays of the channel margins between different points in time (channel margins extracted from Ordnance Survey maps and recent aerial imagery) give a good indication of the total amount of adjustment that has occurred (Figure 5.11). This type of analysis implicitly incorporates any changes that have occurred in channel width or length in addition to lateral migration. Figure 5.11 shows areas that were channel in two different time periods (no change), areas that were river in the first time period and then land in the second (deposition) and areas that were land in the first time period and river in the second (erosion). All reaches showed substantial changes over time, with perhaps the exception of Reach 7. When the deposited and eroded areas are compared, it becomes clear that most reaches have shown a distinct and continuous reduction in channel area since 1889 (Figures 5.12). These trends are likely to be robust, since the Ordnance Survey use a consistent definition of the channel boundary (the normal winter flow level), and interpretation of aerial imagery used the same definition. Such a definition can be robustly applied to the channels of the Frome, because of its typically steep banks.

The decrease in channel area is accompanied by stable or increasing channel lengths, as evidenced by cumulative changes in channel sinuosity between 1889 and 2013 (Figure 5.13c). The notable exception is Reach 11, a short reach which experienced a large cutoff

---

[15] Domesday Book, Open Domesday. http://domesdaymap.co.uk, accessed on 31-Jan-2014.

between 1960 and 2013 (Figure 5.13b). There is no change in the number of active channels over the last 100 years; therefore for most reaches, the cause of changes in channel area over time is a reduction in channel width.

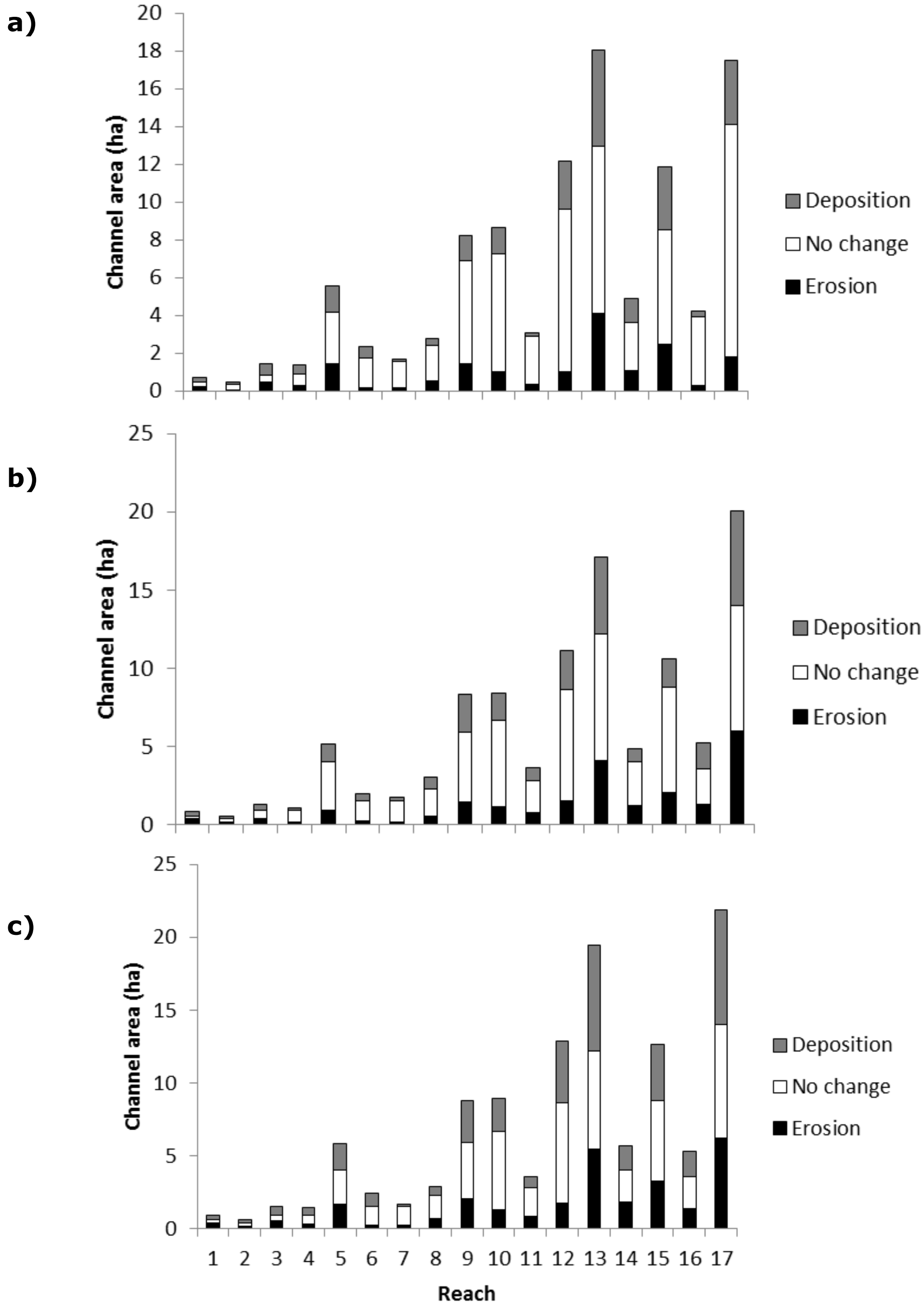


Figure 5.11 Channel adjustment over time (erosion or deposition) represented by change in channel area by reach between (a) 1889 and 1960/75, (b) 1960/75 and 2013 and (c) 1889 and 2013

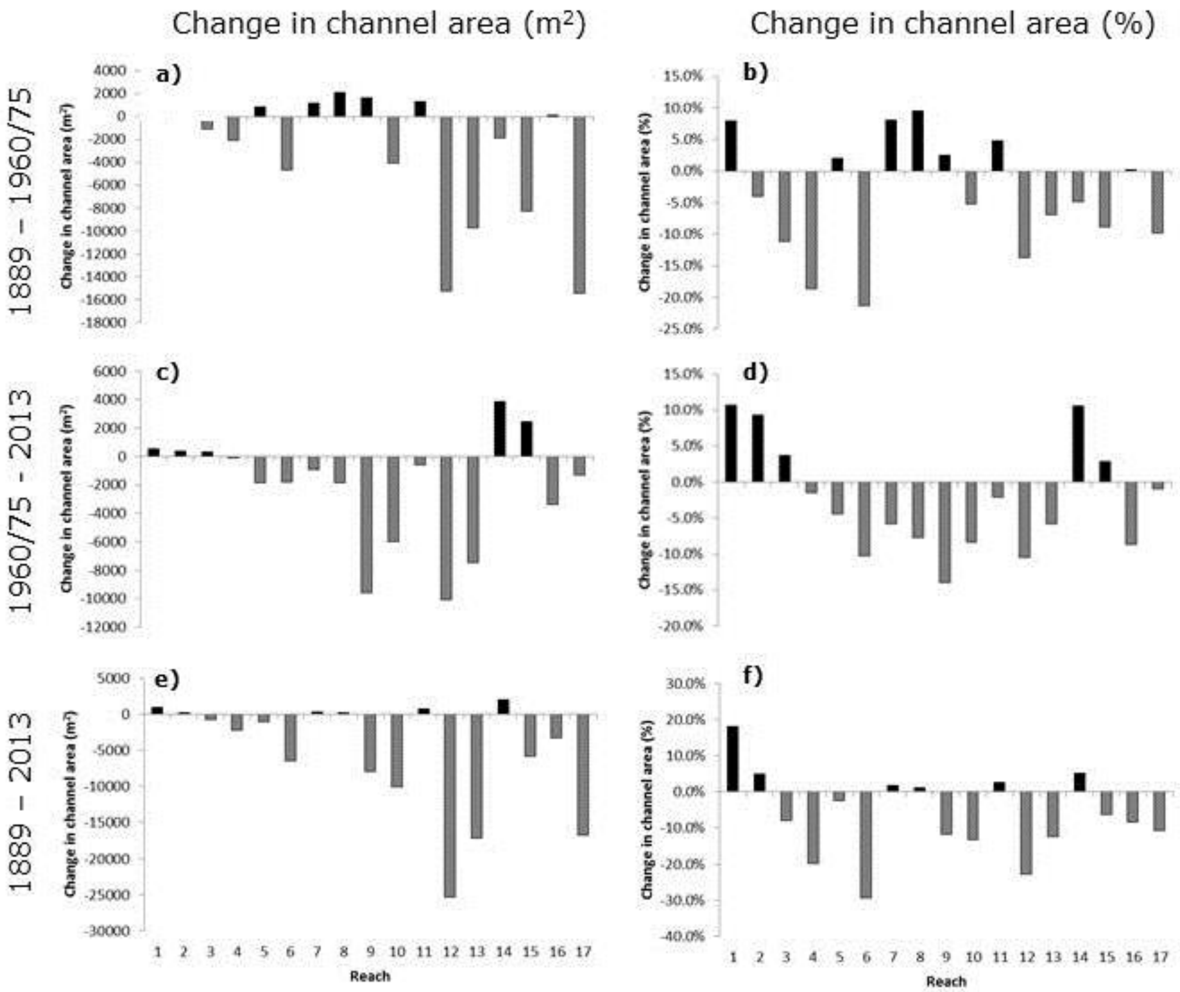


Figure 5.12 Change in channel area by reach between (a,b) 1889 and 1960/75, (c,d) 1960/75 and 2013 and (e,f) 1889 and 2013, and reported as (a,c,e) total area and (b,d,f) percentage out of total area area occupied

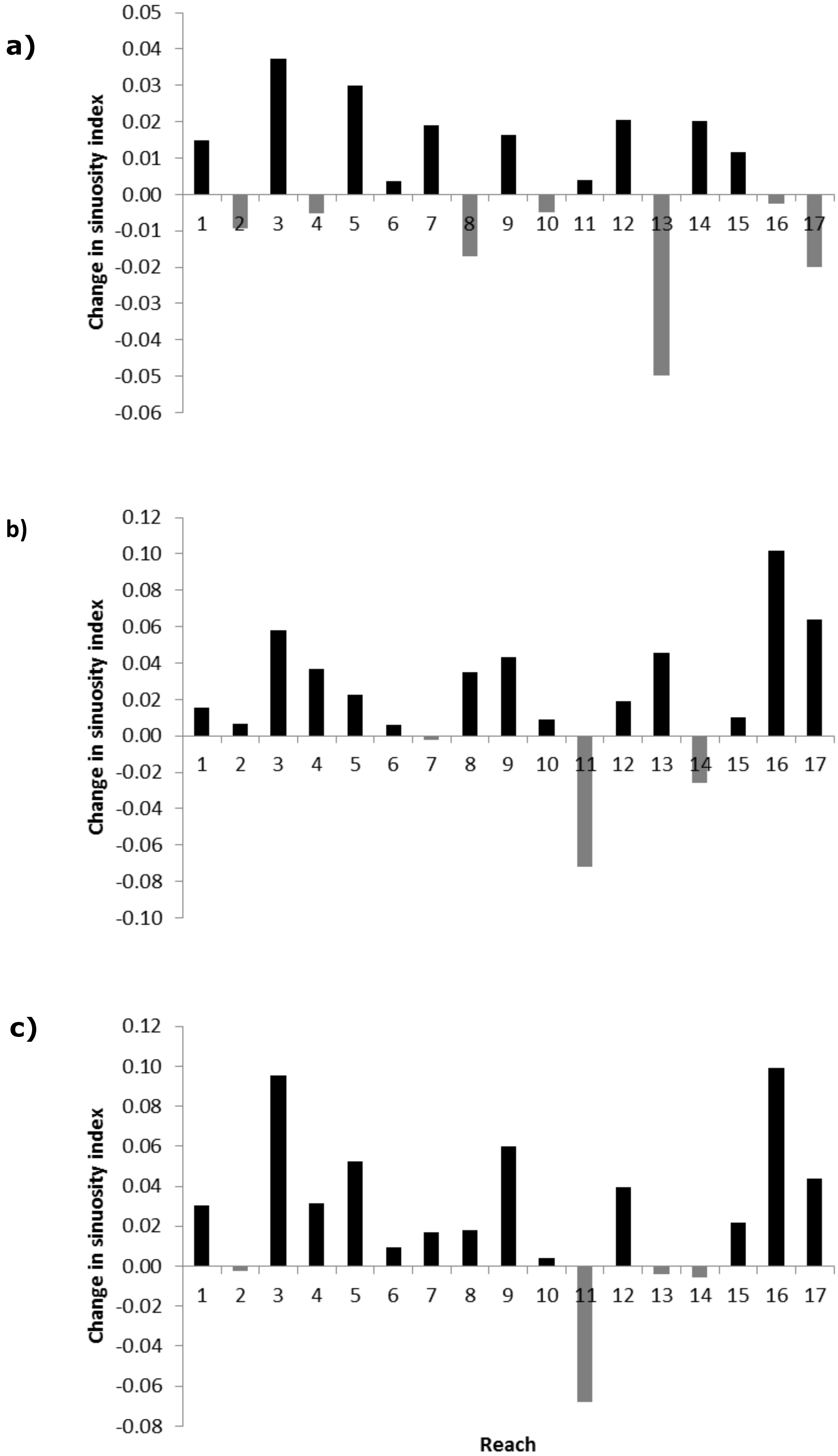


Figure 5.13 Change in sinuosity index for the main channel by reach between (a) 1889 and 1960/75, (b) 1960/75 and 2013 and (c) 1889 and 2013.

5.4.2 Channel geometry

Changes in channel width varied between reaches and over time (Figure 5.14). Overall, the time period from 1889 to 1960/75 saw a general increase in channel widths (Figure 5.14a), whereas 1960/1975 saw a general decrease. Over the entire time series (1889 – present (Figure 5.14b), 3 reaches experienced significant changes in channel width, when using positional accuracy as minimum thresholds for change detection: Reaches 10 and 12 narrowed significantly, whilst Reach 14 widened significantly (Figure 5.14c).

No data is available on temporal changes in channel cross sectional profile.

5.4.3 Bed sediment calibre

No data is available on long-term changes in bed sediment calibre.

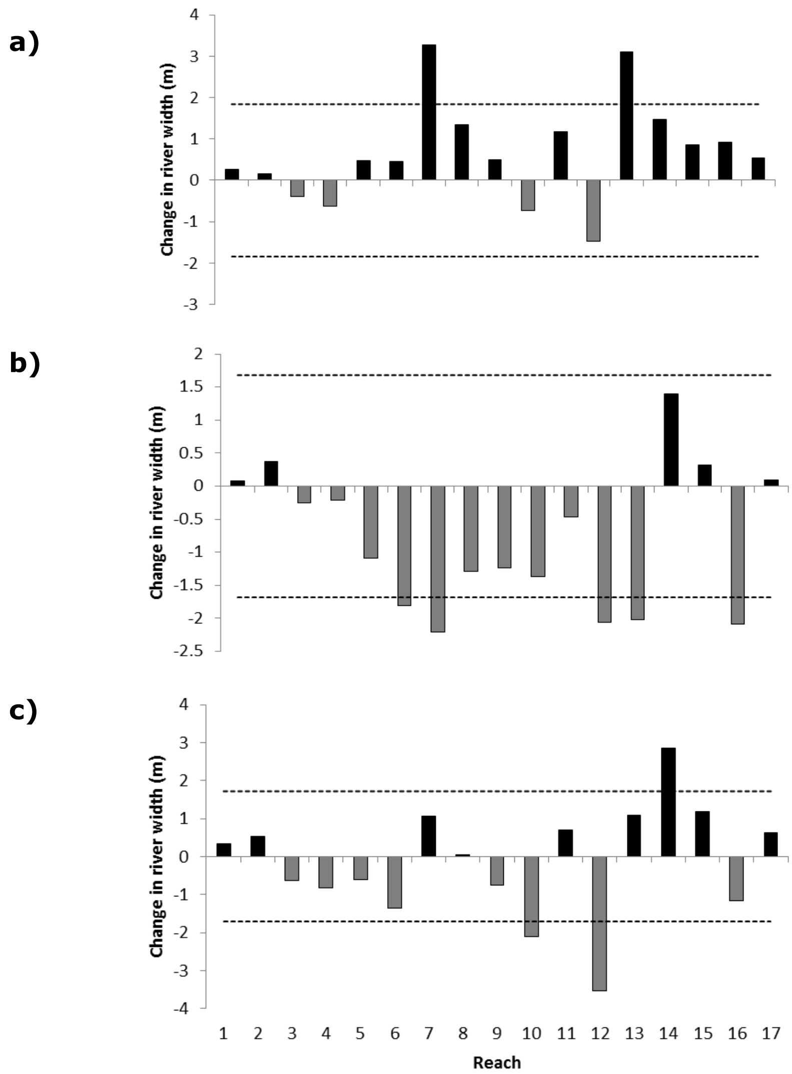


Figure 5.14 Change in river width over time by reach between (a) 1889 and 1960/75, (b) 1960/75 and 2013 and (c) 1889 and 2013. Dashed line indicates minimum threshold for change detection.

6. Extended River Typology

Reaches in the River Frome are classified as one of three morphological types (Table 6.1). All reaches are alluvial, unconfined, and have a mixed gravel and finer sediment bed, therefore morphological types differ only by planform. Given the limited bedform development, fine cohesive banks and low gradients of the Frome channels, morphological types reflecting a fine gravel-sand bed (and low slope) rather than a (coarser) gravel – sand bed were selected. Type 17 is single thread sinuous/straight, Type 18 is single-thread meandering and Type 19 is multi-thread low-energy anabranching.

Table 6.1 River and floodplain type by reach for the River Frome

LU	Seg.	Reach	River Type	Threads	Planform	Floodplain Type
1	1	1	17	Single	Sinuous	Degraded G
	2	2	17	Single	Sinuous	Degraded G
		3	18	Single	Meandering	Degraded G
		4	17	Single	Sinuous	Degraded G
2	3	5	17	Single	Sinuous	Degraded G
		6	19	Multi-thread	Anabranching	Degraded G / J
		7	17	Single	Sinuous	Degraded G
	4	8	17	Single	Sinuous	Degraded G
		9	19	Multi-thread	Anabranching	Degraded G / J
	5	10	19	Multi-thread	Anabranching	Degraded G / J
		11	19	Multi-thread	Anabranching	Degraded G / J
3	6	12	19	Multi-thread	Anabranching	Degraded G / J
		13	19	Multi-thread	Anabranching	Degraded G / J
		14	19	Multi-thread	Anabranching	Degraded G / J
		15	19	Multi-thread	Anabranching	Degraded G / J
		16	19	Multi-thread	Anabranching	Degraded G / J
		17	18	Single	Meandering	Degraded G

The floodplain of the River Frome as viewed from aerial images (or in the field) is relatively featureless apart from the occasional remnants of old channels, such as oxbows. Lidar data reveals many more old channel remnants evidencing past channel changes (meandering reach 17 - Figure 6.1, anabranching reach 14 – Figure 6.2), but also extensive human modification in some reaches through the construction of dense feeder and distributory channels associated with historical water meadows and drainage systems (anabranching reach 15, Figure 6.3). Where such human modifications are not evident, the floodplain is gently undulating with occasional wetlands and lakes formed in oxbows or other channel remnants, such that it is best described as a subdued version of floodplain types G (lateral migration, backswamp) in the sinuous and meandering reaches and possibly J (organic rich anabranching) in the anabranching reaches. The floodplain soils (as observed in the field and inferred from the bank material recorded in RHS surveys) are appropriate to these classes, but are not as organic rich as would be expected, likely reflecting their long history of agricultural use. Further support for floodplain types G and J is the channel gradients, which are < 0.005 in all reaches apart from Reach 1 (Table 4.18), and specific stream power, which is < 50 $W.m^{-2}$ in all reaches and < 15 $W.m^{-2}$ in the anabranching reaches (Figure 4.14).

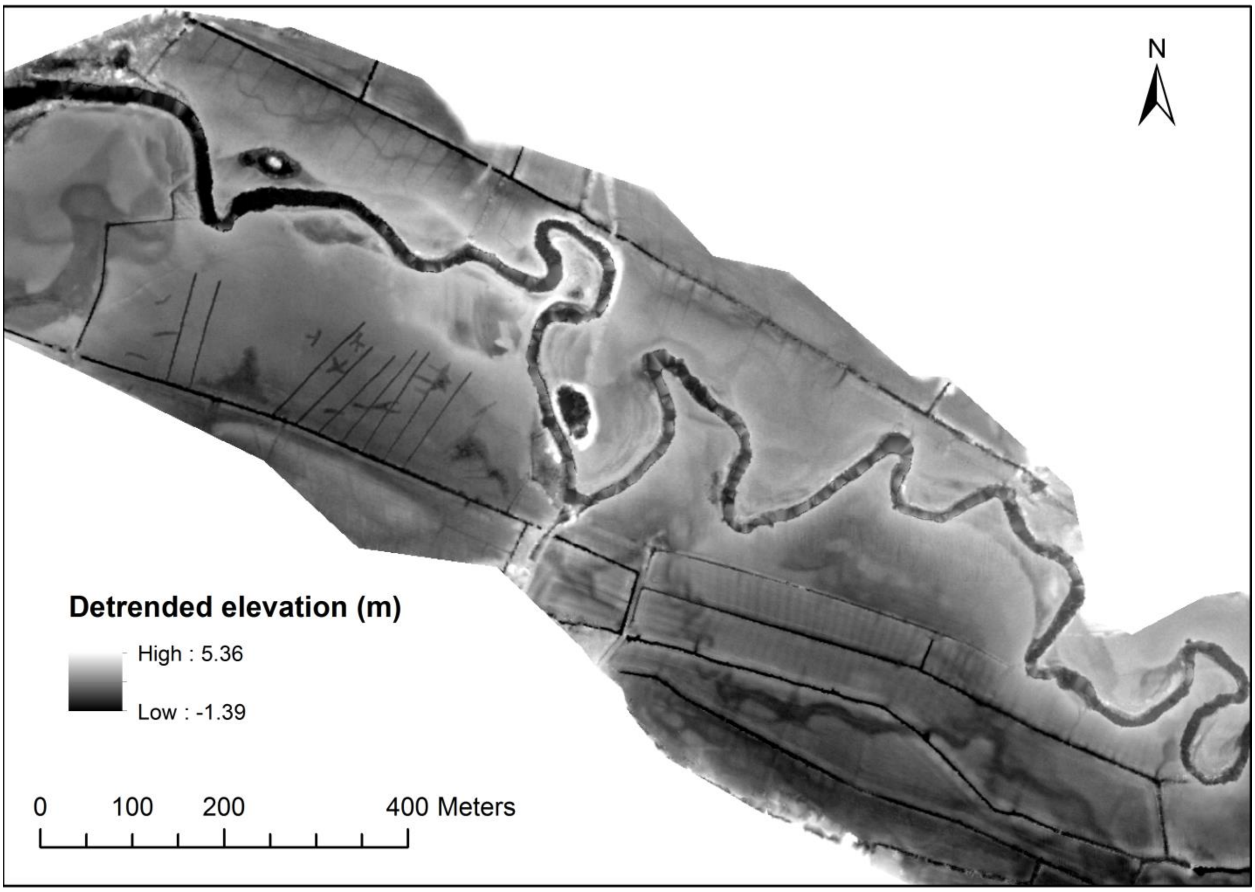


Figure 6.1 Meandering reach 17 showing evidence of scrolls created by channel migration (centre) and major changes of course (left)

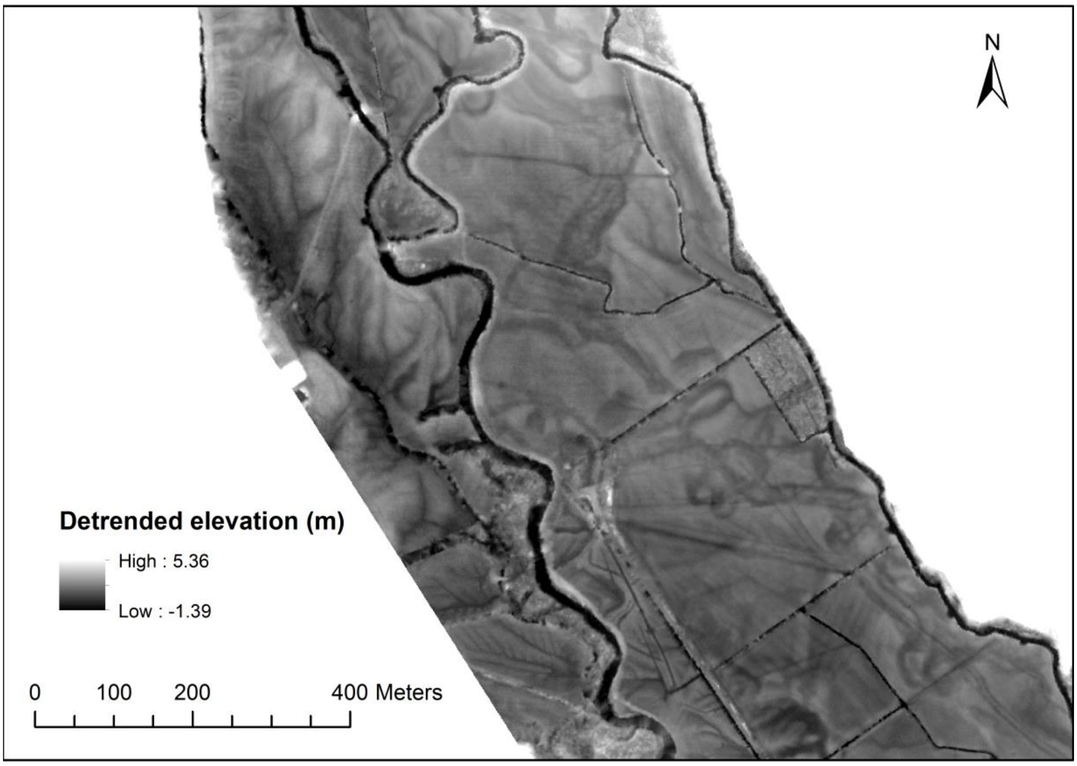


Figure 6.2 Anabranching reach 14 showing evidence of dynamic sinuous old channels, particularly across the floodplain to the right of the current main channel. Evidence of artificial channel networks is also widespread

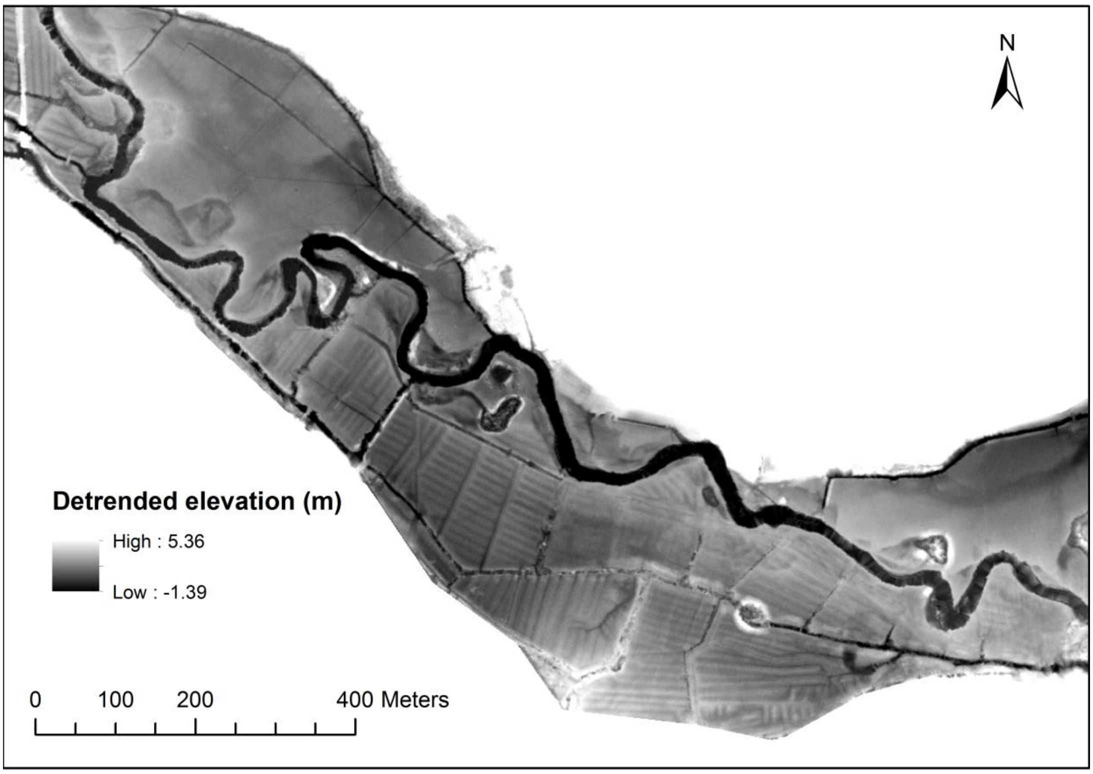


Figure 6.3 A section of reach 17 where most of the floodplain surface has been subject to human modification

7 Indicators of Present and Past Condition

This section briefly reports values of the indicators that can be extracted from the characterisation information, referring back to their detailed evaluation in sections 4, 5 and 6, as appropriate.

7.1 Catchment

7.1.1 Catchment Area

The River Frome has an actual (and functioning) catchment area of 459 km2.

It is a medium-sized catchment according to WFD.

7.1.2 Water yield and Runoff Ratio / Coefficient

Average annual rainfall for the catchment to the East Stoke gauging station is 968 mm for the 1961-1990 period and 1022 mm for the 1941-1970 period. The average annual streamflow at East Stoke is 6.66 $m^3 s^{-1}$, the subcatchment area for the gauging station is 414.4 km^2.

Therefore, the average annual water yield is 507 mm and the average annual runoff ratio / coefficient is 0.52 (based on 1961-1990 average annual rainfall).

(N.B. It is not possible to calculate a runoff ratio for the two 30 year time periods of average annual rainfall because river flow records do not extend back to 1961. However no significant temporal trends in runoff ratio are implied by the analysis of rainfall at Yeovilton rainfall and river flow at East Stoke; Figure 5.8).

7.1.3 Geology and Land Cover

The catchment scale geology indicators are % calcareous 60%; % siliceous 40% with no significant areas of organic or mixed geologies present.

Land cover comprises % agricultural 86%; % forests and semi-natural areas 11%; % artificial surfaces 4%. There are no significant areas of wetland.

Land cover has changed little in the catchment over the last century, except for a small expansion of urban areas in the middle and lower catchment. Changes in land use, based on county agricultural census records (Section 5.2.1), reveal negligible change in total agricultural area. However, there has been a shift from grass and rough pastures to arable land, particularly cereal production (Figures 5.1 - 5.3), combined with an intensification of production resulting in increased cereal crop yields (i.e. tonnes produced per hectare of land) (Figure 5.4).

Livestock numbers were high in the early 20th century, dropped to a minimum by mid-century (post WWII) and increased to highs in the 1980s and 1990s (Figure 5.4). The type of livestock has changed from predominantly sheep at the beginning of the 20th century to cattle from 1940 to 1995, and also an increase in pigs, which are increasingly being reared outdoors.

7.2 Landscape unit

7.2.1 Exposed Aquifers and Soil / Bedrock Permeability

An unconfined aquifer extends over much of the catchment, particularly in the upper and middle catchment (Figure 3.6; Table 4.6). The % area of exposed aquifers are 98%, 85% and 26% for Landscape Units 1, 2 and 3, respectively.

The % area of (soil and rock) permeability classes (based on hydrology of the soil substratum, Figure 4.2) is permeable - 73%, 98%, and 77%; affected by groundwater (i.e. at least seasonally impermeable) – 27%, 2%, 23% for Landscape Units 1, 2 and 3, respectively (Table 4.6).

7.2.2 Land cover

Table 4.7, based on the 2006 Corine dataset, summarises the proportion of different land cover types in each Landscape Unit, leading to the following land cover contributions to likely runoff response:

% area of delayed runoff production is attributable to forest cover and is 3%, 2%, 13% for Landscape units 1, 2, 3, respectively.

% area of rapid runoff production is attributable to urban, industrial, commercial and transport and is 0%, 4%, 4% for Landscape units 1, 2, 3, respectively.

% area of intermediate runoff production is attributable to arable land, pasture and open spaces and is 97%, 94%, 83% for Landscape units 1, 2, 3, respectively.

Thus, the land cover present in the catchment is predominantly associated with intermediate runoff production. There is little variation in runoff potential between landscape units, though LU 3 has a larger proportion land cover associated with delayed runoff (Figure 7.1).

Over the last 80 years, land cover / use has changed very little. However, there has been a shift in agricultural use of the land, switching from pasture-dominated to arable crop-dominated agriculture. The area of land cultivated for arable crops has increased from 22% to 41% of the catchment from 1930/40 to 2006; whereas pasture has decreased from 67% to 41%. These changes have been uniformly expressed across the landscape units (Figure 7.1). Small interannual changes occur in reaction to EU/UK agricultural policy and market forces. There has been an increase in artificial surfaces over time due to urbanisation of the towns of Dorchester and Wool, which are adjacent to the river. The changes in area are small and the resolution of the land cover maps is too coarse to accurately resolve these changes.

7.2.3 Sediment production

Soil erosion rates are relatively low for the entire catchment (Figure 3.7; Table 4.8), estimated at 0.09, 0.28 and 0.17 t ha^{-1} yr^{-1} for Landscape Units 1, 2 and 3, respectively.

No major sources of coarse sediment were identified in the catchment. River bank erosion is a potential source, although banks are mainly comprised of 'earth' (defined as crumbly material of mixed particle size typically < 2mm, and thus containing little potential bed material). Average bank erosion rates were estimated in the temporal analysis of channel position and used to estimate average annual rates of gravel delivery. This analysis was summarised at the segment scale in Section 5.3.2, and is presented at the reach scale in Section 7.4.3.

7.3 Segment

7.3.1 Water Flow

Water flow analysis was conducted in relation to three gauging stations, one located in each of the Landscape Units. A finer resolution to segment level was not possible because of insufficient gauging station data.

Flow regime type was perennial super stable, perennial stable, perennial superstable for Landscape Units 1, 2, 3, respectively, indicating a heavily groundwater-dominated flow regime (Tables 4.9 and Table 7.1).

Average annual flow is 0.18, 3.30, 6.66 $m^3.s^{-1}$.

Average monthly flows show similar patterns for each gauging station with relatively high flows in the winter and low flows in the summer (Figure 4.7, repeated as Figure 7.2), which is typical of a lowland chalk river in the UK.

Baseflow indices (BFI), Morphologically meaningful discharges (Qp_{median}, Qp_2, Qp_{10} in $m^3.s^{-1}$) and Extreme flow indicators are summarised (from Table 4.12) in Table 7.2, including Q95 and Q70, two low flow indicators used for managing abstractions within each WFD management area (Environment Agency, 2012).

The temporal analysis of river flows found no significant trends in mean, minimum and maximum annual flows for the East Stoke gauging station (Figure 5.9), but a flow regime analysis indicated a change in baseflow index, flood frequency and flood predictability over time (Table 7.2): the lower River Frome has become more baseflow-dominated in the last 20 years (1992-2011) than previously (1966-1985).

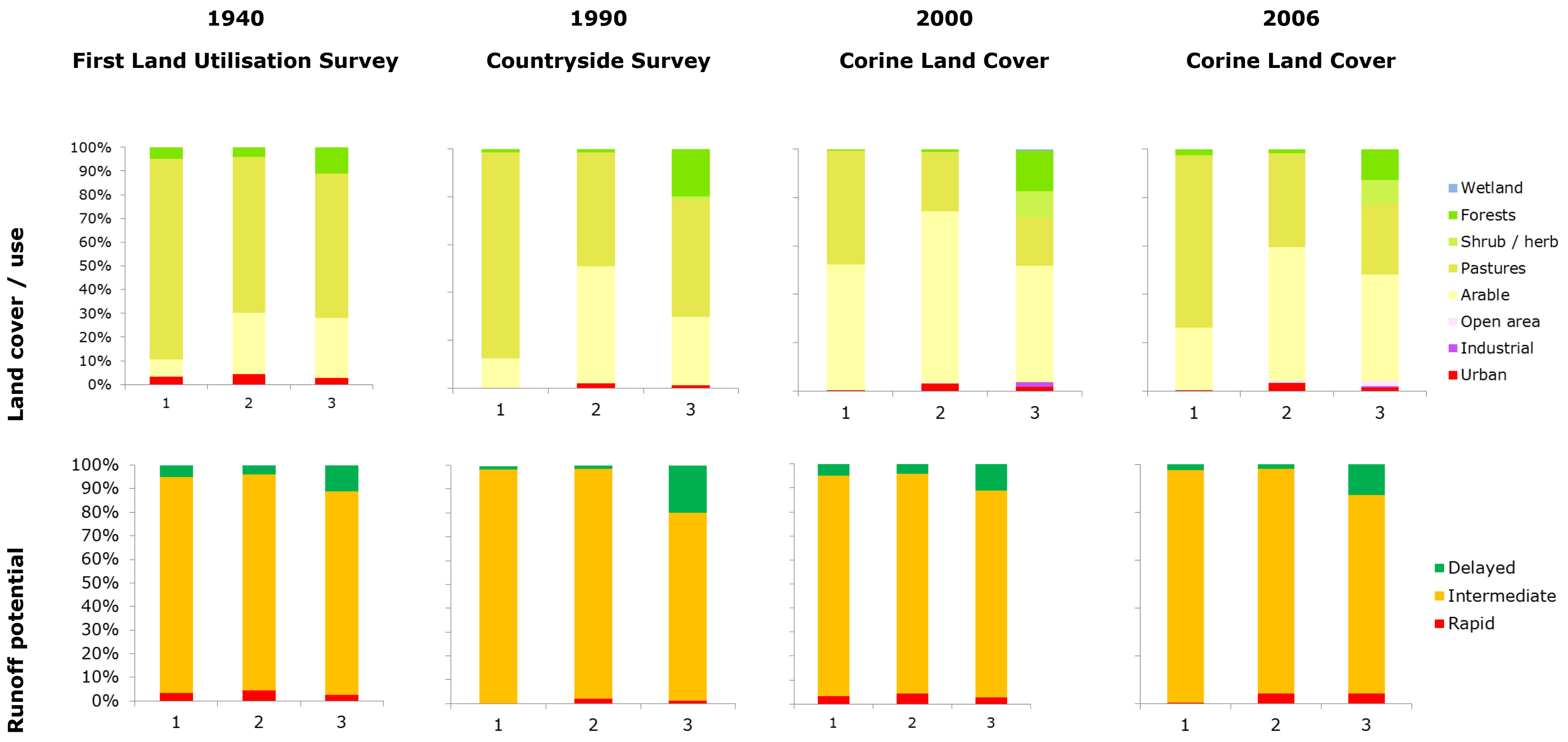


Figure 7.1 Temporal changes in land cover / land use classes (top) and land runoff potential (bottom) for landscape units (1-3) in the Frome catchment.

Table 7.1 Summary of selected water flow indicators from gauging stations in the River Frome catchment calculated using mean daily flow records.

	LU 1 River Hooke	**LU 2 - Segment 5 Frome (Dorchester)**	**LU 3 - Segment 6 Frome (East Stoke)**
Catchment area (km^2)	11.60	205.54	413.46
Flow regime type	Superstable	Stable	Superstable
Average annual flow ($m^3\ s^{-1}$)	0.18	3.30	6.66
Morphologically meaningful discharge ($m^3\ s^{-1}$)			
$Q_{pmedian}$	0.62	11.71	20.72
Q_{p2}	0.65	11.41	20
Q_{p10}	1.12	15.14	24.25
1-day minimum flow			
LQ	0.07	0.74	2.22
Median	0.08	0.90	2.57
UQ	0.08	1.09	2.89
30-day minimum flow			
LQ	0.08	0.85	2.39
Median	0.09	1.08	2.84
UQ	0.10	1.24	3.14
1-day maximum flow			
LQ	0.49	10.11	19.26
Median	0.62	12.40	20.72
UQ	0.81	14.36	22.64
30-day maximum flow			
LQ	0.28	6.25	12.71
Median	0.36	7.30	14.07
UQ	0.45	9.09	16.22
Q95	0.08	0.85	2.48
Q70	0.11	1.52	3.72

Table 7.2 Flow regime analysis for the first and last 20 years of the 46 year long East Stoke gauging station mean daily flow record.

Start YEAR	**End YEAR**	**BFI**	**FLD FREQ**	**FLD PRED**	**FLD TIME**	**ZERO DAYS**	**DAY CV**	**FLOW REGIME TYPE**
1966	1985	39.86	0.75	0.53	1 (Jan-Feb)	0.00	57.02	PS
1992	2011	58.75	0.65	0.69	335 (Dec-Jan)	0.00	58.90	PSS

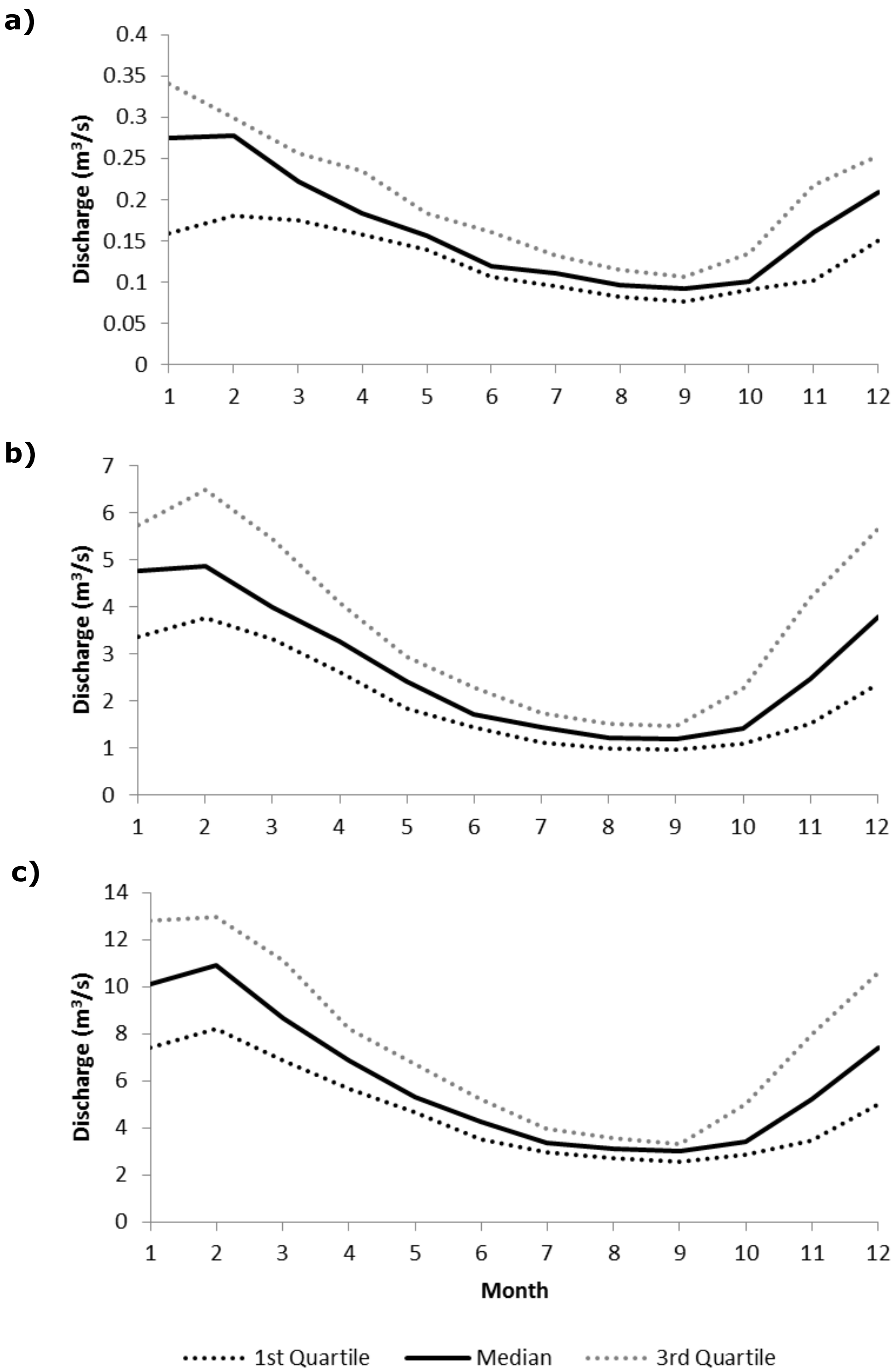


Figure 7.2 Annual hydrograph (by calendar month) for (a) Landscape Unit 1 (River Hooke); (b) Landscape Unit 2 (River Frome at Dorchester, Segment 5); (c) Landscape Unit 3 (River Frome at East Stoke, Segment 6).

7.3.2 Sediment Flow

The amount of eroded soil delivered to the channel varies substantially by segment. Estimates using Pesera data and a 500m buffer around the river network indicate 0.0, 3.7, 4.4, 24.3, 39.4,2.0 $t.yr^{-1}.km^{-1}$ main channel length or 0.0, 3.1, 3.5, 11.2, 12.6, 1.1 $t.yr^{-1}.km^{-1}$ total active channel length, for Segments 1 to 6, respectively. Thus, Segments 4 and 5 within Landscape Unit 2 have delivery rates several times greater than segments further upstream and downstream (Figure 7.3), reflecting the fact that Landscape Unit 2 is associated with soils that are more susceptible to erosion (Figure 7.4), and many of the areas with high predicted soil erosion are associated with arable land and cereal production, as would be expected given the importance of Corine data to Pesera modelling. Sediment delivery to the channel is difficult to accurately measure or model over large areas. The estimates generated by the Pesera model give an average soil loss at 1-km resolution based on average climate, soil, land cover and topography data. They are measures of erosion potential, as opposed to actual predictions of sediment production / soil loss and in the context of the current analysis they are best viewed as relative measures that serve to identify likely spatial variations in delivery.

There are no Land surface instabilities connected to channel and no measurements of suspended sediment load or bedload for the River Frome. However, SIAM modelling indicates properties of the sediment budget and associated sediment transport conditions within the river network. Estimated soil erosion is low compared to other catchments in Europe. However, chalk rivers would naturally have had low fine sediment input because of the subdued topography and high permeability of the underlying geology and a low ability to remove fine sediment once it reaches the river channel because of their very low energy, reflecting low channel gradients and baseflow-dominated (stable, superstable) flow regime. This is supported by bedload transport estimates from the modelled SIAM sediment budget, which suggests that bedload transport is minimal in most of the river network (Section 4.5.3.iii). The model, which represents the river as a single thread river with flows based on the annual flow duration curve, predicts low transport potentials for sand and gravel. Transport capacity is predicted to be insufficient to transport sand and gravel though most of the main stem (Figure 7.5). Consequently, sand and gravel inputs to the system are predicted to result in channel aggradation (Figure 7.6)

Blocking and spanning structures are found along the entire length of the River Frome (Figure 4.12). On average there is a blocking structure every 1.26 km along the river and a spanning structure every 0.52 km.

Number of high blocking structures. There are 3 in segment 6

Number of medium blocking structures. There are 0, 3, 3, 4, 7, 12 in segments 1 to 6, respectively

Number of high (impact) spanning structures. There are 0, 2, 3, 3, 9, 6 in segments 1 to 6, respectively

Number of medium (impact) spanning structures. There are 0, 3, 3, 5, 17, 20 in segments 1 to 6, respectively.

Therefore, the only segment that is minimally impacted by blocking and spanning structures is Segment 1. Segment 5 has the greatest number of blocking structures per km of river (1.3; Figure 4.13) and the greatest number of high impact spanning structures (9 in total). Segment 6 had the greatest number of blocking and spanning structures, as well as the only high impact blocking structures on the river. Segment 2 has high numbers blocking and spanning structures per km of river (Figure 4.13), caused predominately by the large number of bridges and weirs in and around Maiden Newton.

All of the above adverse indicators are supported by documentation for the River Frome SSSi, which includes most of the river downstream of Dorchester (Segments 4-6). The SSSi currently fails to meet favourable condition because of high suspended sediment loads (Punchard, 2013), and the presence of numerous intermediate and high impact blocking structures is cited as a significant problem in relation to its restoration (Environment Agency, 2011).

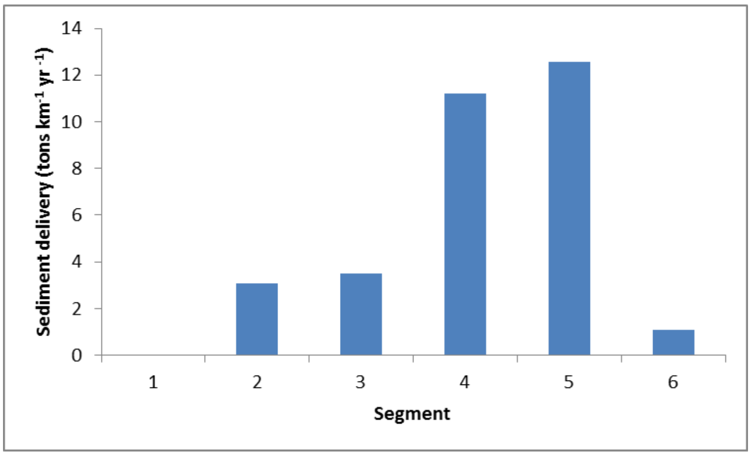


Figure 7.3 Estimated delivery of eroded soil to the channel for the segments of the River Frome. Channel length is based on the total length of all anabranches.

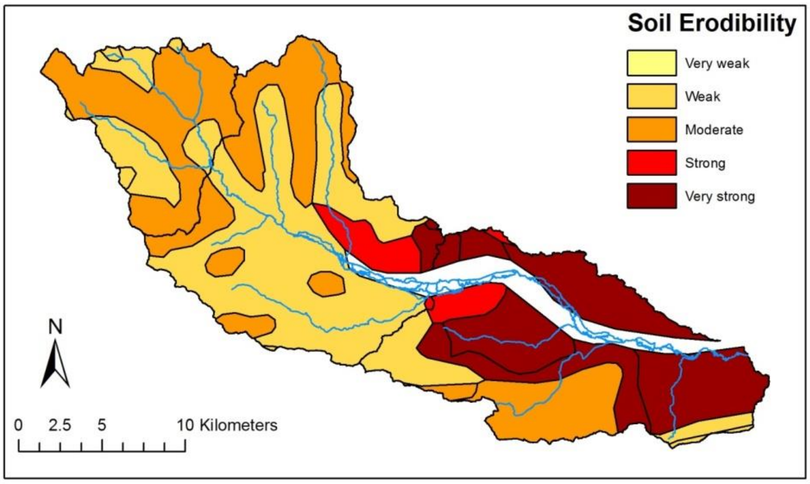


Figure 7.4 Soil erodibility for the Frome catchment. Note that much of Landscape Unit 2 has weak soil that is susceptible to erosion.

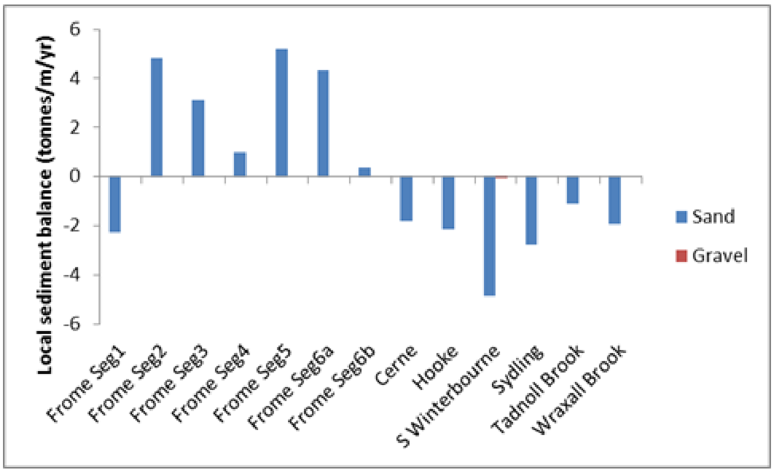


Figure 7.5 Local sediment budget for segments and tributaries of the River Frome, indicating if sand or gravel will deposit (balance > 0) or erode from the channel bed.

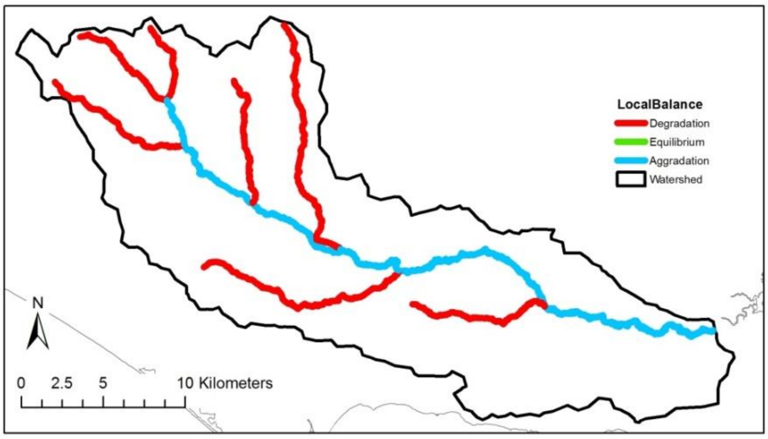


Figure 7.6 Predicted aggradation or degradation of bed material by sediment reach for the base SIAM model (Yang transport equation, wash load maximum diameter = 0.062 mm, Pesera 500m buffer strip soil erosion source).

7.3.3 River Morphology Adjustment

The valley setting is similar for all segments (Table 4.14).

Average valley gradient is 0.011, 0.005, 0.003, 0.003, 0.002, 0.002 for segments 1 to 6, respectively (i.e. it is low in all segments);

Valley confinement is unconfined in all segments;

River confinement index is 25.1, 13.8, 20.1, 20.1, 27.8, 28.1 for segments 1 to 6 respectively (i.e. low for all reaches).

Therefore, the River Frome has the potential to adjust laterally over most of its length.

The potential riparian corridor is coincident with the active floodplain. Riparian vegetation could potentially establish over the entire floodplain because the River Frome is situated in a humid temperate environment, has low gradients, minimal floodplain topography, high groundwater levels and connectivity to flood waters. Functioning riparian vegetation, though, is sparse and discontinuous over much of the riparian corridor and the location of functioning riparian vegetation is largely a matter of land management, or lack thereof (Tables 4.16, 4.17).

Average riparian corridor width is 70, 122, 227, 345, 603, 585 m for segments 1 to 6, respectively. (Average riparian corridor area is 0.36, 0.38, 1.41, 1.61, 3.48, 12.96 km^2)
Proportion of riparian corridor under functioning riparian vegetation is 44, 61, 19, 9, 10, 12% of riparian corridor width and 32, 35, 10, 5, 8, 10% of the riparian corridor area for segments 1 to 6, respectively.
Riparian corridor continuity is 42, 30, 27, 9, 18, 21% of river length for segments 1 to 6, respectively.

Thus, the majority of the riparian corridor is occupied by agricultural land. Segments 1 and 2 have the highest proportion of riparian vegetation cover relative to the riparian corridor width or area, and Segments 4 and 5 have the lowest. Riparian vegetation continuity is low for the Frome as a whole (20%), but is higher in the upper catchment (Segments 1, 2, 3). Non-coniferous tree/scrub is the dominant riparian vegetation type in most segments (Figures 4.10 and 4.11).

The naturally-functioning riparian corridor vegetation cover / structure is mature (Segments 1, 3, 5) or balanced (Segments 2, 4, 6) when viewed as a whole by segment (Figure 4.11).

This assessment of the poor state of riparian vegetation in the catchment is supported by the rehabilitation plan for the River Frome SSSi (Environment Agency, 2011). Riparian tree planting; a reduction in channel and riparian vegetation management; and a reduction of livestock access to riparian zones were amongst the recommendations for immediate action to improve the ecological status of this protected stretch of the river.

7.3.4 Wood production

Potential wood delivery low: 14% on average with 32, 14, 24, 8, 13, 13% of river length abutting non-coniferous trees and tree / scrub for segments 1 to 6, respectively.

It is lower than riparian continuity, because coniferous trees were excluded as these are not a natural riparian species and typically indicate the presence of a plantation. This low assessment of wood delivery potential is supported by the Frome Rehabilitation Plan (Environment Agency, 2011), which recommends re-establishment of riparian trees and the introduction large woody debris.

7.4 Reach

7.4.1 Flooding

The majority of the River Frome floodplain is accessible to floodwaters. The floodplain was delineated based on the 1 in 100 year flood extent and thus incorporated the impacts of floodplain topography and infrastructure. An investigation of the potentially floodable area outside of the delineated floodplain identified small areas in Reaches 3, 16 and 17 that would have been accessible to floodwaters if rail/road embankments did not exist (maximum 8% of floodplain area in Reach 3).

% floodplain accessible by floodwater is 0, 1, 3% for reaches 3, 16, and 17, and 100% for all other reaches.

7.4.2 Channel self-maintenance / reshaping

Specific stream power at Q_{median}, $Q_{p2,}$ and Q_{p10} is presented in Table 7.3. It is greatest in Reach 1, decreases through Reach 9, and is relatively consistent within the remaining reaches. Specific stream power is lowest in Reaches 10-12 where anabranches indices are highest, indicating that sediment transport potential is lowest in these reaches.

Bed sediment size is predominantly gravel-sized sediment (2 – 64 mm diameter) based on RHS spot checks (Figure 7.7 left), although the gravel is heavily infiltrated and often buried by finer sediment (Section 4.5.5) and thus is best described as gravel-sand or sand-gravel when based on MTR surveys of proportional bed cover (Figure 7.7 right).

Bank sediment size is predominantly 'earth' (crumbly material of mixed particle size typically < 2mm) as measured in RHS spot-checks (Figure 4.17). For more information on bed and bank sediment, see Section 4.5.3.

Table7.3 Specific stream power for reaches in the River Frome as calculated based on annual maximum 1-day flow from the mean daily flow record and annual maximum instantaneous flow from the 15-min flow record.

Reach	Based on maximum 1-day flow			Based on maximum instantaneous flow		
	Qp_{median}	Qp_2	Qp_{10}	Qp_{median}	Qp_2	Qp_{10}
1	27.9	27.4	38.7	45.5	32.2	57.2
2	17.5	17.2	24.2	28.3	20.1	35.5
3	15.9	15.6	21.9	25.6	18.2	32.1
4	18.7	18.3	25.7	30.0	21.4	37.6
5	13.3	13.0	18.0	20.7	15.0	25.9
6	15.7	15.4	21.2	24.3	17.6	30.4
7	10.2	10.0	13.7	15.6	11.4	19.6
8	13.0	12.7	17.3	19.5	14.4	24.4
9	13.9	13.6	18.4	20.6	15.3	25.7
10	9.0	8.8	11.7	12.8	9.7	15.9
11	7.9	7.7	10.3	11.2	8.5	13.9
12	9.6	9.3	12.1	12.8	10.0	15.8
13	15.3	14.8	19.0	19.7	15.7	24.4
14	15.7	15.1	19.0	19.1	15.7	23.4
15	10.7	10.3	12.7	12.3	10.5	15.1
16	12.3	11.8	14.4	14.0	11.9	17.1
17	13.0	12.4	14.9	13.9	12.3	16.8

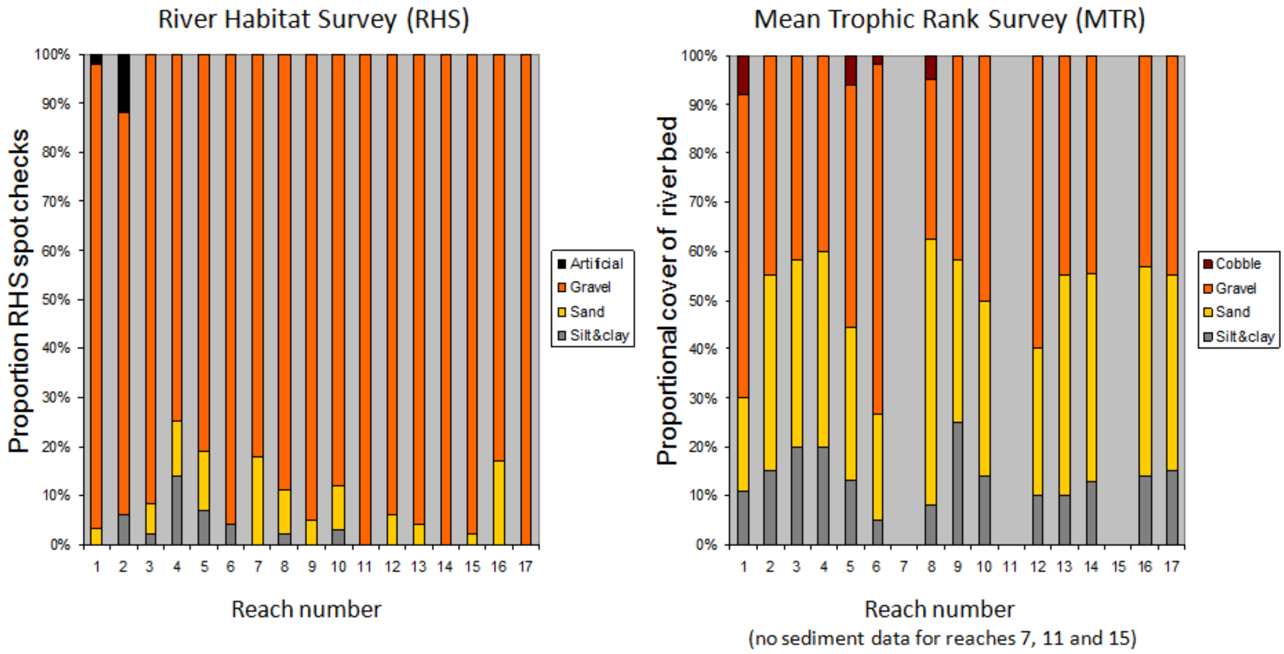


Figure 7.7 Dominant bed sediment size estimated as (left) the proportion of RHS spot-checks conducted within the reach and (right) the average proportion of the bed covered by sediments of different calibre (MTR data).

Current river channel characteristics and dimensions were presented and discussed in Section 4.5.1 (Tables 4.18 and 4.19) and the following indicators are summarised for convenience in Table 7.4: Channel gradient, Mean bankfull channel width, Mean average bankfull channel depth, Bankfull channel width:depth ratio, Bankfull sinuosity index, Braiding Index, Anabranching Index. In addition the river type is listed (from Table 6.1).

Presence of channel and floodplain geomorphic units / features typical of the river type is categorised as 'some'.

The river channel in most of the reaches in the River Frome displays few geomorphic units, which, based on RHS surveys and aerial imagery, are riffles with some pools, and occasional bars, but most reaches have less than 2 features per kilometre of river (Figure 4.38). Reaches 3, 5, 14 and 17 have higher abundances of geomorphic units, but average numbers only reached 3 to 5 per km. However, parts of reaches 3, 4 and 5 have been investigated in the field, confirming the presence of subdued riffles and occasional pools, and also revealing a variety of vegetation-associated bar, bench, and wood jam features retaining fine sediment within the channel. This evidence suggests that 'some' is likely a reasonable assessment for all reaches, but more field surveys are needed to confirm this. Floodplain geomorphic units are generally subdued and most easily recognised from Lidar data (e.g. Figures 6.1, 6.2, 6.3), which reveals the presence of old channels left by cutoffs, channel migration and major changes in channel course and also scroll-type features in most reaches. These are sufficiently widespread for 'some' to describe the abundance and range of floodplain features typical of the river types present.

% area of the bankfull channel occupied by bars, benches and islands can only be assessed for those parts of reaches 4, 5 and 6 inspected in the field. For reach 4, between 10 and 15% of channel area shows fine sediment retained in bars, benches and islands. Reaches 5 and 6 show approximately 10% and 5%, respectively.

7.4.3 Channel changes / adjustments

Of the three contemporary indicators of channel dynamics (Eroding banks, Laterally aggrading banks, In-channel retention of sediment) only Eroding banks can be estimated for all reaches, based on RHS spot checks of eroding banks (Table 4.25). This provides the following % of spot checks showing Eroding banks as 0.03, 0, 0.08, 0.06, 0.1, 0, 0.05, 0, 0.01, 0.02, 0.03, 0.02, 0.06, 0, 0.05, 0.08, 0.06%. However, the RHS definition of eroding banks is restrictive.

In the three sites within reaches 4, 5 and 6, where field surveys were undertaken, the following approximate values of the three indicators were found:

Eroding banks 23, 40, 0% bank length in reaches 4, 5 and 6, respectively.

Laterally aggrading bank 21, 15, 30% bank length in reaches 4, 5 and 6, respectively (includes major lateral bars that aggrade into benches and the bank)

In-channel retention of sediment 5, 2, 0% channel area in reaches 4, 5 and 6, respectively (includes mid-channel bars and islands)

Historical analysis found the River Frome has adjusted its course over the last 100 years (Figure 5.11). From 1889 to 2013, Reaches 1 and 3 changed the most relative to total channel area, whilst reaches in the middle catchment changed the least, particularly between Reaches 6 and 10 (Figure 5.11c). Much of this change in area appears to be the result of natural processes, indicating that the channel is capable of adjustment despite the presence of significant in-channel blocking structures that impact water and sediment flows.

Analysis of information from historical sources (OS maps and aerial imagery) reveals a general trend of decreasing channel area (Figure 5.12) and width, although river length and sinuosity have remained largely constant. Thus:

Table 7.4 Channel characteristics and dimensions for the River Frome. All characteristics are for the main channel only, except for braiding and anabranching indices, which incorporate all major and secondary channels.

Reach	Channel Gradient	Bankfull width	Bankfull depth	W:D Ratio	Sinuosity Index	Braiding Index	Anabranch Index	River Type
1	0.010	3.1	0.95	3.3	1.12	1.00	1.00	17
2	0.004	4.5	1.38	3.3	1.13	1.00	1.00	17
3	0.003	5.5	1.18	4.7	1.51	1.00	1.04	18
4	0.006	6.5	1.15	5.6	1.06	1.00	1.41	17
5	0.002	10.0	1.45	6.9	1.28	1.00	1.06	17
6	0.004	14.1	0.97	14.5	1.03	1.00	1.75	19
7	0.002	14.7	1.52	9.7	1.20	1.00	1.00	17
8	0.002	11.0	1.13	9.7	1.28	1.00	1.43	17
9	0.003	9.8	0.87	11.3	1.21	1.00	2.39	19
10	0.002	12.0	0.87	13.9	1.21	1.00	2.93	19
11	0.002	10.3	1.13	9.1	1.30	1.00	4.67	19
12	0.002	11.6	1.14	10.2	1.45	1.00	2.87	19
13	0.002	13.9	1.12	12.5	1.34	1.00	2.00	19
14	0.002	11.8	1.00	11.8	1.18	1.00	3.00	19
15	0.001	13.1	1.18	11.1	1.39	1.00	2.23	19
16	0.001	12.2	1.36	9.0	2.11	1.00	2.00	19
17	0.001	14.2	1.13	12.6	1.59	1.00	1.20	18

Change in sinuosity shows small increases between 1889 and 2003 for all reaches except Reach 11; Figure 5.13, Table 7.5).

Change in braiding index is not relevant to the Frome, which retains an index of 1.0 for all reaches and times.

Change in anabranching index is also not reported since the number of anabranches has been stable over the last century.

As river lengths / sinuosity remained largely constant and the number of channels (i.e. anabranching index) has not changed, the decreases in channel area reflects a decrease in channel widths (Table 7.5).

Change in active channel width (Figure 5.14, Table 7.5) showed a width increase in most reaches between 1889 and 1960/75, although only Reaches 7 and 13 showed an increase that exceeds the potential error in the analysis. This was followed by channel narrowing in most reaches between 1960/75 and 2013, although only reaches 6, 7, 12, 13, and 16 showed reductions that exceed the potential error in the analysis. As, information on temporal changes in bed levels is unavailable, the indicators changes in active channel depth and changes in active channel width:depth ratio could not be calculated.

In relation to other contemporary signs of adjustment only information gained by field survey in reaches 4, 5 and 6 can provide information on the following indicators (although historical provides an indication of the average bank advance and retreat within each reach, Table 7.5):

Presence of geomorphic units / features indicative of narrowing: none were seen as features tended to be confined to one river bank

Presence of geomorphic units / features indicative of widening: none were seen, even in reach 5, where bank erosion was extensive, it was confined to one river bank

Changes in bed sediment structure indicating incision: no true armouring was observed.

Changes in bed sediment structure indicating shallowing / bed aggradation: widespread evidence of fine sediment infiltration of the gravel bed and accumulation on the gravel bed surface was observed. However only the upstream sections of the area surveyed within reach 4 showed burial of the gravel bed across > 90% of its area.

Vegetation encroachment was significant in the downstream section of the area of reach 4 that was surveyed. Here, the branches of riparian trees were rooting into the river bed and retaining fine sediment, although this was usually accompanied by erosion of the opposite bank, indicating channel migration rather than narrowing. Additionally, potential vegetation encroachment was observed from aerial images of Reaches 11-14 between 2000 and 2009 from a time series of aerial images (e.g. Figures 4.39 and 4.40).
The high suspended sediment loads in the river (Section 7.3.2) and vegetation-induced fine sediment geomorphic features observed in the field in Reaches 3, 4 (Figures 4.44 – 4.47) and 5 indicates that fine sediment is being retained by vegetation to contribute to channel planform changes, through narrowing and lateral migration of the channel and the formation of lateral and mid-channel bars, benches and islands.

The Width of the erodible corridor is 'wide' over the entire length of the River Frome (> 10 bankfull width) (Figure 4.31b)

The Proportion of potentially erodible channel margin averages 93% and exceeds 90% on all reaches apart from Reach 1 (89%) and 10 (78%, Figure 4.31a). Reach 10 flows through the town of Dorchester, and has high levels bank reinforcement or infrastructure within 0.5 bankfull channel width along 22% of the reach

Proportion of river bed that is artificially reinforced is negligible (Table 4.18; Figure 7.7 (left)). Reaches 1 and 2 were the only ones where artificial material was identified as the dominant bed material in RHS spot-checks (2% and 11% of spot-checks in Reaches 1 and 2), respectively.

Table 7.5 Reach values of average channel width and sinuosity of the main channel in 1889, 1960/75 and 2013, and reach average bank advance/retreat between 1960/75

Reach	Channel width (m)			Sinuosity			Average bank retreat ($m.yr^{-1}$)	Average bank advance ($m.yr^{-1}$)
	1889	1960/75	2013	1889	1960/75	2013	1960/75 - 2013	1960/75 -2013
1	2.50	2.70	2.80	1.08	1.09	1.11	0.05	0.04
2	4.10	4.20	4.60	1.09	1.08	1.08	0.05	0.04
3	5.50	5.10	4.80	1.42	1.46	1.52	0.06	0.06
4	5.20	4.60	4.40	1.26	1.26	1.29	0.03	0.04
5	9.00	9.50	8.40	1.39	1.42	1.44	0.05	0.05
6	11.00	11.40	9.60	1.01	1.02	1.02	0.03	0.05
7	9.90	13.20	11.00	1.17	1.19	1.19	0.03	0.04
8	10.40	11.80	10.50	1.21	1.19	1.22	0.05	0.07
9	8.60	9.10	7.80	1.25	1.26	1.30	0.07	0.11
10	10.90	10.10	8.70	1.14	1.14	1.15	0.05	0.08
11	7.40	8.50	8.10	1.33	1.34	1.26	0.04	0.05
12	15.30	13.80	11.80	1.42	1.44	1.45	0.05	0.09
13	10.80	13.90	11.90	1.34	1.29	1.34	0.10	0.12
14	8.60	10.10	11.50	1.22	1.24	1.22	0.10	0.07
15	10.90	11.70	12.00	1.37	1.39	1.40	0.07	0.06
16	12.70	13.60	11.50	1.98	1.98	2.08	0.09	0.11
17	13.40	14.00	14.10	1.50	1.48	1.54	0.12	0.13

Blocking structures are found throughout the River Frome, with the exception of Reach 2 (Figure 4.29), and spanning structures are found in all reaches. Table 7.6 summarises the numbers of high, medium and low blocking and spanning structures by reach. The number of blocking structures per channel length is greatest in Reaches 4 – 10, but high impact structures are clustered in the lower catchment. High impact spanning structures are found along the entire River Frome, and have the potential to significantly impact large wood transport. On average there is a blocking structure every 1.26 km along the river and a spanning structure every 0.52 km. Spanning structures are found in all reaches, most commonly low impact structures (148), typically small pedestrian bridges or railway brides with wide spans. The 47 medium impact and 21 high impact spanning structures, are predominantly road bridges with central piers and/or abutments that extend into the channel (Figure 4.32a). The greatest number of high impact structures per km of river length is found in the middle catchment (Reaches 4 – 13) (Figure 4.32b).

Table 7.6 The number of blocking and spanning structures per reach within the River Frome, classified as having high, medium or low impact on hydromorphology.

Reach	Blocking			Spanning		
	High	Medium	Low	High	Medium	Low
1			1			3
2						5
3			1		1	
4		3	1	**2**	2	12
5		3	2	**1**	1	4
6			2	**1**		3
7			2	**1**	2	
8		1	2	**1**	1	1
9		3	7	**2**	4	20
10		5	19	**7**	12	28
11		2	3	**2**	5	5
12	**1**	2	5		5	14
13		3	4	**2**	3	17
14		2	3		1	7
15	**2**	1	4	**1**	4	17
16		2				4
17		2	5	**1**	6	18

7.4.4 Vegetation Succession

The River Frome is well-known and indeed protected for its diverse and abundant aquatic macrophytes, particularly the submerged morphotypes. In mid summer, total macrophyte cover of the channel may exceed 90% in unshaded reaches (e.g. Figure 4.28). However, emergent macrophytes, like *Sparganium erectum*, have the most influence on channel morphodynamics. These are usually confined to the channel edges and so their total cover is relatively small.

Based on analysis of the MTR data presented in Figure 4.27 and Table 7.7, Aquatic vegetation extent averages 23% for the entire River Frome. Table 7.7 presents reach averages of all aquatic plants, emergents, and submerged species / rooted species with floating leaves, based on MTR surveys. Cover is low for reaches in the upper catchment (Reaches 1-5) and increases generally with distance downstream. Emergent morphotypes have a lower cover than submerged, Reach 17 has the greatest extent of emergent vegetation (17%); and Reach 12 has the greatest extent of submerged macrophytes (69%). Based on mid-summer field surveys in Reaches 5 and 6, cover of emergent (all) macrophytes was ca. 5% (40%), 10% (60%) in Reaches 5 and 6, respectively. Reach 4 was not surveyed in summer but is heavily shaded and only occasional small patches of submerged macrophytes were observed.

Aquatic vegetation species: The River Frome supports an extremely diverse community of aquatic plants (Table 4.24). In MTR surveys, *Ranunculus penicillatus* ssp. pseudofluitans was the most widely-encountered macrophyte (found at 68% of sites) and had the highest percent covers. R. pencillatus was one of only 2 species of plants that were recorded at extents greater than 10% and the only one greater than 50%. R. penicillatus comprised over half of the submerged/floating-leaved plants recorded. Other relatively-common species were *Myriophyllum alterniflorum* (15% of sites) and *Oenanthe fluviatilis* and *Zannichellia palustris* (10% each). *Sparganium erectum* was the most widespread of emergent species and was found at 66% of sites. The second most widespread species were *Apium nodiflorum* and *Phalaris arundinacea* (49%), followed by *Veronica anagallis-aquatica* (46%) *and Myosotis scorpioides* (42%). For reaches 5 and 6, where summer surveys were conducted the number of emergent (all) Aquatic vegetation species were 4 (7) and 6 (11) in Reaches 5 and 6, respectively.

Based on field observations in Reaches 4, 5, and 6, Aquatic vegetation patchiness can be described as 'moderate' in reaches 5 and 6, but the cover was 'occasional' in reach 4

Specifically-designed field surveys are needed to identify aquatic plant dependent geomorphic units/features. The high proportion of vegetated features identified in the aerial imagery analysis suggests that vegetation is an important control on geomorphic feature formation / stabilisation (Figure 4.38).

In Reaches 4, 5 and 6, Presence of aquatic-plant-dependent geomorphic units / features. Is occasional, frequent small features, frequent small features, for Reaches 4, 5 and 6, respectively.

A detailed description of riparian vegetation distribution and cover classes is provided in Section 4.5.4.i, and is summarised in Table 7.8.

Proportion of the riparian corridor under mature trees, shrubs and shorter vegetation averages to 10% for the entire river, with a maximum reach cover of 58% (Reach 4) and a minimum of 5% (Reaches 5, 8, 9) (Figure 4.19). Based on the proportional mix of the three types of cover identified (mature, intermediate, early), naturally-functioning riparian vegetation is classified as 'mature' or 'balanced' in all reaches in the River Frome. However, no areas of bare ground exist, and early and intermediate vegetation types are probably maintained by management (e.g. grazing).

Lateral gradients in riparian vegetation cover classes are highly variable between reaches (Figures 4.22 - 4.24). Several reaches show substantial shifts in vegetation with distance from the riverbanks. For example, the proportion of vegetated area covered in marsh increases with distance from the riverbank in Reach 3 (Figure 4.22), whilst tree cover increases in Reach 11 (Figure 4.23). The reach with lateral gradients in vegetation structure that most suggest reworking by riverine processes is Reach 17 (Figure 4.23). This meandering reach shows decreases in the area of marsh and rough grassland, and increases in scrub and trees with distance from the river banks.

Patchiness in riparian vegetation cover types could not be assessed within the often small pockets of riparian vegetation present, since the datasets used did not have sufficient resolution to discriminate small-scale variations in structure beyond that which was identified in the lateral gradients.

Table 7.7 Average percentage cover of all, emergent, and submerged aquatic vegetation in each river reach, based on MTR data

Reach	Total aquatic vegetation cover (all)	Emergent aquatic vegetation cover	Submerged aquatic vegetation and rooted with floating leaves
1	1%	1%	0%
2	2%	0%	2%
3	6%	1%	6%
4	5%	1%	4%
5	6%	1%	5%
6	6%	4%	2%
7	4%	1%	4%
8	47%	6%	41%
9	11%	5%	6%
10	33%	4%	29%
11	20%	1%	20%
12	78%	9%	69%
13	48%	6%	41%
14	6%	3%	4%
15	72%	11%	62%
16	47%	3%	44%
17	58%	17%	41%

The River Frome supports a diverse community of riparian tree species, although these are often present as isolated individuals or in narrow patches along the river margins.

Dominant riparian tree species in the reaches subject to field survey were Alnus glutinosa, Fraxinus excelsior, Salix caprea, Salix fragilis, Salix triandra, Salix viminalis, Prunus spinosa (Reach 4); Alnus glutinosa, Salix cinerea, Salix fragilis, Salix viminalis (Reach 5); Alnus glutinosa, Salix cinerea (Reach 6).

Presence of wood- or riparian tree- dependent geomorphic units / features. Consistent and complete information on wood- or riparian tree-dependent geomorphic units is not available for most of the River Frome. RHS data identified vegetated bars in several reaches (Figure 4.37), and an analysis of aerial imagery found that vegetated bars were the most abundant type of emergent depositional features and were most numerous in the lower reaches (Figure 4.38). Within the three reaches surveyed in the field, only Reach 4 had a heavily wooded margin and the wood- or riparian tree-dependent geomorphic units / features present can be described as 'abundant and diverse'. Reaches 5 and 6 can be described as 'occasional'. Field surveys are needed to formally assess the abundance of riparian tree and wood-induced geomorphic features in other reaches.

Table 7.8 Proportion of the naturally functioning riparian vegetation within different age classes, which is used to classify the vegetation coverage as mature, balanced or immature.

Reach	Proportion Riparian Corridor under Riparian vegetation	Cover class	Proportion of Functioning Riparian Area		
			Mature (Trees)	Intermediate (Shrubs)	Early (Grass / Wetland)
1	32%	Mature	82%	4%	14%
2	8%	Mature	91%	9%	0%
3	23%	Balanced	33%	4%	63%
4	58%	Balanced	19%	7%	74%
5	5%	Balanced	77%	23%	0%
6	21%	Mature	100%	0%	0%
7	12%	Mature	100%	0%	0%
8	5%	Balanced	42%	9%	48%
9	5%	Balanced	76%	21%	3%
10	6%	Balanced	79%	11%	10%
11	10%	Mature	84%	15%	1%
12	6%	Balanced	48%	16%	37%
13	7%	Mature	89%	4%	7%
14	11%	Balanced	71%	1%	27%
15	16%	Mature	83%	8%	9%
16	31%	Balanced	37%	0%	63%
17	10%	Balanced	40%	20%	40%

7.4.5 Wood delivery

Wood delivery was estimated from RHS data (Figure 4.25) and is presented below in Table 7.9. Large wood and fallen trees decrease in abundance from upstream to downstream within the catchment, and no large wood was identified downstream of Reach 10 and no fallen trees downstream of Reach 14 in RHS surveys (Figure 4.25).

Table 7.9 The proportion of RHS surveys reported fallen trees and wood within the river channel. Present: <33% of channel area, extensive: >33% of channel area.

Reach	Fallen trees		Wood	
	Present	Extensive (>33% of channel)	Present	Extensive (>33% of channel)
1	53	13	73	0
2	100	0	100	0
3	60	0	80	20
4	67	0	33	0
5	9	0	36	0
6	33	0	67	0
7	25	0	25	0
8	0	0	20	0
9	13	0	13	0
10	0	0	11	0
11	0	0	0	0
12	11	0	0	0
13	19	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0

8 Interpreting condition and trajectories of change

8.1 Stage 1: Synthesis of current reach condition

Current reach condition is summarised in Table 8.1. Tables 8.2 to 8.7 illustrate how the components of Table 8.1 were generated. In most cases the derivation follows the methods suggested in section 9 of the D2.1 main report. However, where information was lacking, other approaches were substituted:

(i) Because of the narrow width of the river and the presence of overhanging trees on many reaches, indicators relating to particular types of geomorphic feature / unit were lacking or unreliable and yet field surveys were only available for parts of three reaches (4, 5 and 6). As a result, the hydromorphological function assessment (Table 8.3) was only based on a field data set for Reaches 4, 5 and 6. Recent (since 1960/1975) historical channel movement estimates were used to replace direct observations of eroding banks, giving sufficient data to derive a reasonably robust assessment for all reaches. For the same reasons, the assessment of hydromorphological adjustment was based on the analysis of historical data for the elements relating to channel narrowing and widening, and MTR survey data were interpreted in relation to in-channel retention of sediment, using field knowledge of reaches 4, 5 and 6 to support these interpretations.

(ii) Assessment of riparian corridor function and artificiality (Table 8.6) and wood budget function and artificiality (Table 8.7) were based, respectively, on the analysis of land cover data and fallen tree / wood information from RHS surveys. In both cases, field knowledge of Reaches 4, 5 and 6 confirmed the appropriateness of the assessments. In the case of Table 8.6, a different assessment of function and artificiality were used from that suggested in the D2.1 main report section 9.2. Since information on patchiness was not available and information on lateral gradients was unreliable, riparian vegetation function was classified entirely on the basis of the 'age structure' of the riparian vegetation, with a balanced structure leading to an assessment of partial function, and all other reaches classified as having poor function. Without additional information, it was not possible to identify truly functioning reaches. In relation to the assessment of artificiality, additional information on the proportion of the riparian corridor under riparian vegetation was included. Riparian vegetation was only deemed to be artificial if it occupied less than 20% of the riparian corridor or it was not classified as balanced. Since RHS data on fallen tree / wood abundance only refers to the river channel, the assessment of the wood budget and its artificiality could not include the entire riparian corridor. The wood budget was deemed to be functioning when fallen trees and wood were both present or extensive in more than 50% of RHS surveys, and poor when both fell below 40%.

The majority of reaches in the River Frome have intermediate hydromorphological function, high levels of artificiality, poorly functioning and highly artificial / degraded riparian vegetation and wood budgets (Table 8.1). Most reaches show some hydromorphological adjustment with a general tendency towards narrowing and bed aggradation through infiltration and overlaying of the bed gravels by sand and finer sediment. Despite high levels of hydromorphological alteration and artificiality, all reaches have at least intermediate levels of hydromorphological function in the context of the relatively low energy river types that are present, and the upstream reaches (1, 2, 3, 4, 6) show at least a partially functioning wood budget.

Table 8.1 Current reach condition: reach type (see section 6 for details), hydromorphological condition: function, alteration / artificiality / adjustment, riparian corridor function (vegetation, wood)

Reach	Type	Function	Hydromorphology		Riparian vegetation		Wood budget	
			Artificiality	Adjustment	Function	Artificiality	Function	Artificiality
1	17	Intermediate	Artificial	None	Poor		Functioning	
2	17	Intermediate	Low Artificiality	Widening & aggrading	Poor	Artificial	Functioning	
3	18	Intermediate	Some artificial elements	Aggrading	Partial		Functioning	
4	17	Good	Artificial	Aggrading	Partial		Partial	
5	17	Good	Artificial	Narrowing	Partial	Artificial	Poor	V. degraded
6	19	Good	Artificial	Narrowing	Poor		Partial	
7	17	Good	Artificial	Narrowing	Poor	Artificial	Poor	V. degraded
8	17	Intermediate	Artificial	Narrowing & aggrading	Partial	Artificial	Poor	V. degraded
9	19	Intermediate	Artificial	Narrowing & aggrading	Partial	Artificial	Poor	V. degraded
10	19	Intermediate	Artificial	Narrowing & aggrading	Partial	Artificial	Poor	V. degraded
11	19	Intermediate	Artificial	None?	Poor	Artificial	Poor	V. degraded
12	19	Intermediate	Artificial	Narrowing	Partial	Artificial	Poor	V. degraded
13	19	Good	Artificial	Narrowing & aggrading	Poor	Artificial	Poor	V. degraded
14	19	Intermediate	Artificial	Widening & aggrading	Partial	Artificial	Poor	V. degraded
15	19	Intermediate	Artificial	None?	Poor	Artificial	Poor	V. degraded
16	19	Good	Artificial	Narrowing & aggrading	Partial	Artificial	Poor	V. degraded
17	18	Intermediate	Artificial	Aggrading	Partial	Artificial	Poor	V. degraded

Table 8.2 Control and descriptor indicators used to assess the river type

Reach	Specific stream power $Q_{pmedian}$	Q_{p2}	Q_{p10}	Bed sediment	Bank sediment	Channel gradient	Width	Depth	W:D	Threads	Planform	Reach type
1	46	32	57	Gravel/sand	Earth (Silt/Sand)	0.010	3.1	0.95	3.3	Single	Sinuous	17
2	28	20	35	Sand/gravel	Earth (Silt/Sand)	0.004	4.5	1.38	3.3	Single	Sinuous	17
3	26	18	32	Sand/gravel	Earth (Silt/Sand)	0.003	5.5	1.18	4.7	Single	Meandering	18
4	30	21	38	Sand/gravel	Earth (Silt/Sand)	0.006	6.5	1.15	5.6	Single	Sinuous	17
5	21	15	26	Gravel/sand	Earth (Silt/Sand)	0.002	10	1.45	6.9	Single	Sinuous	17
6	24	18	30	Gravel/sand	Earth (Silt/Sand)	0.004	14.1	0.97	14.5	Multi-	Anabranching	19
7	16	11	20	Sand/gravel	Earth (Silt/Sand)	0.002	14.7	1.52	9.7	Single	Sinuous	17
8	20	14	24	Sand/gravel	Earth (Silt/Sand)	0.002	11	1.13	9.7	Single	Sinuous	17
9	21	15	26	Sand/gravel	Earth (Silt/Sand)	0.003	9.8	0.87	11.3	Multi-	Anabranching	19
10	13	10	16	Sand/gravel	Earth (Silt/Sand)	0.002	12	0.87	13.9	Multi-	Anabranching	19
11	11	9	14	Gravel/sand	Earth (Silt/Sand)	0.002	10.3	1.13	9.1	Multi-	Anabranching	19
12	13	10	16	Gravel/sand	Earth (Silt/Sand)	0.002	11.6	1.14	10.2	Multi-	Anabranching	19
13	20	16	24	Sand/gravel	Earth (Silt/Sand)	0.002	13.9	1.12	12.5	Multi-	Anabranching	19
14	19	16	23	Sand/gravel	Earth (Silt/Sand)	0.002	11.8	1	11.8	Multi-	Anabranching	19
15	12	10	15	Sand/gravel	Earth (Silt/Sand)	0.001	13.1	1.18	11.1	Multi-	Anabranching	19
16	14	12	17	Sand/gravel	Earth (Silt/Sand)	0.001	12.2	1.36	9	Multi-	Anabranching	19
17	14	12	17	Sand/gravel	Earth (Silt/Sand)	0.001	14.2	1.13	12.6	Single	Meandering	18

Table 8.3 Indicators used to assess hydromorphological function

Reach	Hydromorphology function assessment	% area of bankfull channel occupied by bars, benches, islands	Eroding + aggrading banks	Aquatic-plant dependent geomorphic units	Wood / tree dependent geomorphic units	Channel / floodplain geomorphic features typical of type
1	Intermediate	ND	N*[2]	ND	ND	Some
2	Intermediate	ND	N*[2]	ND	ND	Some
3	Intermediate	ND	N*[2]	ND	ND	Some
4	Good	10-15%*[1]	44%*[1]	Occasional*[1]	Abundant and diverse*[1]	Some
5	Good	10%*[1]	55%*[1]	Frequent small features*[1]	Occasional*[1]	Some
6	Good	5%*[1]	30%*[1]	Frequent small features*[1]	Occasional*[1]	Some
7	Good	ND	N*[2]	ND	ND	Some
8	Intermediate	ND	N*[2]	ND	ND	Some
9	Intermediate	ND	N*[2]	ND	ND	Some
10	Intermediate	ND	N*[2]	ND	ND	Some
11	Intermediate	ND	N*[2]	ND	ND	Some
12	Intermediate	ND	N*[2]	ND	ND	Some
13	Good	ND	Y*[2]	ND	ND	Some
14	Intermediate	ND	N*[2]	ND	ND	Some
15	Intermediate	ND	N*[2]	ND	ND	Some
16	Good	ND	Y*[2]	ND	ND	Some
17	Intermediate	ND	N*[2]	ND	ND	Some

ND = no data.
*[1] = from on field observations in part of the reach.
*[2] = Y if change in active channel width (1960/75-2013) is statistically significant and average reach bank advance / retreat exceeds 5% main channel width in 10 years

.Table 8.4 Indicators and an assessment of hydromorphological alteration / artificiality

Reach	Artificiality Assessment and Score	Longitudinal continuity - Blocking structures					Lateral continuity			Adjustment potential			
		Class Score	Total	Low	Int	High	Class Score	Floodplain accessible	Erodible corridor	Class Score	Adjustment potential	Reinforced banks	Reinforced bed
1	Artificial 5	Intermed. 2	1	1			Good 1	100%	22	Intermed. 2	7%	3%	4%
2	Low Artificiality 3	Good 1					Good 1	100%	15	Intermed. 2	10%	5%	5%
3	Some artificial elements 4	Intermed. 2	1	1			Good 1	92%	11	High 1	2%	1%	1%
4	Artificial 6	Poor 3	4	1	3		Good 1	100%	14	Intermed. 2	7%	3%	4%
5	Artificial 6	Poor 3	5	2	3		Good 1	100%	22	Intermed. 2	9%	5%	5%
6	Artificial 6	Poor 3	2	2			Good 1	100%	17	Intermed. 2	7%	3%	3%
7	Artificial 5	Poor 3	2	2			Good 1	100%	18	High 1	1%	1%	0%
8	Artificial 6	Poor 3	3	2	1		Good 1	100%	19	Intermed. 2	6%	5%	1%
9	Artificial 6	Poor 3	10	7	3		Good 1	100%	17	Intermed. 2	8%	4%	4%
10	Artificial 6	Poor 3	24	19	5		Good 1	100%	25	Intermed. 2	12%	6%	6%
11	Artificial 6	Poor 3	5	3	2		Good 1	100%	28	Intermed. 2	7%	3%	3%
12	Artificial 5	Poor 3	8	5	2	1	Good 1	100%	38	High 1	1%	1%	1%
13	Artificial 5	Poor 3	7	4	3		Good 1	100%	31	High 1	4%	2%	2%
14	Artificial 6	Poor 3	5	3	2		Good 1	100%	21	Intermed. 2	6%	3%	3%
15	Artificial 6	Poor 3	7	4	1	2	Good 1	100%	19	Intermed. 2	5%	2%	2%
16	Artificial 6	Poor 3	2		2		Good 1	99%	20	High 1	1%	1%	0%
17	Artificial 6	Poor 3	7	5	2		Good 1	97%	28	Intermed. 2	10%	5%	5%

Table 8.5 Assessment of hydromorphological adjustment (non-standard indicators used – see text / footnotes for explanation)

Reach	Adjustment assessment	Channel narrowing*1	In-channel retention of sediment*2	Channel widening*3	Channel incision*4	Main channel W:D	% main channel width change 1960/75-2013	% bed covered by sand and finer
1	None	N	N	N	N	3.3	4	30
2	Widening & aggrading	N	Y	Y	N	3.3	10	55
3	Aggrading	N	Y	N	N	4.7	-6	58
4	Aggrading	N	Y	N	N	5.6	-4	60
5	Narrowing	Y	N	N	N	6.9	-12	44
6	Narrowing	Y	N	N	N	14.5	-16	27
7	Narrowing	Y	ND	N	N	9.7	-17	0
8	Narrowing & aggrading	Y	Y	N	N	9.7	-11	63
9	Narrowing & aggrading	Y	Y	N	N	11.3	-14	58
10	Narrowing & aggrading	Y	Y	N	N	13.9	-14	50
11	None?	N	ND	N	N	9.1	-5	0
12	Narrowing	Y	N	N	N	10.2	-14	40
13	Narrowing & aggrading	Y	Y	N	N	12.5	-14	55
14	Widening & aggrading	N	Y	Y	N	11.8	14	56
15	None?	N	ND	N	N	11.1	3	0
16	Narrowing & aggrading	Y	Y	N	N	9	-15	57
17	Aggrading	N	Y	N	N	12.6	1	55

ND = no data
*1 for reaches other then 4, 5, 6, historical analysis is used to identify channels that have narrowed > 10% of their width between 1960/75 and 2013
*2 for reaches other than 4,5,6 this is interpreted from MTR surveys bed sediment calibre, where > 50% of the gravel bed is obscured by sand or finer sediments
*3 for reaches other then 4, 5, 6, historical analysis is used to identify channels that have widened > 10% of their width between 1960/75 and 2013
*4 incision indicated if W:D ratio < 1 or armouring of the bed indicated by > 80% bed material gravel or coarser

Table 8.6 Assessment of 'natural' riparian corridor function / artificiality (non-standard indicators used – see text for explanation)

Reach	Riparian corridor artificiality	Riparian corridor function	Functioning riparian vegetation class	Lateral gradient in riparian vegetation cover classes	Patchiness in riparian vegetation cover classes	Proportion (%) functioning riparian corridor under mature riparian vegetation	Proportion (%) functioning riparian corridor under intermediate riparian vegetation	Proportion (%) functioning riparian corridor under early riparian vegetation	Proportion (%) riparian corridor under riparian vegetation
1		Poor	Mature	Absent	ND	82	4	14	32
2	Artificial	Poor	Mature	Absent	ND	91	9	0	8
3		Partial	Balanced	Subdued	ND	33	4	63	23
4		Partial	Balanced	Absent	ND	19	7	74	58
5	Artificial	Partial	Balanced	Absent	ND	77	23	0	5
6		Poor	Mature	Absent	ND	100	0	0	21
7	Artificial	Poor	Mature	Absent	ND	100	0	0	12
8	Artificial	Partial	Balanced	Absent	ND	42	9	48	5
9	Artificial	Partial	Balanced	Absent	ND	76	21	3	5
10	Artificial	Partial	Balanced	Absent	ND	79	11	10	6
11	Artificial	Poor	Mature	Subdued	ND	84	15	1	10
12	Artificial	Partial	Balanced	Absent	ND	48	16	37	6
13	Artificial	Poor	Mature	Absent	ND	89	4	7	7
14	Artificial	Partial	Balanced	Absent	ND	71	1	27	11
15	Artificial	Poor	Mature	Absent	ND	83	8	9	16
16		Partial	Balanced	Absent	ND	37	0	63	31
17	Artificial	Partial	Balanced	Subdued	ND	40	20	40	10

ND – no data (patchiness not detectable form the information sources available)

Table 8.7 Assessment of wood budget function / artificiality (non-standard indicators used – see text for explanation)

			Percentage of RHS surveys			
			Fallen trees		Wood	
Reach	Wood budget artificiality / degradation	Wood budget assessment	Present	Extensive (>33% of channel)	Present	Extensive (>33% of channel)
1		Functioning	53	13	73	0
2		Functioning	100	0	100	0
3		Functioning	60	0	80	20
4		Partial	67	0	33	0
5	Severely degraded	Poor	9	0	36	0
6		Partial	33	0	67	0
7	Severely degraded	Poor	25	0	25	0
8	Severely degraded	Poor	0	0	20	0
9	Severely degraded	Poor	13	0	13	0
10	Severely degraded	Poor	0	0	11	0
11	Severely degraded	Poor	0	0	0	0
12	Severely degraded	Poor	11	0	0	0
13	Severely degraded	Poor	19	0	0	0
14	Severely degraded	Poor	0	0	0	0
15	Severely degraded	Poor	0	0	0	0
16	Severely degraded	Poor	0	0	0	0
17	Severely degraded	Poor	0	0	0	0

8.2 *Stage 2: Controls on change*

8.2.1 Catchment

The River Frome lies in a medium-size agricultural catchment that has not experienced any significant changes in land cover or hydrology over the last 50+ years (Table 8.8).

Table 8.8 Catchment scale indicators of hydromorphology and evidence of change over time

Indicators	Value	Change
Drainage area (km^2)	459	No
Geology (WFD types)		
% siliceous	40%	
% calcareous	60%	
% organic	0%	No
% mixed /other	0%	
Land cover (CORINE level 1)		
% forest and semi-natural areas	11%	No
% wetlands	0%	No
% artificial surfaces	4%	No
% agricultural areas	86%	No
Water yield (mm)	507	No
Annual runoff ratio (coefficient)	0.52	No

8.2.2 Landscape units

Characteristics at the landscape unit scale have changed little over time (Table 8.9). There has been a slight increase in land cover associated with rapid run-off generation due to expansion of towns in Landscape units 2 and 3. Whilst the scale of urban development is relatively small, it is clustered near the river so may have an impact on surface water and sediment delivery to the channel, particularly for Dorchester (Landscape Unit 2).

Whilst land cover in general has not changed markedly over the last 100 years, the character of agricultural land use has changed. Agricultural land was dominated by pasture in the early 20th century, with the arable area being approximately 30% that of pasture up to the 1930s, but there has been a marked shift towards arable crops since then, such that they now cover a similar land area by the end of the 20th century (Figure 5.2). At the same time, there has been a shift to cereal production with yields increasing dramatically through the 20th century (Figures 5.3a and 5.4). In relation to livestock production, sheep dominated in the first half of the 20th century but since the 1950s, there has been a trend of increasing livestock numbers, with cattle showing the largest numbers, followed by sheep, and with pigs also present in significant numbers (Figure 5.5). Finally, there was a short but significant increase in potato production during WWII

(570% increase between 1935 and 1945) (Figure 5.3b). In combination, these land use changes suggest a trend of increased fine sediment production from ca. 1930 through the 20th century, which has undoubtedly generated enhanced fine sediment delivery to the river.

Table 8.9 Hydromorphological characteristics and evidence of change over time at the landscape unit scale

Indicators	1	2	3	Change
% area of exposed aquifers	98%	85%	26%	
% area of permeable soil substratum	73%	98%	77%	
% glaciers and perpetual snow	0	0	0	No
% large surface water bodies	0	0	0	No
Land cover / Runoff production				
% area of rapid	0%	4%	4%	Slight increase
% area of intermediate	97%	94%	83%	No
% area of delayed	2%	2%	13%	No
Soil erosion rate (t. ha^{-1}. y^{-1})	0.09	0.28	0.17	Probable increase
% area with potential sources of coarse sediment	0	0	0	No

8.2.3 Segments

The River Frome is a low gradient, unconfined, groundwater-dominated river over its entire course (Table 8.10). The flow regime in all segments with gauging stations (segments 1, 5, 6) is classified as perennial stable / superstable with peak flows in the winter and minimum flows in the summer/autumn, as expected for a chalk river. The temporal analysis of river flows found no significant trends in mean, minimum and maximum annual flows, so a detailed analysis of temporal change in flow characteristics was not conducted. A flow regime analysis conducted on the gauging station records from Segment 6 indicated a slight increase in the baseflow index, though the river was and remains a strongly baseflow-dominated system. As stated in the preceding landscape unit section, an increase in fine sediment delivery is inferred from changes in agricultural land over the 20th century that are related to increased fine sediment production. Fine sediment is a significant pressure on the River Frome that came to the attention of researchers and regulators in the 1990s, and is the major reason why the River Frome SSSi fails to reach favourable condition (Punchard, 2013).

Table 8.10 Hydromorphological characteristics and evidence of change over time at the segment scale. Note: there was no evidence of temporal changes in river flows so they were not analysed (N/A). PS – perennial stable, PSS – perennial superstable.

Indicators	1	2	3	4	5	6	Change
Valley gradient (m.m-1)	0.011	0.005	0.003	0.003	0.002	0.002	
Valley confinement	Unconf.	Unconf.	Unconf.	Unconf.	Unconf.	Unconf.	
River confinement	25.06	13.77	20.07	20.08	27.81	28.07	
Flow regime type	PSS				PS	PSS	More stable
Baseflow index (BFI)	53.64				49.69	55.74	Increase
Average annual flow ($m^3 s^{-1}$)	0.18				3.3	6.66	No
Average monthly flows ($m^3 s^{-1}$)	See Fig. 4.7				See Fig. 4.7	See Fig. 4.7	N/A
Morph. meaningful discharges, ($m^3 s^{-1}$)							
$Q_{pmedian}$	0.62				11.71	20.72	N/A
Q_{p2}	0.65				11.41	20	N/A
Q_{p10}	1.12				20	24.25	N/A
Extremes: 1- and 30-day maximum and minimum flows							N/A
1-day low	0.08				0.90	2.57	N/A
30-day low	0.62				1.08	20.72	N/A
1-day high	0.09				12.40	2.84	N/A
30-day high	0.36				7.30	14.07	N/A
Hydropeak frequency (number / year)	0				0	0	N/A
Eroded soil delivery (tons/km/yr)	0	3.09	3.52	11.22	12.56	1.08	Probable increase
Land surface instabilities	none	none	none	none	none	none	No
Estimated suspended sediment load (t.y-1)	0.518	16.6	90.7	395	1293	1501	
Estimated bedload (t.y-1) (bedload input, SIAM)	0	25000	23500	18500	32400	75700	Unknown
Sediment budget	loss	gain	gain	gain	gain	gain	Probable increasing gain
Number of channel blocking structures							
High impact	0	0	0	0	0	3	No
Intermediate impact	0	3	3	4	7	12	No
Riparian corridor							
Width	70	122	227	345	603	585	
Continuity	42%	30%	27%	9%	18%	21%	Minimal change
Cover / structure	Mature	Bal.	Mature	Bal.	Mature	Bal.	
Active channel bordered by trees	32%	14%	24%	8%	13%	13%	

8.2.4 Space-time inventory

Given the constraints of the historical data that are available, the inventory for the Frome focuses on the last century. Synthesising the information that has been assembled, the River Frome has:

(i) A highly artificial river channel network affected by numerous blocking and spanning structures, channel realignments associated with extensive water spreading and drainage systems, and a highly artificial riparian corridor with restricted areas of functioning riparian vegetation and degraded wood budgets. However, this high level of artificiality stems from centuries of interventions to the river and floodplain, rather than any significant changes over the last century, and so is not included in the space-time inventory.

(ii) There is no evidence of a significant change in the river's flow regime based on the data that is available for analysis, and this lack of change is supported by the limited changes in land cover classes that may affect catchment runoff response and knowledge of the likely minimal effects of groundwater abstractions on river flows. Therefore, flow regime change is also excluded from the inventory

(iii) However, based on analysis of land cover change and sediment production at landscape unit scale and analysis / estimation of sediment delivery and budgets at segment scale, fine sediment production and delivery to the river network appears to have changed significantly over the last 100 years. Therefore, the space-time inventory for the Frome is rather simple. It focuses on sediment production, delivery, budgets at both landscape unit and segment scales, and is represented by the schematic shown in Figure 8.1.

8.3 Stage 3: Assess reach sensitivity

Parts of four reaches are used to illustrate the hydromorphological response and thus sensitivity of the River Frome to the above changes:

Reach 6 is historically straightened and is subject to regular if light maintenance;

Reach 4 is historically straightened but has experienced minimal maintenance in recent decades;

Reach 3 is a meandering reach with functioning riparian vegetation and wood budget.

Reach 5 contains a short section of actively meandering channel that is largely unmanaged and provides evidence of the mechanisms of channel adjustment that are occurring in actively meandering sections of the river.

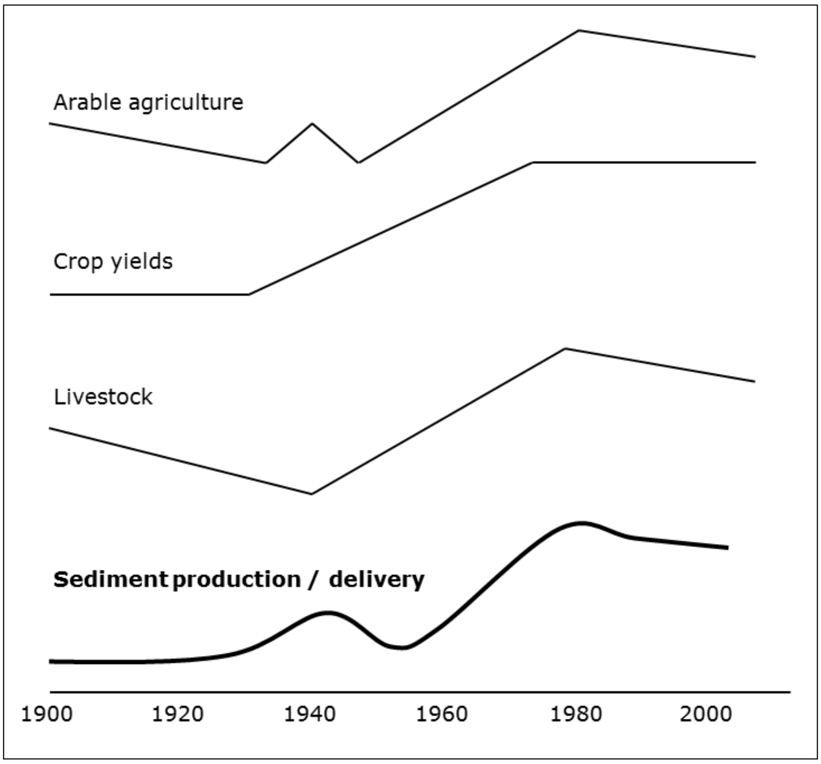


Figure 8.1 Sediment production and delivery increased over the 20th century due to expansion of arable agriculture, intensification of farming practices and increased livestock numbers.

8.3.1 Reach 6 – an artificially straightened reach that remains subject to some maintenance

Reach 6 is located in Landscape Unit 2, Segment 3. It is an anabranching reach with several secondary channels bisecting the floodplain. The main channel is purported to have been straightened and widened in the medieval period by monks from a nearby monastery, and its straight course is currently maintained through the removal of aquatic macrophytes and wood when they develop to the stage that they start to trap sediment and divert flow. The reach is classified as having good hydromorphological function but is artificial as a result of the presence of low blocking structures. It has poor riparian vegetation function (because it is comprised of predominantly mature trees, Table 8.6) and a partially functioning wood budget (Table 8.1). There are some geomorphic and vegetation-related units within the channel (Table 8.3) – according to RHS surveys, these are few in number and mainly comprise occasional silt deposits, mid-channel unvegetated bars, vegetated side-bars, eroding and undercut banks, fallen trees, wood debris and exposed underwater roots. According to field surveys of the downstream half of the reach, approximately 5% of the channel bed is occupied by bars, benches and islands, 30% of the banks are eroding / aggrading and there are frequent aquatic plant-dependent features and occasional wood / tree dependent geomorphic units (Table 8.3).

The temporal analysis of planform change found a decrease in channel area (Figures 5.12) and a significant narrowing of the main channel width (Figure 5.14, Table 8.5). However, channel position and width has remained unchanged, according to the historical sources, over most of the length of the reach (Figure 8.1). The upstream section has shown some lateral mobility, whereas the downstream section has narrowed significantly. Channel planform and the number and size of anabranches have not changed over the last 100+ year (Figure 8.1). Lidar data (Figure 8.2) shows little evidence of lateral channel dynamics, apart from an apparently artificial cutoff at the upstream end of the reach and some textural evidence of channel narrowing in the downstream section.

The downstream section of Reach 6, has experienced some increase in woodland cover on the right bank, but the floodplain was and continues to be used primarily as pasture (Figure 8.3). Naturally-functioning riparian vegetation is found clustered along the upstream section of anabranches and along the left bank of the upstream section of the main channel (Figure 8.4). According to RHS surveys, aquatic vegetation is present in very few locations in Reach 6, and is extensive in none (Figure 4.26). This probably reflects channel shading. However, in field surveys extensive cover of both emergent and submerged aquatic vegetation was observed in the most downstream, unshaded part of the reach (Figure 8.5a), and also in the unshaded central part, just upstream of the road bridge crossing. Within the more shaded central section, immediately downstream of the road bridge, aquatic vegetation is present wherever there is sufficient light penetration through the overhanging trees (Figure 8.5b).

Based on the above data and field observations, Reach 6 has shown significant channel narrowing despite management interventions. The channel narrowing probably reflects the increasing fine sediment delivery to the river and this has resulted in the development of a range of vegetation-related landforms, that have either persisted to induce narrowing or have been removed to prevent the river developing a sinuous course, including medial bars and islands, and lateral benches initiated mainly by emergent macrophytes, but with wood contributing to the development of some of these features. Figure 8.6 provides an aerial view of some of these features.

Overall reach 6 has been subject to significant straightening in the past and continued management that maintains a relatively straight channel course. However, hydromorphological adjustment has occurred within the river channel, induced by increased fine sediment supply and sediment trapping by plants to build in-channel landforms that aggrade, narrow the channel, and, if left unmanaged, to induce an increase in channel sinuosity. Undoubtedly, these processes are reducing in-channel retention of sediment within the channel bed (Table 8.5) relative to some other reaches of the Frome, and further dispersal of sediment to floodplain aggradation undoubtedly occurs during over bank flow events. Thus, despite the artificial hydrogeomorphic state of reach 6, it is showing adjustments to changes in sediment supply that are having a positive effect on channel form and dynamics and are partially absorbing the potentially adverse effects on the channel bed. These changes appear to be gradual and progressive.

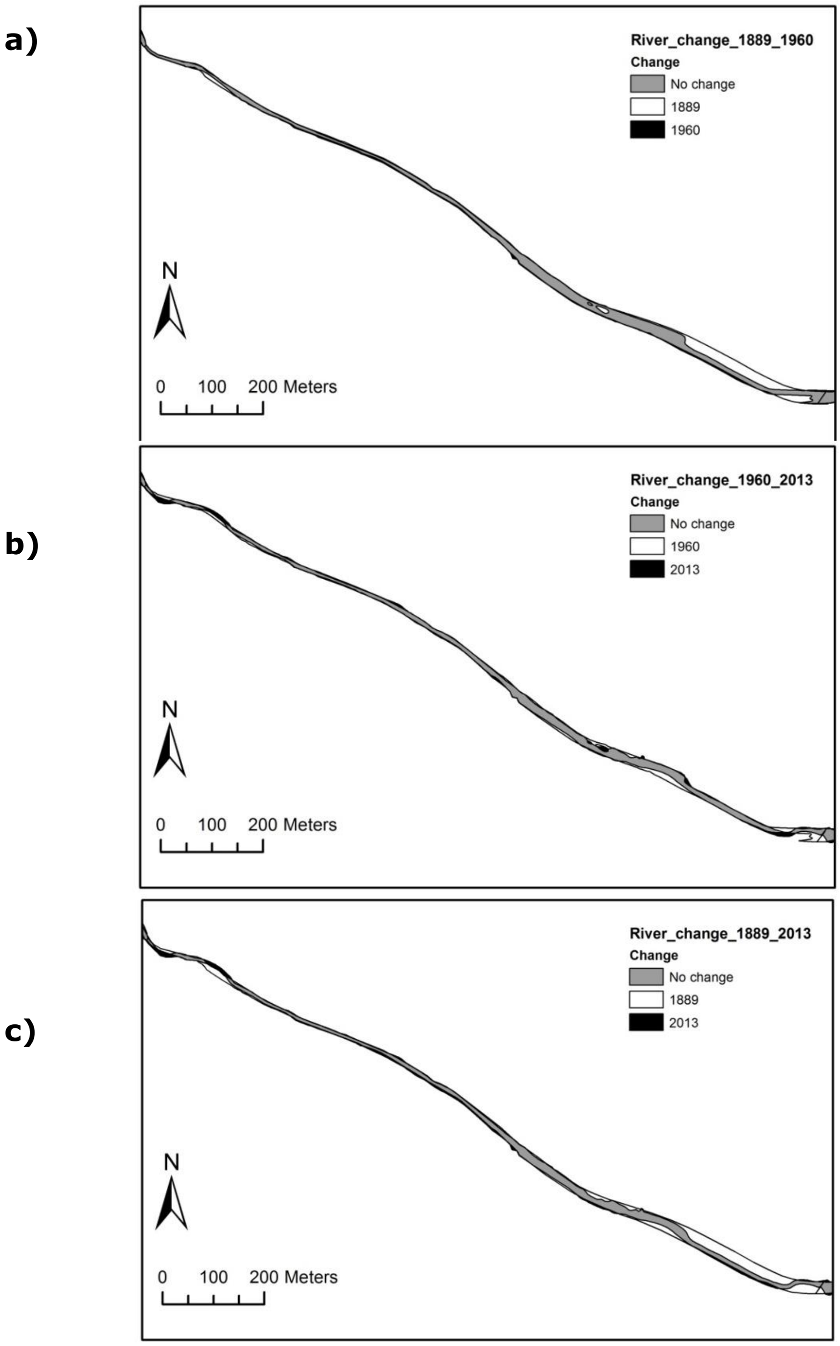


Figure 8.1 Overlays of channel position showing where channel position has not changed between time points (grey), where deposition occurred (white), and where erosion occurred (black): (a) 1889 and 1960, (b) 1960 and 2013, and (c) 1889 and 2013. Note that the river flows from left to right in the above images.

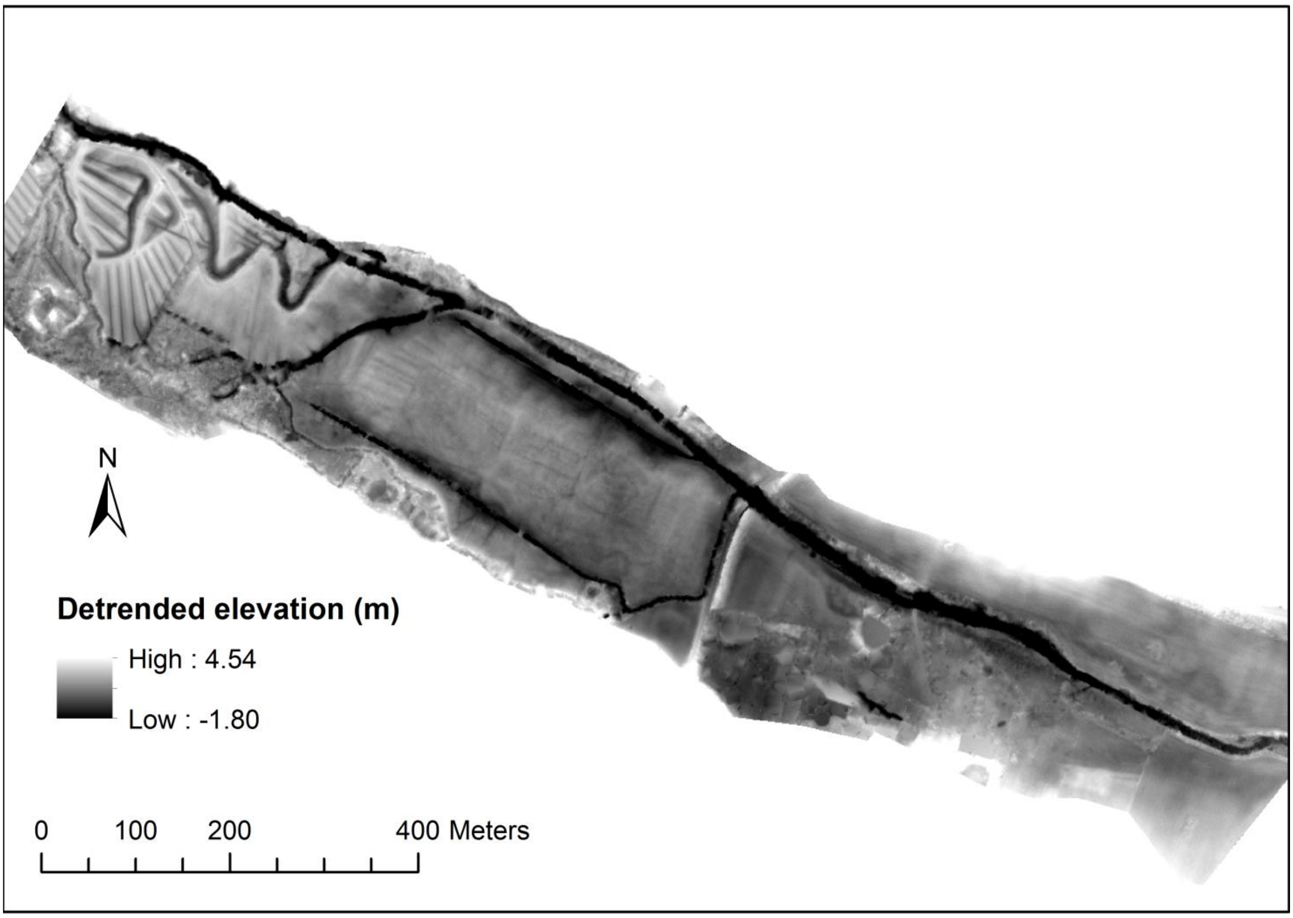


Figure 8.2 Relatively featureless floodplain and limited evidence of lateral channel dynamics revealed in Lidar data for reach 6. Note the apparently artificial cutoff and straightening of the main channel at the upstream end of the reach. Note that the river flows from left to right in this image.

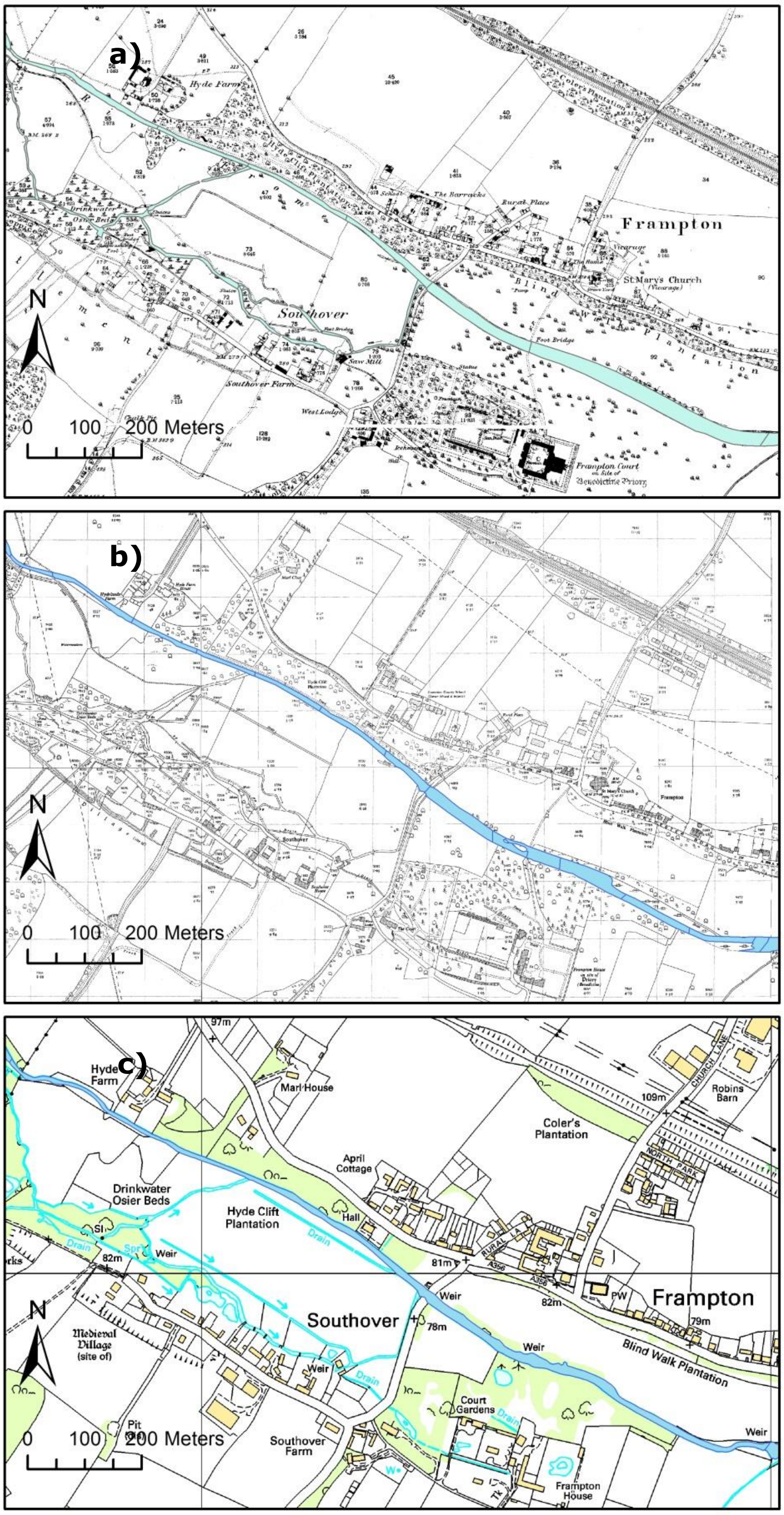
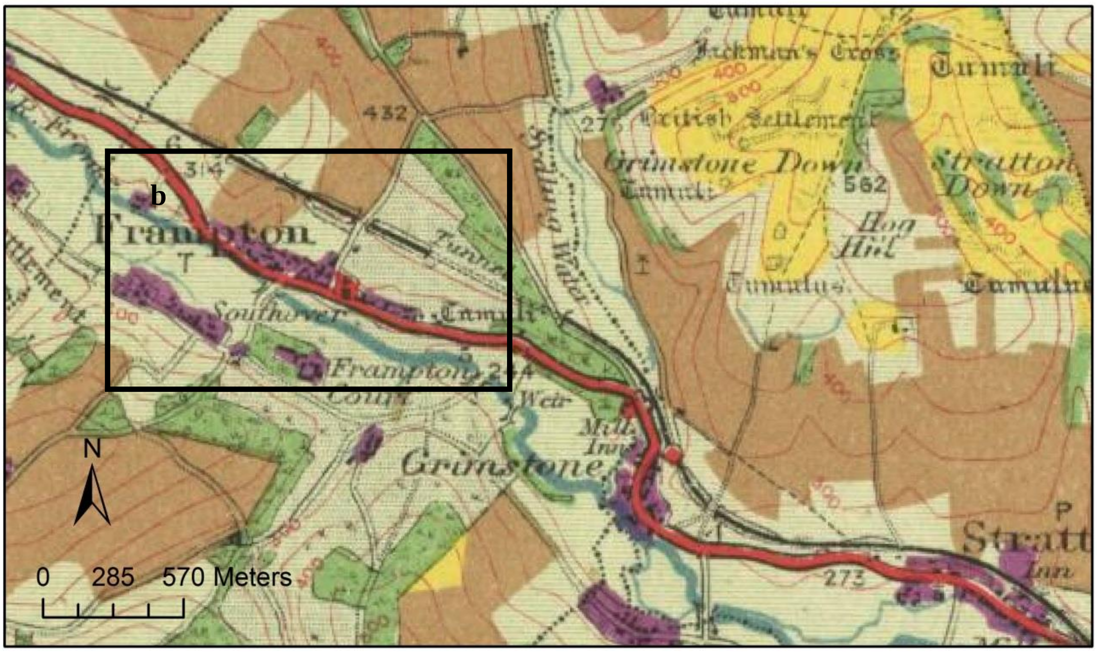


Figure 8.3 Ordnance survey maps of Reach 6 in (a) 1889, (b) 1975 and (c) 2013. Note that the river flows from left to right in the above images.

a)



b)

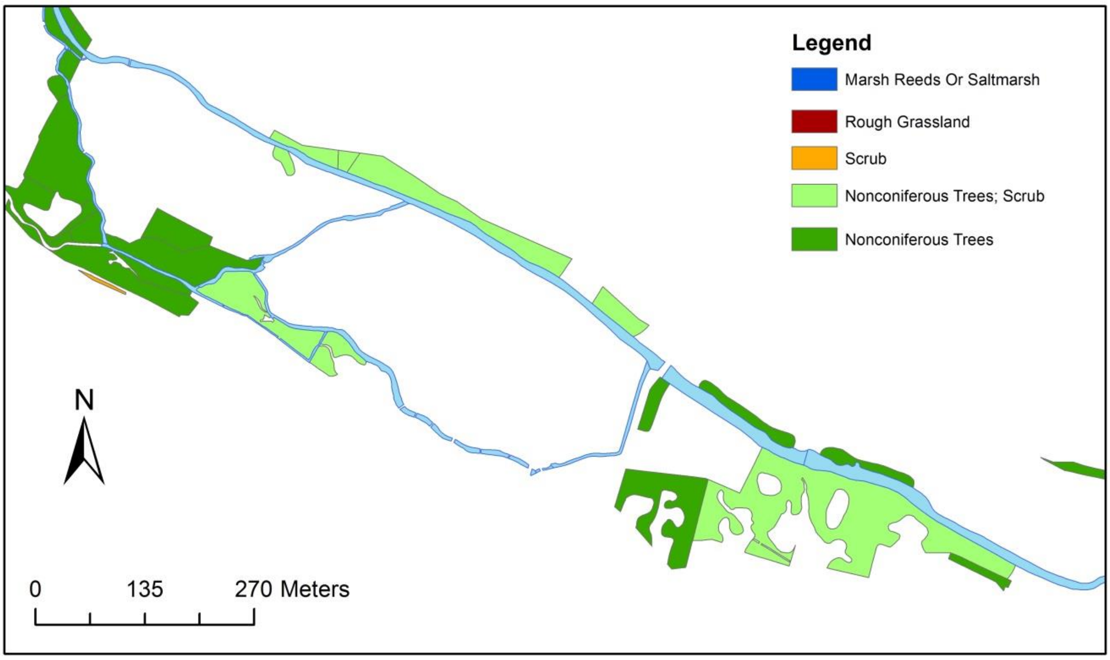


Figure 8.4 Land cover for Reach 4 from (a) the First Land Utilisation Survey (1943) and (b) the current OS Mastermap data (2013). Note that the river flows from left to right in the above images.

Figure 8.5

a) **Extensive macrophyte cover in the downstream unshaded part of reach 6 in mid-summer**

b) **Patches of emergent macrophytes in unshaded areas of a tree lined part of reach 6, immediately downstream of the road bridge crossing. Note the gentle bank profile adjacent to the macrophyte stands indicating bank accretion through bench development and extension associated with the emergent macrophytes.**

c) **Island developing on a mid-channel bar, now covered by riparian vegetation but probably initiated by emergent macrophytes.**

d) **Bank extension led by macrophyte sediment trapping.**

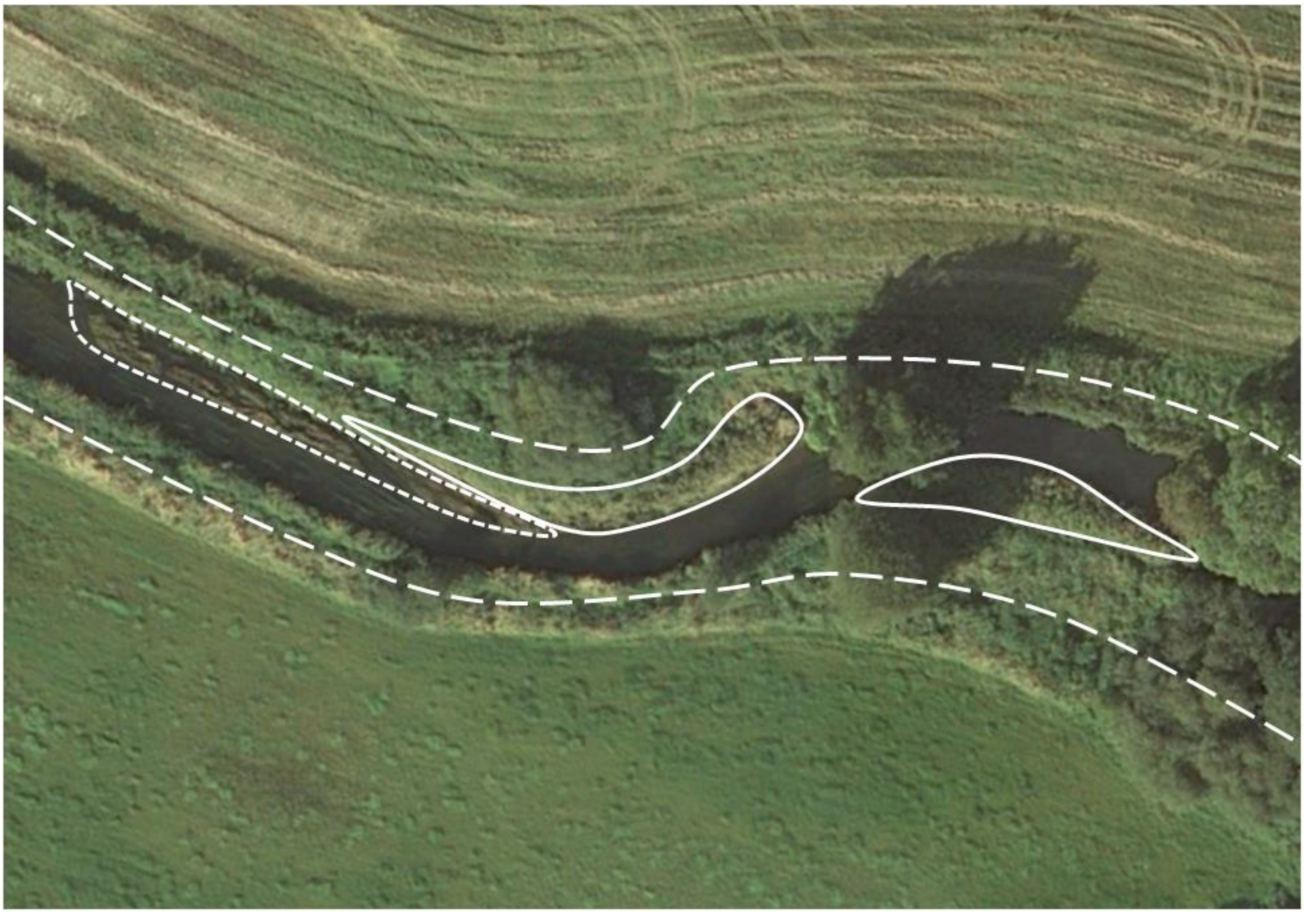


Figure 8.6. Aerial image of part of the downstream, unshaded part of reach 6, showing a large stand of emergent macrophytes (*Sparganium erectum*) trapping sediment within the edge of the channel (dotted line); emergent benches (solid line), and a break of slope, probably indicating a previous position of the river banks (dashed lines).

8.3.2 Reach 4 – an artificially straightened reach that is undergoing natural hydromorphological recovery

Reach 4 is located in Landscape Unit 1, Segment 2. The reach is classified as being predominantly single thread and sinuous with good hydromorphological function but is artificial as a result of the presence of both low and intermediate blocking structures. It has partially functioning riparian vegetation and partially functioning wood budget (Table 8.1). 'Partial' is the highest rating possible for riparian vegetation function because of the restricted data available to support the assessment (Table 8.6). However, this reach has the highest proportion of riparian corridor under riparian vegetation (58%) of all reaches of the Frome. There are some geomorphic and vegetation-related units within the channel (Table 8.3) – according to RHS surveys, these mainly comprise occasional extensive vertical and vertical-undercut (i.e. eroding) banks, mid-channel unvegetated and vegetated bars, vegetated and unvegetated side-bars, fallen trees, wood debris, exposed and underwater roots. According to field surveys of the upstream half of the reach, approximately 10-15% of the channel bed is occupied by bars, benches and islands, 44% of the banks are eroding / aggrading and there are occasional aquatic plant-dependent features and abundant and diverse wood / tree dependent geomorphic units (Table 8.3). The discussion focuses on this upstream part of the reach, which was straightened when an embanked railway line was built in the mid-19th century. This upstream reach does not contain any blocking structures. The downstream part of the reach passes through the town of Maiden Newton and so is difficult to access in the field.

A temporal analysis of the channel position for Reach 4 as a whole, found no significant change in the position or dimensions of the channel (Figures 5.12 and 5. 15). However overlays of channel positions suggest a narrowing of the channel in the upstream half of the reach, particularly between 1889 and 1975, and some lateral mobility (Figure 8.8). Other relevant information from historical maps (Figure 8.9) is the long-term presence of drainage ditches and springs across a wide floodplain in this upstream section. Furthermore, the maps confirm that the floodplain is largely covered by wetland vegetation including marshy areas and discrete areas of riparian woodland.

The area under riparian vegetation cover appears to have increased significantly over the last 100 years (Figure 8.9). In the late 19th century the area was used primarily as pasture and there was limited to no riparian vegetation (Figure 8.9a). Trees and shrubs established in the downstream end of the floodplain and rough grass / wetland in the centre between 1889 and 1975 (Figure 8.9 a,b). The timing of this change is uncertain but likely began in the mid-20th century; the First Land Utilisation Survey from 1943 shows the floodplain covered in pasture (Figure 8.10). Current land cover data shows the floodplain covered primarily in rough grassland with trees and scrub clustered near the river channel and floodplain drains (Figure 8.10).

Field survey of the upstream part of Reach 4 revealed remnants of past bank reinforcement (Figure 8.11) but also a wide diversity of geomorphic features within the channel. The bed material is classified as sand/gravel based on MTR surveys (Table 8.2) and, in the field, it is apparent that large areas of the river bed are covered in thick layers of fine sediment (Figure 4.41) and that many of the geomorphic units represent accumulations of fine sediment, usually associated with living riparian vegetation or wood. Because of extensive shading of the channel by riparian vegetation (and possibly smothering by fine sediment), there is very little aquatic vegetation in this reach. The formation of many of these geomorphic units is contributing to channel narrowing and the early stages of channel migration. In addition to riffles (e.g. Figure 4.41 right), pools (e.g. Figure 4.42 left) and gravel bars (Figure 4.43), there are numerous fine sediment bars and small islands (Figure 4.44, 4.47), fine sediment benches (Figure 4.45, 4.48 c and d) often with ridge/scroll-like features on their surface (Figure 4.46), large wood jams and riparian trees within the channel (e.g. Figure 4.41 right, Figure 4.42, Figure 4.48) that are trapping fine sediment and inducing bar and bench development, and varied bank profiles both eroding and depositing.

Based on the above, Reach 4 has and is showing significant channel adjustment, albeit within a planform that has been fairly stable. This adjustment reflects interactions between fluvial processes and riparian vegetation and wood under a regime of increased fine sediment supply and negligible vegetation management. Furthermore, although there are early signs of channel migration, this may be restricted partly because of the well-developed riparian tree cover lining the banks.

Overall the upstream part of Reach 4 has been subject to significant straightening in the past and its movement is restricted on the left bank by a high railway embankment. Nevertheless, hydromorphological adjustment has occurred within the river channel, induced by an abundant supply of fine sediment interacting with riparian trees and wood to build numerous in-channel landforms that aggrade, narrow the channel, and are starting to induce an increase in channel sinuosity. Unfortunately, despite these adjustments, sizeable areas of the channel bed are covered with fine sediment (confirming the aggradation suggested in Table 8.1), and there is evidence of floodplain surface aggradation (buried layers) in some eroding bank profiles. Despite the artificial hydromorphic state of reach 4 through straightening in the past, it is showing significant and complex adjustments to changes in sediment supply that are having a positive effect on channel form and dynamics. These changes appear to be gradual and progressive.

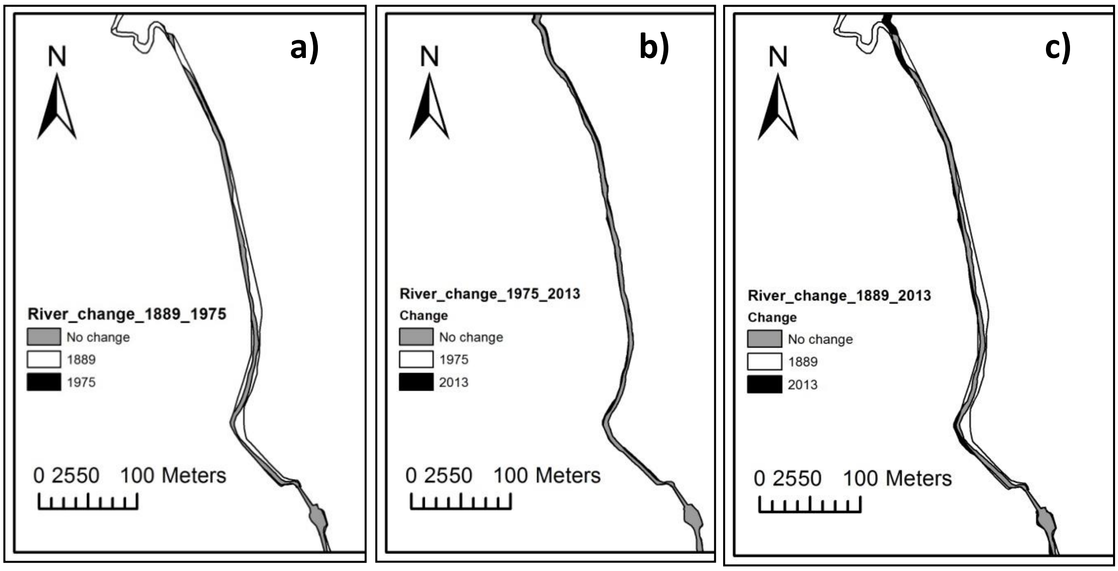


Figure 8.8 Overlays of channel position in the upper section of Reach 4, showing where channel position has not changed between time points (grey), where deposition occurred (white), and where erosion occurred (black): (left) 1889 and 1975, (middle) 1975 and 2013, and (right) 1889 and 2013.

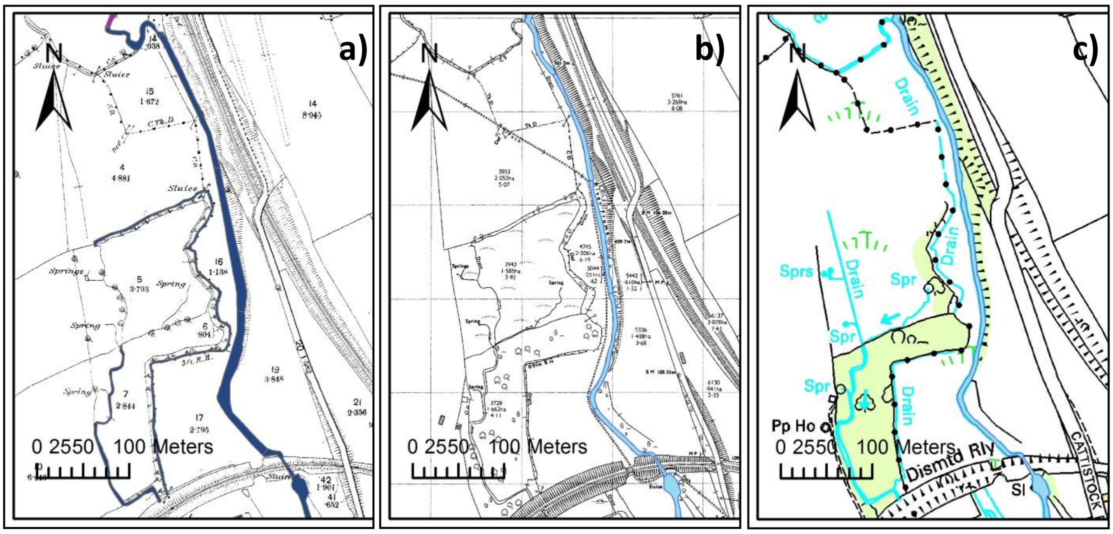


Figure 8.9 Ordnance survey maps of upper half of Reach 4 in (left) 1889, (middle) 1975 and (right) 2013.

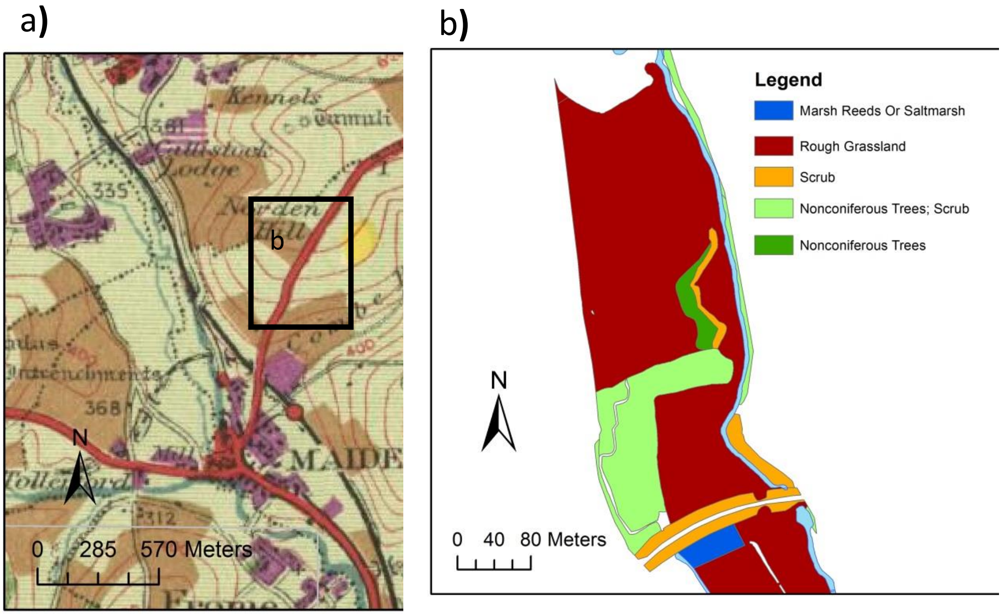


Figure 8.10 Land cover for Reach 4 from (a) the First Land Utilisation Survey (1943) and (b) the current OS Mastermap data (2013).

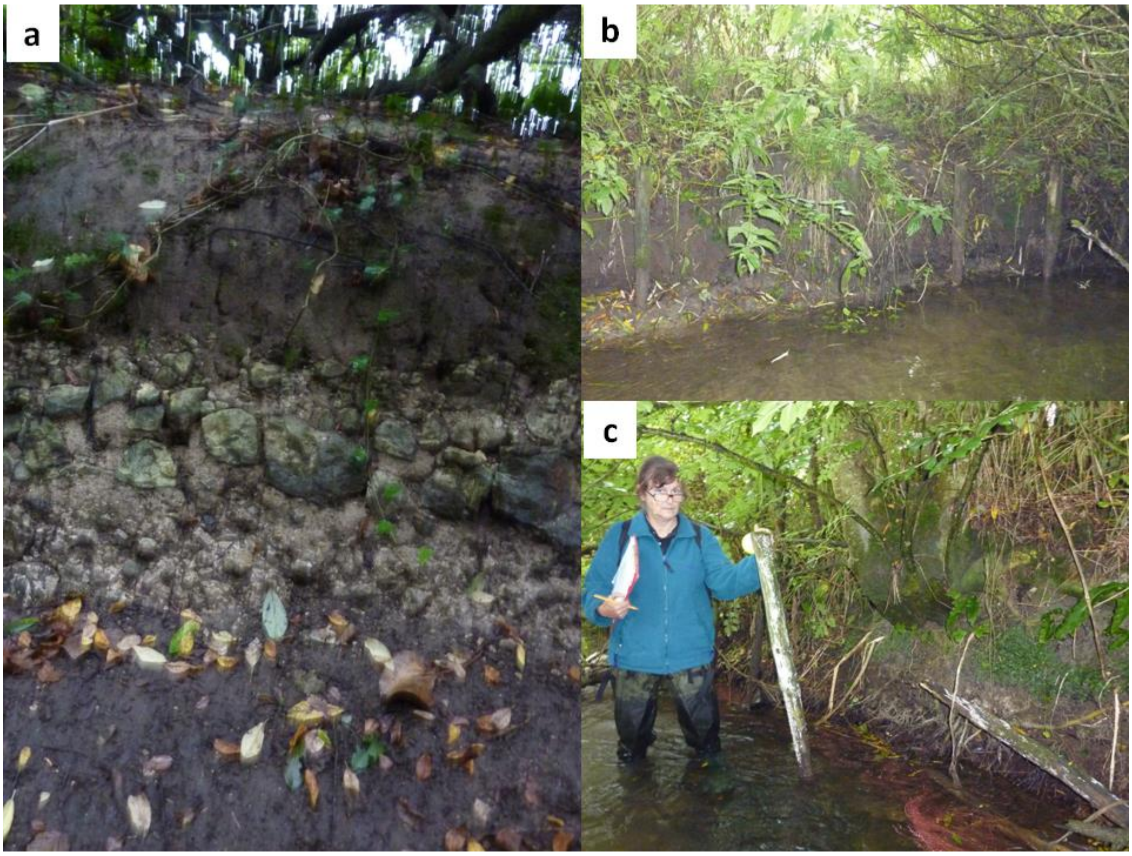


Figure 8.11 Exposures of old bank reinforcement: a) stones, b) wooden stakes facing the bank, c) wooden stakes exposed by bank erosion and retreat.

8.3.3 Reach 3 – a meandering reach

Reach 3 is a single-thread meandering reach located in Landscape Unit 1, Segment 2, and immediately upstream of the previously discussed Reach 4. Permission for access could not be obtained for a field visit, and so the following description is based on secondary sources. Reach 3 was assessed as having intermediate hydromorphological functioning with some artificial elements, partial riparian vegetation function and a functioning wood budget (Table 8.1). The reach contains some geomorphic and vegetation-related units within the channel (Table 8.3) – according to RHS surveys, the reach contains the highest frequency of pools and second highest (after reach 1) frequency of riffles per unit channel length of all of the Frome reaches. In addition mid-channel and marginal vegetated and unvegetated bars are present and (from Google Earth), there are wetland areas on the floodplain.

Temporal analysis reveals that the channel has altered its position substantially over the last 100 years. Reach 3 saw the greatest amount of change in channel position out of all of the Frome reaches (Figure 5.11a). Of the total area that the channel occupied in both 1889 and 1975, only 27% remained unchanged over that period. There was a decrease in channel area over that time period (Figure 5.12) and an increase in channel sinuosity (Figure 5.13), but no significant change in average width was detected (Figure 5.14). Channel overlays show meanders progressing downstream over time (translation), extending further outwards (extension), and a combination of the two (rotation) (Figure 8.12). The 1899/1975 overlay also shows neck cutoffs. The timespan is too long to determine the mode of cutoff exactly, but it appears to be via chute channels, as opposed to neck closure. Lidar data (Figure 8.13) also indicates significant past channel migration by flood plain depressions in the upstream and downstream thirds of the reach.

Functioning riparian vegetation is limited to the upper and middle sections of Reach 3, although the channel margin is marked by a line of tress for virtually the entire length of the reach (Figure 8.16). The woodland at the upstream end of the reach was once actively managed (Yew Cliff Coppice) but is now classified as tree and scrub, and has likely been left to naturalise (Figures 8.14 and 8.15). The riparian corridor along the left bank is classified predominately as rough grassland but there is a small pocket of tree/scrub nestled between two meanders that are confined against the railway embankment (Figures 8.14 and 8.15a). Further downstream a marsh (i.e. backswamp) is present in what was classified as pasture in 1889 (Figures 8.14a,b and 8.15). The rest of the reach has isolated trees (Figure 8.15) but no significant riparian vegetation (Figure 8.14c).

Reach 3 provides a good comparison to Reach 4 in that it retains its natural planform and is actively migrating. However, the mechanisms underpinning that migration cannot be interpreted without a field visit. Nevertheless, field observations were made within an actively meandering section of Reach 5. These are discussed below and provide insights into the likely functioning of Reach 3.

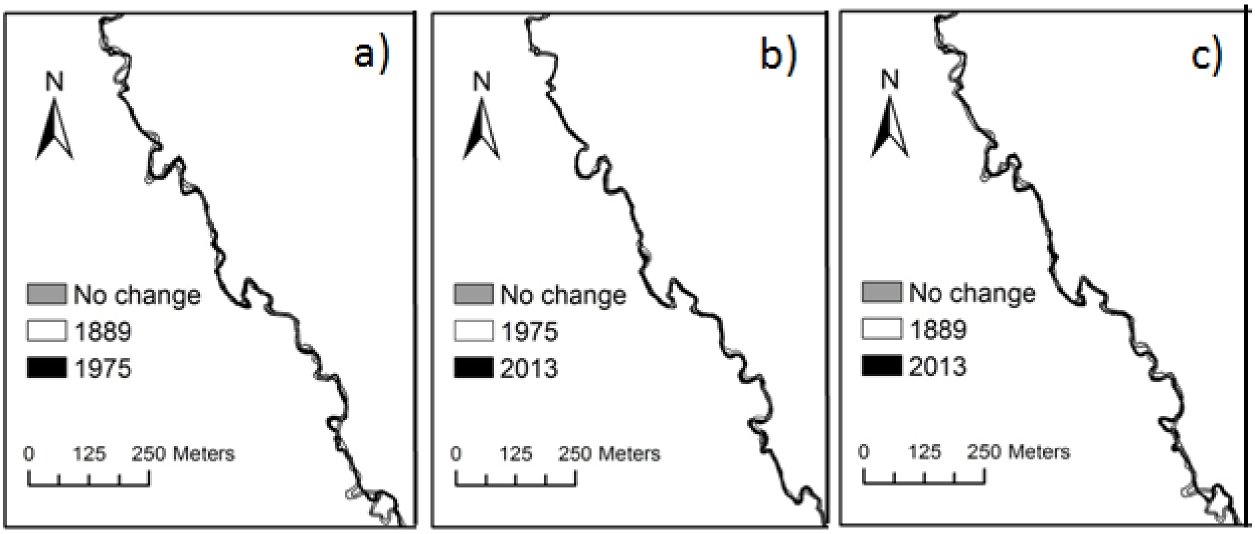


Figure 8.12 Overlays of channel position in Reach 3, showing where channel position has not changed between time points (grey), where deposition occurred (white), and where erosion occurred (black): (a) 1889 and 1975, (b) 1975 and 2013, and (c) 1889 and 2013.

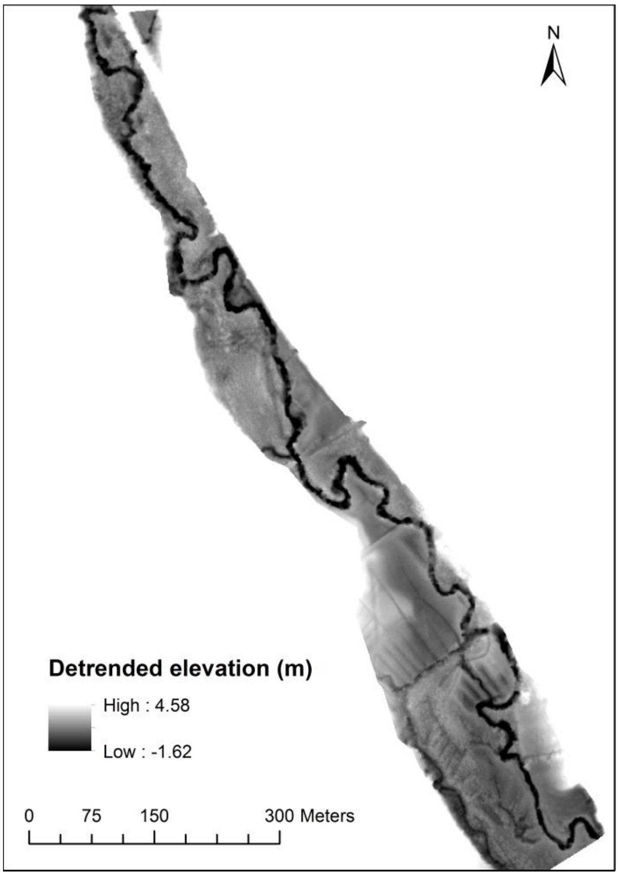


Figure 8.13 DEM of reach 3 based on Lidar data. Unfortunately, the data was supplied pre-processed to remove vegetation, but this does not seem to have been done well. Nevertheless, there is evidence of significant lateral channel movements, leaving old channel remnants on the floodplain in the upstream and downstream thirds of the reach.

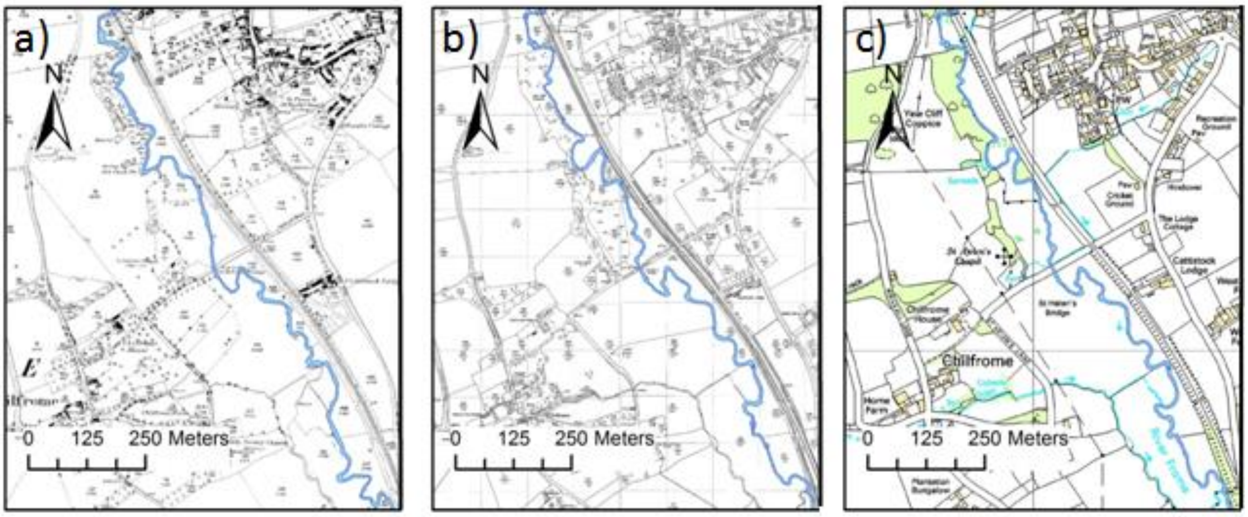


Figure 8.14 Ordnance survey maps of Reach 3 in (a) 1889, (b) 1975 and (c) 2013.

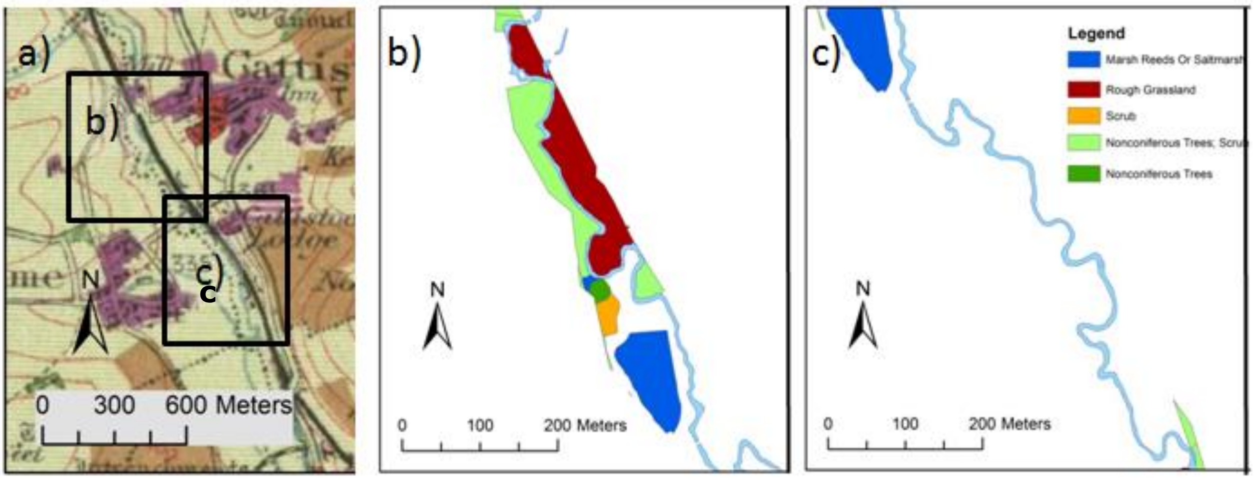


Figure 8.15 Land cover for Reach 3 from (a) the First Land Utilisation Survey (1943) and (b,c) the current OS Mastermap data (2013) for the (b) upper and (c) lower half of the reach.

Figure 8.16 Aerial photographs showing (left) the naturally functioning riparian vegetation in the upstream half of Reach 3, and (right) the isolated trees and riffle sequence along the lower half of the reach (Google Earth, © 2014 GetMapping).

8.3.4 Reach 5 – a short section of dynamic meandering river.

Although Reach 5 as a whole is classified as sinuous, some sections are sufficiently sinuous to be categorised as meandering, including one reach within the upstream part of Reach 5 (Figure 8.17), which is described below.

Reach 5 is located in Landscape Unit 2, Segment 3. It is a sinuous reach with some meandering sections. The reach is classified as having good hydromorphological function but is artificial largely as a result of the presence of low blocking structures, and has partial riparian vegetation and a very degraded wood budget (Table 8.1). There are some geomorphic units within the channel and floodplain and, based on MTR surveys, the bed material is described as gravel / sand, indicating a lower presence of fine sediment than in Reaches 3 and 4.

Temporal analysis of the channel position in the whole of Reach 5 shows a progressive increase in sinuosity and decrease in channel width since 1889. The upstream part of Reach 5 (Figure 8.17) shows significant shifts in channel position since 1889, particularly in the meandering reach that was visited in the field, where there has been both progression / downstream translation and lateral extension of the main meander bend. Analysis of Lidar data (Figure 8.18) reveals that such dynamics are typical of the reach and have left numerous sinuous depressions reflecting historical channel positions typical of actively meandering river floodplains.

Ordnance survey maps (Figure 8.19, 8.20 b) show areas of riparian trees and shrubs towards the upstream and downstream ends of the upper part of Reach 5, although these do not appear on the First Land Utilisation Survey (Figure 8.20 a). Only isolated trees are marked along the banks of the meandering site, which are represented in recent aerial imagery as a line of riparian trees along the left bank of the river. In the field, this riparian vegetation is seen to occupy a narrow band on the left bank of the river (Figure 8.21). Figures 8.21 to 8.23 illustrate various features of this meandering reach that provide some detail of the processes involved in channel adjustment.

Figure 8.22 provides a close-up of the neck of the meander in early spring, before the leaves of the aquatic vegetation have started to shoot. Erosion of the upstream (right) side and extension of the downstream side (left) of the meander neck can be seen, and extension and erosion of the outer bank of the meander was also present (not visible in Figure 8.22), indicating active downstream migration of the meander. Bed forms include a deep pool at the meander apex and riffles upstream and downstream, of which the downstream (left) riffle is the larger. Although there is extensive fine sediment within the channel, a gravel bed is exposed throughout the reach. Figure 8.23 illustrates some geomorphic units within the channel, which demonstrate interactions between vegetation and fluvial processes. Extending channel margins are usually edged by emergent macrophytes (Figure 8.23 a and b), although riparian trees also colonise the bank toe in some parts of this reach. The adjacent fields are used for grazing, which may have reduced the ability of young riparian shrubs to establish on the river margins. Indeed, no riparian tree seedlings or young plants were observed on the river banks. The trapping and stabilisation of fine sediment at the toe of extending river banks by aquatic plants can be clearly seen in Figure 8.23 b. In addition to vegetation contributing to river bank extension, it also contributes to the stabilisation and aggrading of mid-channel bar surfaces. The vegetated bar developing on a riffle (Figure 8.22d) and the island (Figure 8.22c) both show emergent aquatic plants and some *Salix* shrubs as well as a range of wetland plant species.

Overall, vegetation appears to be contributing to the process of meander migration by trapping and stabilising fine sediment that is then absorbed into the river banks or mid-channel aggrading bars and islands. Fine sediment does not seem to be such a significant issue in this reach as in those investigated upstream, since areas of gravel bed were exposed along the entire reach. Nevertheless, fine sediment is accumulating within the channel edges and, presumably, contributing to the long term trend of channel narrowing as well as increasing sinuosity. Furthermore, areas of the floodplain quite recently occupied by the river have almost completely filled with fine sediment, leaving only shallow depressions. The reach appears to be adjusting to changes in fine sediment supply within the process of meander migration, with vegetation playing a key role in stabilising the fine sediment and absorbing it into the channel margins.

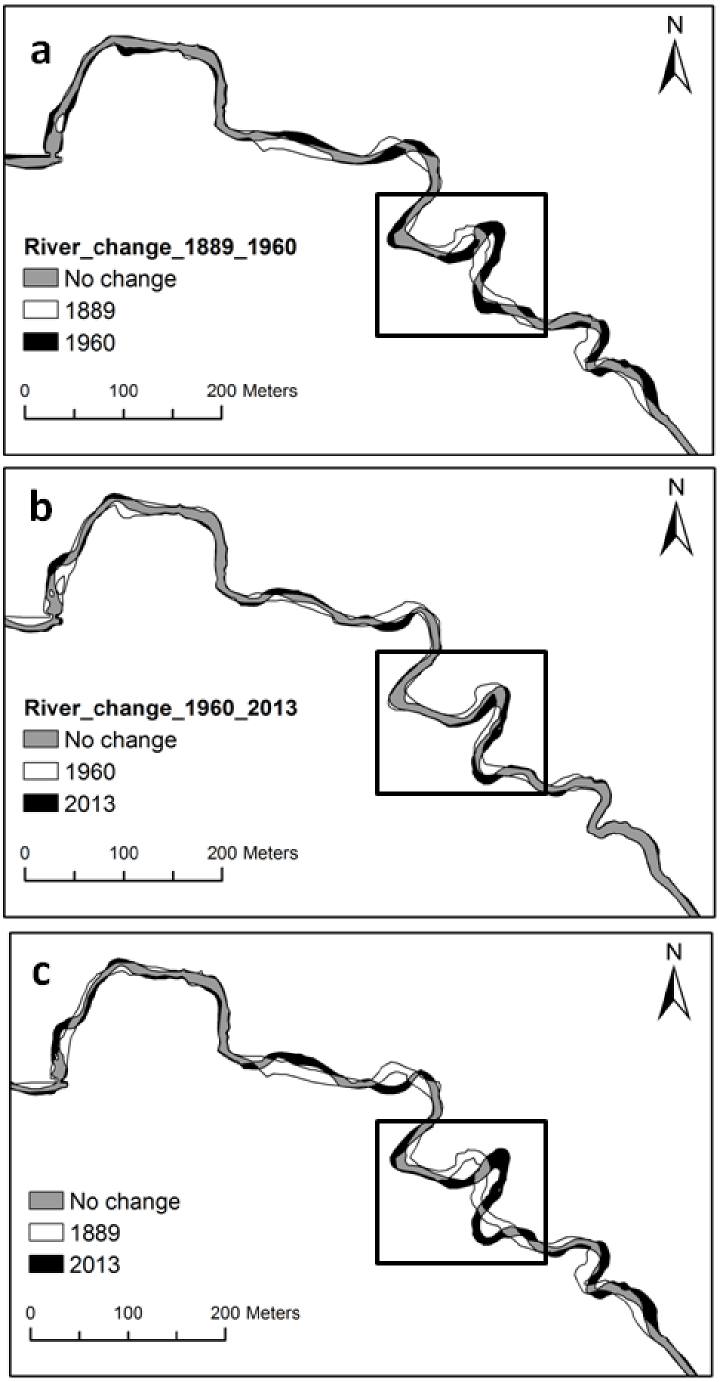


Figure 8.17 Overlays of channel position in upper reach 5, showing where channel position has not changed between time points (grey), where deposition occurred (white), and where erosion occurred (black): (a) 1889 and 1960, (b) 1960 and 2013, and (c) 1889 and 2013. Insets are the area studied in the field.

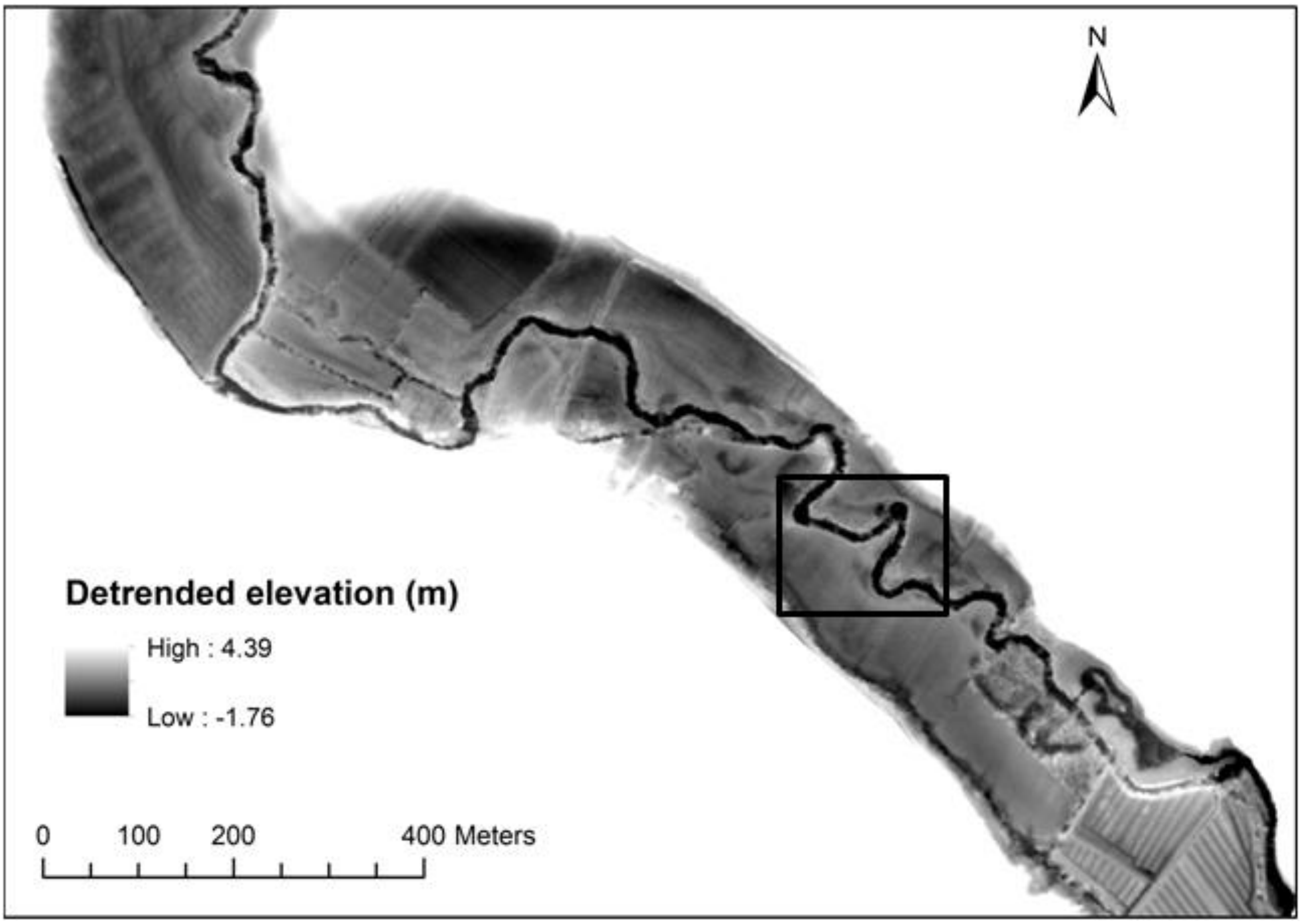


Figure 8.18 Detrended DEM from Lidar data for upper reach 5. Inset is the area studied in the field.

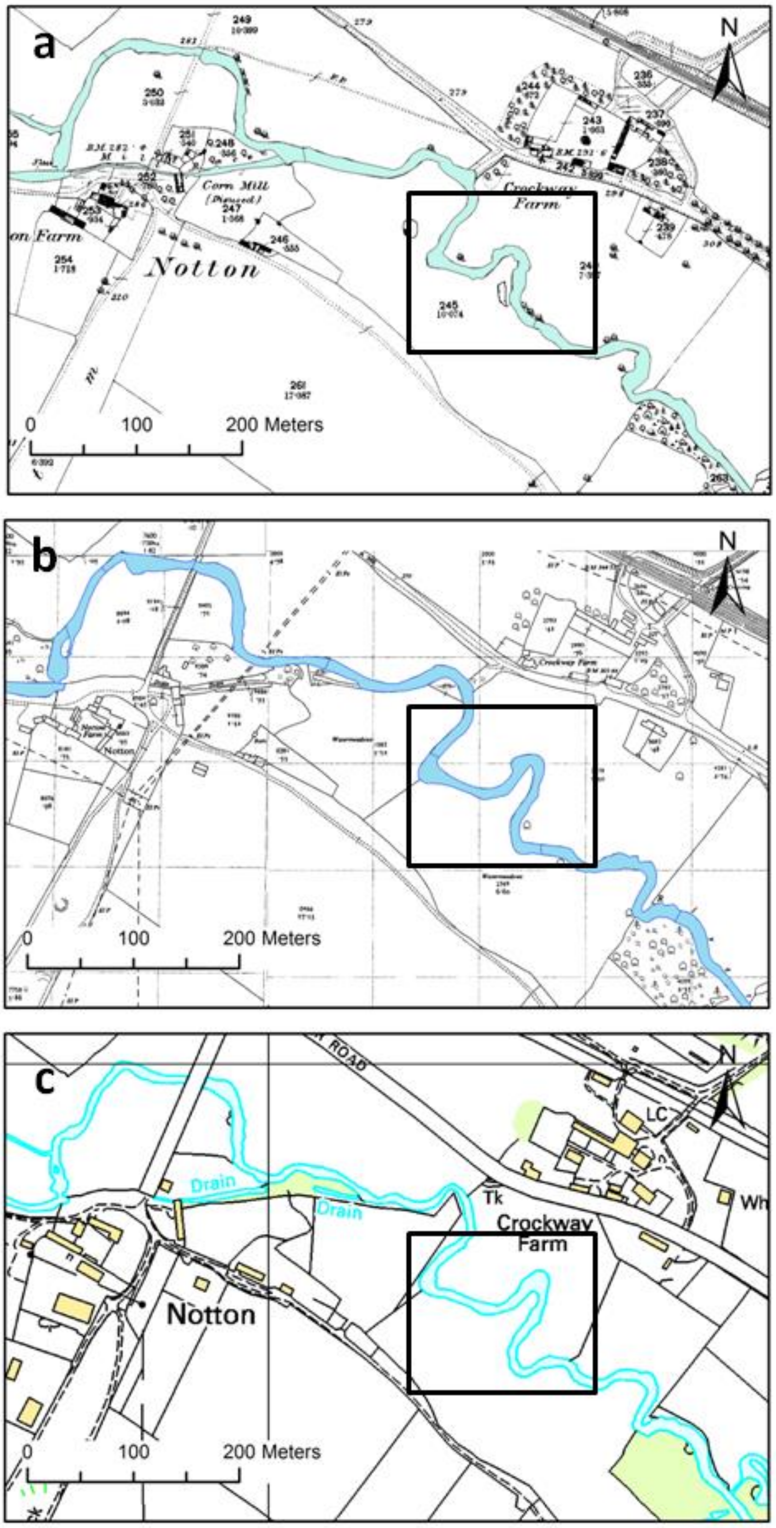


Figure 8.19 Ordnance survey maps of upper Reach 5 in (a) 1889, (b) 1960 and (c) 2013. Insets are the area studied in the field.

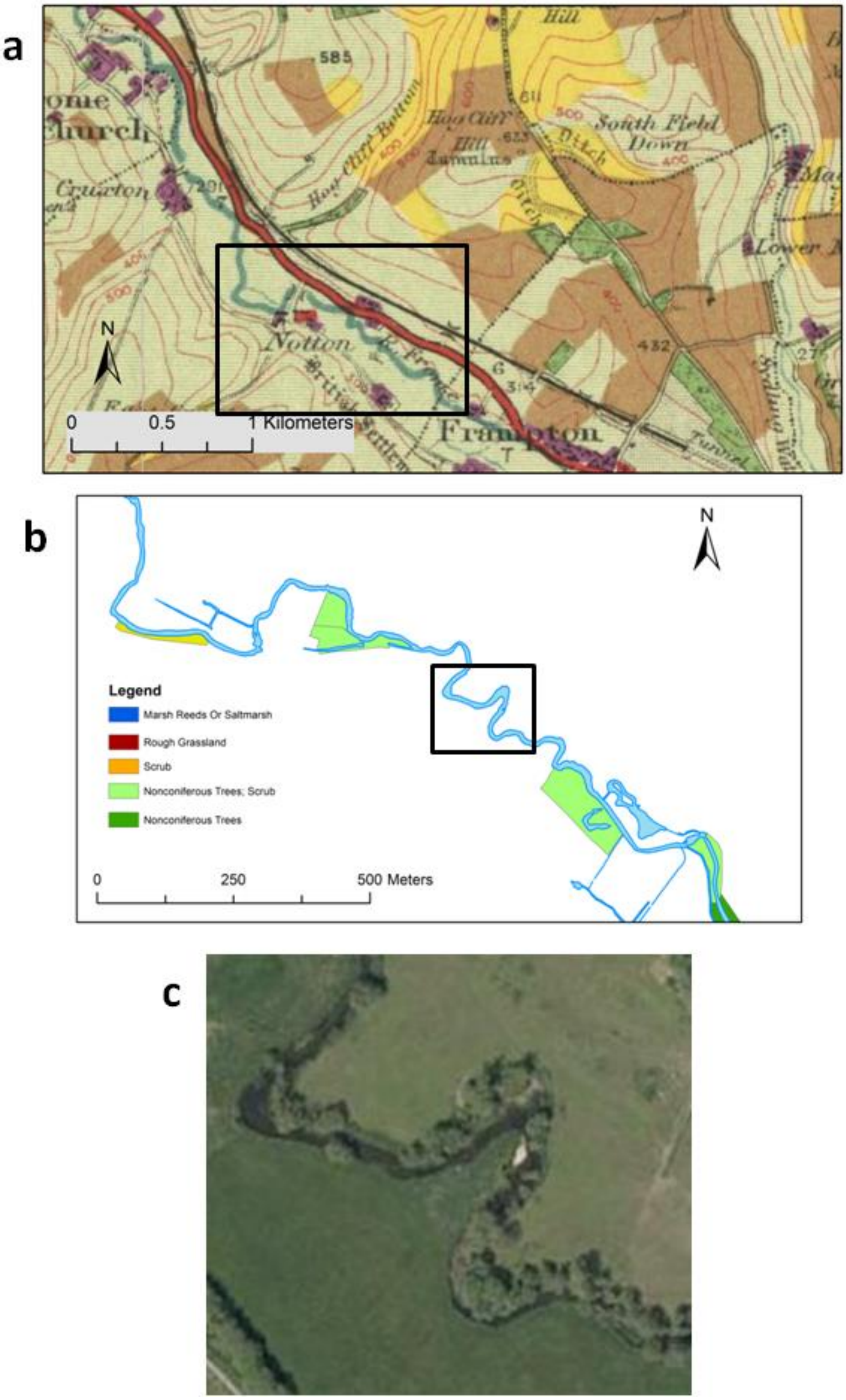


Figure 8.20 Land cover for upper Reach 5 from a) the First Land Utilisation Survey (1943) – see inset area; b) the current OS Mastermap data (2013); c) aerial image (2010) for the reach studied in the field (located as inset in b)).

Figure 8.21 Meandering section of reach 5 in early spring, facing south. Note the old channels picked out by floodwater on the floodplain and the line of riparian trees along the near (left) bank (the river flows from right to left of the photograph).

Figure 8.22 Meandering section of reach 5 in early spring, facing south at the apex of the meander. Note the deep pool at the bend apex and riffle downstream (left); eroding banks on the upstream side of the meander neck (right) and aggrading banks and mid-channel bars on the downstream side of the meander neck.

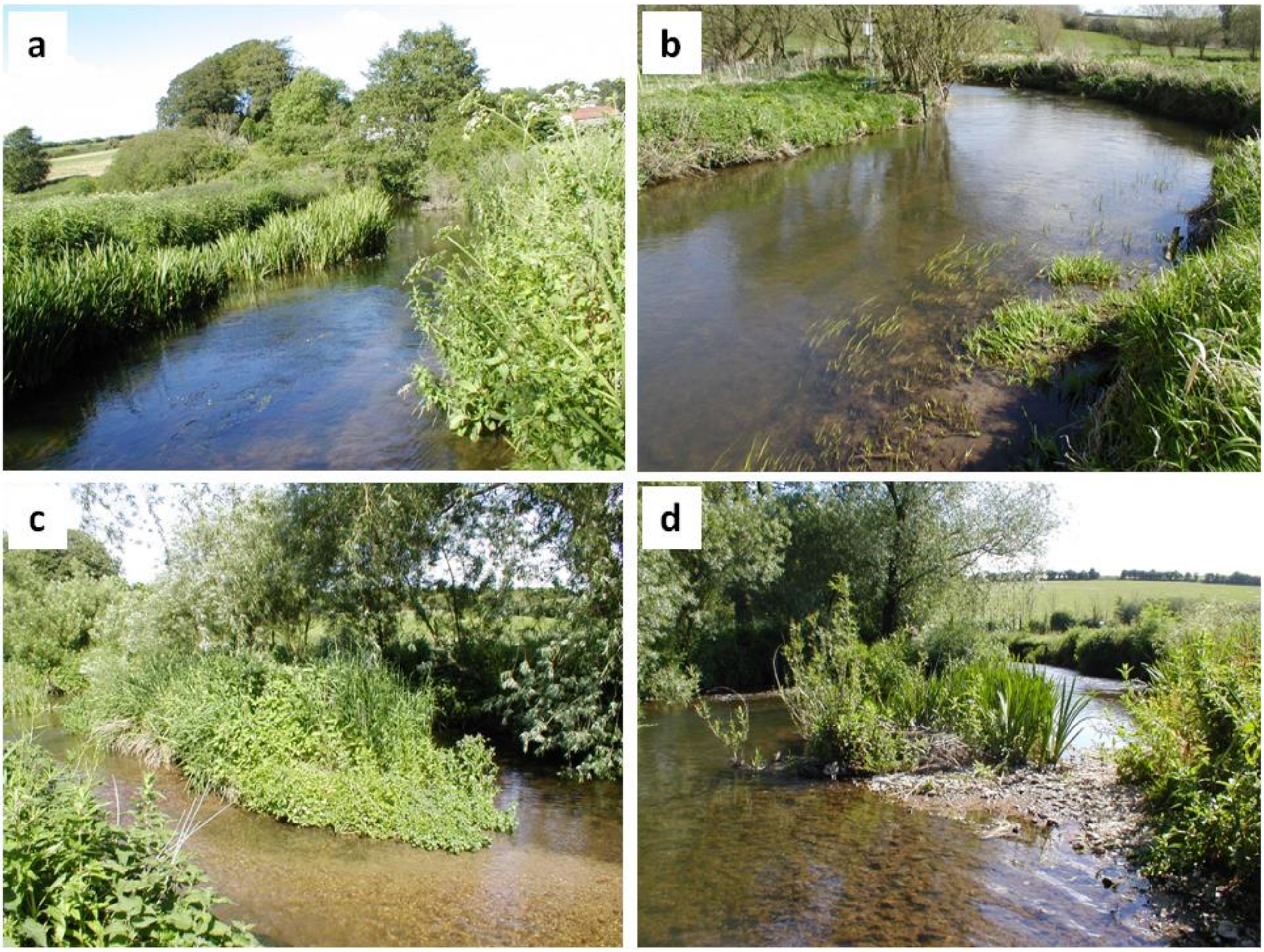


Figure 8.23 .Summer (a) and early spring (b) photographs of extending and aggrading banks edged by fine sediment that has been trapped and stabilised by the emergent aquatic plant, *Sparganium erectum*. (c) a mid channel bar and (b) a riffle – both colonised by aquatic plants and salix fragments to form a vegetated bar (d) that aggrades to an island (c).

8.3.5 Sensitivity of reaches of the River Frome to imposed changes in fine sediment delivery

The Frome is a low gradient (all reaches have channel gradient $\leq$ 0.01), low energy (unit stream power at Q median < 20 $W.m^2$ in all but Reach 1), unconfined river system with a sand / gravel, gravel / sand bed and 'earth' banks. Under these conditions, there is a restricted range of river types that are likely to occur (namely types 13 to 22) of which types 17, 18 and 19 were observed.

(i) *River characteristics preceding the detailed historical record (>> 100 years ago and preceding all major interventions)*. The impact of interventions that extend back beyond 100 years could not be assessed from the evidence available, so the following assessment is based largely on speculation. Historical land management changes and the associated installation of blocking and bridging structures and channel realignments will undoubtedly have reduced the energy of the river system below pre-intervention levels. Land use changes over the last 100 years have increased fine sediment production and delivery to the river leading to aggradation of the river bed in many reaches, and a fining of the bed material. Where the floodplain morphology still retains evidence of past river dynamics, it appears that the river has been laterally active in the past. All of this evidence suggests, that in the absence of all of these interventions, more active river types may have been present in the past (e.g. 13, 14), where the river bed material may have been coarser, and the gravel component may have been more mobile. Furthermore, less intensive land management practices would have combined with channel dynamics to support a more extensive area of riparian vegetation, which would have shown greater patchiness and lateral structure than is currently present. However, in the lowest gradient and lowest energy (downstream) reaches, poorer land drainage, more sinuous (unstraightened) channels and extensive fine sediment retention within and between channels by aquatic and riparian vegetation may have supported natural, self-sustaining anabranching systems of type 22.

(ii) *Changes in the last 100 years*. Virtually all reaches of the river have shown narrowing and /or bed aggradation in response to increases in fine sediment delivery. In general, aquatic and riparian plants and large wood provide structures to trap and stabilise fine sediment and thus absorb it into the channel margins or mid-channel landforms. As a result, despite the limited movement of coarse bed material, channel narrowing has occurred. There is very little bank reinforcement along the Frome and so channel narrowing has been accompanied by channel migration in sinuous reaches and by the development of geomorphic units indicative of the early stages of lateral movement towards a more sinuous planform in straightened channels. A further consequence of the increased delivery of fine sediment appears to be rapid sedimentation of old channel features on the floodplain, resulting in relatively featureless floodplains even in reaches where the floodplain has not been severely modified by human interventions.

(iii) *Rates of change.* All of the adjustments appear to be taking place at a relatively slow and steady pace. They represent <u>progressive changes, which may well be lagged by the time taken for fine sediment to reach the river channel</u> and then to pass downstream. Therefore, it is uncertain whether the observed differences in the amount of fine sediment retained in different reaches represents different lags in sediment delivery-transfer or different responses to the same delivery-transfer rates. Figure 8.24 attempts to summarise these changes in relation to key processes and river types.

(iv) *Sensitivity.* Even incorporating the speculation regarding the river's characteristics several centuries ago (i.e. (i) above), the river appears to have absorbed the majority of the changes to which it has been subjected and continues to absorb these changes, in that there is no evidence of any dramatic adjustments in river position or type. Thus, so far, the river has has been surprisingly *resilient* under the interventions and process changes to which it has been subject, at least in terms of its limited lateral dynamics and planform adjustment. It has also maintained a range of geomorphic units, particularly those that are vegetation-related, and sustaining areas of exposed gravel on the bed. Furthermore, in straightened reaches, the river has displayed an ability to regain sinuosity through interactions between vegetation and sediment, particularly fine sediment. Nevertheless, given the river type, which is not expected to show high lateral dynamics, the lack of geomorphic units that are attributable entirely to fluvial processes, and the significant accumulation of fine sediment within the channel, which is leading to channel narrowing, some significant in-channel sensitivity is being displayed, that is of importance for the fisheries of the river.

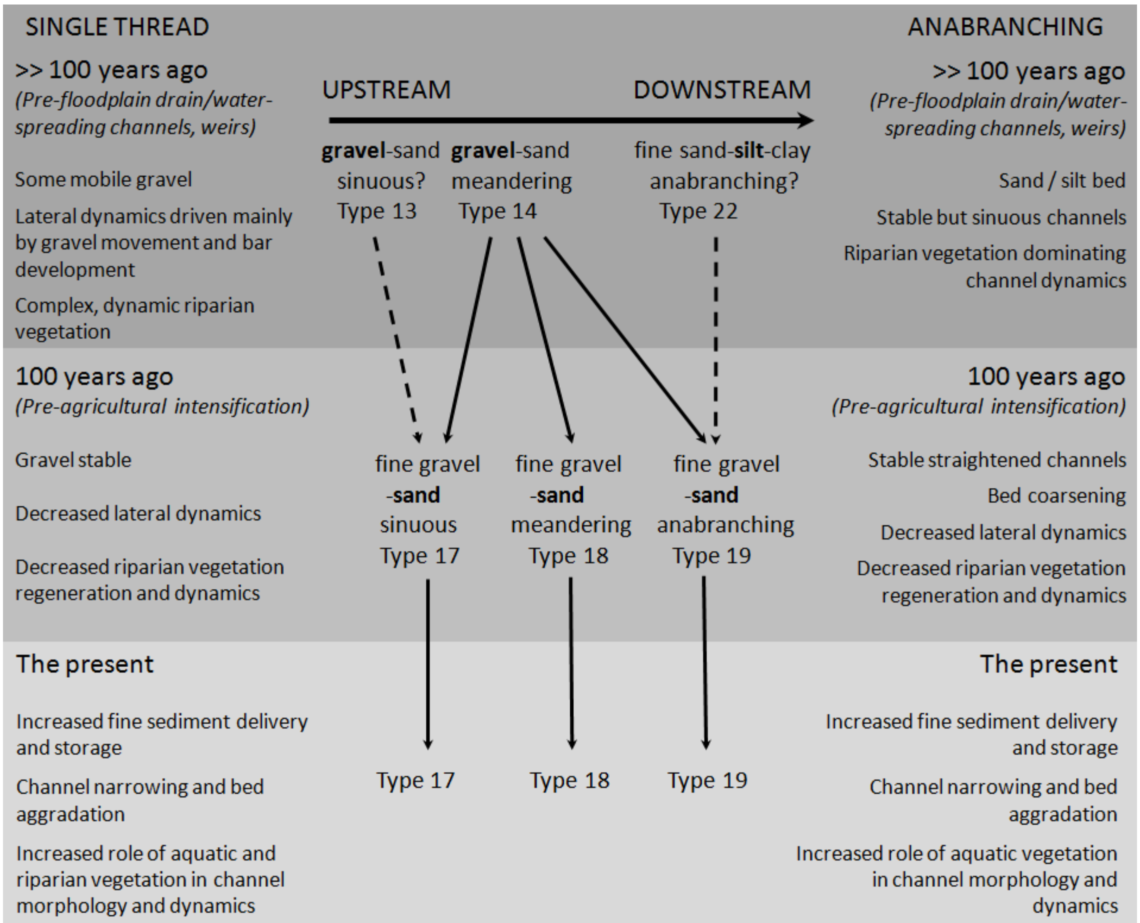


Figure 8.24 Summary of the likely changes in key processes and river types found in the Frome catchment over the last few centuries.

8.4 Stage 4: Assess scenario-based future changes

The previous sections have attempted to characterise the changing functioning and form of the Frome over the last century. These have illustrated a history of increasing land and river management interventions, the intensification of agriculture that has resulted in increased delivery of fine sediment to the river network, increasing isolation and management of areas of riparian vegetation, and some management of in-channel vegetation through summer cutting. These suggest four likely scenarios over the next 50 years:

(i) A warming climate with increased intensity of rain storms but no change in the way the catchment and river is managed

(ii) Removal of some structures from the river network

(iii) A change in agricultural land cover and management practices

(iv) A relaxation of riparian and aquatic vegetation management.

The likely consequences of each of these is considered below:

8.4.1 Scenario 1: A warming climate with increased intensity of rain storms but no change in the way the catchment and river is managed

Increased air temperatures under a warming climate are likely to be accompanied by increased water temperatures if there is no change in river and catchment management. Background water temperatures in the Frome are very stable because of the high groundwater component in river flows. Futhermore, channel shading by riparian trees and the canopies of emergent and floating-leaved aquatic plants, help to maintain relatively cool temperatures. However, if the latter are maintained at current levels, warming of river water will undoubtedly result, and may exceed critical thresholds for some aquatic fauna.

The flow regime of the River Frome is classified as perennial super stable / stable, with an indication of increasing stability over recent decades. This reflects the chalk-dominated geology of the catchment and so is unlikely to change in the coming decades. More intense rainfall events may induce more peaked flow hydrographs but this change is unlikely to be significant. However, intense rainfall on arable fields, particularly from autumn through to early spring when arable fields show extensive areas of bare soil, is likely to result in increased fine sediment delivery to the river network. This will exacerbate fine sediment problems within river channels, with likely adverse consequences for river biota. In terms of the morphodynamics of the channel network, increased fine sediment delivery is likely to result in increased fine sediment retention, leading to further channel narrowing, siltation of the channel bed, and potential siltation and blockage of side channels, where flow energy is at its lowest. Ultimately, the reduced conveyance caused by this siltation could lead to more frequent floodplain inundation. Because of the low gradient and extremely low energy of the river, this is more likely to lead to floodplain aggradation than the incision of new channels. However, new anabranches may be created in some locations.

8.4.2 Removal of some structures from the river network

The Frome river network contains numerous blocking structures, particularly from reach 4 downstream (Table 8.4). Although only three high blocking structures are present, intermediate structures are present in all reaches downstream of reach 7. These structures reduce the flow energy in what is already a very low energy system, as well as providing a physical barrier to transport of all but the finest sediment. Removal of some of these barriers, or their replacement by flexible barriers that can be fully opened, would improve sediment transport through the river network and would allow some local sediment flushing. This might help to counteract the build-up of fine sediment within the river network, although it is unlikely to fully resolve the problem because of the inherently low energy of the river.

8.4.3 A change in agricultural land cover and land management practices.

Fine sediment delivery and retention in the Frome catchment has been attributed to changes in agriculture, particularly since the 1960s (Figure 8.1). Such changes reflect market forces and may also reflect climate changes, so it is difficult to forecast likely changes in the balance of crops and livestock over the next 50 years. Nevertheless, small changes in the methods used to produce the same crops as at present, could help to counteract increasing soil loss and sediment delivery to the river under forecast climate changes. Numerous measures could help to alleviate soil erosion and loss, but the following measures would be easy to introduce and could be particularly effective:

(i) Use of crop production methods that maintain some cover on fields at times of year when rainfall is likely to be most intense. Under the current climate, the period of year with the highest energy rainfall events is Autumn (Gurnell: unpublished analysis of rainfall data for Hampshire). Therefore, spring planted crops are likely to result in lower soil erosion than autumn planted crops, with fields left under stubble / fallow during autumn and winter).

(ii) Planting of grass strips around field edges and across very large fields would break up the length of downslope surface across which soil erosion can develop.These would intercept mobilised fine sediment before it reaches the river. Such plantings can be beneficial in other ways. For example, the inclusion of flowering plants can support pollinating insects.

The implementation of such measures would, at least, help to maintain fine sediment delivery to the river network at current levels under a changing climate. Under these circumstances, river channel narrowing could lead to an equilibrium condition, where the narrowed channel generates sufficient water depths to increase flow velocities enough to transport the delivered sediment.

8.4.4 A relaxation of riparian and aquatic vegetation management

Riparian vegetation is highly managed in the Frome catchment leading to only partial riparian corridor function, at best (Table 8.6), and a poor, severely degraded wood budget (Table 8.7) in all reaches downstream from reach 6. In addition, although no quantitative data were available to the present analysis, aquatic weed cutting is known to have been widely practiced in the Frome catchment, at least until recently. As acknowledged under scenario 1 (8.4.1) shading by vegetation is important for maintaining cool water temperatures in summer. At the same time, field observations in reaches 4 (section 8.3.2) and 5 (section 8.3.4) have illustrated how riparian and aquatic vegetation are important in influencing in-channel and marginal habitats and channel dynamics. Finally, the presence of a band of riparian vegetation along river channel margins, helps to trap fine sediments before they enter the river channel.

More than any other measure, a relaxation of riparian and aquatic vegetation management within a corridor bordering the river network, is likely to induce major changes in the condition of the river. These changes will be particularly large because vegetation is so crucial to the morphodynamics of low energy rivers in humid temperate regions, such as the Frome. Furthermore, their precise form is likely to differ between the narrow headwaters and side channels, and the relatively large main channel in the downstream reaches. In particular, a distinction can be made between channels that are less than 10m wide (e.g. reaches 1-5), where vegetation features such as tree roots, smaller wood pieces (e.g. single tree branches and small accumulations), and single stands of aquatic plants can have a significant impact on physical habitat formation and channel morphology, and larger channels, where significant morphological effects of vegetation are associated with larger vegetation features such as the presence of entire uprooted trees in the channel, large trees growing into the channel, large accumulations of wood, and entire assemblages of aquatic plants. For more detail on the impacts of vegetation on river morphodynamics, please refer to Deliverable 2.2.

A relaxation of riparian and aquatic vegetation management, at least along a narrow corridor (e.g. 50m wide) bordering the river network, would have the following effects:

(i) Reduced fine sediment entry into the river network.

(ii) Increased complexity of in-channel and marginal landforms, many of which would be built of fine sediment retained by vegetation, leading to improved gravel bed exposure between the features, more variable connectivity between the main and side channels, and potential activation or even initiation of anabranches.

(iii) Increased channel sinuosity and migration, leading to..

(iv) Improved riparian vegetation turnover and age structure, leading to increased riparian vegetation patchiness and, through variable light receipt, increased aquatic vegetation patchiness and less likelihood of channel blockage by aquatic vegetation.

(v) Overall improvement in riparian and aquatic habitat diversity and turnover, which, coupled with lower fine sediment delivery and more stable, cooler water temperatures, should lead to an improvement in the size and diversity of faunal populations. However, the degree to which these beneficial effects could overcome and counteract the opposing effects of climate change (scenario 1) is uncertain.

9. Details of the methodologies employed for delineation and characterisation

The delineation was conducted in ArcGIS 10.0 with 3D Analyst and Spatial Analyst extensions.

9.1 Catchment

Delineation of the catchment boundaries was conducted according to standard procedures in ArcGIS using the Hydrology toolset in the Spatial Analyst Toolbox[16] (Figure 9.1).

9.1.1 Catchment delineation

1) Import DEM into ArcGIS, ensuring that the appropriate projection is indicated in the Layer properties.
2) Fill - This step removes any outliers in the DEM dataset (sinks and peaks) that would cause discontinuities in the derived drainage network.
3) Flow Direction - This step calculates the direction the water would flow across the individual cells of the raster. This is determined based on the elevation of the cell in relation to the eight adjoining cells.
4) Flow Accumulation - This step calculates the number of cells that flow into each cell, based on the flow directions raster. This can be converted to area by multiplying the accumulation value by the raster resolution (e.g. 0.3 x 0.3 km for an ASTER DEM).
5) Set Outlet point – Examine the Flow Accumulation raster and identify the individual cell along the main flow accumulation line that best corresponds to the end of your catchment. For the River Frome, we selected the Normal Tidal Limit, which is the location at which the river begins to be affected by the tides, as marked on the Ordnance Survey map (1:10 000 maps). Bear in mind that the location of the outlet point may not line up with the exact location of the river, and must be placed on the main flow accumulation line. The point shapefile should be created in ArcCatalog and added to ArcMap. Right-click on the shapefile in the table of contents window, select Edit Features>Start Editing and then Create feature using the point tool (a new template may need to be created in Editor, if none are visible in the Editor window).
6) Snap-to-Raster step ensures the point is correctly located.

[16] ArcGIS 10.0 Resource Center, http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/Deriving_runoff_characteristics/009z0000005p000000/). Accessed on 15 March 2013

7) Watershed – This step generates a raster file of the catchment boundaries, which can be converted to a more useful polygon format using the Raster to Polygon (ArcToolbox > Conversion tools > FromRaster). This polygon can then be used to clip other layers that are in the same projection using the Clip tool in the Geoprocesing menu for shapefiles, or the Clip tool (ArcToolbox> Data Management Tools > Raster > Raster Processing).

9.1.2 Deriving characteristics from shapefiles.

1) Import layers to ArcGIS and examine the spatial patterns in the attributes.
2) Convert raster layers to shapefiles. You can reclassify rasters beforehand, if, for example, you would like to display and summarise elevations as WFD ranges. (ArcToolbox > 3D Analyst > Raster Reclass > Reclassify)
3) Clip them with the watershed outline shapefile.
4) Calculate areas for the shapefiles in the attribute table. To do so, right click on the name of the layer in the Table of Contents, open the Attribute Table, Insert a new column by right clicking the column heading, and then right click in the new heading and calculate area using the 'Calculate geometery' tool.
5) Then export the attribute table, open in Excel, and use pivot tables to sort and summarise.

9.2 Landscape unit delineation and characterisation

Landscape units are defined as portions of a catchment with similar morphological characteristics (topography/landforms), and are delineated using information on elevation, geology and land cover in the catchment.

9.2.1 Deriving landscape unit characteristics

1) After deciding on preliminary landscape units, create outlets points for each landscape unit. In other words, identify the locations along the main stem of the river (using the flow accumulation raster) that represent the most downstream location in each landscape unit. Follow the same procedures for setting your catchment outlet point in the catchment delineation phase. If you have 3 landscape units, then you should have 3 outlet points, the most downstream one will match up with your catchment outlet point
2) Create a landscape unit shapefile – Run the watershed tool in the hydrology toolset (ArcToolbox > Spatial Analyst > Hydrology > Watershed). Input your flow directions raster, and your new landscape unit outlets shapefile as your 'pour points". You can then convert the output raster to a shapefile using the Conversion tool (ArcToolbox > Conversion tools > From Raster > Raster to Polygon).

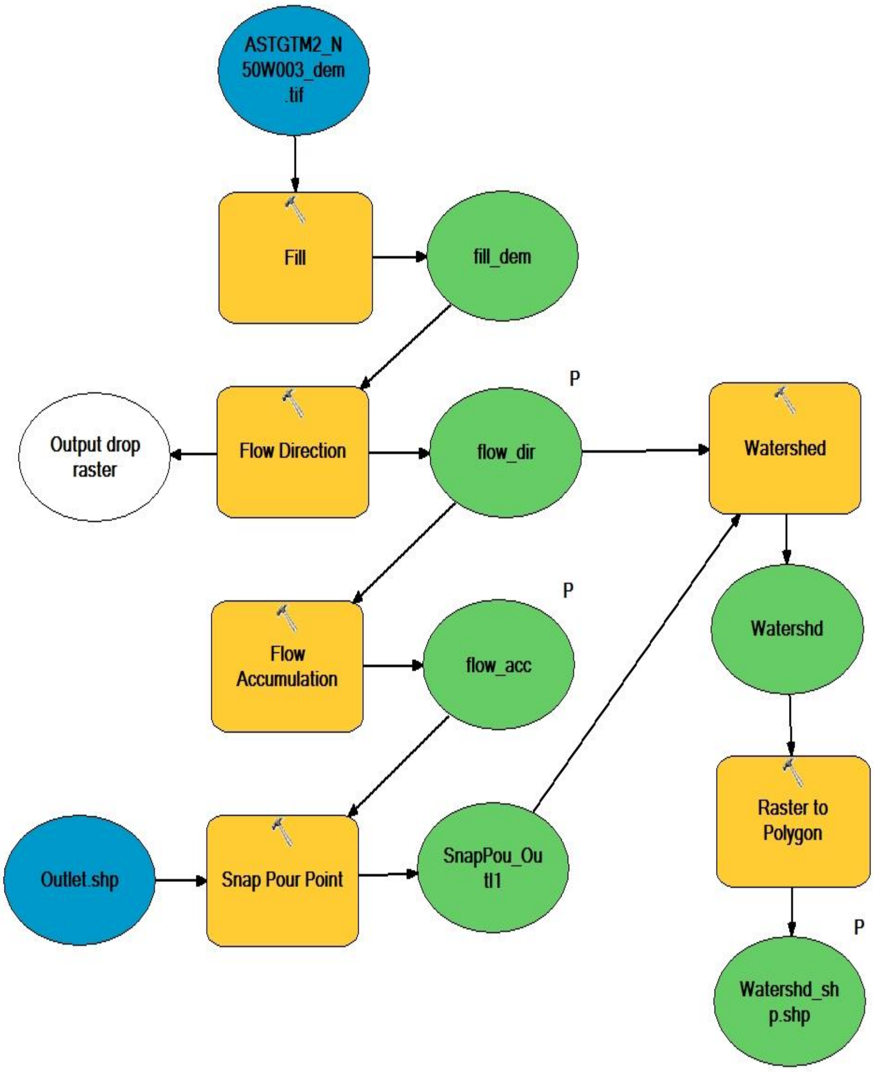


Figure 9.1 Example of an ArcGIS Model to delineate a catchment. Note that there are two inputs, the original DEM raster and an Outlet shapefile. The Outlet.shp is a single point shapefile created in ArcCatalog and the ArcMap Editor and it corresponds to the location of the river mouth as it relates to the derive flow accumulation lines.

3) To derive landscape unit characteristics, spatial join your landscape unit to your shapefile layers (ArcToolbox > Analysis > Overlay > Spatial Join), and then follow the steps listed above (6.1.2, step 4))

9.2.2 Define a stream network based on the DEM

1) Raster Calculator – Set a minimum flow accumulation threshold to define the stream network. The threshold value will depend on the characteristics of your catchment and the resolution of your DEM. For the River Frome, a threshold of 25500 cells was used with the Profile DTM, which is equivalent to 2.55 hectares. You may need to try several different thresholds before finding the most

appropriate. Using the Raster calculator, calculate a new raster using a Map Algebra expression ("%flow_acc%" > 25500) & ("%watershd%" == 0) (ArcToolbox> Spatial Analyst> Map Algebra> Raster Calculator).

2) Stream order – Use the output of the last step as the input stream raster and the flow directions raster calculated in the previous catchment delineation process to calculate Stahler stream orders for the derived network (ArcToolbox > Spatial Analyst > Hydrology > Stream Order).

3) Stream to feature - Input the flow direction raster and use the stream order raster as the input stream raster to generate a raster of as the (ArcToolbox > Spatial Analyst > Hydrology > Stream to Feature). This can be converted to a shapefile using the Conversion Toolset

4) If you find that the DEM-derived stream network varies significantly from the actual network, the process can be repeated with the stream network burned into the DEM, e.g. DEM reconditioning using the AGREE methodology (Arc Hydro Toolset[17])

9.2.3 Potential fine sediment availability

1) Import the PESERA GeoTIFF into ArcGIS, and transform the coordinate system if it is not in the correct projection (ArcToolbox > Data management > Projections and Transformations > Raster > Project Raster).

2) Convert the raster to a shapefile (ArcToolbox > Conversion Tools > From Raster > Raster to Polygon). Only integer rasters can be converted to polygons using this function, so several preliminary steps may be necessary in order to preserve the level of precision.

    a. Multiply the raster by 1000 (ArcToolbox > Spatial Analyst > Math > Times)

    b. Covert to ASCIIi using the Conversion toolset.

    c. Convert back to raster, specifying integer as the output raster type using the Conversion toolset.

    d. Convert raster to polygon using the Conversion toolset

3) A 500 m buffer was created around the river network polyline. (Geoprocessing > Buffer), selecting 'All' for dissolve type so that the output is a single feature.

4) Intersect the buffer with a landscape unit shapefile the landscape unit. (Geoprocessing > Intersect). Then intersect with the PESERA shapefile. Calculate areas within the attribute table and export to Microsoft Excel.

5) Multiply the erosion rates by the shape area to calculate erosion rates per year for each shape in the shapefile (remember to divide the rate by 1000 if the preliminary raster processing steps were used). A pivot table can then be used to

[17] http://blogs.esri.com/esri/arcgis/2011/10/12/arc-hydro-tools-version-2-0-are-now-available/

total the erosion rates for each landscape unit, which can then be divided by the area of the buffer within each landscape unit to obtain the average soil erosion rate (and divided by river lengths for the reach level analysis).

6) Note: During the reach scale analysis, PESERA raster cells that were missing soil erosion values were assigned the average erosion rate for the reach.

9.3 Segment delineation and characterisation

River segments are sections of river that experience similar valley-scale influences and energy conditions. Important characteristics include major increases in catchment area from tributaries, discontinuities in valley gradient, valley confinement and significant changes in riparian and aquatic vegetation species composition or distribution. This information can be obtained from the long profile, the DEM layer (and a contours layer created from it using 3D analyst or Spatial Analyst toolsets in ArcToolbox), and national or European biological databases.

9.3.1 Extract a Long-Profile

1) Flow Length – Calculate the flow length for your catchment using the flow direction raster as an input (ArcToolbox > Spatial Analyst > Hydrology > Flow Length).
2) Set Source point – Create a point shapefile that marks the location of the river source, using the same methodology as described above for the outlet point.
3) Cost Path – Input the source point shapefile create in the previous step as your "Raster or feature destination data". Use the flow accumulation raster for the "Cost distance" and the flow direction raster as the "Cost backlink raster". Then specify a name for the output raster (ArcToolbox > SpatialAnalyst > Distance > CostPath).
4) Sample – Input your layers that you want to sample (e.g. the filled DEM, flow length, flow accumulation) and input the cost path as your raster or point feature (ArcToolbox>Spatial Analyst>Extraction>Sample).. Specify a dbf output, and make sure that you include the .dbf extension.
5) Open the DBF file in Excel, and sort the columns by flow length. You will need to multiple flow accumulation by the cell resolution (e.g. 10 m x 10 m for Profile DTM) to obtain catchment area. Create figures of elevation and catchment area with distance downstream.

9.3.2 Semi-automated process for floodplain delineation

1) Detrend the river profile

a. Convert the river polyline to points (ETGeowizards > Points > Create Point Stations). Note: The polyline can be simplified first, e.g. using mapshapper.com, to reduce its complexity.

b. Extract elevation data from the DTM to the point shapefile (ArcToolbox > Spatial Analyst > Extraction > Extract Multi Values to Points)

c. Create Theissen (Voronoi) polygons from the point shapefile, and include a buffer to ensure the entire floodplain is included in the resulting polygon file[18].

d. Clip the polygon with a buffer created around the river polyline that incorporates the entire floodplain.

e. Convert the polygon to raster.

f. Subtract the Theissen raster from the DTM, and clip with the buffer to produce a detrended DTM

2) Flood plain delineation based on elevation

a. Determine the maximum floodplain level relative to the channel. For the Frome, I used the 1 in 100 year flood water level, which I obtained from online flood maps on the Environment Agency's website, and compared with the detrended DTM. The estimated flood level for the Frome was 1.85 m.

b. Use Raster Calculator to select only the cells in the detrend DTM that are less than the max floodplain elevation (i.e. < 1.85 m).

c. Convert the raster to polygon, and clean edges using the Editor in ArcMap. This is your floodplain extent polygon layer

3) Valley centreline

a. Convert floodplain polygon to polyline (ETGeowizards > Convert). Remove the polylines at the top and bottom ends of the floodplain. Label the two reaming polylines according to their location (e.g. leftbank and rightbank) (add a field in the attribute table, e.g. Bank). Make sure that the lines are running in the downstream direction. You can check this by double clicking the polyline inside Editor, and can 'Flip' the line if necessary.

b. Convert polylines to points (ETGeowizards > Points > Create Point Stations).

c. Create Theissen (Voronoi) polygons from the point shapefile, and include a buffer to ensure the entire floodplain is included in the resulting polygon file.

[18] Voronoi diagram and Delauney Triangulation tool, ArcGIS Resource Centre, created by Dan Patterson, http://resources.arcgis.com/gallery/file/geoprocessing/details?entryID=1E56696E-1422-2418-3462-F19FDA7E8B86.)

   d. Spatial Join the point data to the Theissen polygon shapefile to transfer the location attributes (e.g. Bank)
   e. Dissolve the Theissen polygon shapefile based on the location attribute (Geoprocesseing > Dissolve)
   f. Convert the polygon shapefile to a polyline (ETGEowizards > Convert). The polyline made need to be cleaned up in Editor, or clipped with the buffer to ensure that it is the correct length. This is your valley centreline, which will be used to create valley cross sections.

4) Floodplain widths
   a. Convert the valley centreline polyline to points (ETGeowizards > Points > Create Point Stations). Point spacing is very important in this step. Choice a spacing that corresponds to 0.25 – 1 times the width of the active channel or maximum width of the wetted channels. You can create several different point shapefile with different spacings, which can be clipped and joined later, if the floodplain width varies over the length of the river (I used 50, 100 and 250 m spacings for the Frome).
   b. Create Theissen (Voronoi) polylines from the point shapefile, and include a buffer to ensure the entire floodplain is included in the resulting polygon file.
   c. Clip with the floodplain extent polygon layer, to produce a polyline layer of floodplain cross sections. You might find it useful to add in an attribute for segment or reach. I did this by intersecting the polyline shapefile with a polygon shapefile that outline the reaches (e.g. the floodplain extent polygon spilt by reach).
   d. To obtain floodplain width measurements, add a new field in the attribute table, and calculate the lengths of the polylines (Calculate Geometry). Export the table as a dbf file and open in excel to summarise.

9.3.3 Riparian vegetation

1) Width/area of riparian corridor
   a. Insert the ArcGIS layer that describes vegetation cover (For the Frome, this is the OS MultiMap series)
   b. For widths, intersect the vegetation shapefile with the floodplain cross sections shapefile, recalculate the length in the attribute table, and export it as a dbf to Excel for summary
   c. For area, clip the vegetation shapefile with the floodplain extent shapefile, recalculate areas in the attribute table, and export it as a dbf to Excel for summary.

2) Continuity

a. For this, you will need a polyline shapefile layer that marks the banks of the river (e.g. water theme in the OS MasterMap series) and a vegetation polygon layer.

b. Convert the river polyline to points (e.g. 2 m spacing) (ETGeowizards > Points > Create Point Stations).

c. Spatial Join with a shapefile that contains information on segments and reaches (see above, 0 - 4c).

d. Select the points based on distance from the vegetation. For the Frome, I used a distance of 1 m). (Selection > Select by Location, Select Features from the point shapefile, Source layer - vegetation, Spatial selection method - Target layers(s) features are within a distance of the Source Layer feature, Search distance - 1 m).

e. Export the shapefile (selected features only) and save as a new shapefile. Export the attribute tables for full river bank point shapefile and the shapefile for the points adjacent to vegetation as dbf, open in Excel, and calculate continuity by dividing the number of points near vegetation by the total number of riverbank points in each segment.

f. Wood delivery potential was calculated as in the previous steps, but the vegetation shapefile was restricted to non-coniferous tree forests.

9.4 Reach delineation and characterisation

River reaches are sections of river and floodplain along which boundary conditions are uniform. Segments are subdivided into reaches based on their planform morphology and presence of anthropogenic obstructions to water and sediment transport (e.g. dams and weirs).

9.4.1 Sinuosity index

1) Digitise the river channel centreline or thalweg (If the river banks are already digitised, the Theissen polygon method described above can be used to obtain a river centreline).

2) Divide the river into sinuosity units based on changes in the axis of the overall planimetric course, i.e. when the overall direction of the planimetric course changes. A polygon shapefile can be created with a new feature for each sinuosity unit and with the segment delineation as the first level of division.

3) Intersect the river channel centreline with the sinuosity unit shapefile, calculate the length in the attribute table, and export the attribute table to Excel.

4) Measure the axis of the planimetric course for each sinuosity unit using the Measure tool, and calculate sinuosity as the ratio of channel length and planimetric course length for each reach.

9.4.2 Semi-automated process for channel widths

1) Copy the floodplain cross-section polyline shapefile in ArcCatalog (created in Section 0 – 4c). Insert into ArcMap, and open in Editor.
2) Add inflection points into the cross-sections to ensure that each line crosses the river channel perpendicularly, paying careful attention to multiple channels in anastomosing systems.
3) Intersect the channel cross-section polyline shapefile with the river channel polygon shapefile (e.g. OS MasterMap). Add a new field in the attribute table, calculate length, exported dbf to Excel and summarise using a pivot table.

9.4.3 Lateral gradient in vegetation structure

1) Create a series of buffers around the riverbank polylines with a range of widths (Geoprocessing > Buffer).
2) Intersect the buffers with the vegetation shapefile, and calculate the area of the features in the attribute table.
3) Union the buffers together (depending on your license you may have to do this 2 at a time). Ensure that reach and segments are included in the attribute table (if not, then Spatial Join with a shapefile that contains that information).
4) Export the attribute table as a dbf file, open in Excel and summarise with a pivot table.

References

Collins, A.L. and Walling, D.E., 2007. Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. Hydrological Processes, 21(11): 1448-1459.

Cotton, J.A., Wharton, G., Bass, J.A.B., Heppell, C.M. and Wotton, R.S., 2006. The effects of seasonal changes to in-stream vegetation cover on patterns of flow and accumulation of sediment. Geomorphology, 77(3-4): 320-334.

Environment Agency, 2004. The state of England's chalk rivers. In: U.B.A.P.S.G.f.C. Rivers (Editor), Bristol, UK.

Environment Agency, 2011. River Frome geomorphological assessment and rehabilitation plan. In: F.r.t.E.A.a.N. England (Editor). Royal Haskoning.

Environment Agency, 2012. Dorset WFD management area abstraction licensing strategy: Dorset Stour and Frome, Piddle and West Dorset CAMs. In: E. Agency (Editor), Bristol UK.

Grabowski, R.C., Wharton, G., Davies, G.R. and Droppo, I.G., 2012. Spatial and temporal variations in the erosion threshold of fine riverbed sediments. Journal of Soils and Sediments, 12(7): 1174-1188.

Gurnell, A., Goodson, J., Thompson, K., Clifford, N. and Armitage, P., 2007. The river-bed: a dynamic store for plant propagules? Earth Surface Processes and Landforms, 32(8): 1257-1272.

Gurnell, A.M., van Oosterhout, M.P., de Vlieger, B. and Goodson, J.M., 2006. Reach-scale interactions between aquatic plants and physical habitat: River Frome, Dorset. River Research and Applications, 22(6): 667-680.

Heppell, C.M., Wharton, G., Cotton, J.A.C., Bass, J.A.B. and Roberts, S.E., 2009. Sediment storage in the shallow hyporheic of lowland vegetated river reaches. Hydrological Processes, 23(15): 2239-2251.

Holmes, N., Boon, P. and Rowell, T., 1999. Vegetation communities of British rivers - a revised classification. In: J.N.C. Committee (Editor), pp. 120.

Lewin, J., 2010. Medieval Environmental Impacts and Feedbacks: The Lowland Floodplains of England and Wales. Geoarchaeology-an International Journal, 25(3): 267-311.

Natural England, 1991. SSSi citation: River Frome, http://www.sssi.naturalengland.org.uk/citation/citation_photo/2000220.pdf, accessed on 18 July 2013.

Punchard, N., 2013. Frome and Piddle catchment initiative: Final catchment plan. In: F.a.P.C.I. Partnership (Editor), www.fromeandpiddle.co.uk.

Catchment Case Study 2

The Upper Esla River (Duero basin, NW Spain)

Marta González del Tánago, Vanesa Martínez-Fernández, Diego García de Jalón

E.T.S. Ingenieros de Montes, Universidad Politécnica de Madrid (UPM), Spain

1. Introduction and Methodology

This report represents an application of the multi-scale framework defined within the REFORM Project (see D2.1) to the upper Esla River in North-West Spain.

The Esla River is a main tributary of the Duero River and drains a large part of the NW quadrant of the Spanish part of the Duero Basin. Its catchment area is 16,080 km^2 which is 16.5 % of the Duero Basin and 20% of the Spanish Part. It rises at 2500 m in the Southern slopes of the Cantabrian Mountains and joins the Duero River at the Villalcampo reservoir, shortly before the frontier with Portugal. The river has a predominant north-east to south-west direction along his 275 km total length (Figure 1.1). The studied area comprises the Upper Esla river and its major tributaries, the Porma and Bernesga Rivers, with their respective main effluents the Curueño and Torío Rivers.

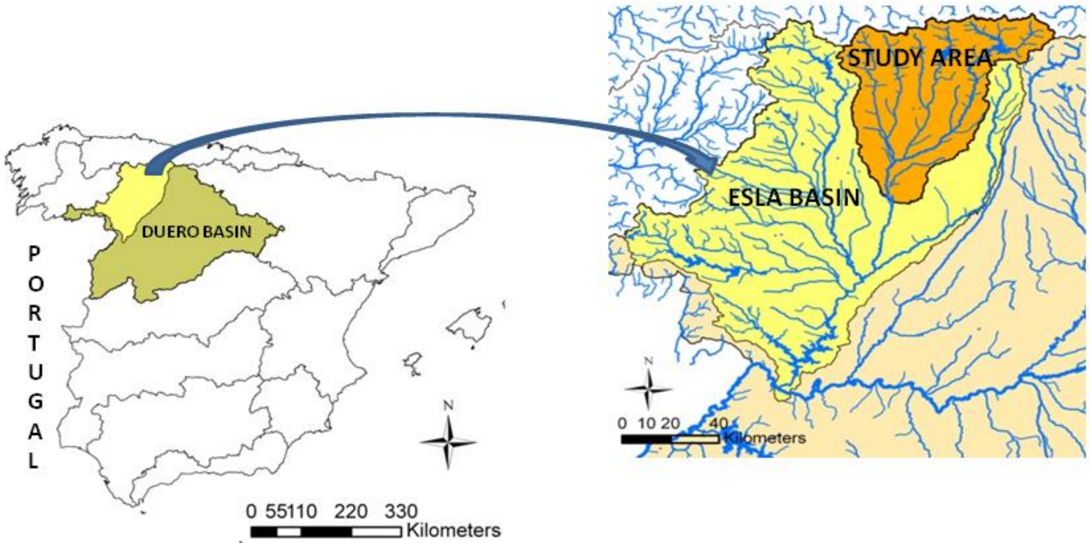


Figure 1.1 Location of the study area (Upper Esla river basin, Duero River Basin, NW Spain).

Following the multi-scale framework, the study area was characterised at the following spatial scales: biogeographic region, catchment, landscape unit, river segment and river reach. The Esla, Porma and Curueño rivers were characterized to the reach scale, whereas the Bernesga and Torío rivers studied studied only to the segment scale.

The criteria and the basic information required to delineate units at these spatial scales are summarized in Table 1.1. The biogeographic regions and subregions were identified following the online maps of biogeographic regions in Europe available at www.bioclimatics.org. The catchments were delineated based on digital elevation models derived from LIDAR surveys (DEMs) with a 5 m spatial resolution that are available online from the Instituto Geográfico Nacional of Spain (IGN). Deliniation of Landscape Units used topographic information (DEM), geological map information (1:50.000 scale) available from Instituto Geominero Español and land cover information from CORINE Land Cover dataset available from IGN. Segment delineation reflected major confluences and valley changes identified from DEMs. Reach delineation was only applied to the Esla, Porma and Curueño rivers. Two different approaches were followed, automated delineation using the Pettitt test (see Alber & Piégay, 2011) and expert criteria according to significant features (dams and reservoirs and changes of landscape unit) (see Deliverable D2.1, part 2, Annex Afor more information on automated delineation).

The criteria and methodology used for characterizing the different spatial scale elements are presented in Table 2.2. In many cases these criteria were the same as were used for delineation (DEM, Geological maps and Corine Land Cover). Other information needed for characterizing landscape units, segments and reaches included flow regime data collected from the Spanish gauging station network; soil erosion rates collected from erosion maps (1:400.000 scale) and hydrogeology information based on geotechnical Maps from IGME.

Table 1.1 Criteria and available documents for delineation hierarchical spatial units in the Upper Esla River.

Spatial scale	Criteria	Available documents
Region	Biogeographic Region	Biogeographic Maps (www.globalbioclimatics.org)
Catchment	Topographic Divide	DEM (5m resolution, Instituto Geográfico Nacional of Spain, wwww.ign.es)
Landscape Unit	Topography Geology Land Cover	DEM Geological Maps (Instituto Geominero Español, CORINE Land Cover Map (www.ign.es)
River Segment	Major confluences Major valley changes	DEM Aerial Photographs (www.ign.es)
River Reach	Channel morphology	DEM Aerial Photographs (www.ign.es)

Table 1.2 Available documents for characterizing spatial units of the Upper Esla River.

Spatial scale	Characteristics	Available information/ Methodology
Region	Biogeographic Region	Biogeographic Maps (www.globalbioclimatics.org)
Catchment	Relief characteristics Geological types Land Cover	DEM (wwww.ign.es) Geological maps (www.igme.es) First level of Corine Land cover (www.ign.es)
Landscape Unit	Relief characteristics Rainfall Geology Land Cover Groundwater Sediment delivery Vegetation	DEM (AEMET,2011) Geological Maps (www.igme.es) Second level of Corine Land Cover Map (www.ign.es) General Geotechnical Map (www.igme.es) Soil erosion Maps (ICONA, 1990) Field sample and ortophotograps
River Segment	Flow regime Valley characteristics Bed sediment Riparian corridor Physical pressures	Gauge stations http://hercules.cedex.es/anuarioaforos/default. asp DEM Field sample Aerial Photographs (www.ign.es)
River Reach	Channel morphology (pattern, active width, gradient) River Energy Bed and bank sediment Riparian and Aquatic vegetation Physical pressures	Field sample Aerial Photographs (www.ign.es) Automated Delineation (Pettitt´s test)

2. Delineation and Characterisation

2.1 Region Scale

2.1.1 Basin District

The study area is located in the Spanish North-Western side of the Iberian Duero Basin District (see Figure 1.1).

2.1.2 Biogeographic Region

According to the Biogeographic Map of Europe (www.globalbioclimatics.org), the Northern part of the study area belongs to the Eurosiberian Region, Atlantic-Central European Subregion, Cantabroatlantic Province. The central and Southern parts correspond to the Mediterranean Region, Western Mediterranean Subregion, lying in the Carpetan-Leonese Province.

2.2 Catchment Scale

2.2.1 Size

The studied region has a total area of 4.345 km^2. According to the size classes of the Water Framework Directive (WFD), this is a “large” catchment (1000 to 10000 km^2). The length of the Esla river within this area is 95 km. There are three main sub-catchments, corresponding to the main river and two main tributaries, the Porma (1145 km^2) and Bernesga (1177 km^2) rivers, which also correspond to “large” drainage areas.

2.2.2 Relief

The Esla River rises in the Cantabrian Mountains and flows to the Duero plateau with a range in elevation within the studied area of between 2.500 and 739 m, from the Atlantic-Central European Subregion to the Western Mediterranean Subregion. Figure 2.1 shows the altitudinal distribution for the entire upper Esla basin. Most of the area lies between 1 200 and 800 m above sea level (Figure 2.1 A). According to the guidance from the WFD, more than 90 % of the catchment is “high” in terms of relief (> 800 m), and the rest (< 10 %) is “mid-altitude” (200-800 m) (Figure 2.1 B).

The longitudinal profiles of the rivers are shown in Figure 2.2. Although most of the longitudinal gradients are smaller than 0.5 %, the headwaters exhibit gradients >2 %. Some tributaries, notably the Curueño River, followed by the Torío and Bernesga rivers (Figure 2.1B) have steeper slopes values than the Porma and Esla rivers, with higher gradients along their entire length (see section 4.2).

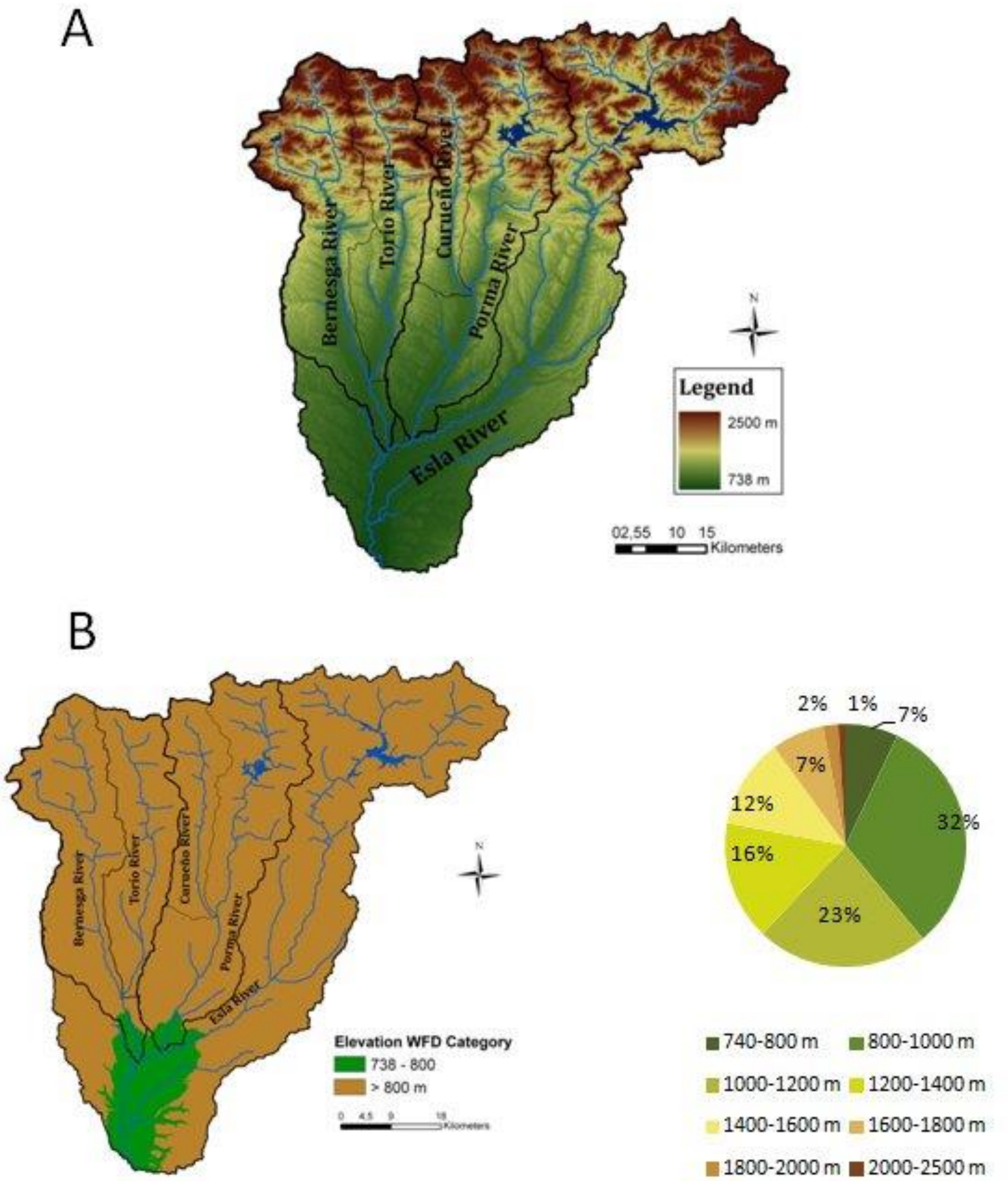


Figure 2.1 Upper Basin of the Esla River. A. Topography (DEM). B. Altitudinal distribution of the Upper Esla Basin and WFD elevation classes.

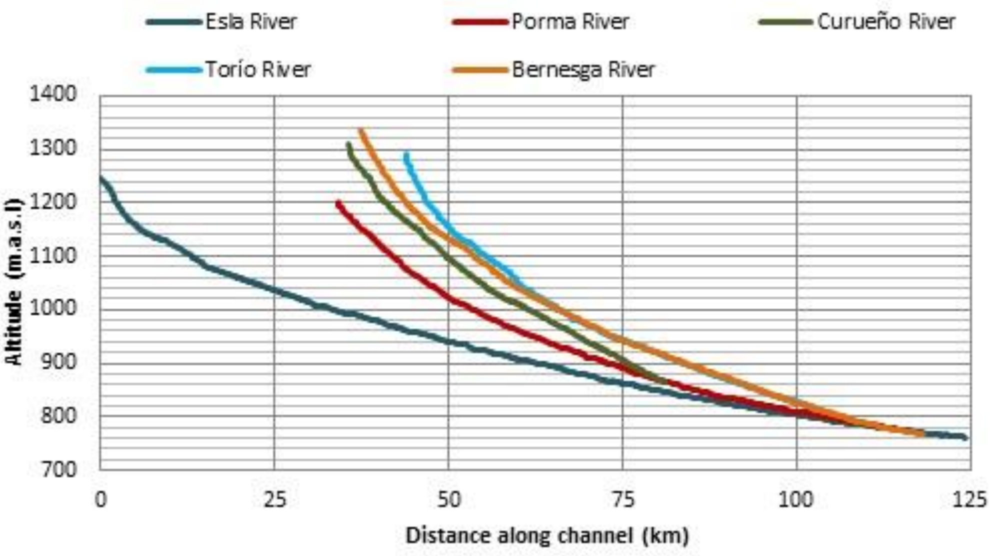


Figure 2.2 Longitudinal profiles of the studied rivers.

2.2.3 Geology and Hydrogeology

Siliceous and mixed materials dominate the geology of the study area (Fig.6). The oldest materials (cambric sedimentary rocks, with eventual calcareous rocks and coal from the Carboniferous) are located in the Northern part of the basin, whereas siliceous conglomerates from the Tertiary are predominant in the centre and Southern parts, alternating with Quaternary fluvial deposits along the valleys.

Hydrogeology characteristics of the area follow this geologic pattern (Fig. 7). Most of the area contains permeable rocks, which occupy the middle parts of the studied catchment with siliceous conglomerates and quaternary deposits. Impermeable lithologies are located at the upper part of the basin, corresponding to the oldest materials (information extracted from 1:200.000 hydrogeologic maps, www.igme.es).

2.2.4 Land Cover

According to the Corine Land Cover map (level 1), the Northern and central parts of the catchment are covered by forests and natural or semi-natural vegetation, representing approximately two thirds (65 %) of the total area. The rest is occupied by agricultural land (32 %), with very little cover of artificial areas and water bodies (less than 3 %) (Figure 2.4).

Table 2.1 summarizes the main studied attributes for characterizing the Upper Esla Basin at catchment scale.

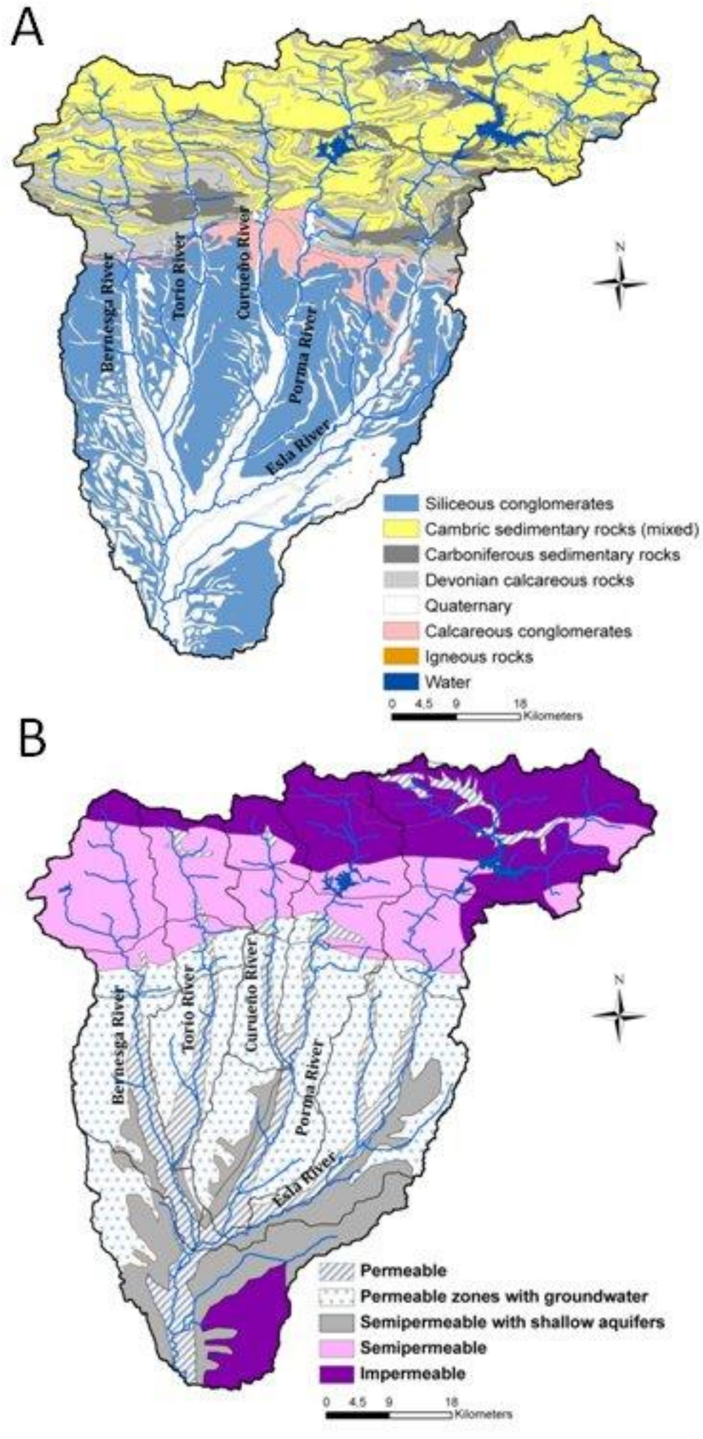


Figure 2.3 Upper Esla basin

A. Geology (modified from www.igme.es);

B. Bedrock hydrogeology (modified from www.igme.es).

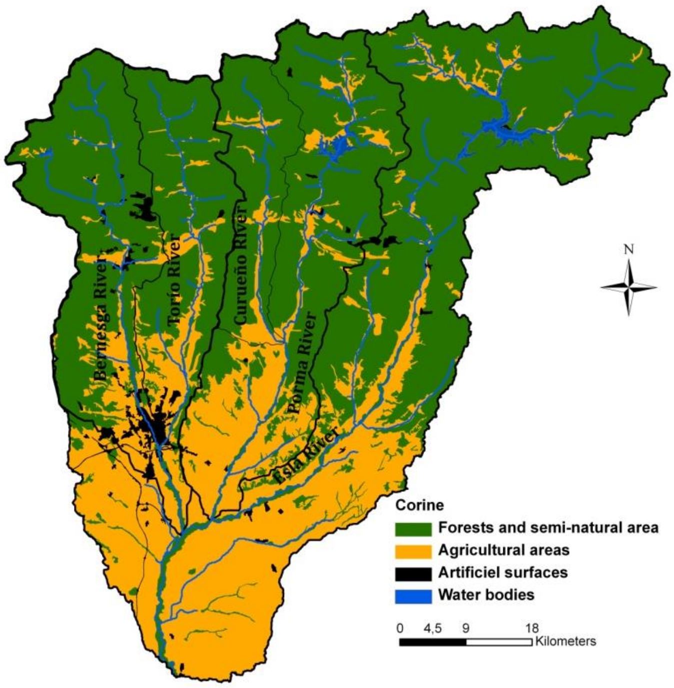


Figure 2.4 Upper Esla Basin: Land cover (CORINE level 1).

Table 2.1 Main characteristics of the major sub-catchments within the Upper Esla Basin

		UPPER ESLA	PORMA	CURUEÑO	BERNESGA	TORÍO
SIZE	Catchment area (km^2)	4345	1145	293	1177	485
	WFD Size class	Large	Large	Medium	Large	Medium
	River length (km)	95	80	48	77	63
ELEVATION	Max. (m)	2494	2160	2151	2181	2156
	Min. (m)	767	777	865	769	804
	Average (m)	1145	1176	1325	1189	1210
GEOLOGY	Rock types:					
	% Siliceous	40	49	36	53	39
	% Calcareous	14	16	26	7	16
	% Mixed	25	18	26	22	25
	% Quaternary	21	17	12	18	20
	WFD Geological class	Siliceous	Siliceous	Mixed	Siliceous	Siliceous
	Bedrock hydrogeology:					
	% Rocks with no groundwater	31	22	46	4	5
	% Flow through fractures	11	17	48	43	35
	%Intergranular flow	58	61	6	53	60
LAND COVER	% Artificial surfaces	2	1	0	3	2
	% Agricultural areas	32	28	14	18	22
	% Forest and semi-Natural areas	63	71	86	79	76
	% Wetlands	0.06	0.02	0	0.01	0

2.3 Landscape Unit Scale

2.3.1 Delineation

Four different landscape units were differentiated in the study area, following discontinuities in topography, geology and land cover. Due to the relative homogeneity of the spatial distribution of these discontinuities within the sub-basins, the same attributes (i.e. topography as primary criterion and geology and land cover as secondary criteria) were used to delineate the landscape units within each sub-basin (Figure 2.5).

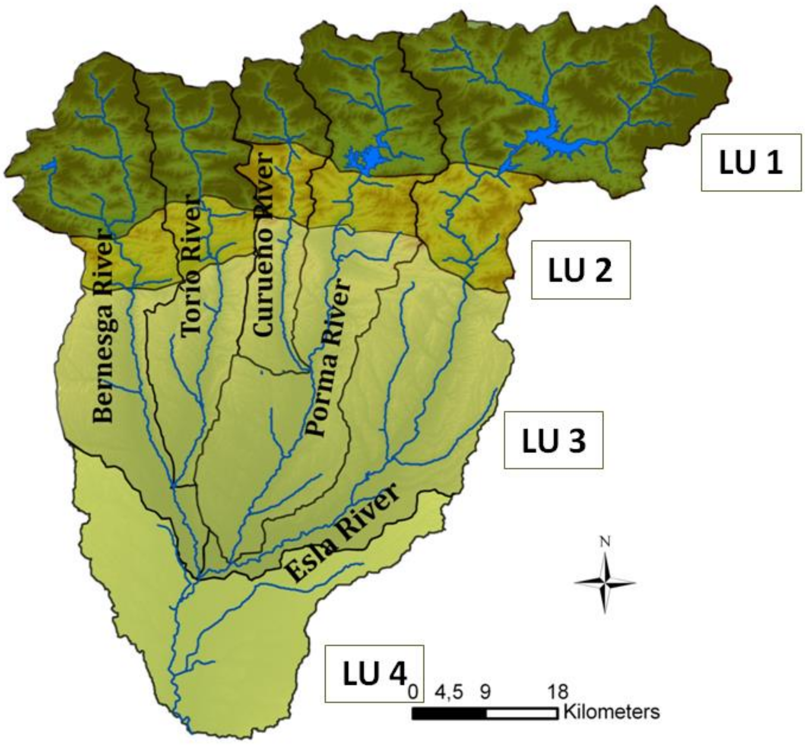


Figure 2.5 Landscape units of the Upper Basin of the Esla River.

2.3.2 Characterization

Table 2.2 summarizes the characterization of landscape units of the studied area, offering similar information but at higher spatial resolution than that was given at catchment scale.

Closely related to water and sediment delivery potential within the basin is the longitudinal valley gradient within the respective landscape units (Figure 2.6). Although the studied rivers drain areas of similar topography and geologic context, they exhibit differences in valley gradients, which explain the differences in channel gradients (see Figure 2.2).

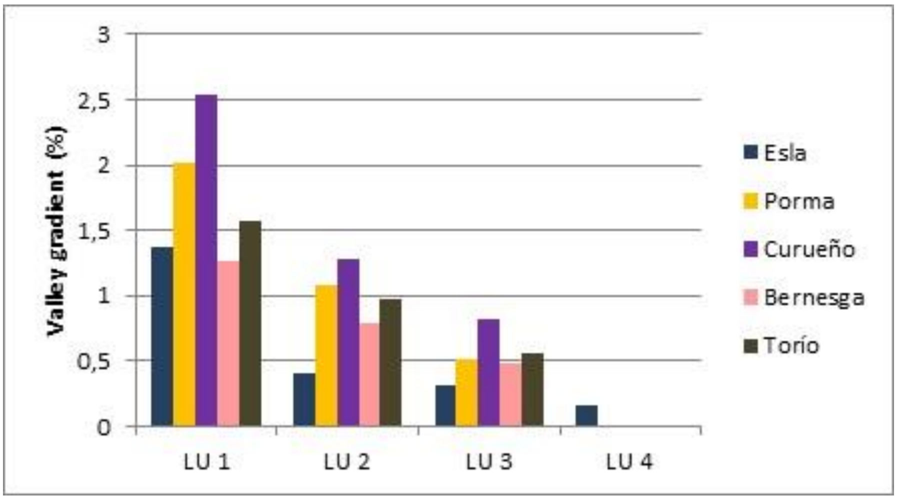


Figure 2.6 Valley gradients of the river segments located in the respective landscape units (LU).

(i) Water delivery potential

Rainfall. Water is supplied to the catchment by precipitation. Over the standard period 1971-2000 (source; www.aemet.es), the upper parts of the basin (landscape unit 1) received an annual rainfall of between 1400 and 2000 mm. Reflecting the altitudinal range (2200-1050 m), a proportion of the precipitation fell as snow during the winter months, particularly in areas above 1500 m. The middle of the basin (landscapes 2 and 3) received an annual rainfall of between 800 and 1000 mm across its altitudinal range of 800 to 1300 m. The lower basin (landscape 3 and 4) received an annual rainfall of between 500 and 600 mm, over its elevation range of 700 to 850 m. These precipitation data corresponds to the period 1971-2000 (www.aemet.es).

Relief. Landscape unit 1 has a high mountainous relief whereas landscape unit 2 is defined by "gorge" formations along the river courses. Small hills and piedmonts areas define landscape unit 3, and plateau landforms dominate the lowest part of the study area, which corresponds to landscape unit 4. Hypsometric curves (Figure 2.7) show average patterns of elevation and gradient within the landscape units of the studied sub-catchments.

Geology. There are lithological differences among the landscape units. The oldest rocks (Cambric sedimentary rocks) predominate in landscape units 1 and 2. More recent (Siliceous conglomerates) and Quaternary sediments occupy the majority of landscape units 3 and 4, with correspondingly wider river valleys in these lower areas.

Land cover. Land cover classes (CORINE level 1) within the study area are shown in Figure 2.8. Landscape units 1 and 2 show a relatively high coverage (> 70 %) of forests and semi-natural shrub and herbaceous vegetation, with very little arable land. Agricultural land-use increases downstream, occupying nearly 40 % of the area in landscape unit 3, and more than 90 % in landscape unit 4.

Table 2.2 Characterization of the landscape units (LU) of the Upper Esla basin.

Main characteristics of landscape units		**LU -1**	**LU- 2**	**LU -3**	**LU -4**
Water delivery potential	Annual Rainfall (mm)	1400-1800	800-1000	700-800	500-600
	Relief topography	High mountainous	High mountainous	Hilly and Piedmont	Plateau
	Altitudinal range (m)	2200-1050	1300-950	1100-770	850-740
	WFD Altitudinal class	High altitude	High altitude	High altitude	Mid- altitude
	Drainage density (km/km^2)	0.167	0.204	0.219	0.181
	Surface / Groundwater:				
	% area impermeable or not affected by aquifers	51.2	3.5	6.8	22.0
	% area permeable or with aquifers	48.8	96.5	93.2	78.0
	Geology distribution (%)				
	Calcareous Conglomerates	0	4.0	8.7	0
	Cambric Sedimentary rocks	67.8	39.2	1.1	0
	Carbonífero Sedimentary rocks	7.0	16.6	0.9	0
	Devonic calcareous rocks	15.2	31.8	2.5	0
	Igenous rocks	0.2	0.4	0.0	0
	Quaternary	5.6	5.9	35.1	59
	Siliceous conglomerates	2.0	2.1	51.7	41
	Water	2.2	0	0	0
	Land Cover (%)				
	Artificiel surfaces	0.3	2.2	2.6	2.0
	Arable land	0.0	0.1	19.9	75.5
	Heterogeneous agricultural areas and pastures	6.1	8.5	20.0	14.6
	Forests	41.7	46.4	39.1	4.1
	Shrub and/or herbaceous vegetation associations	34.7	22.5	17.7	3.8
	Open spaces with little or no vegetation	15.1	20.1	0.7	0
	Water	2.1	0.12	0	0

Table 2.2(ctd.)

Main characteristics of landscape units		**LU -1**	**LU- 2**	**LU -3**	**LU -4**
Sediment delivery potential	Potential fine sediment availability Average soil losses (Tm/ha, year)	Low 17.2	Low 12.4	Low 10.9	Low 10.2
	Potential coarse sediment availability: % area with mass movements or gullies connected with main channel at gradients > 15%	Low 7.82	Low 1.25	Low 2.57	Low 0.09
Vegetation/ Land use along the network	Natural vegetation	Willow shrub galleries with *Fraxinus excelsior*	Willow shrub galleries with *Fraxinus excelsior*	Willow shrub galleries with *Fraxinus angustifolia*	Willow shrub galleries with *Fraxinus angustifolia*
	Land occupation	Natural vegetation	Natural vegetation	Agriculture and Poplar plantations	Agriculture and Poplar plantations

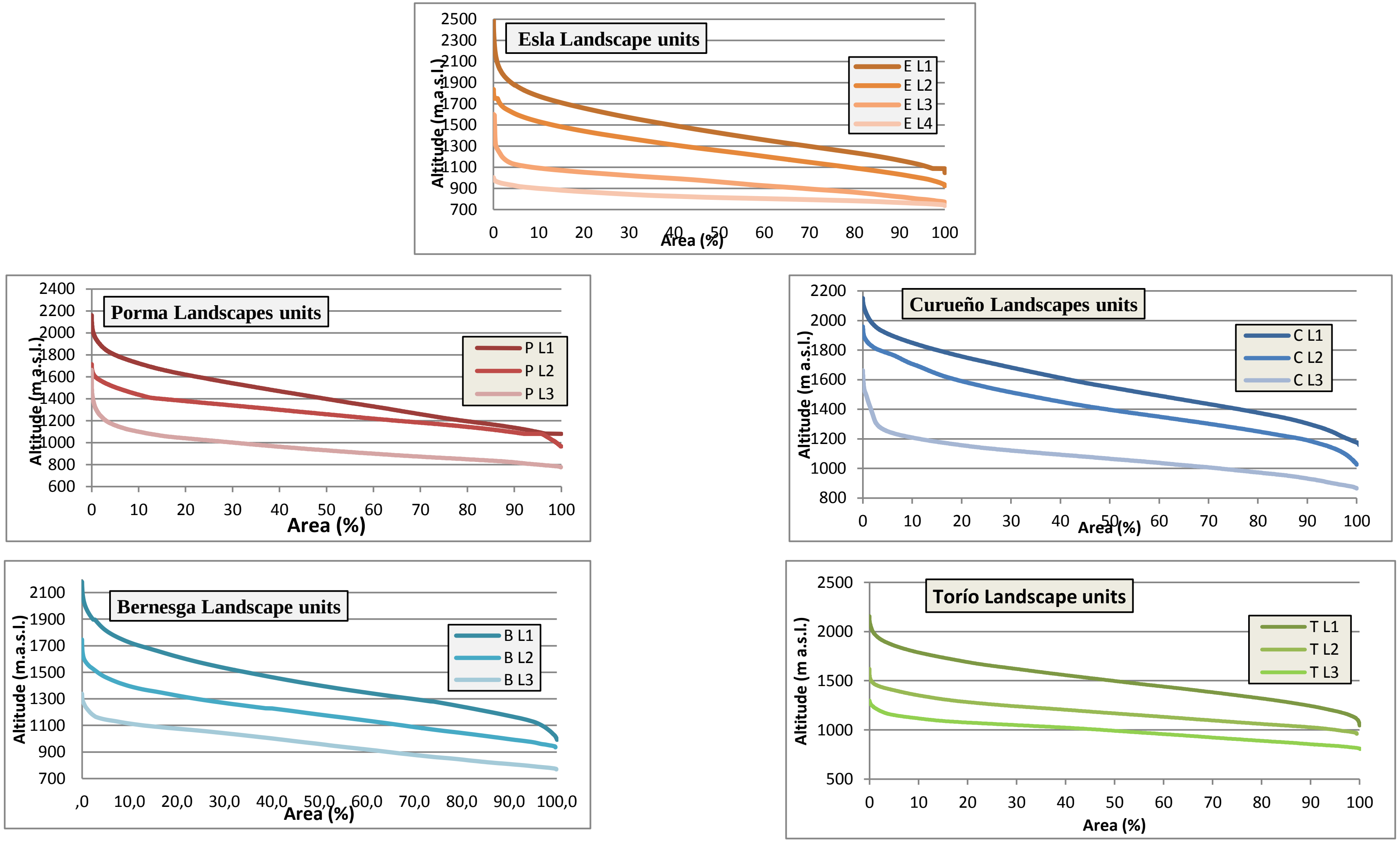


Figure 2.7 Hypsometric curves for landscape units of The Upper Esla basin and its sub-catchments.

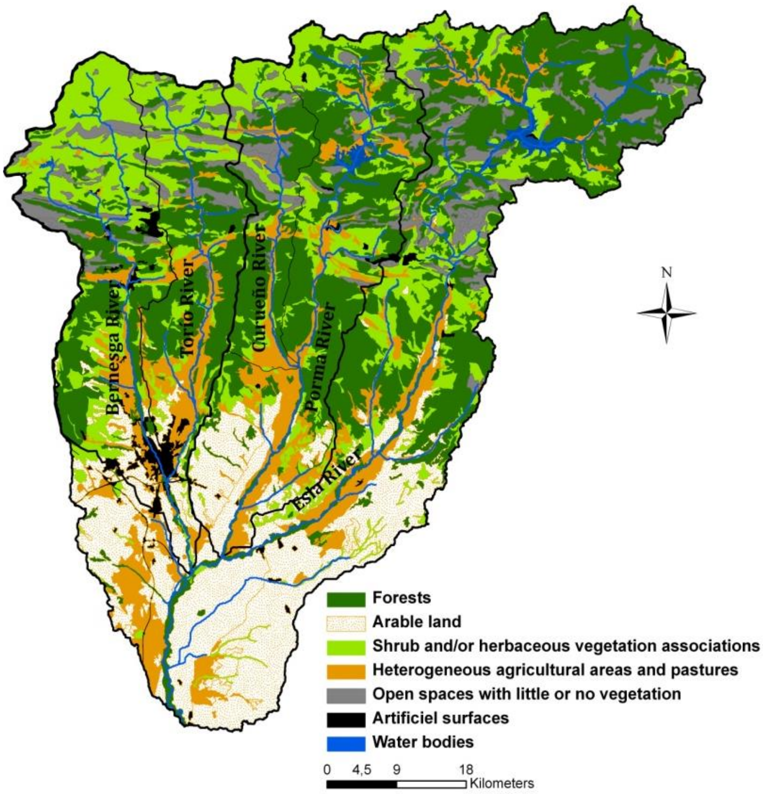


Figure 2.8 CORINE Land cover classes (level 1) in the Upper Esla basin.

(ii) Sediment delivery potential

Fine sediment. Maps of soil losses at 1:400.000 (ICONA, 1990) based on the USLE equation are available for the Duero Basin. From these maps, estimated rates of annual soil loss for the study area are shown in Figure 2.9. The LS factor (runoff length and gradient) of the USLE equation seemed to be mainly responsible for the relatively high values obtained in local upper reaches, whereas the K factor (soil erodibility) related to soft conglomerates in the middle parts of the main valleys results in the highest soil loss values in some restricted patches. From this information, the fine sediment delivery potential appears to be relatively low across the studied area, taking into account the current status of forest cover in the upper reaches.

Coarse sediment. Potential coarse sediment delivery has been qualitative assessed based on the percentage area with mass movements or gullies connected with main channel at gradients > 15 %. These estimates were made using recent air photographs, from which these potential coarse sediment delivery areas were identified and 195mmobiliz. In general, the size of these potential areas is relatively small. Additionally, two large dams exist at the downstream end of the landscape unit 1 on the Esla and Porma rivers, which significantly reduce the coarse sediment transfer from upstream to downstream of the dams.

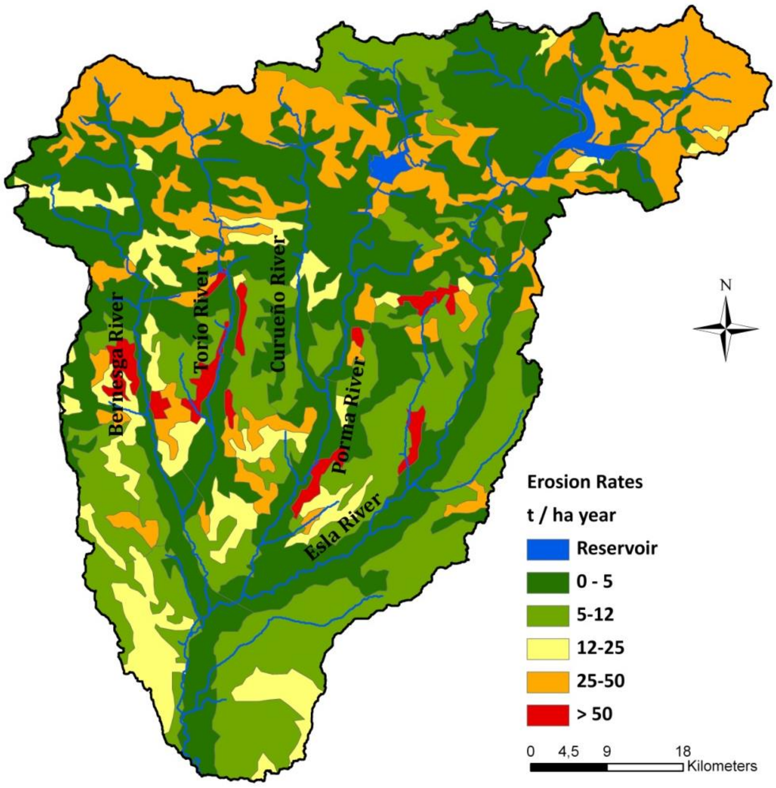


Figure 2.9 Estimated rates of annual soil loss in the Upper Esla basin (data source: ICONA, 1990).

2.4 River Segment Scale

2.4.1 Delineation

River segments along the the studied rivers have been differentiated within each landscape unit, according to valley characteristics (i.e. confinement and width), confluences of major tributaries, and presence of dams. These features may imply discontinuities in water and sediment flows. Figure 2.10 shows the resulting river segments in the study area.

2.4.2 Characterization

A total of 20 river segments were identified in the upper Esla basin. Flow regime, valley characteristics, bed sediment, riparian corridor features and the main hyro-morphological pressures of each river segment were characterized and are detailed in Tables 2.3 to 2.7,which are located at the end of section 2.4. The characterization of hydrologic regimes was conducted for the existing gauging stations, which are located on Figure 2.11.

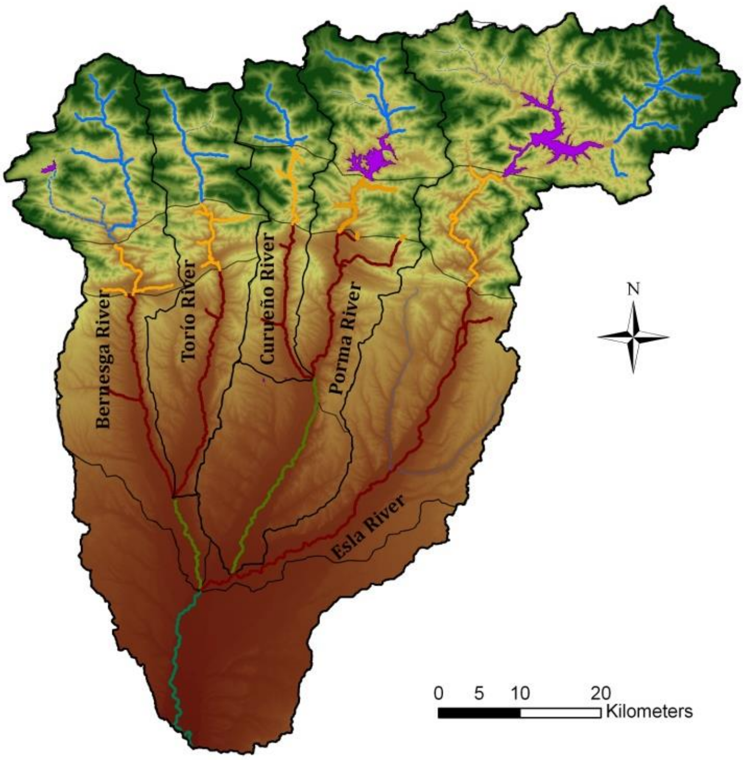


Figure 2.10 River segments identified along the studied rivers in the Upper Esla Basin.

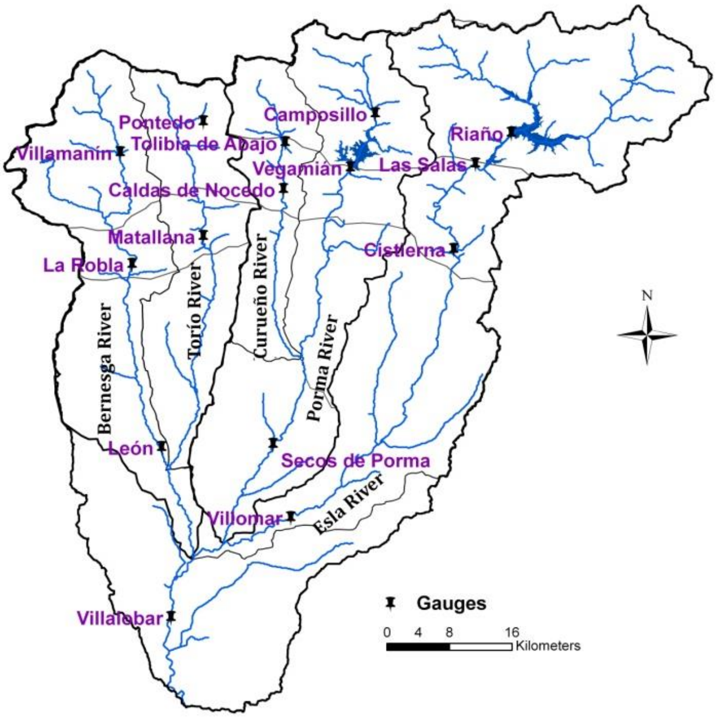


Figure 2.11 Gauging stations located in the studied area.

(i) Esla River

In the Esla River, 5 different river segments have been considered attending to different criteria. Segment 1 is located upstream the Riaño large dam and segment 2 corresponds to the Riaño reservoir, both of them located at landscape unit 1. Segment 3 conforms the gorge section at the following landscape unit 2. Segment 4 is located in the landscape unit 3 and extends to the confluence with the Bernesga river. Finally, segment 5 follows the river below the confluence with the Bernesga river until the end of the studied area. Table 5 summarizes the main hydromorphic characteristics of these river segments, and some of them are briefly commented below.

Flow regime***.*** The river Esla is regulated by the Riaño dam, which has been in operation since 1988. Upstream of the Riaño dam (Es-1) the river flows with a nivo-pluvial hydrologic regime, with two periods of maximum discharges, at the end of the winter (February-March) and during the snow melt months (April-May) (Figure 2.12). Downstream from the dam the discharge is intensively regulated by the storage capacity of the reservoir (664 hm^3), which may contain nearly 90% of the natural runoff. The stored water is mainly used for irrigation, explaining the reversal of the natural Mediterranean pattern observed downstream from the dam. Under the regulation scheme, summer flows are significantly increased (e.g. the post-dam average annual miminum flow is 284 % higher than the pre-dam value) at the expense of decreasing autumn and winter flows. The magnitude and frequency of ordinary peak flows are reduced (the post-dam average annual maximum flow is 72 % lower than the pre-dam value).

Valley characteristics and bed sediment***.*** In the upper reaches (segment 1) the Esla river flows along a partially confined valley to the location of the dam and its reservoir (segment 2). Downstream from the dam the valley narrows significantly through the “gorges” sector (segment 3). Entering landscape unit 3, the valley widens with a continuous floodplain on both sides of the river which widens in a downstream direction. Average valley gradient decreases downstream, from nearly 1.4 % in segment 4 to 0.16 % in the last segment 5. This decreasing gradient corresponds with valley widening from 150-400 m in the narrowest reaches of segment 2 to 7000-10000 m in the widest and most downstream parts of segment 5. Valley/channel width ratio shows a similar longitudinal pattern, yielding values around 20-25 above the main tributary confluences (Porma and Bernesga rivers, segment 4) and 60-160 m below these confluences (segment 5).

All of the upper Esla River is characterized by coarse bed sediment, which decreases downstream from boulders and cobbles at the headwaters (segment 1), to coarse gravel in the middle parts (segments 3 and 4) and mainly gravel in the lowest elevation reaches (segment 5).

Riparian corridor features. A relatively narrow but continuous riparian fringe extends along the upper and partially confined Esla river (segment 1), containing shrub willow galleries with *Betula* sp and *Fraxinus excelsior*. As the valley opens downstream, wider riparian bands of mixed willow galleries with *Populus nigra, Salix cantabrica* and *Fraxinus excelsior* (segment 3) are gradually replaced by a more forested vegetation structure with *Alnus glutinosa, Salix fragilis* and *Fraxinus angustifolia* (segments 4 and 5).

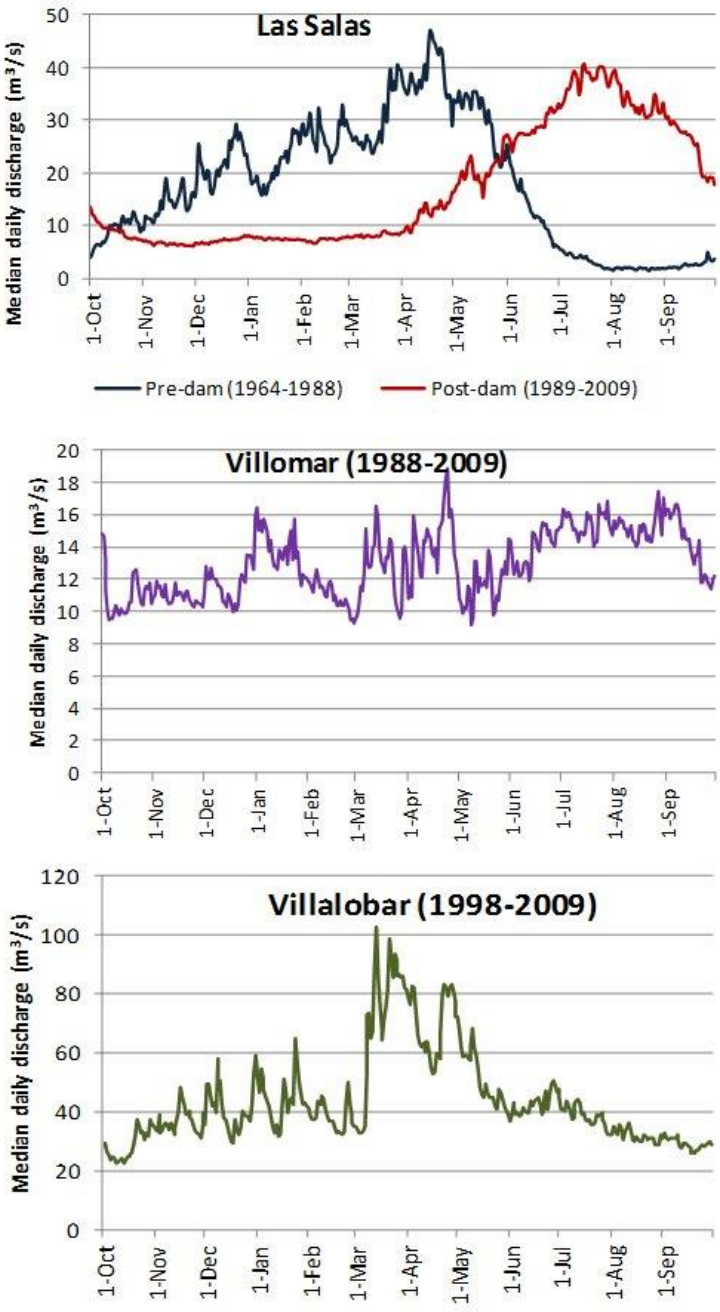


Figure 2.12 Average annual flow patterns at gauging stations along the Upper Esla river: Las Salas (607 km^2, segment 3); Villomar (1354 km^2, segment 4); Villalobar (3980 km^2, segment 5).

Downstream from the Riaño dam the natural riparian vegetation has been partially replaced by poplar plantations which are particularly extensive along the segments 4 and 5.

The proportion of the active channel edge covered by mature trees is relatively high along all the river segments, and also many dead trees exist. Consequently, wood delivery potential is high especially in the reaches maintaining a natural riparian structure. In cases where the riparian corridor is narrower or less abundant in one of the margins, wood delivery potential to the channel has been assessed as intermediate.

(ii) Porma River

Five segments were identified along the Porma River. Segment 1 corresponds to the river upstream of the Porma large dam and segment 2 coincides with the Porma reservoir, both are located in the landscape unit 1. Segment 3 occupies the river length within landscape unit 2. Segments 4 and 5 are located in landscape unit 3, above and below the confluence with the Curueño River, respectively. Table 5 summarizes the main characteristics of these 5 river segments, some of them briefly explained below.

Flow regime. The Porma River has been regulated by a large dam since 1968. This has a water storage capacity of 317.4 hm^3, representing more (106%) than the annual natural runoff. Above the dam (segment 1 and 2) the river has a nivo-pluvial regime (Figure 2.13 upper graph, pre-dam, 1942-1966)with the highest annual peak flows associated with snow melt in spring (April-May), secondary peak flows from rainfall in February-March, and summer baseflows (July-August). Below the dam (segments 3 and 4) the hydrologic regime is reversed (Figure 2.13 upper graph, post- dam, 1968-2009), with, in a normal year, the annual highest flows during the irrigation summer months (July and August) and the lowest discharges during winter months when the reservoir is being filled. Further downstream from the dam (segment 5) the regulation effects are maintained (Figure 2.13 lower graph) although with increased winter flows supplied by unregulated catchment area.

Valley characteristics and bed sediment size. The valley of the Porma River is partially confined for most of its length. Only below the confluence with the Curueño River (segment 5) is the valley enlarged and becomes unconfined within a relatively short segment to its junction with the Esla River. Valley gradient decreases gradually downstream, from around 2% in the headwaters (segment 1) to 0.35% in the lowest reaches. Average valley width increases downstream from narrower sectors (300-500 m width) to the widest reaches located downstream from the confluence with the Curueño River (2000-4800 m width) (segment 5). The entire river has coarse bed sediment, whose size progresses from mainly cobbles (segments 1 to 3) to coarse gravel (segments 4 and 5).

Riparian corridor features. The riparian corridor presents similar characteristics to that of the Esla River, with the same species composition. Relatively narrow bands of willow galleries with *Betula* and *Fraxinus excelsior* exist in the upper parts (segment 1), and *Alnus glutinosa* and *Fraxinus angustifolia* are observed downstream (segments 3 to 5). Wood delivery potential has been assessed as relatively high, due to the frequency of dead trees along the river banks.

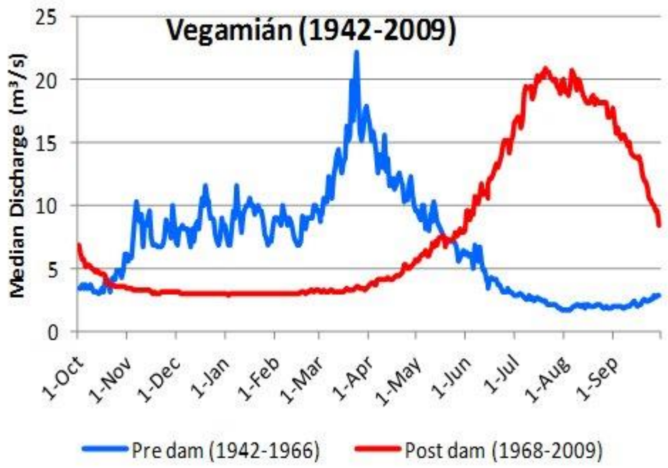


Figure 2.13 Average annual flow patterns at gauging stations on the Porma river at Vegamián (220 km^2, segment 3) and at Secos de Porma (947 km^2, segment 4). Data from Vegamián before the reservoir (1942-1966) represent the natural hydrologic regime of river in its upper and middle parts (segments 1 and 2).

Physical pressures. Physical pressures on longitudinal continuity are mainly related to the presence of the large dam at Vegamián and 18 additional small weirs. All these barriers are devoted to water withdrawal for irrigation. Flood plain occupation is relatively low in the upper part of the river (segments 1 and 3), where pasture represents approximately 20% of the area, and increases downstream. Poplar plantations are common in the middle and lower parts of the river, representing 20% and 60% of the floodplain area in segments 4 and 5, respectively.

(iii) Curueño River

Three river segments were identified along the Curueño River, each located corresponding to a single landscape unit. The catchment is relatively narrow and the main river course has no significant tributaries. The main characteristics of the segments are presented in Table 2.5.

Flow regime pattern. There are two gauging stationson this river: one in the upper reaches (Caldas de Nocedo, at the end of segment 1), where the river shows a nivo-pluvial hydrologic regime (Figure 2.14); a second in the lower part of the river (Ambasaguas, segment 3), relatively close to the Porma confluence, with only 1-year of registered data. At this latter location the Curueño River shows a temporary hydrologic regime, with annual peak-flows associated with autumn and winter precipitation, very sharp annual flow fluctuations, and no flow during summer months. At the downstream end of segment 1 there is a small reservoir located immediately downstream of the first gauge station,. Water is transferred from this reservoir to the Porma reservoir for hydropower generation (no data are available on the transferred water). The temporary flow regime downstream could be exacerbated by this water transfer, although the strong seasonality of the river is part of its natural flow regime.

Valley characteristics and Bed sediment size. The Curueño river flows along a partially confined valley whose average width varies from 300 m (segment 1) upstream to 1200 m downstream (segment 3) where it possesses similar dimensions to the main Porma valley at their junction. In between passes through a “gorge” segment (segment 2) where the valley narrows (20-70 m width) and becomes confined. This valley is relatively steep, with the majority of its longitudinal slope being higher than 1%, the steepest of the studied rivers (Figure 2.7). Valley/channel width ratios are relatively small at the gorges section (segment 2) and become progressively larger downstream. In this case the Curueño river shows a higher valley/channel width ratio than the Porma river at their junction (segment 3). The Curueño River has relatively coarse bed material with cobbles in the segments 1 and 2 and coarse gravel in segment 3.

Riparian corridor features. The riparian corridor of the Curueño River is relatively narrow and fragmented for most of its length because of agriculture on the floodplain. There are mixed dense shrub galleries with *Betula* sp. And *Fraxinus excelsior* in segment 1, which are gradually replaced by *Populus nigra* and *Fraxinus angustifolia* downstream the gorges (segment 3). Within the lower sections, several mature, dense riparian forest patches exist, with *Salix fragilis, Salix elaeagnus* and *Salix purpurea,* a high proportion of climbing species and an understory. Except for the gorges (segment 2) where vegetation is nearly absent because of the rocky margins, there is a high wood delivery potential along the entire river (segments 1 and 3) as abundant dead trees and dense mature forest exist at the channel edge and in the riparian zone.

Physical pressures. Pressures on longitudinal continuity are provided by the small dam in the upper reaches, from which water is 202mmobilized to the Porma river, and 10 small weirs which locally divert water for irrigation. Floodplain occupation is relatively low in the upper parts of the river, with pasture representing approximately 10 % of the area in segment 1 and being nonexistent in segment 2. Poplar plantations cover nearly 40 % of the area along segment 3.

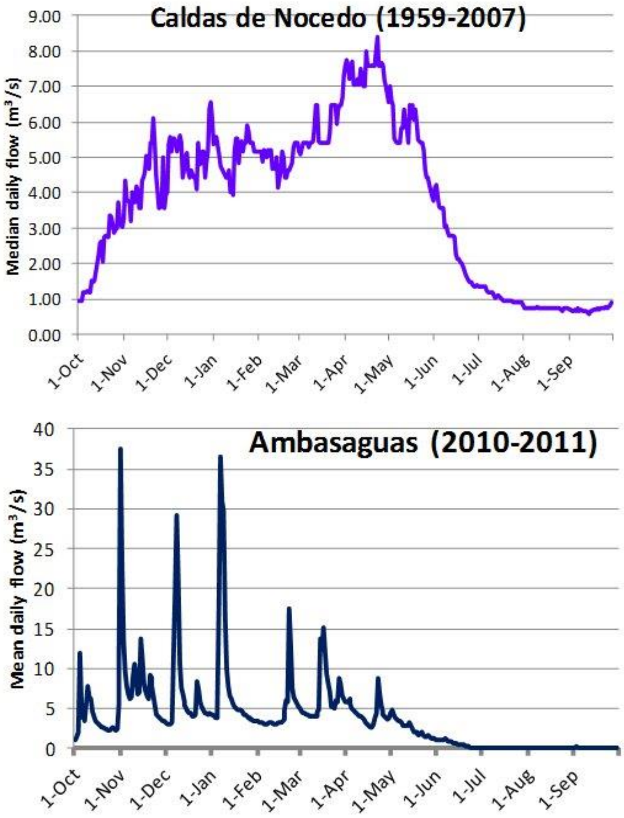


Figure 2.14 Flow regime of the Curueño river at Caldas de Nocedo (154 km^2, segment 1) and Ambasaguas (285 km^2, segment 3).

(iv) Bernesga River

There are 4 segments of the Bernesga River: Segment 1 corresponds to landscape unit 1; Segment 2 to landscape unit 2; Segments 3 and 4 are in landscape unit 3, and are, respectively, upstream and downstream of the Torío confluence. General characteristics of these river segments are presented in Table 2.6.

The hydromorphological conditions of the Bernesga river are similar to the previously described rivers, flowing in the same geographical context with a similar catchment area.

Flow regime. The Berneasga River is a free flowing river, with no dams on the main water course. Two gauging station characterize the flow regime of the river: one located in the upper part of the river (Villamanín, 1997-2009) in segment 1; the other in the lower reaches near León (2002-2009) and upstream of the Torío confluence in segment 3. Both of these stations have very short in records. Figure 2.15 shows the natural nivo-pluvial flow regime of the river along its entire length, with the main peak flows associated with snow melt in April and May and secondary peak flows associated with fluctuating rainfall during autumn and winter (November to February).

Valley characteristics and Bed sediment size. The Bernesga valley is confined and relatively narrow (250-400 m width) in the upper reaches (segment 1). In the gorges section (segment 2) the valley is partially confined, and then gradually enlarges (800-

1900 m width) downstream to the Torío confluence. Downstream of the Torío confluence, which is of similar size to the Bernesga, the valley doubles in size (2200-3100 m width) and becomes unconfined to its confluence with the Esla valley. Bed material is coarse, dominated by cobbles in the upper and middle parts (segments 1 and 2) and coarse gravel in the lower parts (segments 3 and 4).

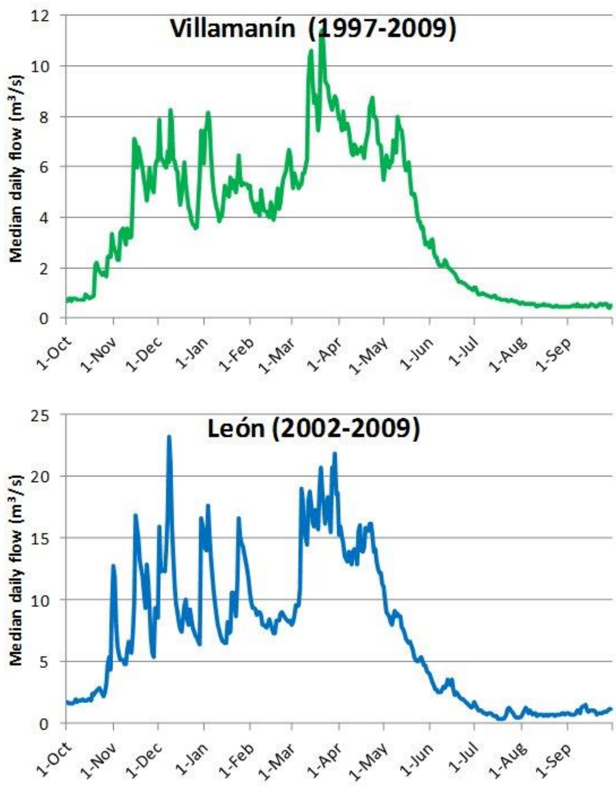


Figure 2.15 Flow regime of the Bernesga river at Villamanín (132 km^2, segment 2) and León (620 km^2, segment 3).

<u>Riparian corridor features</u>. The riparian corridor of the Bernesga River is relatively narrow and appears significantly fragmented along its length. In the upper reaches traditional coal mining associated with a power plant and roads bordering the river significantly reduce the riparian corridor. In the floodplains of the middle and lower reaches, agriculture, poplar plantations and urban pressures are frequent. Urbanization and riparian corridor degradation is particularly intense in segments 3 and 4 where León city, the regional capital, is located. Surviving patches of natural riparian vegetation show similar plant associations and structure to those described for the other rivers, with mixed shrub galleries containing *Betula* and *Fraxinus excelsior* upstream (segment 1), *Salix cantabrica* and *Salix elaeagnus* in the middle reaches (segment 2) and *Alnus glutinosa* with *Fraxinus angustifolia* and *Salix purpurea* in the lower parts (segments 3 and 4). Since the natural mature riparian forest is very reduced in width along the entire river, wood delivery potential has been assessed as intermediate in amount and frequency.

Physical pressures. The hydrologic regime of the Bernesga river is slightly altered by a recent water transfer from one of its upper tributaries, the Casares river, located in landscape unit 1, where a small dam and reservoir (37 hm^3 storage capacity) were constructed in 2000, in an attempt to avoid the natural summer drought of the river. Water is supplied from this reservoir to the Bernesga river in an attempt to maintain permanent summer flows within the urban reach at León city and to supply irrigation demands.

The longitudinal continuity of the river is significantly reduced by a 55 small weirs, many of which are located in the urban reach to stabilize the bed level and the others are distributed along main channel to divert water for irrigation.

In the lower segment, approximately 10 km of the river has been channelized with rip-rap and lateral embankments. Traditional gravel mining in the river bed and channelization works in the urban sector have induced intense channel incision between León city and the Esla confluence.

The floodplain of the Bernesga river in the partially confined, relatively wide valley of segment 1, has been traditionally used for pasture and heterogeneous small agricultural fields. Segment 2 includes a coal mining area with many roads located on the floodplain of this confined valley and several relatively important urban areas. In the lower segments, 3 and 4, the urbanization pressure is more intense, but agricultural fields and extensive poplar plantations are also very significant.

(v) The Torío River

As it was the case for the Curueño river, the Torio has no significant tributaries, nor changes in other features apart from topography and geology already considered in the delineation of the landscape units. Accordingly, three river segments were identified corresponding to the three landscape units.

Flow regime. The Torío river maintains a natural flow regime along its length, with a nivo-pluvial flow pattern similar to the Bernesga river although with smaller discharge values (Figure 2.16). Peak flows related to snow melt occur mainly in May at the upper reaches (Pontedo, segment 1) and nearly a month earlier downstream at Matallana (segment 2). Secondary pluvial peak flows show very sharp daily fluctuations through the year, and very reduced summer flows (close to zero in some years) occur between July and October.

Valley and bed sediment characteristics. The gradient of the Torío river is relatively high even in its lower reaches, where it becomes unconfined. Valley width ranges from 60-300 m in the upper reaches (segment 1) to 3000 m in the widest downstream areas (segment 3). The river has coarse bed material: cobbles in the upper and middle reaches (segment 1 and 2); coarse gravels in the lower parts (segment 3).

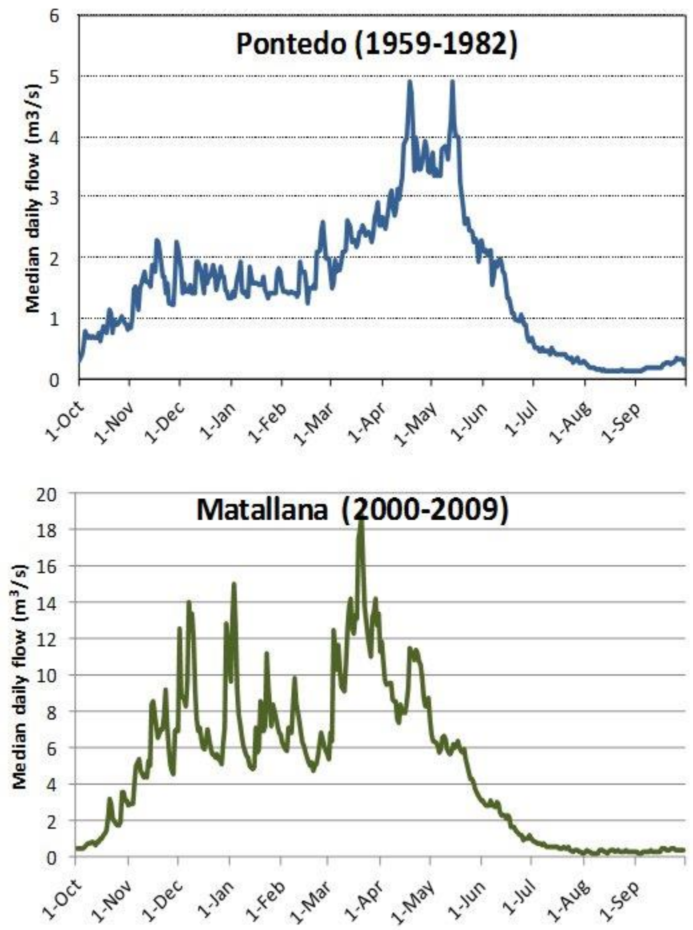


Figure 2.16 Flow regime of the Torío river at Pontedo (43 km^2, segment 1) and Matallana de Torío (222 km^2, segment 2).

Riparian corridor features. The riparian corridor is generally very narrow and fragmented. Patches of natural riparian vegetation exist along the river, with a similar composition and structure to the corridors previously described. Linear mixed galleries with *Betula* and *Fraxinus excelsior* with *Salix cantabrica* and *S purpurea* exist in the upper reaches (segment 1). The first two species are gradually replaced downstream by *Populus nigra*, (segment 2) while in segment 3 mixed forests with *Populus nigra*, *Salix fragilis S. purpurea* and *S. eleagnos* predominate. Particularly interesting is the dominance of *Salix elaeagnus* in the best preserved reaches, being an indicator species of flow fluctuations and sediment dynamics. There are large numbers of dead trees along the river, so the wood delivery potential is relatively high.

Physical pressures. There are no significant hydrologic pressures on the Torío river, apart from local water diversions for irrigation from 22 small check-dams. These may have a significant effect on sediment flows because of their large number.

The floodplain of the Torío river has been traditionally used for agricultur. Pasture, cultivated fields, and more recently poplar plantations have become very frequent. Urban pressures have increased in recent decades and are very intense in the lower reaches around León. In this urban sector the river has been recently dredged and realigned. This together with traditional gravel mining from the river bed for local construction has induced channel incision, which is particularly evident in the urban river reach.

Table 2.3 Main characteristics of the river segments differentiated along the main course of the upper Esla River.

Landscape Unit		**LU -1**		**LU- 2**	**LU- 3**	**LU- 4**
RIVER SEGMENT		**Es-1**	**Es-2**	**Es-3**	**Es-4**	**Es-5**
River Segment length (km)		16.7	15.5	21.3	57.6	21.1
Altitudinal range (m)		1400-1096	1096-1042	1042-935	935-772	772-741
Main features		Headwaters	Reservoir	Gorges	Above Bernesga confluence	Below Bernesga confluence
Flow regime (m^3/s)	Current Status	Natural	Large Dam (1988)	Regulated	Regulated	Regulated
	Gauge station (data period)	Las Salas (1964-1987)	Las Salas (1988-2009)	Cistierna (1988-2009)	Villomar (1988-2009)	Villalobar (1988-2009)
	Mean annual flow	23.42	19.22	22.5	17.95	61.93
	Median annual maximum flow	171.25	53.4	67.1	95.04	280.5
	Median annual minimum flow	0.75	4.31	5.46	5.56	16.88
	2-y peak flow	174	56.2	75.67	96.6	290
	Hydrologic regime	Perennial flashy	Reservoir	Regulated	Regulated	Regulated
Valley characteristics	Valley length (km)	16.2	15.5	20.2	50.1	19.2
	Gradient (%)	1.38	0.53	0.41	0.32	0.16
	Width range (m)	150-400	-	200-500	1200-9000	7000-10000
	Confinement	Partially confined	Partially confined	Confined	Unconfined	Unconfined
	Valley/Channel width ratio	20.7	-	25.5	59.5	155.6
Bed sediment	Sediment type	Boulders	Deposit sediments	Coarse gravel	Cobbles, coarse gravel	Gravel
	Sediment size (d50 mm)	-	-	(25)	(90)	-

Table 2.3 (ctd.)

Landscape Unit		**LU -1**		**LU- 2**	**LU- 3**	**LU- 4**
RIVER SEGMENT		**Es-1**	**Es-2**	**Es-3**	**Es-4**	**Es-5**
Riparian corridor	Average width (m)	2-7	2-7	2-12	2-50	2-40
	Longitudinal continuity: % length river bank with vegetation	70 %	Not applicable (Reservoir)	60 %	70 %	70 %
	Plant associations	Riparian shrub mixed galleries with *Betula sp.* And *Fraxinus excelsior*	Not applicable (Reservoir)	Riparian mixed galleries with *Populus nigra* and *Salix cantabrica*	Riparian mixed galleries with *Fraxinus angustifolia, Cournus sanguinea, Alnus glutinosa*	Riparian mixed galleries with *Fraxinus angustifolia, Alnus glutinosa and Salix fragilis*.
	Wood delivery potential	High	Not applicable (Reservoir)	Intermediate	High	High
Physical Pressures	Hydrological pressures	Absent	Flow regulation	Flow regulation	Flow regulation Water abstraction	Flow regulation Water abstraction
	Pressures for longitudinal continuity	No significant	Large Dam	Intermediate 5 small weirs	High 18 small weirs intercepting the majority of transported sediment and wood	Intermediate 2 small weirs
	% Floodplain occupation	10 % Pastures Local small villages	Reservoir	10 % Pastures Local small villages	60 % heterogeneous agricultural areas and pastures 30 % Poplar plantations	70 % Agricultural fields Irrigation structures Local gravel mining 15 % Poplar plantations

Table 2.4 Main characteristics of the river segments differentiated along the main course of the Porma River.

Landscape Unit		**LU- 1**		**LU- 2**	**LU -3**	
RIVER SEGMENT		**Po-1**	**Po-2**	**Po-3**	**Po-4**	**Po-5**
River Segment length (km)		14.1	6.3	8.9	21	30
Altitudinal range (m)		1205-1087	1087-1052	1052-969	969-866	866-777
Main features		Headwaters	Reservoir	Gorges	Above Curueño confluence	Below Curueño confluence
Flow regime (m^3/s)	Current Status	Natural	Resevoir	Regulated	Regulated	Regulated
	Gauge station (data period)	Vegamián (1942-1966)	-	Vegamián (1968 2007)	-	Secos de Porma (1988-2009)
	Mean annual flow	6.17		9.66		14.01
	Median Annual maximum flow	14.3		29.2		40.5
	Median minimal annual flow	2.41		4.11		5.32
	2-y peak flow	103.5		24.7		71.8
	Hydrologic regime	Perennial flashy	Regulated	Regulated	Regulated	Regulated
Valley characteristics	Valley length (km)	14	6.3	7.2	19.7	25.9
	Gradient (%)	2.01	1.03	1.08	0.52	0.35
	Width range (m)	350-550	----	200-300	600-1200	2400-4800
	Confinement	Partially confined	Partially confined	Partially confined	Partially confined	Unconfined
	Valley/Channel width ratio	25.9	--	8.2	13.9	24.8
Bed sediment	Sediment type	Cobbles	Deposited material	Cobbles	Cobbles, coarse gravel	Cobbles, coarse gravel
	Sediment size (d50 mm)	(138)	-	(130)	-	(113)
Riparian corridor	Average width (m)	2-7	-	2-15	2-40	2-70
	Longitudinal continuity	60 %	-	80 %	40 %	80 %
	Natural Plant associations	Riparian mixed shrub galleries with *Betula* sp and *Fraxinus excelsior*		Riparian mixed galleries with *Populus nigra* and *Salix cantabrica*	Riparian mixed galleries with *Populus nigra* and *Salix eleagnos*	Riparian mixed galleries with *Fraxinus angustifolia, Alnus glutinosa, Salix Purpurea, S.atrocinerea and . fragilis*
	Wood delivery potential	High	Not applicable	Intermediate	High	High

Table 2.4 (ctd.).

Landscape Unit		**LU- 1**		**LU- 2**	**LU -3**	
RIVER SEGMENT		**Po-1**	**Po-2**	**Po-3**	**Po-4**	**Po-5**
Physical Pressures	Hydrological pressures	Absent	Reservoir	Flow regulation Natural runoff increased by water transfer from the Curueño river	Flow regulation Water abstraction	Flow regulation Water abstraction
	Pressures for longitudinal continuity	Intermediate 2 small weirs	Large Dam	Intermediate 4 small weirs Interception of the majority of transported sediment and wood	High 11 small weirs Interception of the majority of transported sediment and wood	High 8 small weirs
	% Floodplain occupation	10 % small pastures And locally small villages	Reservoir	20 % Small pastures and locally urban and gravel mining	20 % pastures 40 % Poplar plantations	20 % Heterogeneous agricultural areas and pastures 80 % Poplar plantations

Table 2.5 Main characteristics of the river segments differentiated along the main course of the Curueño River.

Landscape Unit		**LU- 1**	**LU- 2**	**LU- 3**
RIVER SEGMENT		**Cu- 1**	**Cu -2**	**Cu- 3**
River Segment length (km) Altitudinal range (m)		8 1300-1160	10.8 1160-1029	21.6 1029-866
Main features		Upper reaches	Gorges	Middle and Lower reaches
Flow regime (m^3/s)	Current Status Gauge station (data period) Mean annual flow Median Annual maximum flow Median minimal annual flow 2-y peak flow Hydrologic regime	Natural Tolibia de Abajo (2000-2009) 3.07 26.3 0.22 29.1 Stable	Natural Caldas de N (1959-2007) 5.53 41.1 0.49 42.9 Perennial flashy	Natural Ambasaguas (2010-2011) 3.9 37.4 0.02 NO DATA Perennial flashy
Valley characteristics	Valley length (km) Gradient (%) Width range (m) Confinement Valley/Channel width ratio	7.8 2.53 200-350 Partially confined 16	9.8 1.28 20-70 Confined 6.7	20.6 0.82 900—1500 Partially confined 30.3
Bed sediment	Sediment type Sediment size (d50 mm)	Cobbles (70)	Cobbles (125)	Cobbles, coarse gravel (130)
Riparian corridor	Average width (m) Longitudinal continuity Plant associations	0-10 40 % Ripatian mixed galleries with *Betula* sp. And *Fraxinus excelsior*	2-15 30 % Riparian mixed galleries with *Populus nigra* and *Salix purpurea*	2-50 50 % Riparian mixed galleries with *Populus nigra, Salix fragilis*, *S. eleagnos* and *S. Purpurea*
	Wood delivery potential	High	Intermediate	High
Physical Pressures	Hydrologic pressures	No significant	Natural runoff decreased by water transfer to the Porma reservoir	Natural runoff decreased by water transfer to the Porma reservoir
	Pressures for longitudinal continuity	Intermediate 1 small dam, 2 small weirs	Intermediate 3 weirs	Intermediate 6 weirs
	% Floodplain occupation	10 % small pastures	-	30 % pasture, 70 % Poplar plantations

Table 2.6 Main characteristics of the river segments differentiated along the main course of the Bernesga River.

Landscape Unit		**LU- 1**	**LU-2**	**LU- 3**	
RIVER SEGMENT		**Be -1**	**Be- 2**	**Be- 3**	**Be -4**
River Segment length (km) Altitudinal range (m)		22.5 1250-996	9.6 996-942	28.5 942-806	13.2 806-773
Main features		Upper reaches	Gorges	Above Torío confluence	Below Torío confluence
Flow regime (m^3/s)	Current Status	Natural	Natural	Natural	Natural
	Gauge station (data period)	Villamanín (1997-2009)	La Robla (1989-1995)	León (2002-2009)	-
	Mean annual flow	4.8	10.3	8.8	
	Median maxima annual	45.1	97.2	83.3	
	Median minimal annual	0.3	0.9	0.2	
	2-y peak flow	46	135.15	96.5	
	Hydrologic regime	Stable	Stable	Stable	Perennial flashy
Valley characteristics	Valley length (km)	22	8	26.2	11.6
	Gradient (%)	1.27	0.79	0.48	0.33
	Width range (m)	250-400	580-700	800-1900	2200-3100
	Confinement	Confined	Partially confined	Partially confined	Unconfined
	Valley/Channel width ratio	12.5	23.3	56.4	42.8
Bed sediment	Sediment type	Cobbles	Cobbles	Cobbles, coarse gravel	Coarse gravel
	Sediment size (d50 mm)	-	-	-	-
Riparian corridor	Average width (m)	2-9	2-21	2-40	2-40
	Longitudinal continuity	70 %	70 %	60 %	50 %
	Plant associations	Riparian mixed galleries with *Betula* and *Fra xinus excelsior*	Riparian mixed galleries with *Populus nigra* and *Salix cantabrica*	Riparian mixed galleries with *Populus nigra*, *Salix eleagnos, Fraxinus angustifolia*	Riparian mixed galleries with *Fraxinus angustifolia, Alnus glutinosa* and *Salix Purpurea*
	Wood delivery potential	Intermediate	High	Intermediate	Intermediate

Table 2.6 (ctd.)

Landscape Unit		**LU- 1**	**LU-2**	**LU- 3**	
RIVER SEGMENT		**Be -1**	**Be- 2**	**Be- 3**	**Be -4**
Physical Pressures	Hydrologic pressures	No significant	No significant	No significant	No significant
	Pressures for longitudinal continuity	Intermediate 6 small weirs	Intermediate 7 small weirs	High 30 small weirs Interception of the majority of transported sediment and wood	High 13 small weirs Interception of the majority of transported sediment and wood
	% Floodplain occupation	10 % small pastures and locally urban uses	5 %Pastures and industrial uses	10 % pastures, 50 % Poplar plantations and 40 % urban uses	70 % Poplar plantations

Table 2.7 Main characteristics of the river segments differentiated along the main course of the Torío River.

Landscape Unit		LU- 1	LU- 2	LU- 3
RIVER SEGMENT		**To- 1**	**To- 2**	**To-3**
River Segment length (km) Altitudinal range (m)		9.4 1320-1052	9.6 1052-962	33.6 962-806
Main features		Upper reaches	Gorges	Middle and Lower reaches
Flow regime (m^3/s)	Current Status Gauge station (data period) Mean annual flow Median annual peak flow Median annual minimum flow 2-y peak flow Hydrologic regime	Natural La Pola de Gordón (1959-1982) 2.03 14.7 0.1 15 Perennial flashy	Natural Matallana de Torío (2000-2009) 7.1 74.75 0.13 75.2 Stable	Natural -
Valley characteristics	Valley length (km) Gradient (%) Width range (m) Confinement Valley/Channel width ratio	15.6 1.57 60-300 Partially confined /Confined 6.3	9.5 0.97 700-950 Partially confined 16.2	28.7 0.56 1400-3000 Unconfined 12.2
Bed sediment	Sediment type Sediment size (d50 mm)	Cobbles (90)	Cobbles (106.6)	Coarse gravel (77.4)
Riparian corridor	Average width (m) Longitudinal continuity Plant associations	2-15 40 % Riparian mixed galleries with *Betula* sp., *Fraxinus excelsior, Salix cantabrica* and *S prupurea.*	2-60 70 % Riparian mixed galleries with *Populus nigra*, *Salix cantabrica snd S. Purpurea*	2-80 50 % Riparian mixed galleries with *Populus nigra*, *Salix fragilis* and *S. Purpurea* and *S. eleagnos*
	Wood delivery potential	High	High	Intermediate
Physical Pressures	Hydrologic pressures	No significant	No significant	No signficant
	Pressures for longitudinal continuity	Intermediate 7 weirs	High 11 weirs	High 14 weirs
	% Floodplain occupation	5 % small pastures	50 % Pastures	50 % pasture, 50 % Poplar plantation

2.5 Reach Scale

2.5.1 Delineation

Only the Esla, Porma and Curueño rivers have been analyzed at the reach scale. Two complementary approaches were followed to delineate the river reaches: automated delineation using the Pettitt Test (see Deliverable 2.1, Part 2, Annex A), and expert judgement. For the automated delineation, the longitudinal variation of three morphological variables (gradient slope, valley bottom width and active channel width) were analysed for each river and statistically significant discontinuities along the main course were identified. Once the break points had been detected, the final reaches were defined by applying expert judgment to encompass other important physical features such as dams and reservoirs, major confluences, and changes in landscape units, and, for practical reasons, to achieve a suitable minimum length for a reach. This process identified 7, 5 and 4 reaches for the Esla, Porma and Curueño rivers, respectively, some of which coincide with river segments (Figure 2.17).

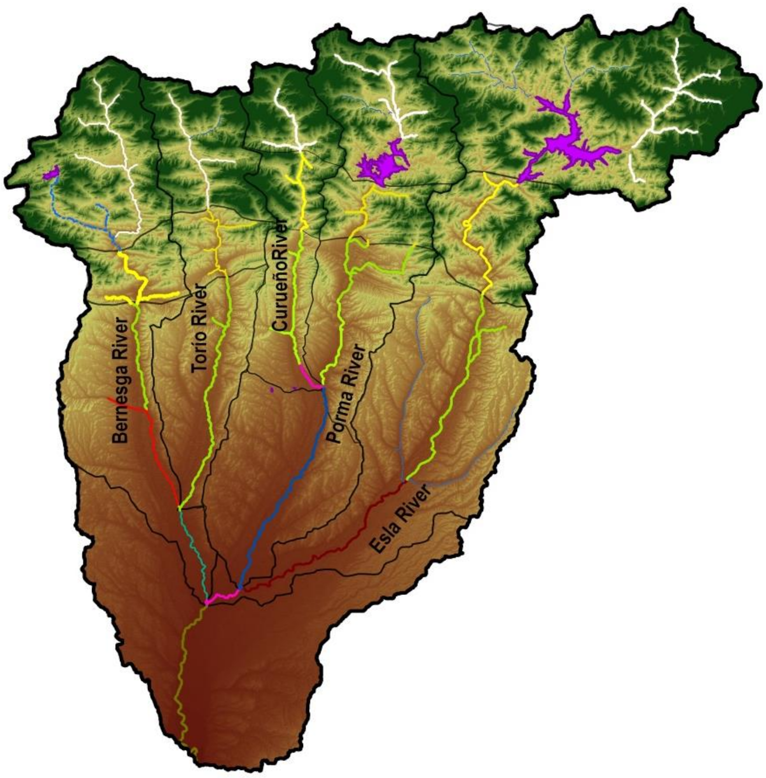


Figure 2.17 River reaches of Upper Esla basin.

2.5.2 Characterization

Tables 2.8, 2.9 and 2.10 list additional attributes of the river reaches that were not included at the segment scale. Channel gradient, estimated along the central line of the active channel, and reach gradient, calculated as the gradient of a rectilinear line between the reach limits, are both estimated. River energy was calculated for the 2 year peak flow and bed shear stress was obtained based on the average depth dimensions at bankfull. The reach gradient (the difference in elevation between upstream and downstream ends of the reach divided by the reach length along the channel centre line) was used to estimate stream power.

Fieldwork was conducted in most of the reaches to characterize the riparian and aquatic vegetation. Vegetation transects perpendicular to the active channel main axis were assessed. Pioneer species (*Salix* and *Populus* spp) and late-seral species (*Betula, Fraxinus, Ulmus* spp) were distinguished, and abundance (dominant, abundant, rare) and age structure (seedlings, young, mature and old forest) were visually assessed. Aquatic vegetation is scarce in the studied rivers, but local, occasional patches were identified in the middle and lower parts of the rivers.

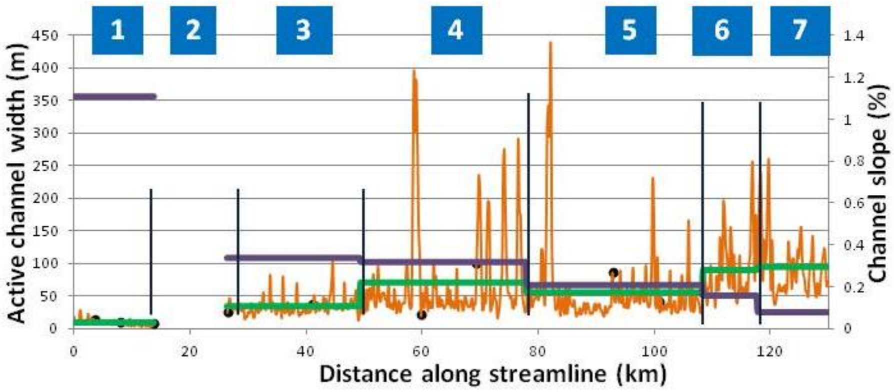
Channel and floodplain geomorphic units were identified during field work and from air-photographs, according to the images included in the D.2.1 main report (Table 5.7).

Physical pressures were assessed in relation to river bed and river bank conditions, riparian corridor connectivity and morphologic adjustment processes.

(i) Channel features: Width, gradient and planform

Upper Esla River. Figure 2.18 shows the delineation criteria and average values of some characteristics for the 7 Esla river reaches. Reach 1 is located in landscape unit 1 above the reservoir, and corresponds to the headwaters, having higher slope gradient and much smaller valley and channel width than the rest. Reach 2 corresponds to the reservoir. Reach 3 is located in landscape unit 2, coincides with segment 3, and is relatively homogeneous with geomorphic characteristics strongly linked to the geology and topography of this “gorge” sector. Reach 4 is in landscape unit 3, with a higher channel gradient and smaller valley bottom width than reaches 5 and 6, which are located in the same landscape unit. Reach 6 is a short length of river between the confluences with the Porma and Bernesga rivers, in which the valley bottom width increases sharply and the active channel width fluctuates greatly but on average progressively increases. Reach 7 is the most downstream reach of the Upper Esla river, located downstream the Bernesga confluence with gradually decreasing channel gradient and increasing active channel width within a valley bottom narrowed between fluvial terraces.

River planform types (Table 2.8), include confined straight sinuous forms in the upper reaches within landscape unit 1 and 2 (reaches 1 to 3), which gradually turn into partly confined or unconfined wandering in reaches 4 and 5, and unconfined meandering in the lowest reaches 6 and 7, where the valley is considerably wider downstream of the Porma and Bernesga confluences.



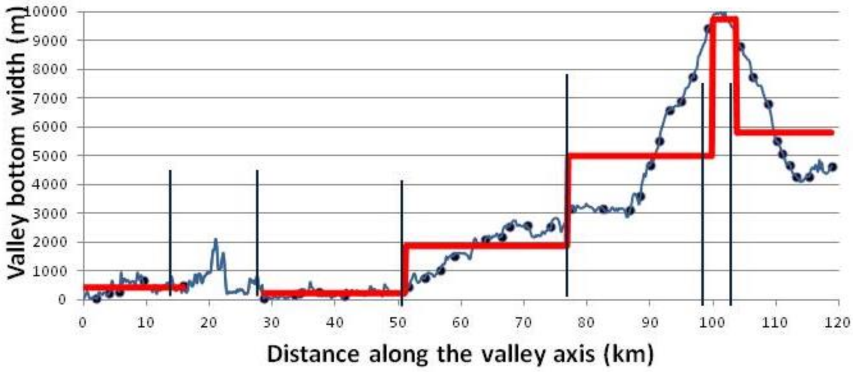


Figure 2.18 Main characteristics of reaches in the Esla River: Average values of channel slope (violet line), active channel width (green line) and valley bottom width (red line). Black points indicate significant breaks in the selected geomorphic variables detected by Pettit´s test, vertical black lines indicate limits of the final delineated river reaches.

Porma River

The Porma river has 5 reaches (Figure 2.19), which are coincident with the 5 river segments previously described. Reach 1 is located in landscape unit 1, above the reservoir, and corresponds to the headwaters where slope gradients are the highest and the width of the valley and the active channel the narrowest. Reach 2 corresponds to the reservoir. Reach 3 is located in landscape unit 2 and coincides with segment 3, presenting shallower gradient values than upstream reaches but similar active channel width and valley width. Reach 4 starts when the river enters landscape unit 3 and extends to the confluence of Curueño river. In this reach the river has a much lower gradient than upstream, and the active channel fluctuates but gradually enlarges within a valley that also gradually enlarges. Reach 5 is also located in landscape unit 3 but downstream the confluence with the Curueño river. In this reach the river has its lowest gradient, the active channel width fluctuates considerably and the valley width is significantly enlarged.

The river planform types are summarized in Table 2.9. The river has a confined, straight sinuous channel in reach 1, which is maintained in reach 3 downstream from the dam, where the relief determines the valley sinuosity. In reach 4, the river presents has an artificially straight pattern as a consequence of the large dam and reservoir effects which reduce flood magnitude and frequency and disrupt the sediment transport downstream. In this reach channel narrowing is evident although the valley bottom enlarges gradually (Figure 2.19) and channel incision occurs. In reach 5, below the confluence with the Curueño river, the river shows a pseudo-meandering planform along a much wider valley filled by coarse sediments transported by the Curueño river.

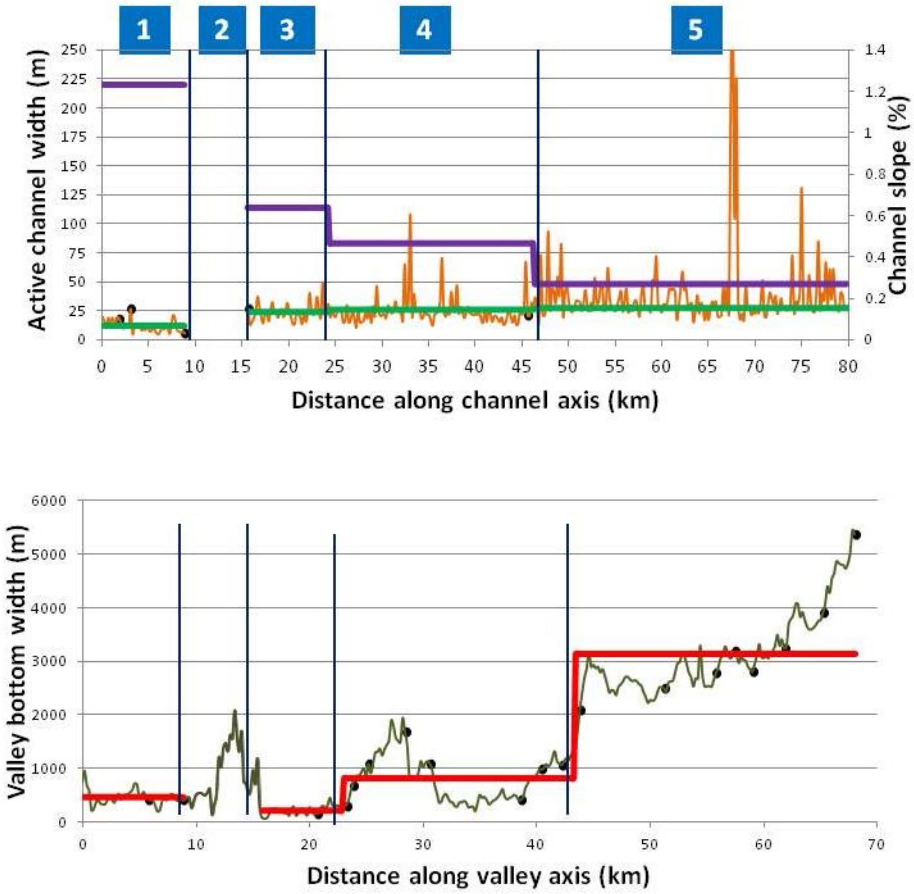
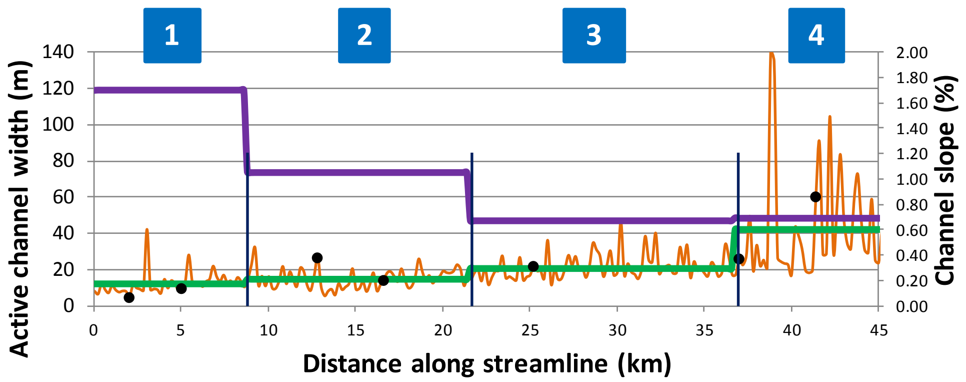


Figure 2.19 Main characteristics of reaches of the Porma River: Average values of channel slope (violet line), active channel width (green line) and valley bottom width (red line). Black points indicate significant breaks detected by the Pettit´s test along the continuous data of the respective geomorphic variables, whereas vertical black lines indicate the limits of the delineated river reaches.

<u>Curueño River</u>

The Curueño river has 4 reaches (Figure 2.20, Table 2.10). Reach 1 (in landscape unit 1) corresponds to the headwaters, where the channel is steeper and narrower. Reach 2 (in landscape unit 2) is located in the "gorges" where the valley significantly narrows. Reaches 3 and 4 (in landscape unit 3) have similar gradients but different widths. Reach 3 is in the upper part of segment 3, where active channel width and valley width enlarge gradually. Reach 4 is the most downstream part of the river where most of transported sediments are deposited forming a kind of "delta" before the junction with the Porma river.

The planform of the river is closely related to the channel and valley gradient and valley width (Figure 2.20). In the upstream, confined/partly confined valley (reaches 1 and 2), the river is mostly straight or sinuous. Downstream along the partly confined /unconfined valley of reaches 3 and especially 4, the river is wandering.



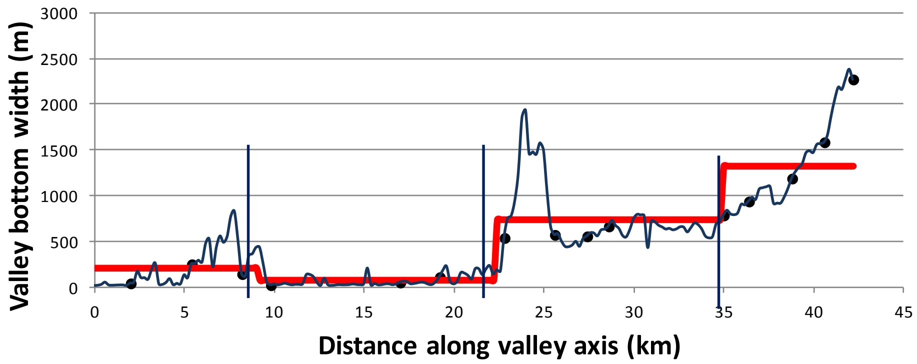


Figure 2.20 Main characteristics of reaches in the Curueño River: Average values of channel slope (violet line), active channel width (green line) and valley bottom width (red line). Black points indicate significant breaks detected by the Pettit´s test along the continuous data of the respective geomorphic variables, whereas vertical black lines indicate limits of the delineated river reaches.

(ii) River Energy

Estimation of energy variables is based on current conditions and, in the case of regulated rivers, on the post-dam discharge data (i.e. 1968-2009 for the Porma River and 1989-2009 for the Esla River) (Figure 2.21). When no gauging station exists, the line in the Figure is discontinuous. The upper Porma and Curueño Rivers have total and specific stream power values of a similar order of magnitude, with higher values than the upper Esla River because of their steeper valley and channel gradients (Figure 2.6).

However, the energy values and longitudinal trends of lower parts of the Porma and Esla rivers are similar. The most downstream reach of the Esla River has the highest total stream power, because it includes the Porma and Bernesga discharges, but the specific stream power does not increase downstream due to the simultaneous increase of channel width.

(iii) Bed and bank sediment

All of the reaches are "gravel-bed rivers", with coarse to very coarse sediments in the upper reaches (cobbles) and coarse gravels in the middle and lower reaches. Bank sediments are of a similar calibre as is the active floodplain which accumulates large quantities of recent alluvial materials.

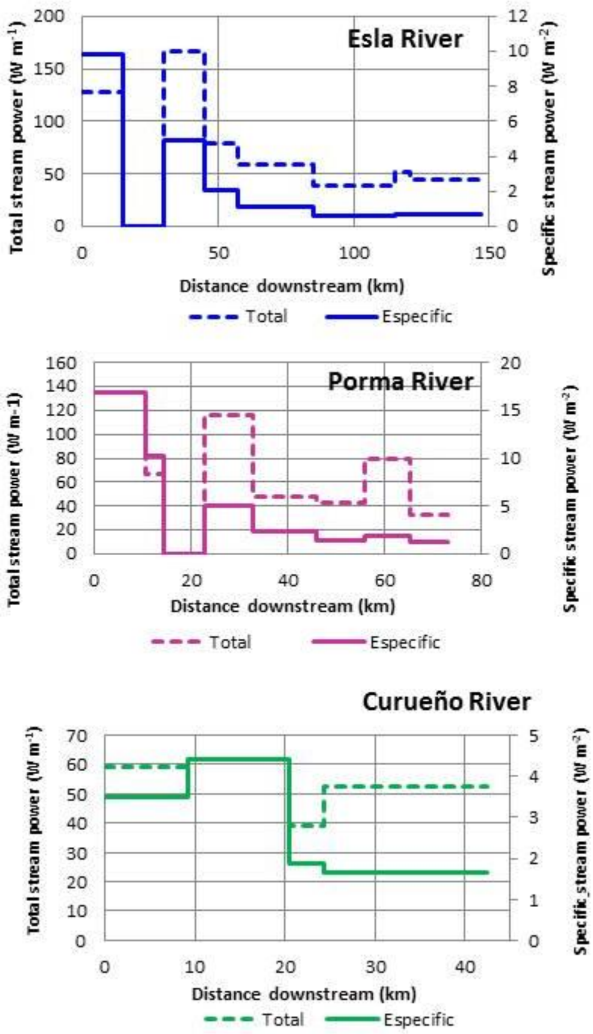


Figure 2.21 Energy characteristics of the studied rivers, estimated for the 2 year peak flow and reach gradient values.

(iv) Channel and Floodplain Geomorphic units

Geomorphic units were identified according to the features reported in Table 5.7 of Deliverable 2.1, Part 1. Figure 2.22 shows the proportion of geomorphic units by reach, which were identified on air-photographs and verified during field work. This proportion was estimated from 200 m spaced transects, along which bankfull channel and marginal and bank features were recorded. *Pools and riffles* were the most frequent channel bed unit in the Porma and Curueño rivers. *Runs* over the total width of the channel were frequent in the Esla river. *Forced pools* (i.e. local pools associated with the presence of large boulders in the channel) were found only in the upper reaches of the Esla and Porma rivers (landscape unit 1) whereas in the Curueño river they were also relatively frequent within landscape unit 2 where the river forms narrow gorges.

Figure 2.23 presents the number of geomorphic units per km of river related to marginal and bank features. The Curueño river channel has the highest diversity of geomorphic units, while the Porma river has more homogeneous marginal and bank conditions. *Mid-channel bars* were most abundant in the Esla river and relatively rare in the smaller Porma and Curueño rivers. Bare sediment point- and lateral-bars are far more frequent in the Curueño than the other rivers, although they are not observed in reach 2, which is located in the "gorge" segment. *Vegetated bars* were the most frequent feature in the regulated rivers Esla and Porma, whereas *bare sediment bars* were much more frequent in the non-regulated Curueño river (Figure 2.24).

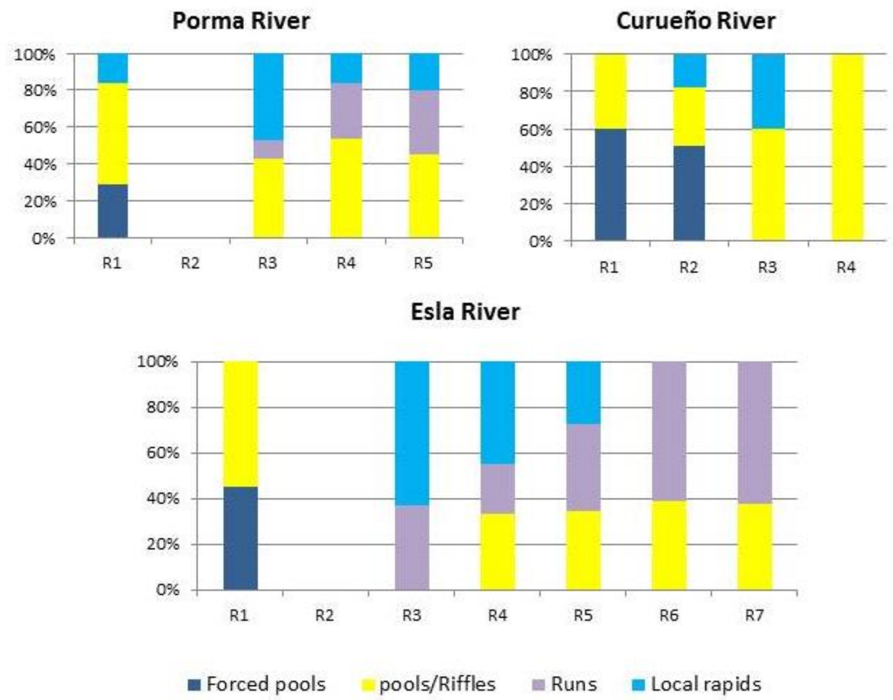


Figure 2.22 Proportion of channel bed geomorphic units per reach in the studied rivers.

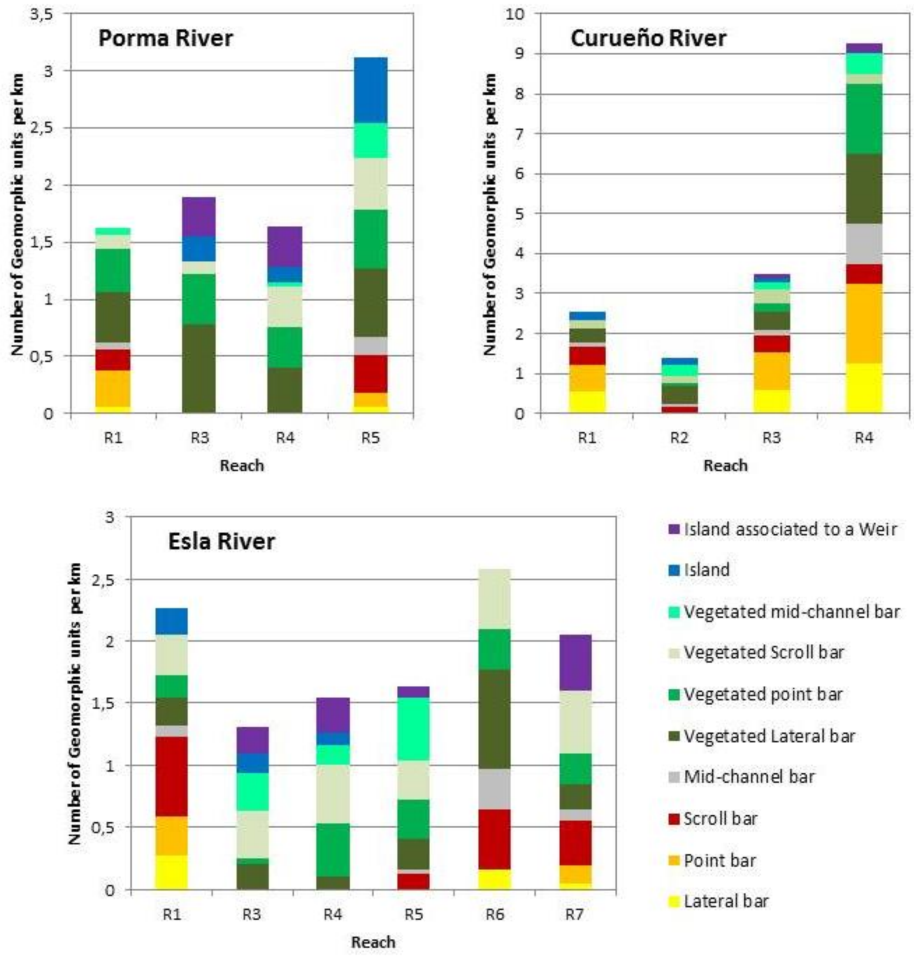


Figure 2.23 Marginal and bank features per reach in the studied rivers

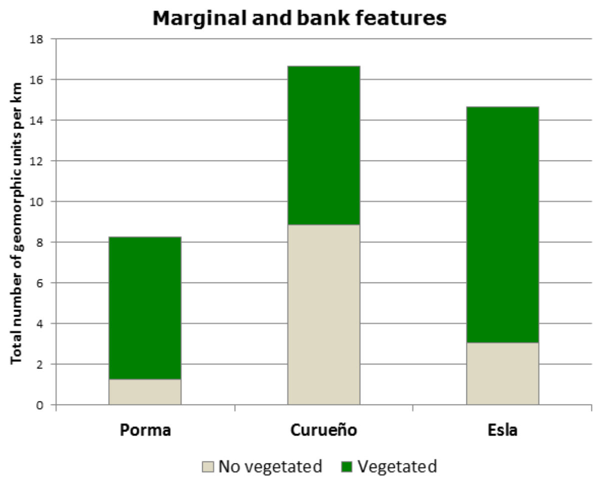


Figure 2.24 Proportion of vegetated and non vegetated marginal and bank features in the studied rivers.

No distinct geomorphic units were identified on the floodplains of the studied reaches, as human occupation is relatively intense with agricultural land and poplar plantations occupy most of the valley area.

(v) Riparian and Aquatic vegetation

The species composition of woody riparian vegetation was very similar along the three rivers (Tables 2.8, 2.9, 2.10). Vegetation age structure (seedlings, young, mature and old classes) of pioneer (i.e. Salicaceae) and late-seral species (e.g. *Fraxinus* spp, *Alnus glutinosa*) were analyzed in the field at reach scale.

In the regulated Esla and Porma rivers, recruitment areas with Salicacea seedlings were observed only in the upper reaches above the dam. Mature and old forest patches of these pioneer species were predominant downstream from the dams where no regeneration existed. Late-seral species were rare in the non-regulated reaches above the dam and very abundant downstream, together with old stands containing frequent dead trees. Along the unregulated Curueño river recruitment of pioneer species is maintained along the entire river; late-seral associations are much less abundant than in the regulated rivers; and Salicacea associations predominate until the confluence with the Porma river.

The relatively high energy of all these rivers and their coarse substratum strongly reduces the potential for aquatic vegetation growth within the channel. Macrophytes are generally very scarce; small stands of *Phragmites, Typha* and *Sparganium* occasionally exist at bank locations; and are only significant in the middle and lower parts of the Esla river.

(vi) Physical pressures

Physical pressures at the reach scale mainly reflect pressures already 224mmobilize at the segment scale, including the large dams in the Esla and Porma river and the numerous small weirs installed along the channels for irrigation water diversion. Apart from these, no other physical pressures exist in terms of channelization works affecting the bed and banks of the channel, although dredging and gravel mining have frequently occurred in the past.

In the case of the Porma river, channel incision is observed downstream from the dam (reach 4) and thus lateral connectivity of the channel with the floodplain has been decreased considerably. As a result, the primitive pioneer shrub formations of *Salix elaeagnos,* which are characteristic of these high energy rivers, are only found as old stands along secondary channels and relatively remote from the current river bank. Floodplain occupation by agriculture and poplar plantations, which are very extensive downstream from the dams, also represent important physical pressures for the maintenance of the integrity of the riparian corridor.

Table 2.8 Main characteristics of the river reaches differentiated along the main course of the upper Esla River.

	Landscape	LU- 1		LU- 2	LU- 3			LU- 4
	Segment	Es-1	Es-2	Es-3	Es-4			Es-5
	REACH	1	2	3	4	5	6	7
Channel dimensions	Channel length (km)	16	Reservoir	23.6	28.4	31.6	8.4	18
	Channel gradient (%) Reach gradient (%)	1.81 3.61	Reservoir	0.517 0.646	0.33 0.37	0.20 0.26	0.07 0.13	0.1 0.11
	Active channel width (m)	10	-	35	71	56	91	95
	Channel sinuosity	1.98	-	1.25	1.14	1.27	1.84	1.08
River energy	Total stream power ($W m^{-1}$) specific stream power ($W m^{-2}$) Average bed shear stress (Pa)	NO DATA NO DATA NO DATA	0 0 -	187.28 5.51 5.45	240.32 6.32 5.08	200.72 3.94 4.16	NO DATA NO DATA NO DATA	426.30 5.47 2.50
Bank and bed sediment		Cobble-gravel	Reservoir	Cobble-gravel , Gravel sand	Gravel sand	Gravel sand	Gravel sand	Gravel sand
River Type		7 Confined, straight sinuous	Reservoir	7 Confined, straight sinuous 11 Confined/partly confined wandering	11 Partly confined /unconfined wandering	11 Partly confined /unconfined wandering	14 Unconfined meandering	14 Unconfined meandering

Table 2.8 (ctd.)

	Landscape	**LU- 1**		**LU- 2**	**LU- 3**			**LU- 4**
	Segment	**Es-1**	**Es-2**	**Es-3**	**Es-4**			**Es-5**
	REACH	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Riparian vegetation	Pioneer species* Abundance Age structure Late-seral species Abundance Age structure Main woody species	Dominant All classes Rare All classes *Betula, S. Fragilis, P. Nigra, Ulmus minor*	-	Abundant Young, Mature, Old Abundant All classes *Populus nigra, Salix atrocinerea, Salix purpurea, Salix cantábrica, Betula, Fraxinus excelsior Coryllus avellana*	Abundant Young, Mature, Old Abundant All classes *Populus nigra, Salix purpurea, Salix atrocinerea, Fraxinus angustifolia, Salix fragilis, Ulmus minor, Salix eleagnos, Ligustrum vulgare*	Abundant Young, Mature, Old Abundant All classes *Populus nigra, Salix purpurea, Salix atrocinerea, Fraxinus angustifolia, Salix fragilis, Ulmus minor Salix eleagnos, Crataegus monogyna, Ligustrum vulgare*	Abundant Young, Mature, Old Abundant All classes *glutinosa, P. Nigra, S.purpurea, S. Atrocinerea, Fraxinus angustifolia, S. Fragilis, Ulmus minor, Cornus sanguínea, S. Eleagnos Crataegus monogyna, Ligustrum vulgare*	Abundant Young, Mature, Old Abundant All classes *Alnus glutinosa Populus nigra, Salix atrocinerea, Fraxinus angustifolia, Salix fragilis, Ulmus minor, Conus sanguínea, Crataegus monogyna,*
Large wood	Large wood abundance	Isolated pieces	None	Isolated pieces	Isolated pieces	Isolated pieces in the active channel; accumulations of large wood in the riparian corridor	Isolated pieces in the active channel; accumulations of large wood in the riparian corridor	Isolated pieces in the active channel; accumulations of large wood in the riparian corridor
Aquatic vegetation	Emergent aquatic vegetation Bank length Main Species	Absent	-	Absent	Occasional patches *Typha, schoenoplectrum, Sparganium erectum Phragmites*	Occasional patches *Typha, schoenoplectrum, Sparganium erectum Phragmites*	Local bankside formations of *Typha, schoenoplectrum, Sparganium erectum Phragmites*	Local bankside formations of *Typha, schoenoplectrum Sparganium erectum Phragmites*

Table 2.8 (ctd.)

		Landscape	LU- 1		LU- 2	LU- 3			LU- 4
		Segment	**Es-1**	**Es-2**	**Es-3**	**Es-4**			**Es-5**
		REACH	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Channel and floodplain geomorphic units				Reservoir	Rapids, step-pool	Rapids and weir influenced pool and riffles	Rapids, weir influenced pool-riffles, vegetated islands & lateral bars	Scroll bars, vegetated islands & lateral bars.	Scroll bars, vegetated islands & lateral bars.
Physical Pressures	River bed condition	Bed armouring (gravel-bed rivers)	NS		Significant	NS	NS	NS	NS
		Bed clogging / burial (gravel-bed rivers)	NS		NS	Significant	NS	NS	NS
		Extent of bed reinforcement	NS		NS	NS	NS	NS	NS
		Number of channel blocking structures	NS	Dam	2	11	4	1	2
		Sediment, wood, vegetation removal	NS		NS	NS	NS	NS	NS
	River bank condition and processes	(1) hard bank reinforcement	NS		NS	NS	NS	NS	NS
		(2) bank edge 227mmobi/embankments	NS		NS	Locally	Locally	Locally	Locally
		(3) set-back 227mmobi/embankments							
		(4) bank top infrastructure							
		(5) 227mmobilized river margin	NS		Locally by roads	NS	NS	NS	NS
		(6) actively eroding river margin	NS		NS	NS	NS	Locally	Locally
		(7) width of erodible corridor							
		(8) number of channel-spanning structures							
	Riparian corridor lateral connectivity and condition	(1) riparian corridor accessible by flood water	Totally		Partially	Partially	Totally	Totally	Totally
		(2) riparian corridor affected by intense woodland management activities;	Partially (grazing)		NS	Totally (Poplar plantations)	Totally (Poplar plantations)	Totally (Poplar plantations)	Totally (Poplar plantations)
		(3) abundance of alien, invasive plant species	NS		NS	NS	NS	NS	NS

Table 2.9 Main characteristics of the river reaches differentiated along the main course of the Porma River.

		Landscape	**1**		**2**	**3**	
		Segment	**1**	**2**	**3**	**4**	**5**
		REACH	**1**	**2**	**3**	**4**	**5**
Channel dimensions		Channel length Channel gradient (%) Reach gradient (%) Active channel width (m) Channel sinuosity	16 2.16 2.42 12 1.12	- - - -	9 1.1 1.3 24 1.25	22.6 0.45 0.52 25 1.15	33 0.27 0.33 38 1.2
River energy		Total stream power (W m^{-1}) specific stream power (W m^{-2}) Average bed shear stress	419.83 64.59 13.72	0 0 -	309.3 13.45 8.77	NO DATA NO DATA NO DATA	188.78 4.39 6.05
Bank and bed sediment		Sediment size (mm)	Cobbles (130)	Deposited material	Cobbles (130)	Cobbles, coarse gravel	Cobbles, coarse gravel (113)
River type			7 Confined, straight sinuous	Dam	7 Confined, straight sinuous	13 Unconfined/ partially confined, artificially straight sinuous	12 Uncofined/ partially confined pseudomeandering
Riparian and aquatic vegetation	Riparian vegetation and large wood	Pioneer species • Abundance • Age structure Late-seral species • Status • Age structure	 Dominant All classes R All classes		 Abundant Y,M,O A All clases	 Abundant Y,M,O A All clases	 Abundant Y,M,O A All clases
		Main woody species	*Betula,* *Pinus sylvestris* *Salix fragilis,* *Populus nigra,* *Ulmus minor*		*Populus nigra, Salix eleagnos, S. Purpurea,* *S. cantábrica,* *S. atrocinerea,* *Fraxinus excelsior,* *F angustofolia* *Coryllus avellana*	*Alnus glutinosa* *Populus nigra, Salix purpurea* *S. atrocinerea* *S. fragilis,* *Fraxinus excelsior* *F. angustifolia Conus sanguinea Crataegus monogyna* *Ligustrum vulgare*	*Alnus glutinosa* *Populus nigra,* *Salix atrocinerea* *S purpurea* *S. eleagnos* *S. salvifolia* *S. fragilis* *Fraxinus angustifolia* *Conus sanguínea* *Crataegus monogyna* *Ligustrum vulgare*
		Large wood presence and abundance	NS	NS	S	S	S
	Emergent aquatic veg.	Bank length Species					

Table 2.9 (ctd.)

		Landscape	**1**		**2**	**3**	
		Segment	**1**	**2**	**3**	**4**	**5**
		REACH	**1**	**2**	**3**	**4**	**5**
Geomorphic unit			Pools- riffles and lateral bars		Pools- riffles induced by check dams	Pools induced by check dams	Pools-riffles, lateral bars and vegetated islands
Physical Pressures	River bed condition	Bed armouring (gravel-bed rivers);	Absent		Absent	Absent	Absent
		Bed clogging / burial (gravel-bed rivers);	Absent		Absent	Absent	Absent
		Extent of bed reinforcement	Absent		Absent	Absent	Absent
		number of channel blocking structures	Absent	Dam	6 weirs	18 weirs	5 weirs
		Sediment, wood, vegetation removal	Absent		Absent	Moderate	High
						Moderate	High
	River bank condition and lateral continuity	(1) hard bank reinforcement;	Absent		Absent	30 %	40 %
		(2) bank edge 229mmobi/embankments;	Absent		10 %	20 %	10 %
		(3) set-back levées/embankments;	Absent				30 %
		(4) bank top infrastructure;	Absent				
		(5) 229mmobilized river margin	Absent		50 %	40 %	30 %
		(6) actively eroding river margin	NS		NS	Locally	Locally
		(7) width of erodible corridor;					
		(8) number of channel-spanning structures			5 low	4 low/9 intermediate	1 low / 6 intermediate
	Riparian corridor lateral connectivity and condition	(1) riparian corridor accessible by flood water	Totally		Totally	Partially	Totally
		(2) riparian corridor affected by intense woodland management activities	Partially (grazing)		NS	Partially (Poplar plantations)	Totally (Poplar plantations)
		(3) abundance of alien, invasive plant species	Absent		Absent	Absent	Absent

Table 2.10 Main characteristics of the river reaches differentiated along the main course of the Cureño River.

		Landscape Unit	1	2	3	
		Segment	1	2	3	
		REACH	1	2	3	4
Channel dimensions		Channel length (km)	9	13	19	4
		Channel gradient (%)	2.04	1.05	0.70	0.59
		Reach gradient (%)	2.22	1.34	0.83	0.67
		Active channel width (m)	12	15	23	42
		Channel sinuosity	1.1	1.3	1.19	1.13
River energy		Total stream power (W m^{-1})	59.12	61.53	NO DATA	NO DATA
		specific stream power (W m^{-2})	3.48	4.40	NO DATA	NO DATA
		Average bed shear stress (Pa)	7.9	10.1	NO DATA	NO DATA
Bank and bed sediment		Sediment size (mm)	Cobbles (70)	Cobbles, boulders (125)	Cobbles, coarse gravel (89)	Cobbles, coarse gravel (73)
River type			7 Confined/partially confined, straight sinuous	6 Confined, straight sinuous	11 Partly confined /unconfined wandering	11 Partly confined /unconfined wandering
Riparian and aquatic vegetation	Riparian vegetation and large wood	Pioneer species				
		• Status	D	D	D	D
		• Age structure	R,Y,M	R,Y,M	R,Y,M	R,Y,M
		Late-seral species				
		• Status	R	R	R	R
		• Age structure	All classes	All classes	All classes	All classes
		Main woody species	*Betula, Salix fragilis, Populus nigra, Ulmus minor S. atrocinerea*	*Betula, Salix fragilis, S. purpurea, S.eleagnos, S.atrocinerea Fraxinus excelsior, Populus nigra,*	*Populus nigra, Salix eleagnos, S. purpurea, S. cantábrica, S. atrocinerea, F angustofolia Coryllus avellana*	*Populus nigra, Salix eleagnos, S. purpurea, S. cantábrica, S.salvifolia S. fragilis*
		Large wood presence and abundance	NS	S	S	S
	Emergent aquatic vegetation	Bank immobile Species			Emergent aquatic vegetation	

Table 2.10 (ctd.)

		Landscape Unit	**1**	**2**	**3**	
		Segment	**1**	**2**	**3**	
		REACH	**1**	**2**	**3**	**4**
Physical Pressures	River bed conditiion	(1) Bed armouring (gravel-bed rivers	Absent	Absent	Absent	Absent
		(2) Bed clogging / burial (gravel-bed rivers);	Absent	Absent	Absent	Absent
		(3) extent of bed reinforcement	Absent	Absent	Absent	Absent
		(4) number of channel blocking structures	2 weirs	1 weir	5 weirs	1 weir
		(5) sediment, wood, vegetation removal	Absent	Absent	Absent	Absent
			Absent	Absent	Moderate	High
	River bank condition and lateral continuity	(1) hard bank reinforcement;	Absent	Absent	Absent	Absent
		(2) bank edge 231mmobi/embankments;	Absent	Absent	20 %	40 %
		(3) set-back 231mmobi/embankments;				
		(4) bank top infrastructure;				
		(5) 231mmobilized river margin	NS		30 %	20 %
		(6) actively eroding river margin	Absent	Absent		
		(7) width of erodible corridor;				
		(8) number of channel-spanning structures;	3 low	10 low	2 low / 5 intermediate	1 low / 2 intermediate
	Riparian corridor lateral connectivity and condition	(1) riparian corridor accessible by flood water;	Totally	Totally	Totally	Totally
		(2) riparian corridor affected by intense woodland management activities;	Partially (grazing)	Partially (grazing)	Totally (Poplar plantations)	Totally (Poplar plantations)
		(3) abundance of alien, invasive plant species	Absent	Absent	Absent	Absent
Geomorphic unit			Pools-riffles, lateral bars	Forced bars, forced pools induced by boulders, occasional rapids	Riffles-pools, lateral and mid channel bars, islands	Riffles-pools, lateral and mid channel bars, islands

2.6 Delineation and Characterization: Applicability in the Context of the Water Framework Directive

The application of the multi-scale characterization approach to the main Upper Esla River and its tributaries have permitted identification of similar longitudinal trends along these rivers, which are situated within the same physiographic and geologic contexts.

Three different "landscape units" based on these main factors (topography, geology and land cover), have been easily recognized. Within each landscape unit, distinct valley features (i.e. confinement, width) and channel morphology (i.e. dimensions, planform, bed sediment size) have been recognized, allowing discrete spatial homogeneous units to be differentiated along the longitudinal continuum of the rivers as "river segments". In turn, within each river segment further details of channel dimensions (i.e. channel width, gradient), river energy, geomorphic units and riparian corridor features (i.e. plant associations, wood delivery potential) have served to identify smaller spatial homogeneous units as "river reaches".

This hierarchical characterization of rivers, describing the main forms and processes at each of the spatial scales, that are nested into major factors acting at wider spatial scales, supports better understanding of the functioning of river networks and represents a solid base for river basin management planning, helping in the understanding current conditions and future trajectories of change.

2.6.1 Identification of water bodies based on hydro-morphological criteria.

The implementation of the Water Framework Directive requires the segmentation of river networks in order to define distinct "water bodies" where different management practices have to be addressed according to their current ecological status.

In many cases and for many reasons, identification of water bodies at a national scale has not always been based on strong scientific, hydrological and geomorphological principles, although management and restoration activities require the improvement of hydromorphological conditions as a pre-requisite for having reference biological communities and achieving good or potential ecological status. With this in mind, it would be very convenient to identify water bodies within the context of the Water Framework Directive based on the proposed multi-scale characterization approach. This would facilitate a common language between scientists and managers and facilitate the improvement of river ecosystems.

In order to highlight this potential utility of REFORM results within the WFD and especially to offer valuable inputs for the next River Basin Management Plans (RBMP), we have compared our characterization approach with the definition of water bodies included in the RBMP of the Duero Basin District.

Figure 2.25 shows the water bodies (river reaches between red dots) established in the Duero RBMP and the river reaches within landscape units of the studied catchments. As it may be observed, in many occasions the limits of the water bodies are in fully agreement with the limits of our river segments, although in some cases the limits of water bodies are not supported by physical evidence, which may make their identification difficult in the field. In addition, some of these limits do not respond to natural features that influence key processes of natural river functioning such as changes in topography or geology (i.e. landscape unit identification), valley features or river confluences which induce significant water and sediment flow regime changes (i.e. segment scale), or morphological channel changes which may result in different instream conditions for biological communities (i.e. reach scale).

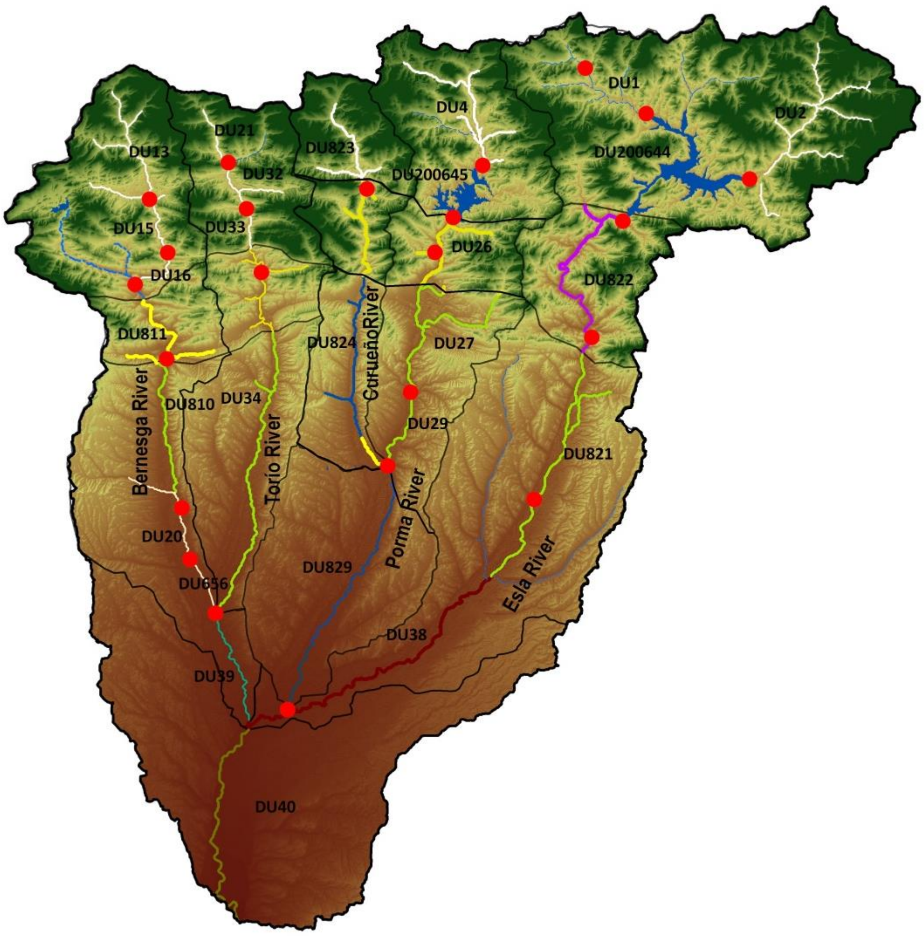


Figure 29.- Water bodies (river length between consecutive red dots) defined in the Duero RBMP and river reaches identified in this report (different river colours within landscape units delineated by black lines within the studied catchments). Black labels correspond to the number of water bodies.

We conclude that the scale of river segment established using the multi-scale framework for characterizing river networks proposed within the REFORM Project, could be a consistent scientific basis for identifying water bodies within the WFD, and further subdivisions related to important natural or man-induced discontinuities along the river continuum should be also based on criteria linked with hydro-morphological principles.

A common procedure to define water bodies following open ended approaches, as is the case of the multi-scale framework, would also contribute to interchange of river classification schemes among European countries and river experiences in river management and river restoration.

2.6.2 Definition of reference conditions and reference reaches.

An important task for improving the ecological status of rivers, a main aim of the WFD, is the definition of reference conditions and the selection of reference reaches where hydro-morphological conditions allow the maintainenance of reference biological communities.

The proposed hierarchical characterization approach exemplifies a valuable tool for identifying similar hydro-morphological conditions of river reaches, that are a result of analogous processes at different spatial scales.

In the presented case study, according to the characterization results, four distinct reference reaches should be considered. All the headwaters of the rivers within landscape unit 1 seem to have similar conditions and all of them could serve as a reference for the others. In landscape unit 2, the Curueño river presents a narrower and steeper valley and may represent different conditions in relation to the rest. For assessing the impacts of the large dams and reservoirs existing in the Esla and Porma rivers, the frequently-adopted approach of comparing characteristics upstream and downstream from the dam would not be valid as the reaches differ considerably in terms of valley confinement and the potential of the river to adjustment. Finally, the differences in valley and channel gradient of the rivers Curueño and Torío which may imply differences in river energy, sediment transport capacity and bed sediment calibre would represent different reference conditions of river reaches within the same landscape unit along the Porma and Bernesga rivers, respectively.

3. Characterising Temporal Change in Spatial Units

3.1 Introduction

This section includes an overview of temporal changes that have occurred in the Porma and Curueño rivers over approximately the last five decades. The main drivers inducing hydromorphological changes in the rivers have been addressed in section 2. Land cover and land use changes have been observed in the region and they may significantly affect runoff and sediment supply at catchment and landscape unit scale. The flow regime has been altered in the Porma river by the operation of a large dam since 1967, which has affected morphological patterns at segment scale (e.g. riparian corridor features) and reach scale (e.g. channel adjustments, riparian vegetation mosaics).

Past (1956-57) and recent (2011) air photographs have been compared to assess temporal changes of land cover, channel horizontal adjustments and riparian corridor features. Historical series of precipitation, temperature and flow regime have been analyzed to quantify temporal trends in hydrological variables. Finally, field surveys have been conducted to assess channel adjustments and riparian vegetation succession stages.

3.2 Catchment And Landscape Unit Scale

3.2.1 Land cover and land use

The catchments of the Porma and Cururreño rivers are mostly highlands, being located between 1300 and 800 m a.s.l. (Figure 2.1B). Agricultural practices have been traditionally devoted to grasslands and small rainfed cereal crops. These traditional farmlands are extensively spread over the catchments but with relatively low development (Figure 2.4 and 2.8, Table 2.2). Open spaces with little or no vegetation and areas with shrubs and herbs used for extensive grazing occupy a large part of the catchments, as marginal traditional mixed farming. Figure 3.1a shows the land cover distribution in 1956 (obtained by interpreting orthophotos using similar land cover classes to CORINE, 2006).

Over recent decades the entire region has undergone a trend of farmland abandonment as a consequence of rural depopulation and many other social and economic reasons, following similar tendencies to those reported in other European mountains (García-Ruiz & Lana-Renault, 2011; MacDonald et al., 2000). As a consequence, forests and shrub land have increased significantly in coverage at the expense of arable land and open areas with shrubs and grasses (Figure 3.1b).

Tables 3.1 and 3.2 show the results of this temporal change in land cover within the study area. Forest vegetation has experienced a significant increase in both catchments, especially in the upper mountain areas (Landscape Unit 1) although this increase is also evident in the lower region (i.e. landscape unit 3) where farming has been maintained.

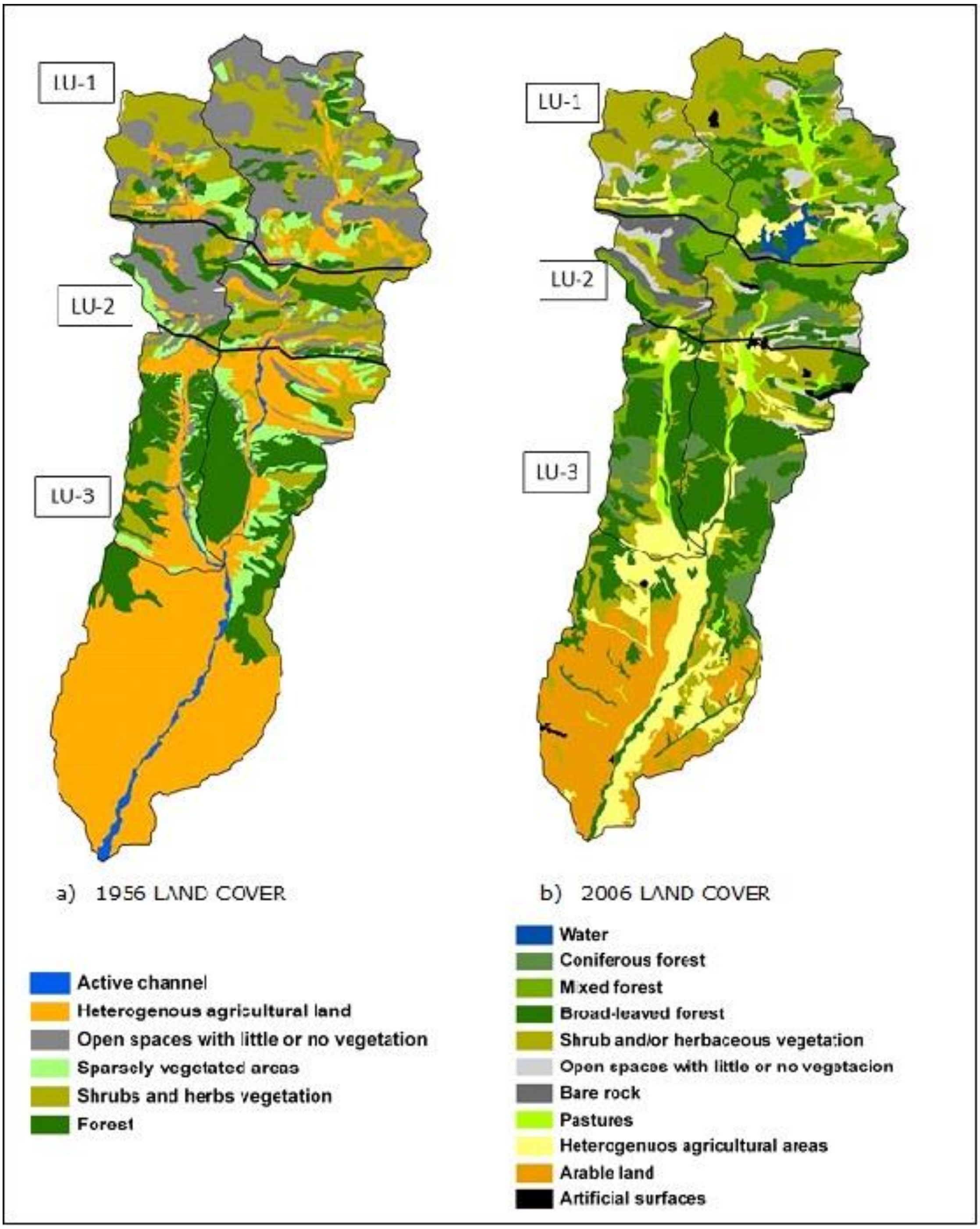


Figure 3.1 Temporal changes in land cover distribution in the Porma and Curueño catchments over the period 1956 (air photograph interpretation) and 2006 (CORINE, 2006). Transverse black lines correspond to landscape unit limits.

Table 3.1 Area of land cover classes identified in 1956 orthophotos and CORINE (2006) corresponding to landscape units (LU) within the catchment of the Porma River

PORMA RIVER (km^2)	LU-1		LU-2		LU-3	
	1956	2006	1956	2006	1956	2006
Agricultural land	24.4	29.5	8.9	3.85	333.6	257.8
Open spaces with little or no vegetation	121.1	21.7	28.9	9.51	44.1	3.7
Shrubs and herbs	79.4	72.1	36.3	23.65	25.2	79.2
Forest Vegetation (% change)	19.5	110.4 (+ 566)	22.3	59.53 (+ 267)	96.2	168.3 (+ 175)

Table 3.2 Area (ha) of land cover classes identified in 1956 orthophotos and CORINE (2006) corresponding to landscape units (LU) within the catchment of the Curueño River

CURUEÑO RIVER (km^2)	LU-1		LU-2		LU-3	
	1956	2006	1956	2006	1956	2006
Agricultural land	9.6	8.2	4.7	2.3	39.3	29.1
Open spaces with little or no vegetation	32.6	12	46.2	31.0	17.2	2.1
Shrubs and herbs	47.3	42.1	6.2	13.3	18.3	16.3
Forest Vegetation (% change)	11.0	37.1 (+337)	13.5	25.0 (+185)	43.3	73.4 (+179)

The increase in forest cover as a consequence of farmland abandonment has taken place at the same time as a progressive decrease in extensive livestock grazing in the mountain areas. Most of the studied catchments were included under the classification of "mountain agricultural areas" (Zonas de Agricultura de Montaña, ZAM) by the 1982 Spanish Law on Mountain Agriculture. The main objective of this Law was to economically subsidise the mountain populations which were suffering a constant depopulation that started in the second half of the twentieth century (Collantes Gutiérrez, 2004). Since then, the number of inhabitants working in the agricultural sector, the number of livestock, and number of farms have continuously declined. Figures 3.2 and 3.3 show the temporal trends of people employed in the mountain region of north of Spain (Norte) encompassing the Cantabrian Mountains, and the more restricted area of the Astur-leonesa region where the Porma and Curueño catchments are located. They show how rural employment in the primary sector was reasonably sustained until 1960, coinciding with very poor development of the secondary and tertiary sectors. Mining and industrialization began in this region during the 1960s and from then the distribution of employment changed dramatically. This tendency occurred also in other mountain areas of Spain and was accompanied by rural depopulation, dam construction and extensive afforestation works at national level.

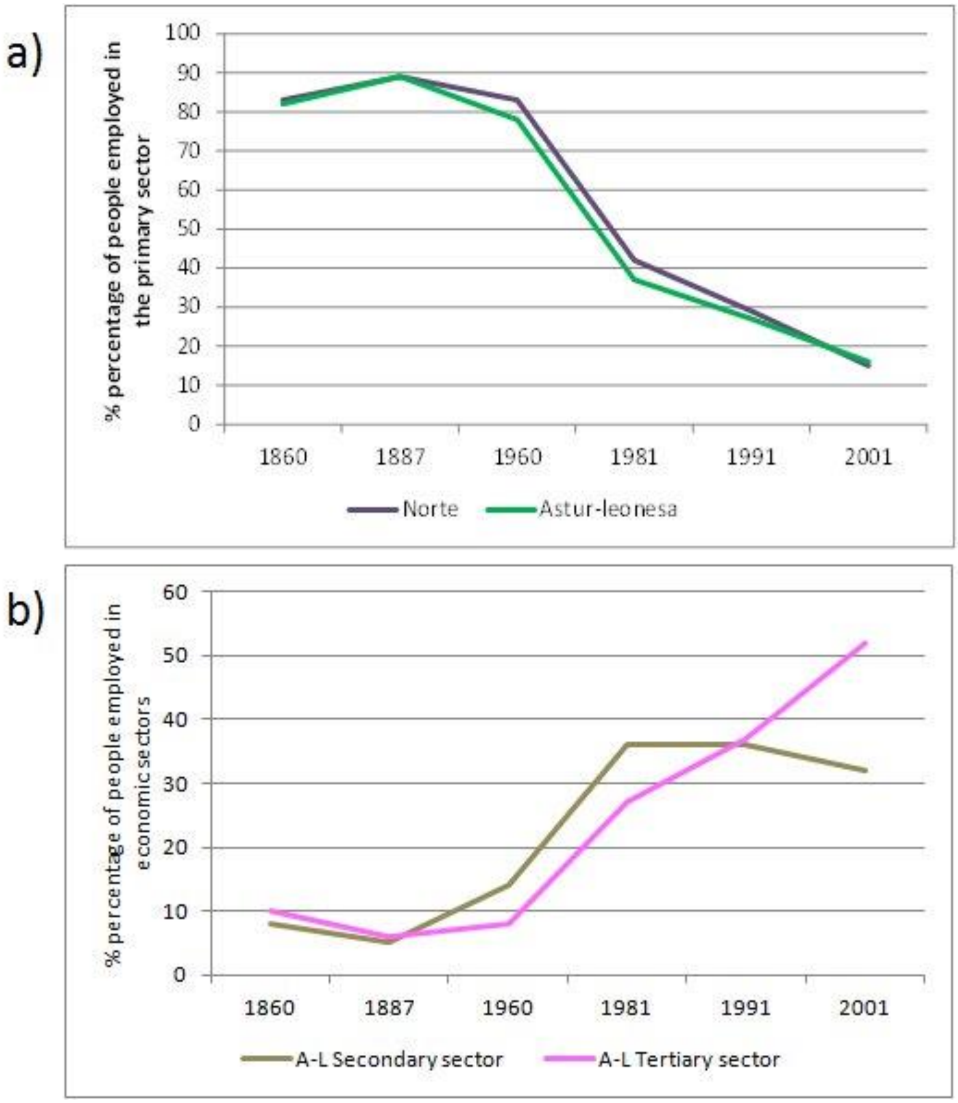


Figure 3.2 Percentage of people working in the main economic sectors. a) data related to the regions "Norte" (all the Cantabrian mountain) and "Astur-Leonesa" restricted to the mountain area of northern Asturias and León provinces where the Porma and Curueño catchments are located). b) data related only to the Astur-leonesa (A-L) region. (Elaborated with data from Collantes Gutiérrez, 2004).

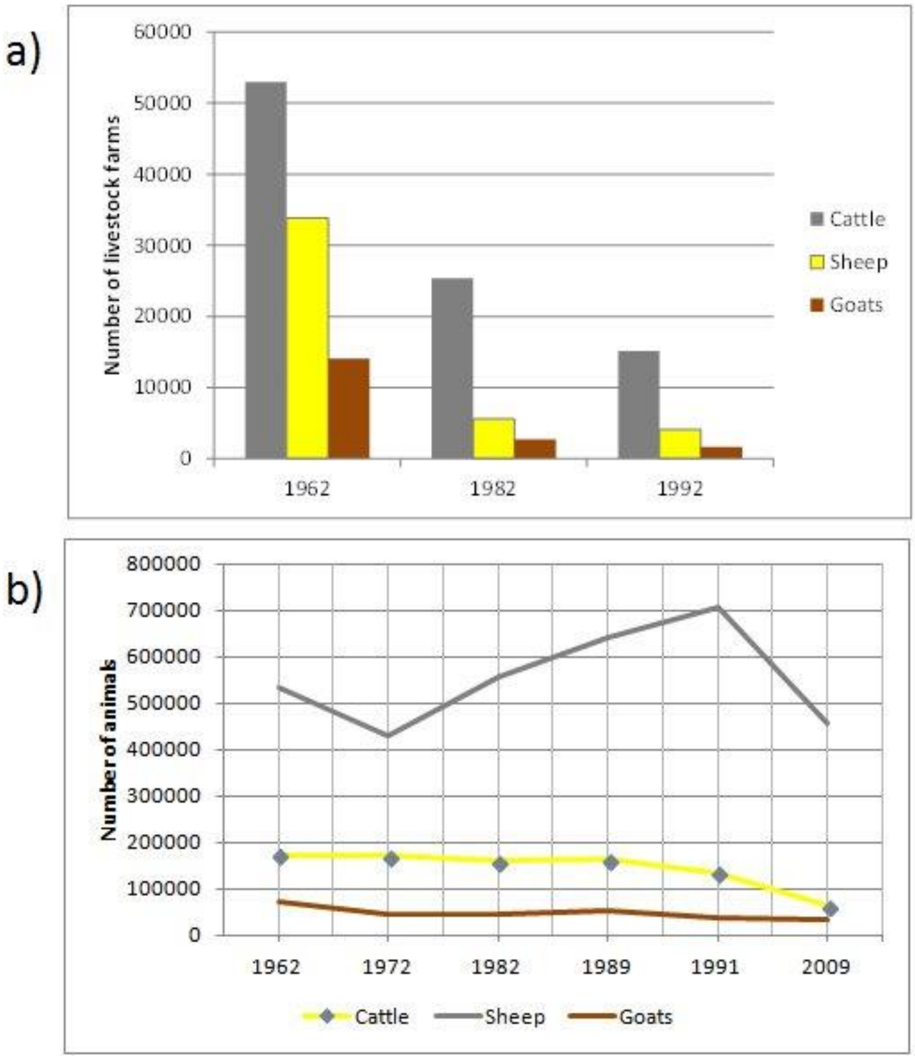


Figure 3.3 Livestock population in León province, in terms of a) number of farms and b) number of animals. (Elaborated with data from INE, Censos agrarios (http://www.ine.es/inebmenu/mnu_agricultura.htm) and data from Collantes Gutiérrez, 2004).

3.2.2 Environmental and hydro-morphological effects of land cover and land-use changes

The socio-economic changes in the study area may lead to environmental, hydrological and geomorphological effects in the river catchments. The impact of agricultural decline in mountain areas has been extensively examined, indicating that the context in which land-use change occurs plays an important role in influencing the temporal and spatial factors that drive successional processes. Farmland abandonment changes landscape and wildlife communities and has resulted in a loss of biodiversity and lower levels of open areas (McDonald et al., 2000). Low intensity farming, in the form of livestock rearing and traditional cultivation methods, has been considered favourable for creating semi-natural habitats and supporting a wider range of species that may be threatened by agricultural abandonment. Approximately half of the European network of Natura 2000 sites are farmed environments which may now need to be maintained by conscious management using the relevant farming practices. In terms of soil erosion and slope stability, an undesirable increased risk of natural hazards has been reported as a result of the build-up of vegetation biomass which in winter time may increase the risk of snow-slides and avalanches (Cernusca et al., 1996), or in Mediterranean areas may increase fire hazard, desertification and loss of maintenance of terraces and other traditional soil conservation measures (Lasanta et al., 2001).

The hydrological and geomorphological effects of farmland abandonment have been recently reviewed by García-Ruiz and Lana-Renault (2011). The most obvious consequence of land abandonment is plant recolonization, with a progressive succession of grasses, shrubs and trees. Forest expansion at the expense of crops or meadows causes a decrease in runoff and annual streamflow, primarily because of an increase in interception losses and water consumption by forests during the summer months (Serrano-Muela et al., 2008). With respect to floods, different authors conclude that the impact of reforestation is more pronounced when flows are low (i.e. floods with a return period less than approximately 5 years) (Andréassian, 2004).

Additionally, progressive increase in forest coverage results in a general decrease in soil erosion and sediment supply to the river network, as a logical consequence of the protective effect of permanent vegetation. As an example of this, a reduction in the area of sediment sources was noted in the Arnás catchment, central Pyrenées, because most of the hillslopes were covered by shrubs and forests, 30-40 years after land abandonment (Lana-Regault and Regüés, 2009). Van Rompaey et al (2001) also reported the significant reduction of erosion processes by farmland set-aside which usually occurs on the steepest land and fields that are more susceptible to erosion.

Changes in streamflow and sediment supply change channel dynamics. Piégay et al (2004), Liébault and Piégay (2001, 2002) and many others have observed channel narrowing and bed degradation as a main effect of land-use change involving reforestation. These changes determine subsequent processes including a reduction of sediment supply, particularly bedload, and restriction of flood plain sedimentation to events associated with large peak flows (Keestra et al., 2005).

Reflecting the above comments and observed changes in land cover and land-use within the Porma and Curueño catchments, we could expect consequential reductions in runoff and sediment supply at catchment and landscape unit scales, and river morphological adjustments at segment and reach scale following a trajectory towards channel narrowing and vertical degradation. These general trends would be overlain by other potential effects that may arise from additional natural changes or man-induced pressures and impacts that may also have occurred at the same time or later at different spatio-temporal scales.

3.2.3 Temporal Precipitation trends

Historical time series of precipitation were analyzed to search for temporal trends influencing changes in the amount of streamflow at annual and monthly rates. MOPREDAS data series (González-Hidalgo et al., 2010) were used for the catchment study area at the landscape unit scale.

Figure 3.4 shows a 3 year running mean of annual precipitation for the Porma catchment. Mean annual rainfall is 1311.5 mm and this value varies through time with some regular fluctuations (Figure 3.4a). A slight decreasing temporal trend can be observed in the total annual rainfall (Figure 3.4b), which could influence mean annual streamflow although in reduced proportions. The same temporal trends can be seen at the landscape unit scale, with similar slight decreasing trend over time at the annual scale (Figure 3.5).

Figure 3.6 shows monthly precipitation values over the studied period (1945-2005). October and July exhibit increasing trends whereas November, March and June present the opposite tendency. Of particular relevance is March, when the soils may be at field capacity, evapotranspiration is still reduced and runoff generation is more likely to occur, but the amount of precipitation shows the most pronounced decreasing trend.

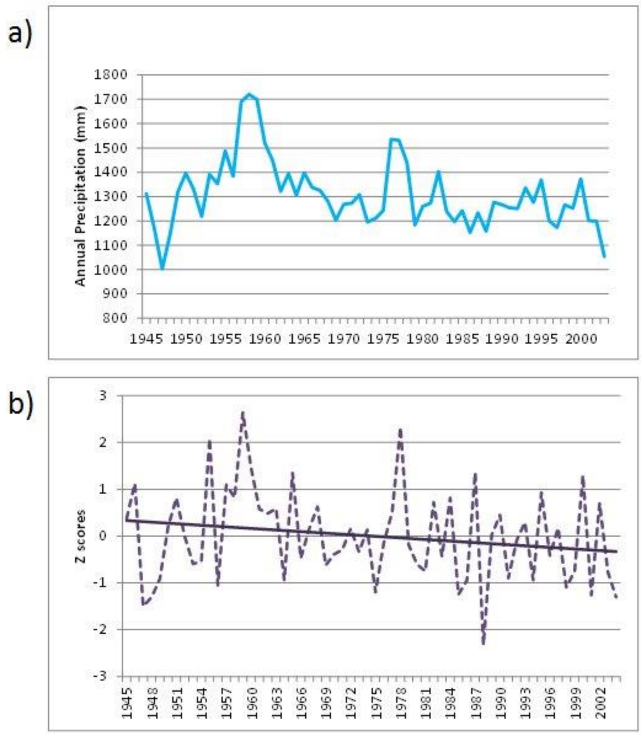
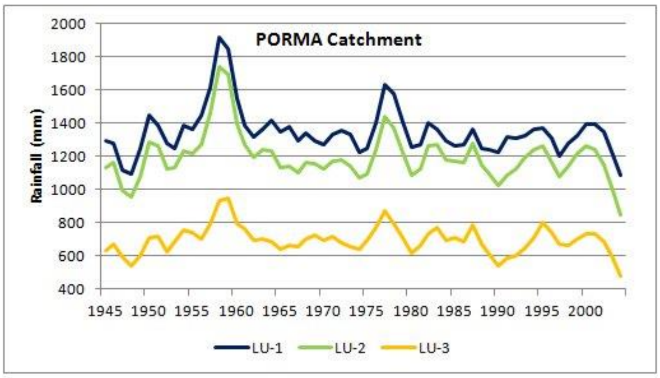


Figure 3.4 Annual precipitation in the Porma river catchment. a) 3 year running average of annual rainfall. b) Standardized annual rainfall.



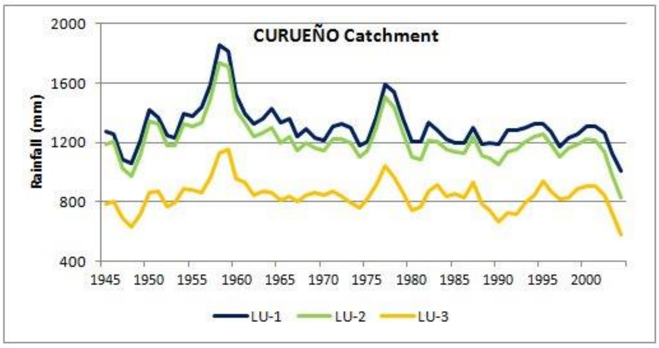


Figure 3.5 3 year running mean of annual rainfall within the landscape units (LU) of the Porma and Curueño catchments.

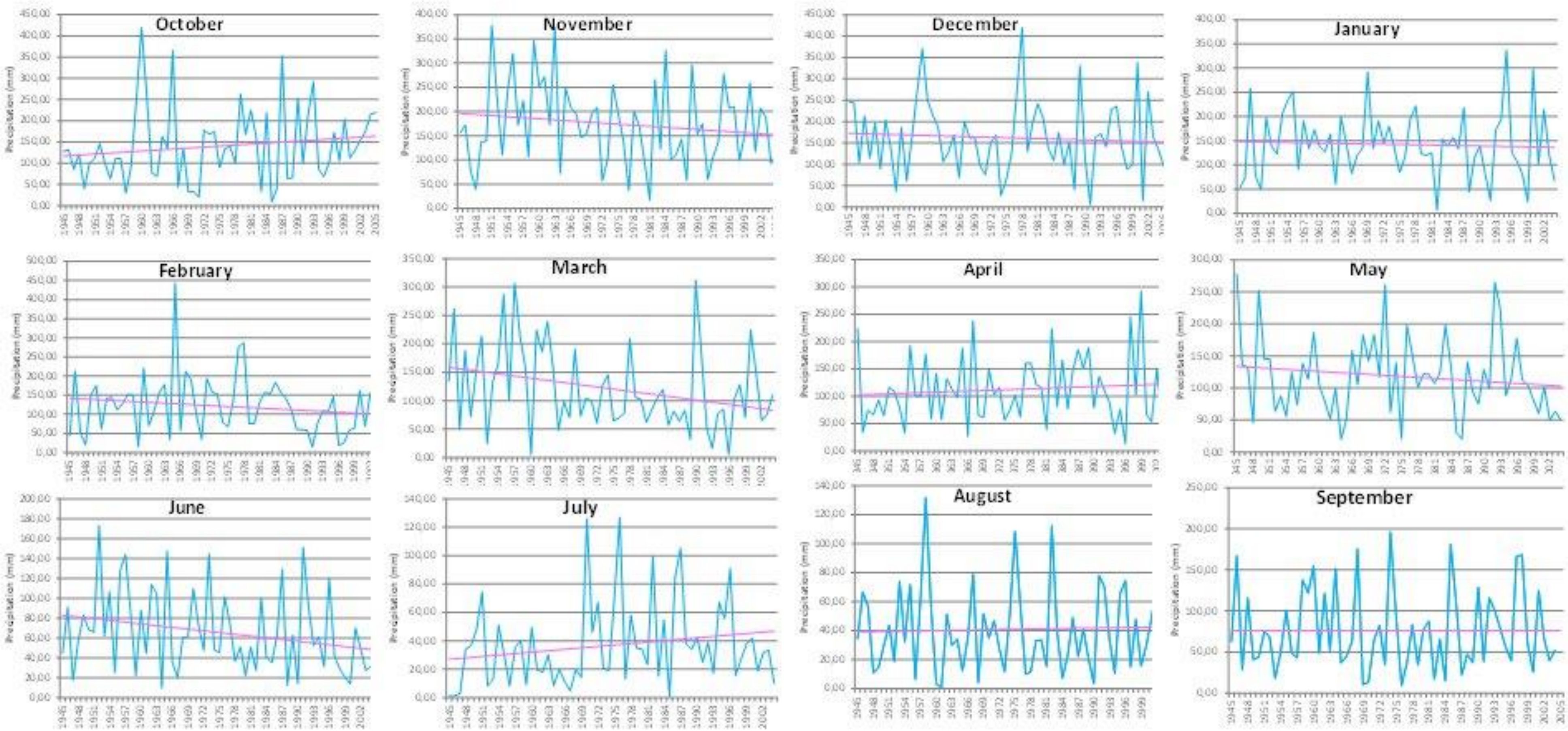


Figure 3.6 Monthly precipitation in the Porma river catchment during the period 1945-2005.

3.2.4 Water production

According to the hydrological effects of land cover and land-use changes which have mainly occurred since 1960 (Figure 3.1), and taking into account the temporal trends of precipitation regime (Figures 3.4 to 3.6), a reduction in the amount of runoff can be expected in the study area. The assessment of this reduction is made at the annual scale and only for landscape unit 1, where changes in vegetation cover are most pronounced and longer historical discharge records are available.

From the analysis of standardized annual precipitation values, two periods were considered: before 1973 where the regression line crosses the zero value of the z scores; and afterwards. Figure 3.7 shows the relationships between annual precipitation and annual runoff in the Curueño river for these two periods (i.e. 1959-1973 and 1974-2005). In both cases a highly significant correlation between variables exists ($p<0.001$). Linear regression models indicate higher runoff coefficients during the first period (i.e. less forest coverage) than during the second period. In addition, the lowest precipitation amounts were registered during the second period.

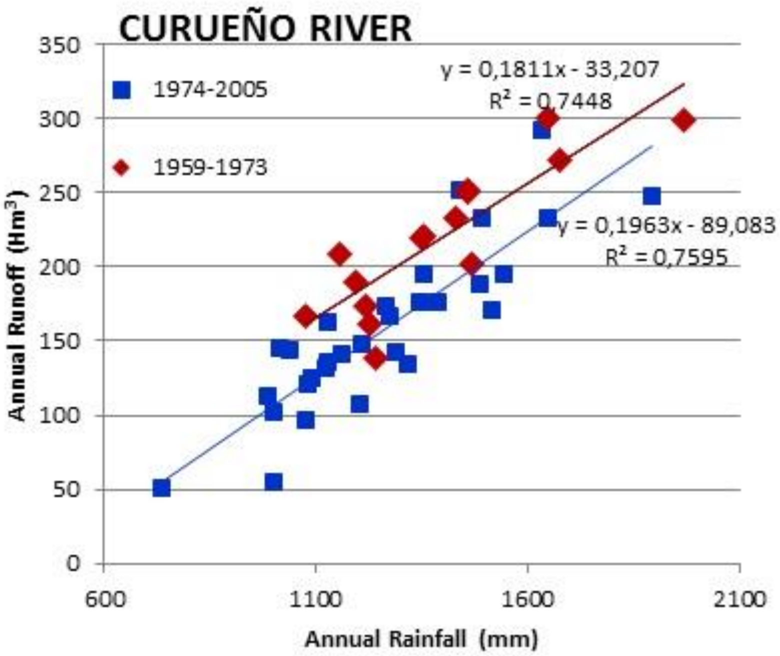


Figure 3.7 Annual Rainfall-Runoff relationships in the Curueño catchment (landscape unit 1) for the indicated periods (Caldas de Nocedo gauge station).

For the Porma river the relationship between annual rainfall and runoff is not as strong (Figure 3.8), but same tendency of higher runoff coefficients is observed during the first period (1945-1973) than for the following years (1974-2005) when there was greater forest coverage, supporting results found in other regions (Andréassian, 2004; García Ruiz & Lana-Renault, 2011)).

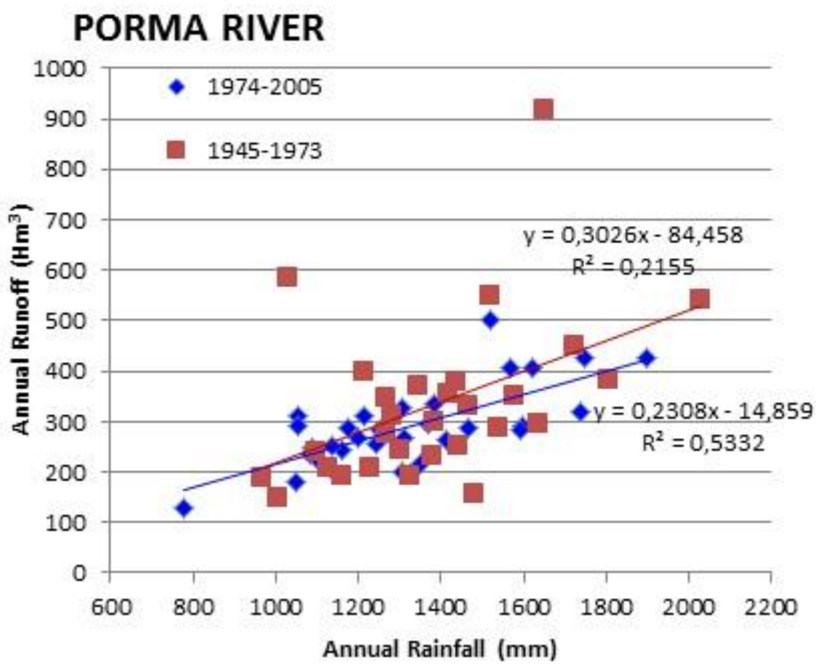


Figure 3.8 Annual Rainfall-Runoff relationships in the Porma catchment (landscape unit 1) for the indicated periods (Vegamián gauge station).

3.3 River Segment Scale

3.3.1 Flow regulation in the Porma River

At the segment scale, the more relevant temporal change that has occurred in the study area is the alteration of the flow and sediment regime of the Porma river by the presence of a large dam in the upper reaches (lower section of landscape unit 1). This large dam was built in 1967 and since then its operation is mainly in relation to irrigation. The reservoir has a water storage capacity of 317.4 hm^3 that represents 106% of the annual natural runoff. This means that the reservoir can accumulate all the rainfall received in the entire wet season and release the water when it is needed, mainly a relatively short period during the summer. The operation of the dam completely changes the natural Mediterranean flow regime, producing a low flow period during the wet season and a high flow period during the dry irrigation season (see Figure 2.13a) and also altering the magnitude of the annual extreme values, significantly reducing maximum flows and increasing the minimum flows (Figure 3.9).

In addition to this, the magnitude and frequency of peak flows are dramatically changed (Figure 3.10). The reduction in flood magnitude and periodicity implies a proportional reduction in sediment transport capacity and for reshaping the channel after flood disturbance. The annual minimum flows show the opposite tendency, as they have been increased by the dam operation to supply irrigation water.

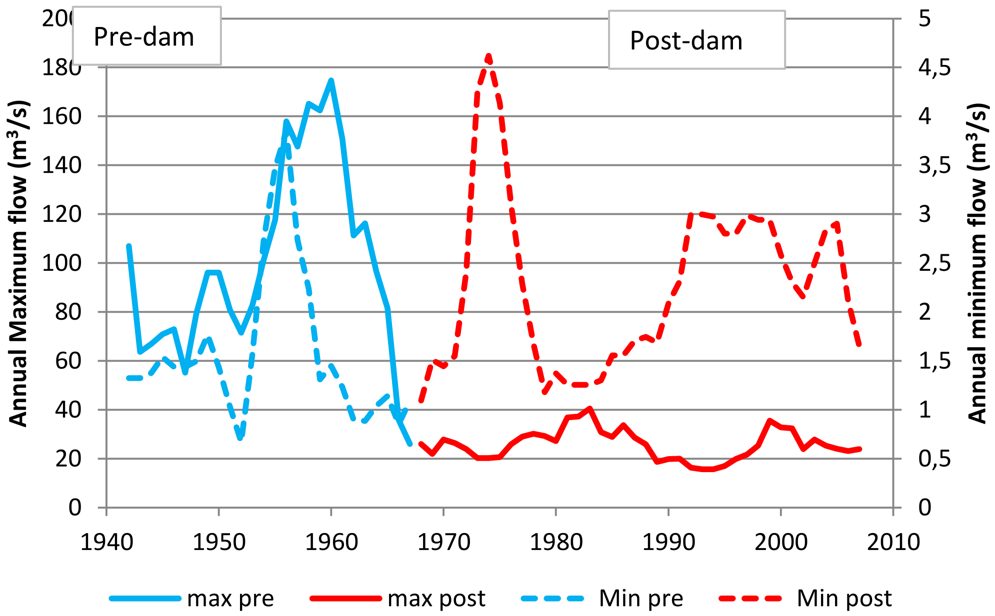


Figure 3.9 Annual maximum (solid line) and minimum (dot line) discharge values during the period 1940-2007, showing significant alteration since the operation of Vegamian dam in 1967.

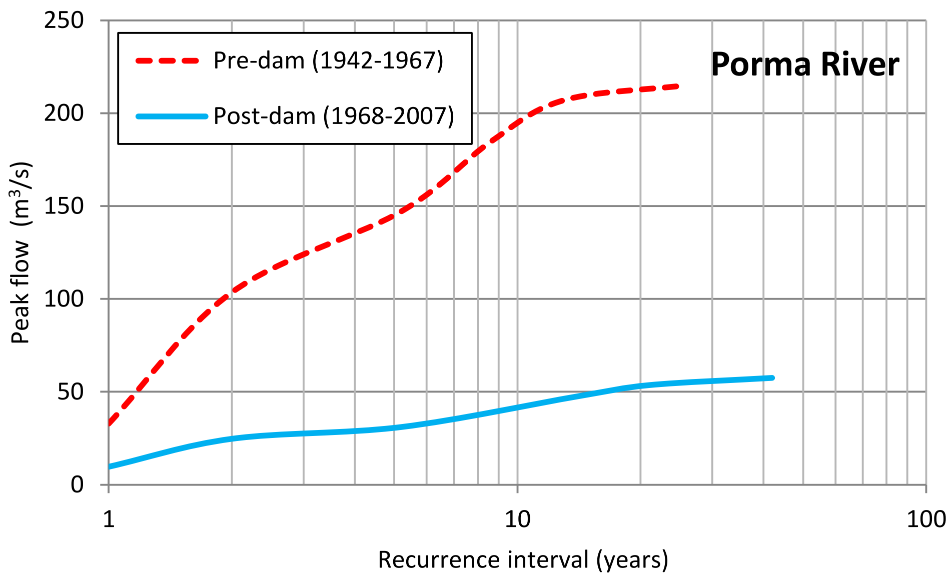


Figure 3.10 Magnitude and frequency of floods in the Porma river before and after the operation of Vegamián dam.

Table 3.3 summarizes the results of flow regime analysis for the Porma River for two periods: pre- and post-dam. The main differences are observed in the BFI (Base Flow Index) which indirectly reflects the monthly flow fluctuation (i.e. average of the ratios between minimum and mean monthly flow). In this case dam operation strongly reduces this fluctuation, mainly by increasing minimum flows and thus determining the increase in the BFI value. The coefficient of variation of daily discharge (DAY CV) decreases for the same reason.

Timing of floods is also changed by the operation of the Porma dam. Whereas the most frequent period of floods under natural flow conditions was at the end of the wet season (February-March), during the post-dam period it is delayed to the summer (July-August), coinciding with the irrigation period.

The general flow regime pattern for monthly flows has been also altered by the dam (Figure 3.11) with a strong alteration in seasonality. The regulated flow regime is characterised by a significant decreasing in high flows from November to March and an increase in low flows from June to September. These conditions may prevent recruitment of pioneer vegetation, as the low bars and bare soil at the channel banks remain under water and are subject to higher shear stresses during the establishment period of Salicacea species.

Table 3.3 Flow regime analysis of the Porma River in Vegamián gauging station. Flood (FLD) variables are estimated over the indicated threshold of 105,03 m^3/s (pre-dam) and (> 25.97 m^3/s (post-dam)

Period	BFI	FLD FREQ	FLD PRED	FLD TIME	ZERO DAYS	DAY CV
1942-1967 (Pre-dam)	24.03	1.34	0.25	32 Feb-Mar	0	115.12
1968-2009 (Post-dam)	31.29	2.51	0.25	182 Jul-Aug	0	77.45

3.3.2 Average volume of annual runoff

Apart from the temporal changes in seasonality and in magnitude and frequency of extreme flows due to the dam operation in the Porma river, a decreasing trend of annual discharge has been observed in the studied rivers, particularly in the case of the free flowing Curueño river (Figure 3.12). Mean and median values present similar results and this tendency is likely to be driven partly by the decreasing temporal trend in precipitation and especially by the land cover and land-use changes that have occured. In both rivers the analysed gauge records are from the upper parts of the catchment where vegetation changes have been most significant.

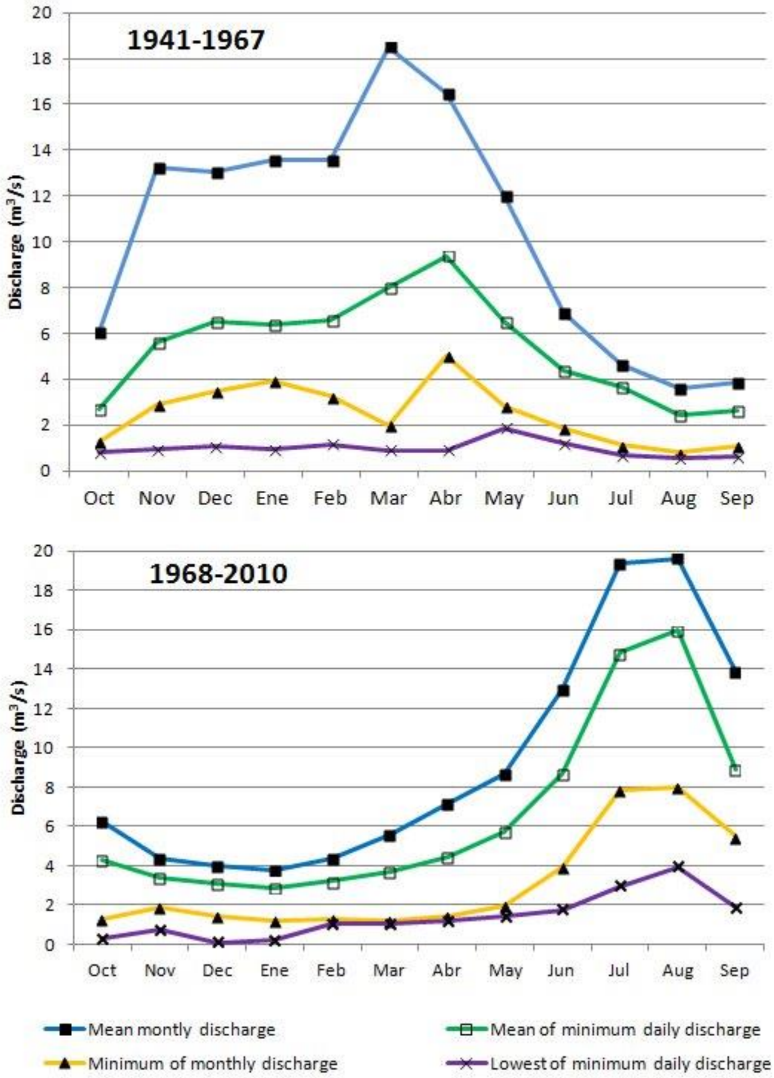


Figure 3.11 Characteristic monthly discharge values for the Porma River at Vegamián gauge station in the pre-dam (above) and post-dam (below) periods.

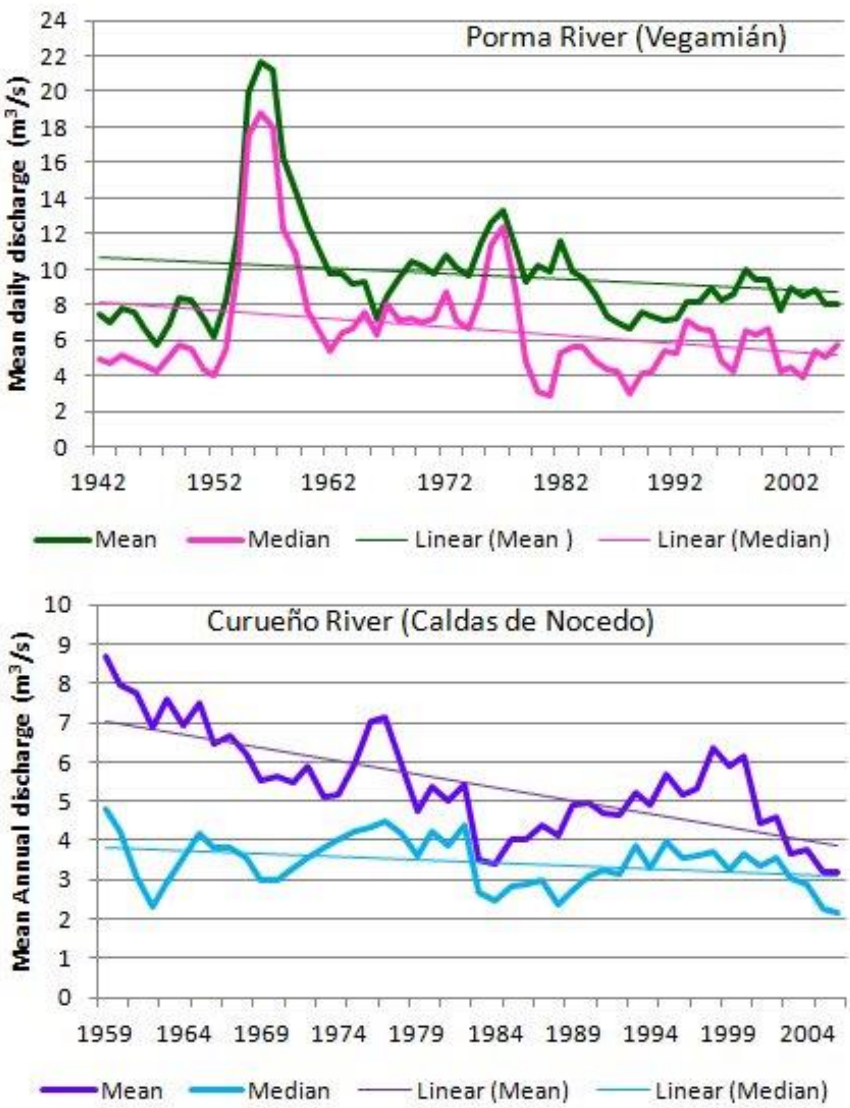


Figure 3.12 3 year running average of mean and median values of annual discharge of the Porma and Curueño rivers showing temporal tendencies over the studied period.

3.4 River Reach Scale

Temporal changes in geomorphology at the reach scale have been observed and are probably a response to the reported temporal changes at catchment, landscape and segment scales. These changes were explored by considering variations of active channel width, riparian corridor width and the lateral mosaics of riparian corridor structure revealed by comparing air photographs from 1956 and 2011.

3.4.1 Geomorphic changes

Tables 3.4 and 3.5 summarize the main geomorphic changes measured in the studied rivers. Channel narrowing is observed in all cases. In lower unconfined reaches where the potential for horizontal adjustments is larger, significant reductions of active channel width have occured. Much smaller changes has been observed along reaches where channel adjustments are restricted by the valley and its geology (i.e. reach 3 in the Porma river and reach 2 in the Curueño river, which possess gorge morphologies within landscape unit 2) .

In the case of the Porma river, channel narrowing could also be related to the presence of the dam, which is not the case in the free flowing Curueño river. Since narrowing has occurred in both rivers, changes in water and sediment production at landscape unit scale as a result of land-cover changes have to be considered. This catchment perspective could also explain the observed temporal changes in river planform towards less sinuous channels and a shift from multi-thread (i.e. island braided) to single thread (i.e. pseudo-meandering) typologies.

Table 3.4 Temporal changes in channel morphology of the Porma river (Reach 2 corresponds to the reservoir).

PORMA RIVER	REACH 1		REACH 3		REACH 4		REACH 5	
	1956	2011	1956	2011	1956	2011	1956	2011
Active channel width (m)	17.1	15.8	23.8	24	124.6	25	330	38
% change		-7.60		+0.84		-79.94		-88.48
Bifurcation Index	1	1	1	1	1.66	1	2.4	1.24
Extended River Type	Straight sinuous 7	Straight sinuous 7	Straight sinuous 7	Straight sinuous 7	Island Braided 9	Straight sinuos 13	Island Braided 9	Pseudo-meandering 12

Table 3.5 Temporal changes in channel morphology of the Curueño river.

CURUEÑO RIVER	REACH 1		REACH 2		REACH 3		REACH 4	
	1956	2011	1956	2011	1956	2011	1956	2011
Active channel width (m)	27.4	12	18.9	14.4	81.8	23.5	202	41.4
% change		-56.20		-23.81		-71.27		-79.50
Bifurcation Index	1.3	1	1	1	1.47	1.11	2.5	1.5
Extended River Type	Wandering 11	Straight sinuous 7	Straight sinuous 6	Straight sinuous 6	Wandering 11	Wandering 11	Island Braided 9	Wandering 11

3.4.2 Riparian corridor

Over the studied period several changes in the lateral zonal mosaic of the river corridor have taken place as a consequence of changes in hydromorphological conditions and human use of the floodplain. The river corridor has maintained its total area but changes in lateral gradients inducing changes in successional stages of vegetation can be observed.

Following the conceptual model of vegetation-hydromorphology interactions developed in Deliverable D2.2 Part 1, different lateral zones within the river corridor according to different dominant fluvial and hydrological processes have been identified. The extension of these lateral zones is summarized in Tables 3.6 and 3.7. In the Porma river small changes have occurred in the riparian corridor of the upper reach but much larger differences are observed downstream (Table 16). The area that in 1956 was occupied by dynamic frequently disturbed vegetation including bare or low covered coarse sediment bars is nowadays covered by a more stable vegetation structure dominated by fine sediment deposition and inundation processes, together with poplar plantations which strongly depend on soil moisture and groundwater (Figure 3.13 and 3.14).

Table 3.6 Lateral riparian mosaics within the river corridor along the Porma river reaches.

PORMA RIVER Lateral zones (Ha)	REACH 1		REACH 2	REACH 3		REACH 4		REACH 5	
	1956	2011		1956	2011	1956	2011	1956	2011
PI	2,2	1,8		4,1	4,1	11,8	8,2	12,8	6,6
FD C	0,0	0,0		0,8	0,0	20,6	0,0	27,3	0,3
FD F	0,0	0,0		0,0	0,0	22,6	16,9	37,9	20,1
ID	0,0	0,0		0,0	0,0	1,7	4,4	0,2	4,2
SM	0,0	0,3		0,0	2,7	0,0	23,2	0,0	48,8
Total River Corridor	2,2	2,1		4,9	6,9	56,7	56,7	78,3	80,1

PI: Perennially inundated; FD C: Fluvial disturbance dominated, coarse sediment erosion & deposition; FD F: Fluvial disturbance dominated, finer sediment deposition; ID: Inundation dominated; SM: Soil moisture regime dominated.

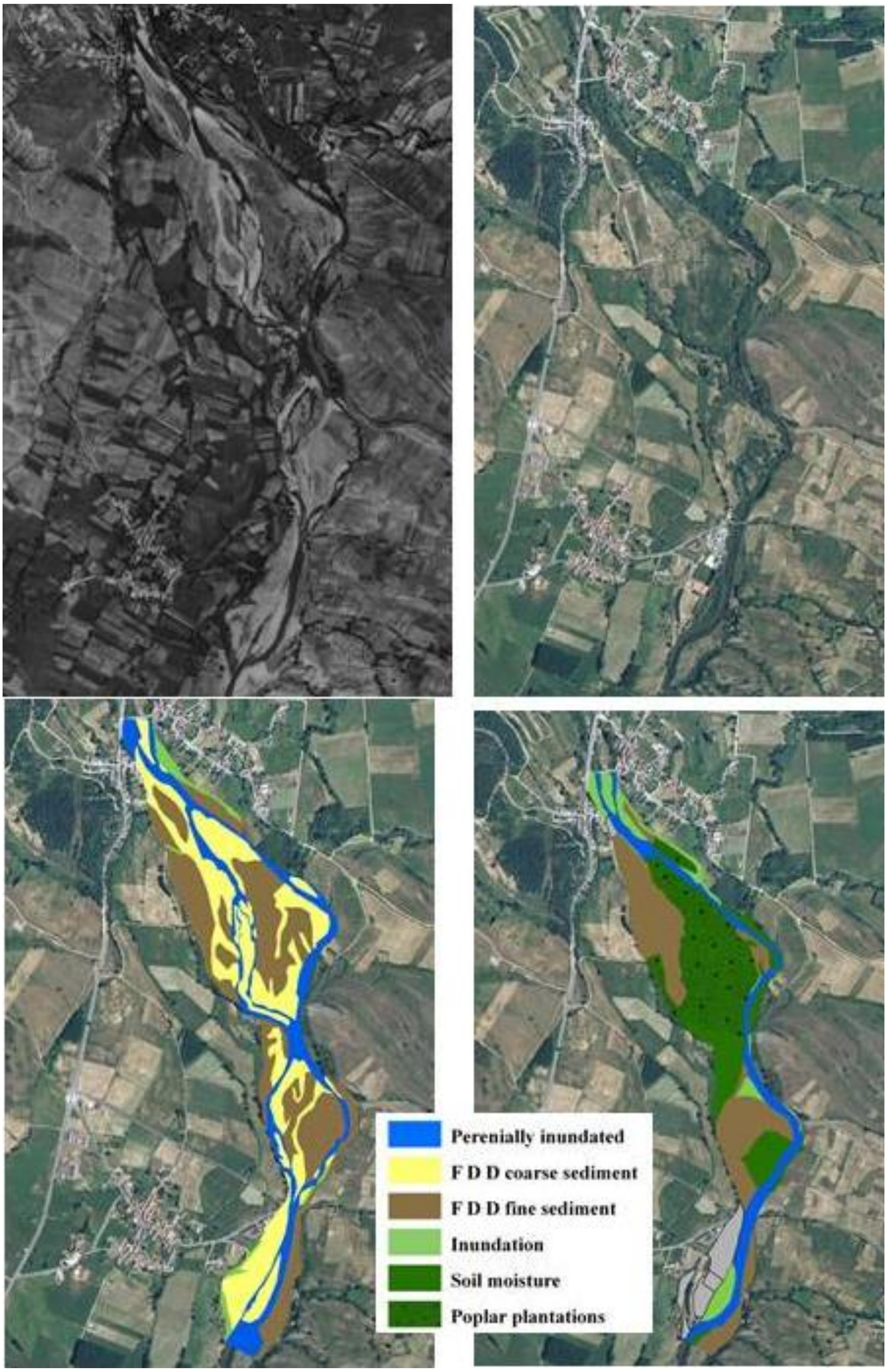


Figure 3.13 Air photographs of reach 4 of Porma river and interpretation of lateral riparian mosaics in 1956 (left) and 2011 (right).

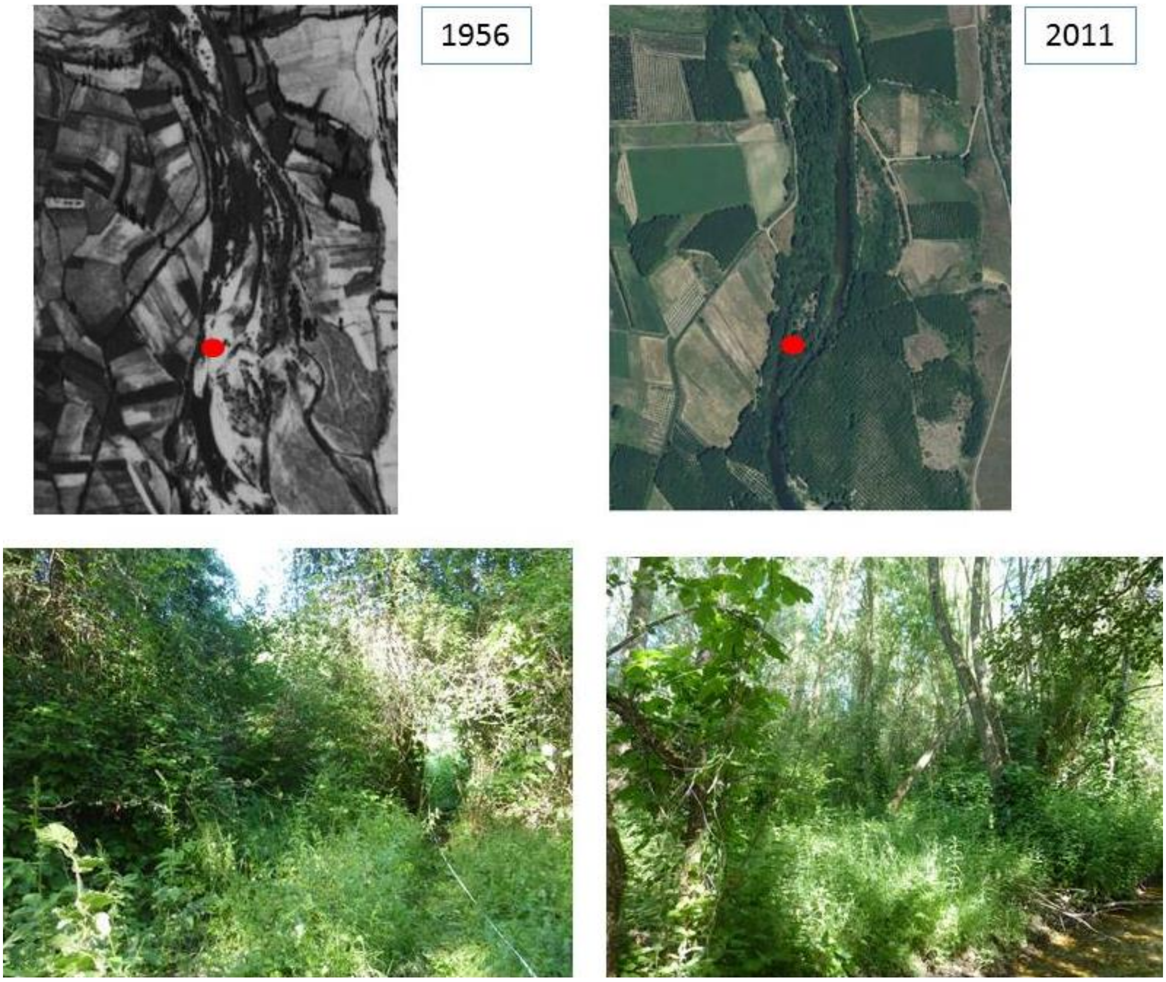


Figure 3.14 River Porma upstream Vegas del Condado, showing vegetation changes over time. Pictures below were taken in July, 2013 and correspond to a mixed forest dominated by Salicacea species with a complete coverage of mixed understory located at the red dot site.

In the Curueño river (Table 3.7) similar changes within the river corridor can be observed. In this case also the upper reach exhibits a tendency towards decreasing fluvial disturbance and an increase in more stable, soil moisture dependent vegetation (Figure 3.15), with fairly strong maintenance of the total river corridor area.

The total variation of lateral riparian mosaics extension along the studied rivers is shown in Table 3.8. The area of the River Corridor has been maintained in both cases but the internal structure of vegetation has changed significantly. There is a large reduction of the area under fluvial disturbance in both rivers. The near disappearance of coarse active sediment bars, affected by both erosion and deposition of sediment is especially significant in the Porma river. In this case, coarse sediment retention in the reservoir together with the reduction of flow disturbance magnitude and frequency because of the dam operation are probably the main factors driving the vegetation changes. However, taking into account similar trends in the Curueño river other additional drivers have to be included, such as land cover and land-use changes affecting water and sediment production, as reported previously.

Table 3.7 Lateral riparian mosaics within the river corridor along the Curueño river reaches.

CURUEÑO RIVER	REACH 1		REACH 2		REACH 3		REACH 4	
Lateral zones (Ha)	1956	2011	1956	2011	1956	2011	1956	2011
PI	2,4	1,2	0,9	0,9	4,3	2,2	7,5	3,3
FD C	3,6	0,5	0,5	0,0	8,9	1,2	17,9	6,3
FD F	5,5	4,4	0,0	0,0	8,8	0,0	9,9	1,2
ID	0,0	0,0	0,0	0,5	5,0	1,0	2,0	1,5
SM	0,0	2,8	0,0	0,0	0,0	21,6	0,0	24,4
Total River Corridor	11,5	8,7	1,4	1,4	26,9	26,1	37,3	36,6

PI: Perennially inundated; FD C: Fluvial disturbance dominated, coarse sediment erosion & deposition; FD F: Fluvial disturbance dominated, finer sediment deposition; ID: Inundation dominated; SM: Soil moisture regime dominated.

Table 3.8 Total changes in the lateral riparian mosaic along the entire rivers Porma and Curueño.

Dominant Process on Lateral zones (Ha)	PORMA			CURUEÑO		
	1956	2011	% change	1956	2011	% change
Perennially inundated	30,9	20,7	-33	15,1	7,6	-50
Fluvial Disturbance, Coarse sediment erosion & deposition	48,7	0,3	-99	30,9	8	-74
Fluvial Disturbance, Fine sediment deposition	60,5	37	-39	24,2	5,6	-77
Inundation by high floods	1,9	8,6	+353	7	3	-57
Soil moisture dominated	0	75		0	48,8	
Total River Corridor	142,1	145,8	+3	77,1	72,8	-6

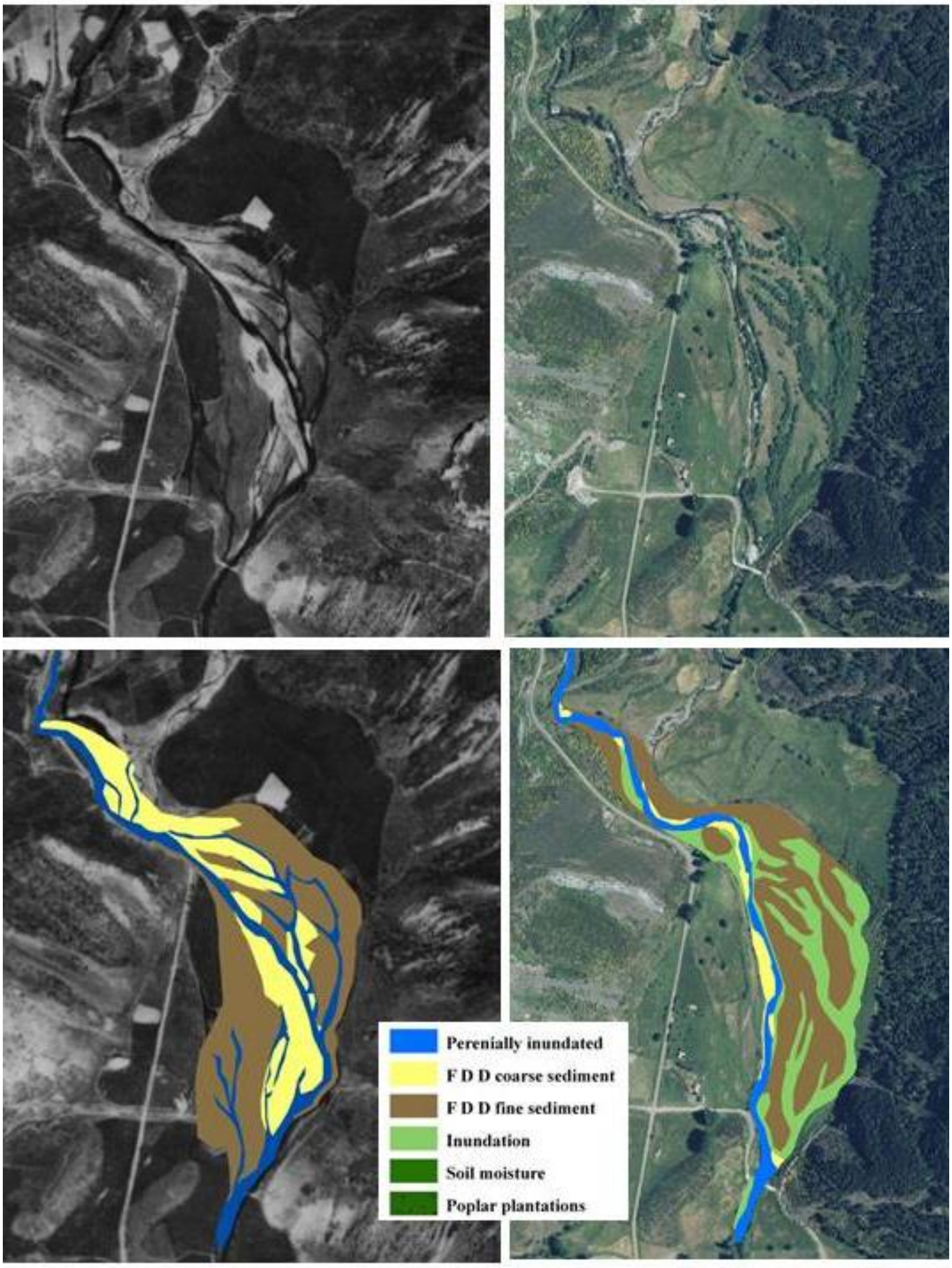


Figure 3.15 Air photographs of reach 1 of the Curueño river and interpretation of lateral riparian mosaics in 1956 (left side) and 2011 (right side) when the increase of forest coverage is also shown.

3.4.3 Channel adjustments

Apart from the horizontal channel adjustment (i.e. channel narrowing) measured in the Porma and Curueño rivers (Table 3.7 and 3.8), vertical degradation of the Porma channel river can be observed in some locations below of the dam. We have no quantitative data but field observations of cut banks, root exposure, fallen and dead trees at the channel banks, etc. (Figure 3.16) can be considered as indicators of channel incision. This vertical channel adjustment could be likely related to the Porma dam and reservoir effects, as this vertical adjustment has not been observed in the Curueño river although sediment supply decreasing linked to land cover changes have occurred in both catchments.

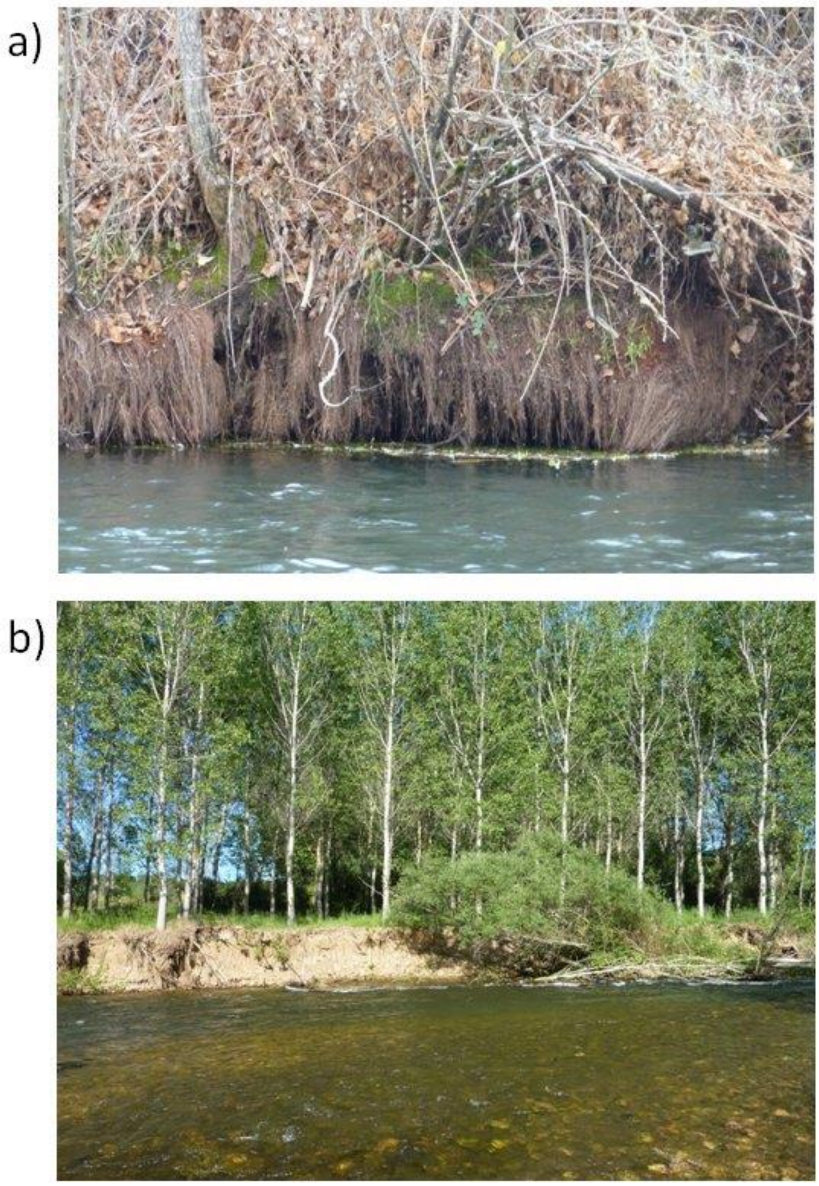


Figure 3.16 Channel bank of the river Porma at different localities showing local incision process a) River Porma at Palazuelo de Boñar (Reach 3); b) River Porma upstream Vegas del Condado (Reach 4).

4. Extended River Typology

The reaches of the studied rivers are mostly high to medium energy with channel slope values range between 1.8% and 2.2% in the upper reaches (i.e. river segments within landscape unit 1); 1.1% to 0.5% in the middle reaches (i.e. river segments within landscape unit 2); and 0.7% to 0.1% in the lower reaches (i.e. river segments within landscape unit 3 and 4) (see Tables 2.8, 2.9, 2.10). The planform of the rivers is linked to valley confinement with multi-thread channels frequently present along the unconfined sectors.

Table 4.1 shows the current river types by reach for the Esla, Porma and Curueño Rivers. Along confined valleys, they are mostly straight to sinuous types, whereas when the valley widens, multiple channel wandering or pseudo-meandering types are present. Traditionally all of these rivers exhibited a much more dynamic planform than at present, with a higher sediment supply and less human intervention on the floodplains. Meandering activity in the Esla river and the number of threads in the wandering segments of the Porma and Curueño river used to be much larger than today, as can be seen in Figure 4.1.

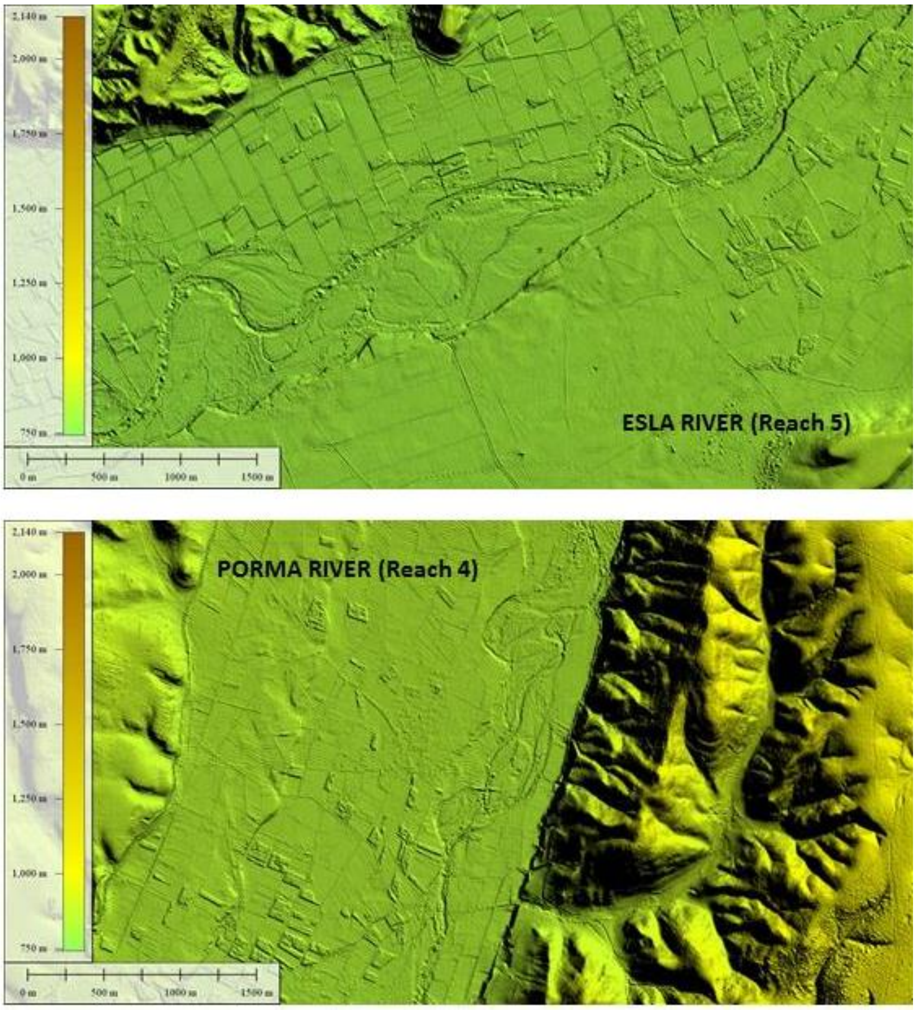


Figure 4.1 Digital Terrain Models of the Esla and Porma floodplains, showing planform changes towards less meandering and braiding than in the past

Table 4.1 Extended typology of the studied rivers. LU: Landscape unit; SEG: River segment; Bi: Bifurcation Index.

RIVER	LU	SEG	REACH	Confinement	THREADS	Bi	PLANFORM	RIVER TYPE	Floodplain status
ESLA	1	1	1	Confined	Single	1	Straight Sinuous	7	Absent
		2	2	Partly confined	-		-	Reservoir	Flooded
	2	3	3	Confined/Partly confined	Single	1	Sinuous	7- 11	Absent
	3	4	4	Partly confined/Unconfined	Transitional	1.16	Wandering	11	Partly occupied (30 %) by Poplar plantations
			5	Unconfined	Transitional	1.22	Wandering	11	Partly occupied (60 %) by Poplar plantations
			6	Unconfined	Transitional	1.16	Wandering	14	Totally occupied by Poplar plantations
	4	5	7	Unconfined	Transitional	1.05	Meandering	14	Partly occupied (20 %) by Poplar plantations
PORMA	1	1	1	Confined	Single	1	Straight Sinuous	7	Absent
		2	2	Partly confined	-		-	Reservoir	Flooded
	2	3	3	Confined	Single	1	Straight Sinuous	7	Absent
	3	4	4	Partly confined/Unconfined	Single	1	Straight Sinuous	13	Partly occupied (40 %) by Poplar plantations
			5	Partly confined/Unconfined	Single	1.24	Pseudo meandering	12	Partly occupied (80 %) by Poplar plantations
CURUEÑO	1	1	1	Confined	Single	1	Straight Sinuous	7	Partly occupied by pasture
	2	2	2	Confined	Single	1	Straight Sinuous	6	Absent
	3	3	3	Partly confined	Transitional	1.11	Wandering	11	Partly occupied (60 %) by Poplar plantations
			4	Unconfined	Transitional	1.5	Wandering	11	Partly occupied (70 %) by Poplar plantations

5. Indicators Of Present And Past Condition

This section briefly summarizes values of the Porma and Curueño indicators that can be extracted from the characterization information (see chapter 2) and temporal changes (see chapter 3). As the Curueño river is a tributary of the Porma river, catchment and landscape scale indicators refer only to the Porma river whereas segment and reach scale indicators refer to both rivers.

5.1 Catchment

The Porma Basin has a drainage area of 1145 km^2. It is a large – sized catchment according to the WFD. The Porma River is 80 km long and its tributary, the Curueño River, is 48 km long. All of the catchment is contained within the "high altitude" class of the WFD,

5.1.1 Water yield and Runoff Ratio/Coefficient

Average annual rainfall for the Porma catchment is 950 mm for the period 1945-2005, according to MOPREDAS database (González-Hidalgo et al., 2010). The more complete gauging station record for the entire catchment is located at Secos de Porma, where available discharge records cover the period 1988-2005. The drainage area to this station is 947 km^2 which represents 83% of the total Porma drainage area. For this recent period (1988-2005), the average annual rainfall for the Porma catchment is 900 mm and the average annual streamflow at "Secos de Porma" gauging station is 13.45 m3/s. Thus, the average annual runoff of the basin amounts to 424.16 Hm^3, with an average annual runoff ratio/coefficient of 0.49 for the period 1988-2005. These runoff values may be gradually decreasing as the forest coverof the catchment increases (see Figures 3.6 and 3.7).

5.1.2 Geology and land cover

The geology of the catchment is 49 % siliceous, 16 % calcareous, 18 % mixed geologies and 17 % Quaternary. Within the WFD geology classes, the Porma catchment corresponds to siliceous.

Land cover comprises 28 % agricultural, 71 % forests and semi-natural areas and 1 % artificial surfaces. There is no significant area of wetlands although the Porma reservoir occupies an area which represents 0.02 % of the catchment.

Current land cover significantly differs from the land cover five decades ago. Forest vegetation now (i.e. 2011) occupies nearly 250 % of the area it occupied in 1956. This increase of forest and naturally vegetated land has occurred as the area under agriculture has decreased (current farmland represents 80 % of the area occupied in 1956) as a result of abandonment of farmland and reforestation of open spaces that previously had little vegetation or was under pasture, which today represent only 18 % of their previous extent (Table 3.1).

5.2 Landscape Unit

5.2.1 Exposed Aquifers and soil/ Bedrock permeability

A large part of the area is underlain by permeable rocks, which occupy the middle parts of the studied catchment with siliceous conglomerates and quaternary deposits, corresponding to Landscape unit 3. The upper basin (i.e. Landscape Units 1 and 2) is underlain by an impermeable lithology, which corresponds to the oldest geologic materials.

Based on hydrology of the soil substratum, 51 %, 3 % and 7 % of the area of Landscape Units 1, 2 and 3, respectively, is impermeable, and 49 %, 97 % and 93 % is permeable. There is no evidence that these percentages have been changed over time.

5.2.2 Water production and Land Cover

Based on the 2006 Corine dataset, and taking into account the proportion of different land cover types in each landscape unit, different contributions to likely runoff response are assessed as follows:

% area of delayed runoff production, attributable to forest cover, is 45.5 %, 61.5 % and 33 % for Landscape units 1, 2 and 3, respectively.

% area of rapid runoff production, attributable to urban and industrial uses, is 0.4 %, 0.9 % and 1.1 % for Landscape units 1,2 and 3.

% area of intermediate runoff production, attributable to arable land, pasture and open spaces with little or no vegetation cover, is 50 %, 37.5 % and 66 % for Landscape units 1,2 and 3.

According to this assessment, the land cover of the Porma catchment is mainly related to delayed and intermediate runoff production in the upper parts (Landscape Unit 1); with intermediate runoff production in the lower part (Landscape 3).

Taking into account the forest cover increase during recent decades, the proportion of the delayed runoff probably has increased and this trend is likely to be maintained in the future.

5.2.3 Sediment production

Soil erosion rates are relatively high in certain parts of the catchment (Figure 2.9, Table 2.3). Estimations based on application of the the USLE model to the catchment in 1990 indicated 13.9, 9.6 and 12.1 t ha^{-1} yr^{-1} erosion rates for Landscape Units 1, 2 and 3, respectively. It is reasonably expected that these rates have decreased considerably under the land cover changes of the intervening decades.

In general, the size of potential source areas of coarse sediment is relatively small for all the entire study area but coarse sediment availability may be high within the goges of

Landscape Unit 2. River bank erosion may be a potential source of coarse sediment, as the valleys are filled with coarse alluvial material.

5.3 Segment Scale

5.3.1 Water flow

The flow regime of the Porma River is perennial flashy for segment 1, and regulated for the rest of the river due to the presence of a large dam at the end of Landscape Unit 1. Average annual flow is 6.17, 9.66 and 14.01 m^3/s for segments 1, 3 and 5, respectively. Baseflow indices (BFI), morphologically meaningful discharges (Qpmedian, Q_{p2},Q_{p10} in m^3s^{-1}) and extreme flow indicators are summarized in Table 5.1.

A flow regime analysis was conducted differentiating natural and regulated periods (Figure 3.11, Table 3.3). This identified a slight increase in the baseflow index and an artificial increase in flood frequency together with a change in the magnitude of floods. Before dam construction, floods used to occur in February-March, whereas in the regulated period higher discharges used to occur during the summer (July-August).

In the case of Curueño River, the flow regime is perennial stable for segment 1 and perennial flashy for segments 2 and 3. Average annual flow is 3.1, 5.5 and 3.9 m^3/s for segment 1, 2 and 3, respectively. Baseflow indices (BFI), morphologically meaningful discharges (Qpmedian, Q_{p2},Q_{p10} in m^3s^{-1}) and extreme flow indicators are summarized in Table 5.2.

5.3.2 Sediment Flow

No bed sediment load data are available for the studied rivers. However the presence of a large dam at the end of landscape unit 1 in the Porma river inevitably places a large restriction on bed sediment transport from upstream to downstream reaches. Additionally, a series of small weirs exist along segments 3 (4 weirs), segment 4 (11 weirs) and segment 5 (8 weirs) and act as blocking structures for coarse bed sediment transport, contributing to the sediment deficit derived from the large dam.

In the Curueño river sediment flow is also affected by a series of small weirs. Three of them are located in segment 1, another three in segment 2, and 6 more in segment 3. Nonetheless, sediment transport may be considerable during high floods, especially in the lower reaches as can be observed in the pictures from segment 3 shown in Figure 5.1.

Table 5.1 Indicators of flow regime characteristics of the Porma river per segment.

Porma river	**LU 1 Camposolillo Gauging station Segment 1**	**LU2 Vegamián gauging station (1968-2009) Segment 2-3**	**LU3 Secos de Porma gauging station (1988-2009) Segment 4**
Catchment area (km^2) Flow regime type Average annual flow (m^3/s)	244.65 Perennial flashy 6.17	96.7 Regulated 9.66	510 Regulated 14.01
Morphological meaningful discharge (m^3/s) * $Q_{Pmedian}$ * Q_{p2} * Q_{p10}	 4.1 35.24 72	 5.96 24.7 38.79	 10.30 71.8 165
1-day minimum flow * LQ * Median * UQ	 0.704 1.1 1.40	 1.64 2.15 2.84	 1.64 2.73 3.59
30-day minimum flow * LQ * Median * UQ	 1.31 1.51 1.94	 1.81 2.55 3.10	 1.80 2.55 3.10
1-day maximum flow * LQ * Median * UQ	 28.29 35.15 54.09	 19.6 24.7 29.67	 45.07 69.57 104.23
30-day maximum flow * LQ * Median * UQ	 12.05 15.44 19.23	 17.30 21.69 25.81	 17.29 21.69 25.81

Table 5.2 Indicators of flow regime characteristics of the Curueño river per segment.

Curueño river	**LU 1 Tolibia Gauging station (2000-2009) Segment 1**	**LU2 Caldas gauging station (1968-2009) Segment 2-3**	**LU3 Ambasaguas gauging station Segment 4**
Catchment area (km^2) Flow regime type Average annual flow (m^3/s)	99.5 Stable 3.07	73.1 Perennial flashy 5.53	120.6 Perennial flashy 3.9
Morphological meaningful discharge (m^3/s) * $Q_{Pmedian}$ * Q_{p2} * Q_{p10}	 29.1 82	 42.9 71.23	 NO DATA NO DATA
1-day minimum flow * LQ * Median * UQ	 0.1495 0.224 0.323	 0.36 0.49 0.66	 NO DATA NO DATA NO DATA
30-day minimum flow * LQ * Median * UQ	 0.24 0.33 0.44	 0.49 0.58 0.76	 NO DATA NO DATA NO DATA
1-day maximum flow * LQ * Median * UQ	 16.22 26.3 32.5	 27.15 41.1 61.3	 NO DATA NO DATA NO DATA
30-day maximum flow * LQ * Median * UQ	 6.37 7.93 8.86	 11.07 14.75 23.37	 NO DATA NO DATA NO DATA

Figure 5.1 View of the Curueño river in segment 3 after large floods occurred at the end of the last winter, 2014.

5.3.3 Valley Controls on River Morphology Adjustments

The average valley gradient of the Porma River is 2.01 %, 1.03 %, 1.08 %, 0.52 % and 0.35 % for segments 1 to 5, respectively. Valley confinement is confined or partially confined in the upper parts of the catchment, being unconfined in the most downstream segment below the confluence with the Curueño River. The channel entrenchment index (valley width/channel width ratio) is estimated as 25.9, 8.2, 13.9 and 24.8 for segments 1,3,4 and 5, respectively.

In relation to the Curueño River, the average valley gradient is 2.53 %, 1.28 % and 0.82 % for segments 1 to 3, respectively. The valley is partially confined in the upper part of the catchment, confined in segment 2 where the gorges are located, and unconfined in the last segment. The channel entrenchment_index is estimated as 16, 6.7 and 30.3 for segments 1 to 3, respectively.

5.3.4 Riparian corridor features

The average riparian corridor width in the Porma river is 7, 15, 40 and 70 m for segments 1, 3, 4 and 5, respectively. These values represent approximately 1.7, 0.6, 1.6 and 2.1 times the average active channel width.

Riparian corridor continuity is relatively high at about 60, 80, 40 and 80 % of river length for segments 1, 3, 4 and 5, respectively.

In the case of the Curueño river, average riparian corridor width is 10, 8 and 40 m for segments 1 to 3, respectively, which represents approximately 0.8, 0.5 and 2.1 times the average active channel width. Riparian corridor continuity is about 40, 30 and 50 % of river length for segments 1 to 3, respectively.

5.3.5 Physical pressures

The Porma River is affected by different pressures that increase towards the lower parts of the catchment. Segments 3, 4 and 5 are affected by flow regulation which is an important driver of change of the riparian corridor. Also in these segments poplar plantations are very frequent, occupying a large part of the floodplain and in many places disrupting the continuity of the natural riparian corridor. In addition, the presence of the large dam in segment 2, and the series of weirs along the river interrupt the continuityof the river flow system.

In the Curueño River the riparian corridor is fragmented in segment 2, mainly due to the configuration of the confined valley. In segment 3, poplar plantations are very frequent and in many places disrupt the continuity of the riparian corridor, in a similar manner to the Porma River.

5.3.6 Wood production

Wood production is assessed as relatively high in both rivers. In the case of the Porma river, fallen trees located at the banks and oriented longitudinally to the channel are relatively frequent below the dam in segments 3 and 4, whereas in the Curueño river large logs are often oriented transversally and considerable quantities of stems and woody debris can be observed along segment 3 (see Figure 5.1).

5.4 Reach Scale

5.4.1. Flooding

On the River Porma, flooding is strongly controlled by the large dam, although riparian and floodplain areas are completely accessible by floods. In the case of the Curueño river, flooding occurs periodically and most of the floodplain is accessible to floodwaters.

5.4.2. Channel self-maintenance/ reshaping

Specific stream power at Qp2 has been estimated to be approximately 13.6, 5. 2.4, 1.4 and 1.2 W/m^2 in reaches 1 to 5 of the Porma river, respectively, and 3.5, 4.4, 1.9 and 1.6 W/m^2 in the reaches 1 to 4 of the Curueño river (Figure 2.21).

Bed sediment calibre is mainly cobbles and gravel in all reaches for both rivers. Median particle diameter was estimated as 130, 130 and 113 mm for segments 1, 3 and 5, respectively, in the Porma River; and 70, 125, 89 and 73 mm for reaches 1 to 4 in the Curueño River.

Actual river channel characteristics and dimensions were indicated in Tables 2.9 and 2.10. Values of the main indicators are presented in Table 5.3.

Table 5.3 Main indicators of channel features.

Porma Reaches	Channel gradient (%)	Active channel width	Channel sinuosity	Braiding index	River type
1	2.16	12	1.12	1	7
2	--	--	--	--	--
3	1.1	24	1.25	1	7
4	0.45	25	1.15	1	13
5	0.27	38	1.2	1.24	12
Curueño Reaches					
1	2.04	12	1.1	1	7
2	1.05	15	1.3	1	6
3	0.7	23	1.19	1.11	11
4	0.59	42	1.13	1.5	11

5.4.3. Channel changes / adjustments

Analysis of information from historical ortophotos (1956 and 1977) and field reconnaissance reveal a general trend of decreasing channel area and width and simplification of channel planform together with vegetation encroachment (section 3.4, Tables 3.4 and 3.5). Table 5.4 summarizes the indicators of these processes.

Channel narrowing and vegetation encroachment seem to be much more evident in the regulated Porma river than in the Curueño river (Figure 5.2). Channel vertical degradation (i.e. incision) is observed in reaches 3 and 4 of the Porma river (see Figure 3.16), probably associated with the bed sediment deficit caused by the large dam.

Table 5.4 Indicator values of channel changes / adjustments

Reach	Channel width		Braiding Index		Average bank retreat ($m \cdot yr^{-1}$)	River type	
Porma River	1956	2011	1956	2011	1956/2011	1956	2011
1	17.1	15.8	1	1	0.02	Straight sinuous	Straight sinuous
2		-		-	-		Reservoir
3	23.8	24	1	1	0	Straight sinuous	Straight sinuous
4	124.6	25	1.66	1	1.8	Island Braided	Straight sinuous
5	330	38	2.4	1.24	5.31	Island Braided	Pseudo-meandering
Curueño river							
1	27.4	12	1.3	1	0.28	Wandering	Straight sinuous
2	18.9	14.4	1	1	0.08	Straight sinuous	Straight sinuous
3	81.8	23.5	1.47	1.11	1.06	Wandering	Wandering
4	202	41.4	2.5	1.5	2.9	Island Braided	Wandering

5.4.4. Vegetation Succession

A detailed description of vegetation species composition and age structure is provided in Tables 2.8, 2.9, 2.10 and section 2.5.2. Dominant riparian tree species based on field reconnaissance were *Betula* sp, *Salix fragilis* and *Populus nigra* in the upper reaches (reach 1 of both rivers). The middle reaches presented mixed galleries of *Fraxinus excelsior*, *Populus nigra*, *Salix eleagnos*, *Salix purpurea*, *Salix cantabrica* and *Salix atrocinerea*. The lower reaches exhibited a Mediterranean mixed gallery of *Alnus glutinosa, Fraxinus angustifolia*, *Salix salvifolia*, *Salix purpurea* and *Salix atrocinerea. Salix elaeagnos* seems to be a good indicator of fluvial disturbance magnitude and frequency, appearing as younger stands in the active banks of the Curueño river and as mature and old stands in the old channel margins of the Porma river.

The relatively high energy of these rivers and their coarse substratum strongly reduce the potential for aquatic vegetation growth inside the channel. Macrophytes are in general very scarce. Small stands of *Phragmites, Typha,* and *Sparganium* are occasionally found in reaches 4 and 5 of the Porma River.

Presence of wood is very frequent in both rivers coming from living and dead fallen trees which remain located at the channel banks in the Porma river and in the banks and the open floodplain in the Curueño river. As a consequence of this, wood is very abundant in both rivers, especially in reaches 3, 4 and 5 of the Porma river and reaches 3 and 4 of the Curueño river (Figure 5.3).

a)

b)

Figure 5.2 Channel and riparian conditions in July, 2014 of the studied rivers. a) River Porma at reach 3, showing high flows released from the reservoir for irrigation and totally vegetated river banks. b) River Curueño at reach 4 showing natural low flows during summer time and unvegetated coarse sediment bars attached to channel banks.

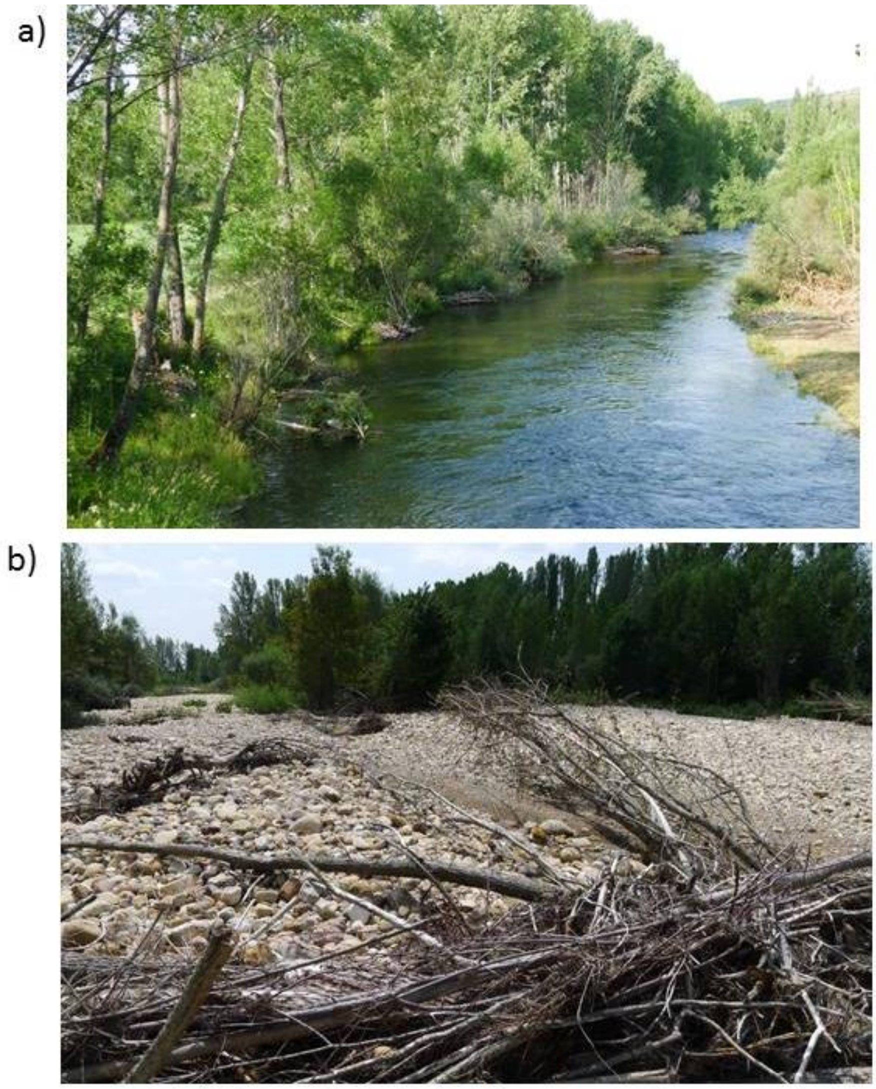


Figure 5.3 Presence of wood in the studied rivers. a) reach 3 of the Porma river and b) reach 4 of the Curueño river.

References

AEMET I. 2011. Iberian climate atlas. Agencia Estatal de Meteorología (España) and Instituto de Meteorología (Portugal), Madrid, Spain.

Alber A, Piégay H. 2011. Spatial disaggregation and aggregation procedures for characterizing fluvial structures at the network-scale: application to the Rhône basin (France). Geomorphology 125 (4): 343–360.

Andréassian V. 2004. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology, 291: 1-27.

Collantes Gutíerrez F. 2004. El declive demográfico de la montaña española (1850-2000). Un drama rural? Publ. Ministerio Agricultura, Pesca y Alimentación, Madrid.

García Ruiz JM, Lana-Renault N. 2011. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region- A review. Agriculture, Ecosystems and Environment, 140: 317-338.

González-Hidalgo JC, Brunetti M, de Luisa M. 2010. A new tool for monthly precipitation analysis in Spain: MOPREDAS database (monthly precipitation trends Decembre 1945-Novembre 2005). International Journal of Climatology, (www.interscience.wiley.com) DOI: 10.1002/joc.2115

ICONA 1990. Mapas de Estados Erosivos. Cuenca hidrográfica del Duero. Publ. Instituto Nacional para la Conservación de la Naturaleza, Ministerio de Agricultura, Pesca y Alimentación. Madrid.

Keestra SD, Van Huissteden J, Vandenberghe J, Van Dam Ol, De Gier J, Pleizier ID. 2005. Evolution of the morphology of the river Dragonja (SW Slovenia) due to land-use changes. Geomorphology, 69: 191-207.

Cernusca A, Tappeiner U, Bahn M, Bayfield N, Chemini C, Fillat F, Graber W, Rosset M, Siegwolf R, Tenhunen J. 1996. ECOMONT Ecological effects of land use changes on European terrestrial mountain ecoystems. Pirineos: 145-172.

Lasanta T, Arnáez J, Oserín M, Ortigosa L. 2001. Marginal lands and erosion in terraced fields in the Mediterranean mountains: a case study in the Camero Viejo (Northwestern Iberian System, Spain). Mountain Research and Development, 21(1): 69-76.

Lana Renault N, Regués D. 2009. Seasonal patterns of suspende sediment transport in an abandoned farmland catchment in the Central Spanish Pyrenees. Earch Surface Processes and Landforms, 27: 445-462.

Liébault F, Piégay H. 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surface Processes and Landforms, 227: 425-444.

McDonald D, Crabtree JR, Wiesinger G, Dax T, Stamou N, Fleury P, Gutiérrez Lazpita J, Gibon A. 2000. Agricultural abandonment in mountain areas of Europe: environmental consequences and policy response. Journal of Environmental Management, 59: 47-69

Piégay H, Walling DE, Landon N, He Q, Liébault F, Petiot R. 2004. Contemporary changes in sediment yield in an alpine montane basin due to afforestation (the upper Drôme in France). Catena, 55:183-212.

Serrano-Muela MP, Lana-Renault N, Nadal-Romero E, Regüés D, Latron J, Martí-Bono C, García-Ruiz JM. 2008. Forests and their hydrological effects in Mediterranean Mountains. Mountain Research and Deveopment, 28 (3 /4): 279-285.

Van Rompaey AJJ, Govers G, Van Hecke E, Jakobs K. 2001. The impacts of land use policy on the soil erosion risk: a case study in central Belgium. Agriculture, Ecosystems and Environment, 83: 83-94.

Catchment Case Study 3

A hydromorphological assessment of the River Narew (Poland): a lowland Central European river

Paweł Marcinkowski[1], Tomasz Okruszko[1], Robert Carl Grabowski[2]

[1] Szkola Glowna Gospodarstwa Wiejskiego (WULS), [2]Queen Mary University of London (QMUL)

1. Introduction

This report describes an application of the hierarchical hydromorphological assessment framework to the River Narew, Poland. The guidelines set out in Deliverable 2.1 Part 1 were followed: (1) to delineate the catchment and river network into spatial units, (2) to characterize the current hydromorphological condition of the spatial units, and (3) to characterize hydromorphological change in the spatial units, which were used (4) to assign a typology to the river reaches, (5) to calculate indicators of present and past hydromorphological condition, and (6) to interpret condition, assess reach sensitivity and predict future trajectories of change.

This hydromorphological assessment focuses on a specific section of the River Narew, the anastomosing reaches of the Narew National Park. Anastomosing rivers of this type would have been historically found throughout lowland Europe but have been lost due to channel realignment, channelisation and land drainage. The anastomosing reaches of the Narew are unique in Europe and have high conservation value for their geomorphology and ecology.

As specified in the main report, when the hierarchical assessment does not encompass the entire river network and only a subset of the reaches are selected for detailed study, the following procedure should be used. The entire river network should be delineated into spatial units and the large-scale spatial units should be characterized in full (e.g. biogeographic area, catchment and landscape units), however characterization of the smaller spatial units should focus on the reaches of interest, the segment in which they are located, and the segment immediately upstream. This report follows those recommendations and the reach-scale characterization and assessment of hydromorphological condition focuses on the anastomosing section of the River Narew.

1.1 Study area

The River Narew is a lowland river situated in north-east Poland (Figure 1.1), a right-bank tributary of the River Vistula, with a total drainage area of *ca.* 75 000 km^2. The river is 484 km long and approximately 36 km of the headwaters lie outside of the Republic of Poland in western Belarus. Because of the large size of the River Narew catchment and the difficulty in accessing data for areas outside of Poland, this study focuses on a subset of the river network extending from the border with Belarus down to the town of Tykocin (53°12’31”N 22°45’54”). A part of the river between Suraż and Rzędziany (ca. 35 km) is preserved in its almost pristine form, with an anastomosing planform. This precious and unique segment of the river is formally protected as it lies within the Narew National Park (NNP).

The content of this report is strongly determined by the format described in Deliverable 2.1 Part 1 and further sections will be consistent with its structure.

Figure 1.1 Location of the River Narew.

2. Materials and methods

2.1 Datasets

In this study remotely sensed data and national datasets (raster and vector geometry) was assembled for analysis (Table 2.1).

Delineation and characterisation of reaches and geomorphic units were supported by satellite imagery from 2012 viewed on Google Earth (Images © 2014 Digital Globe).

A composite Digital Elevation Model (DEM) was created using the SRTM (Shuttle Radar Topography Mission, 80m resolution) and elevation maps from the Main Geodetic and Cartographic Documentation Centre (5m resolution). A more detailed 2m resolution DEM was obtained for reach-scale analysis from LIDAR data.

A (1:500,000 scale) digital map of the bedrock was obtained from the Polish Geological Institute – National Research Institute. The data is freely available from the Institute's website.

The CORINE Land Cover 2006 (CLC2006) dataset, produced by the General Inspectorate of Environmental Protection (as a continuation of the research of the EEA projects CLC1990 and CLC2000) was used to assess land use. The resolution of the dataset is 100m.

2.2 Delineation and characterisation

The delineation and characterisation approach is described in detail Deliverable 2.1 Part 1, sections 4 and 5. A brief overview of the methods used in the delineation process is presented below.

2.2.1 Region

The region type was derived from online maps of biogeographic regions in Europe (www.globalbioclimatics.org; EEA 2002).

2.2.2 Catchment

The catchment was delineated strictly following the procedure of watershed delineation provided in ArcGIS, using its tools in the following order. Profile DTM (5m resolution) was used as an input. In addition the use of a stream network shapefile to "burn in" streams to the DTM was necessary to obtain an accurate delineation output.

Table 2.1 Datasets used in delineation and characterisation of the River Narew

Property	Dataset	Format	Resolution	Version	Source
Aerial Imagery	Satellite	Online	variable	2012	Google Earth
Elevation	Profile DTM LIDAR	GeoTIFF Points' cloud	5 -80 m 2m		SRTM Main Geodetic and Cartographic Documentation Centre
Geology	Polish Geological Map	Shapefile	1:500,000		Polish Geological Institute – National Research Institute
Soil erosion	PESERA	GeoTIFF	1 km		Joint Research Centre (EC)
Land Cover	CORINE	Shapefile	100 m	2006	European Environment Agency
River flows Precipitation records	Mean Daily Daily sum	Discharge Precipitation	2 stations 21 stations		Institute of Meteorology and Water Management – National Research Institute
Vegetation	Field surveys and orthophotos	Shapefile	variable		Narew National Park

2.2.3 Landscape unit

Landscape units represent portions of the catchment that are consistent in respect of their land use, geology and elevation and were delineated in a similar way as the catchment based on available maps of the area.

2.2.4 Segment

Segment delineation was based on discontinuities in gradient and catchment area, and was assessed using a long-profile of elevation and catchment area extracted from the DTM.

2.2.5 Reach

River sinuosity, braiding and anabranching indices were quantified using aerial imagery. The multi-thread attributes were examined at a series of cross sections spaced 0.5 – 1 times the maximum width of the outer wetted channels. Reach delineation was based on confinement, planform and the presence of major weir structures using a range of data sources.

3. Delineation of spatial units

3.1 Region

The biogeographic region in which the catchment is located provides essential information on main flow regime patterns, climate and potential vegetation. The River Narew catchment lies within Continental biogeographic region (Figure 3.1).

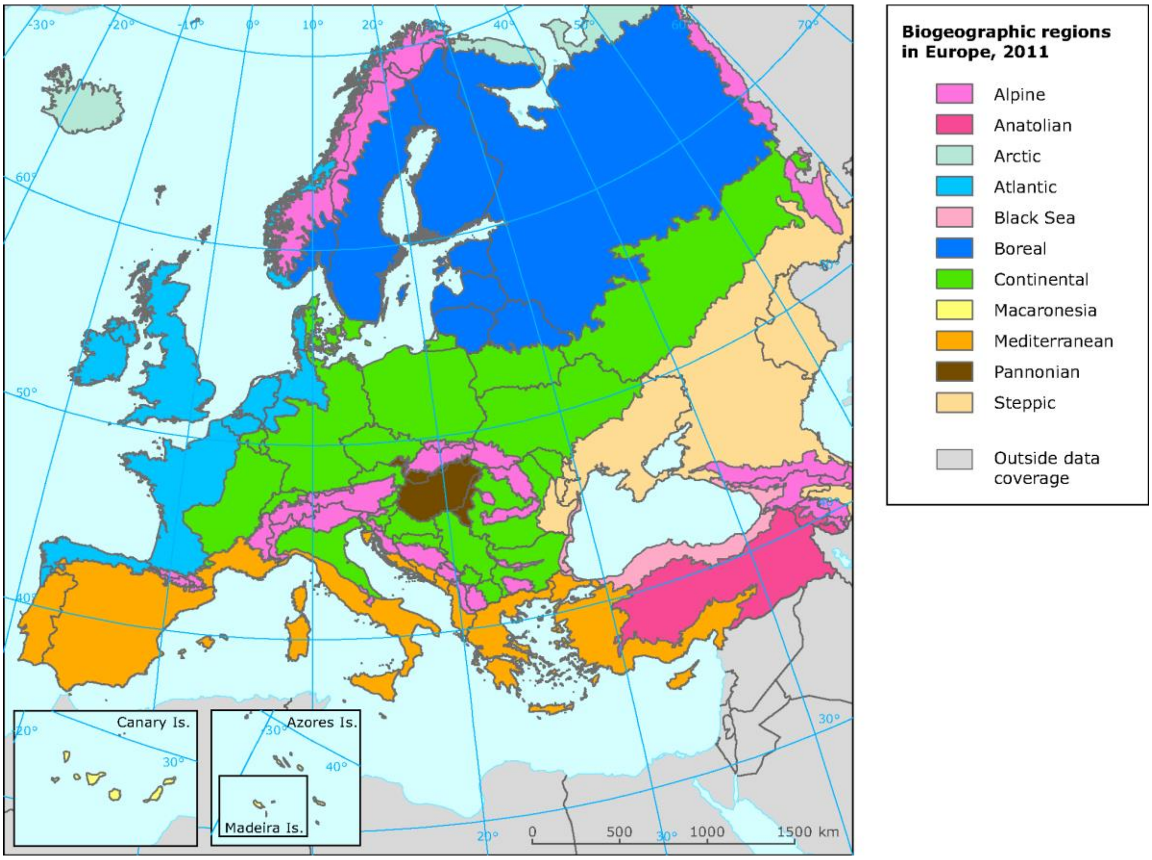


Figure 3.1 The biogeographic regions of Europe. (source: European Environment Agency 2012, http://www.eea.europa.eu/data-and-maps).

3.2 Catchment

The River Narew catchment is a large-sized, lowland, siliceous catchment according to the Water Framework Directive typology. The catchment area is 6656 km^2, and the elevation statistics are as follows: mean = 149.5 m, min = 102.5 m, max = 260m (Figures 3.2 and 3.3).

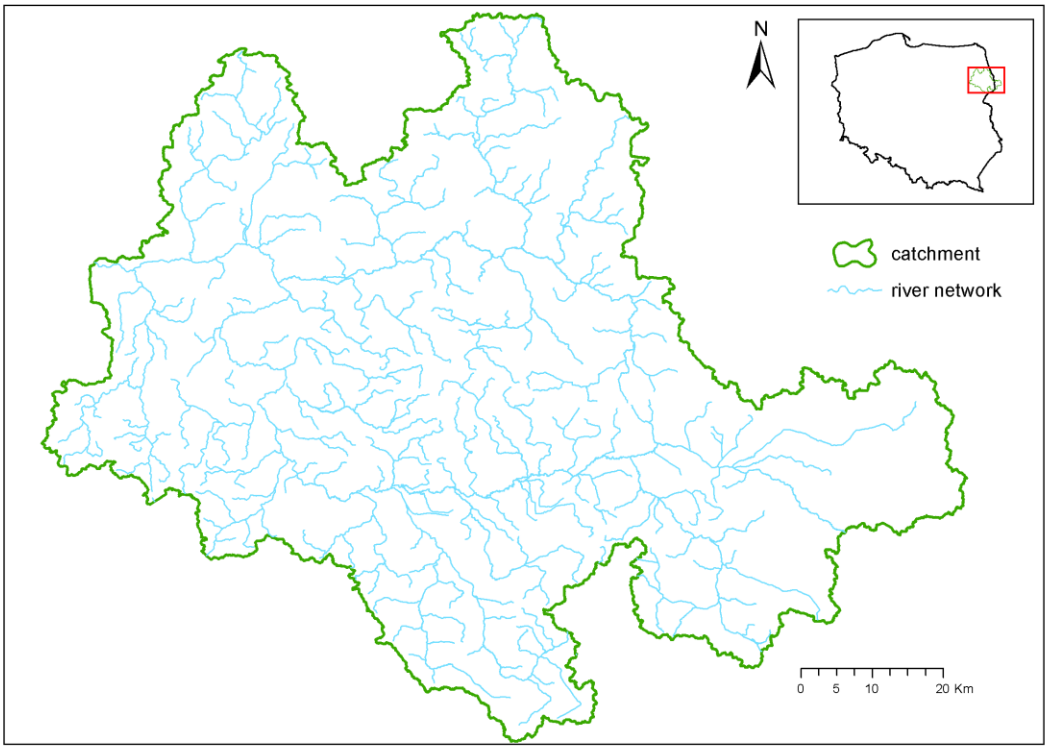


Figure 2.2 Delineated catchment with perennial stream network.

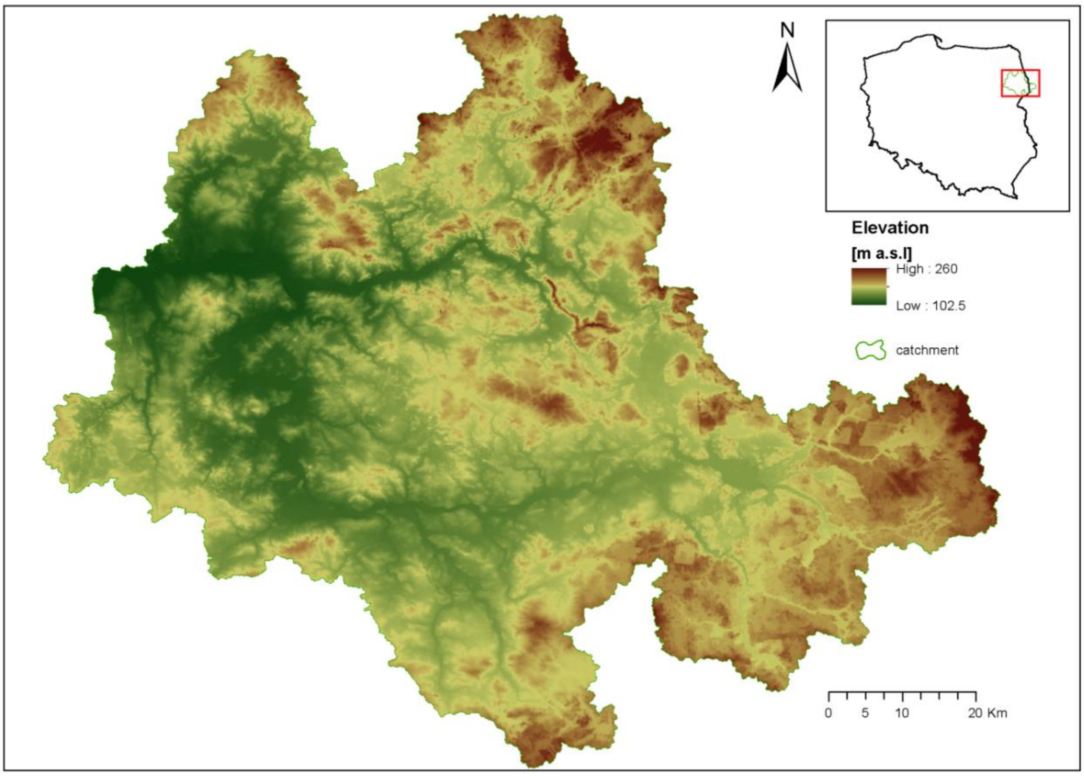


Figure 3.3 DTM within catchment boundaries.

3.3 Landscape units.

The Narew catchment was delineated into 2 landscape units (Figure 3.4) primarily based on land use type (Figure 3.7), since the entire catchment was geologically homogeneous (Figure 3.6) and similar in terms of its elevation typology (Figure 3.5). The first landscape unit encompasses an area dominated by forest land use. The second was mainly occupied by agricultural areas (arable lands and pastures) (Table 3.1).

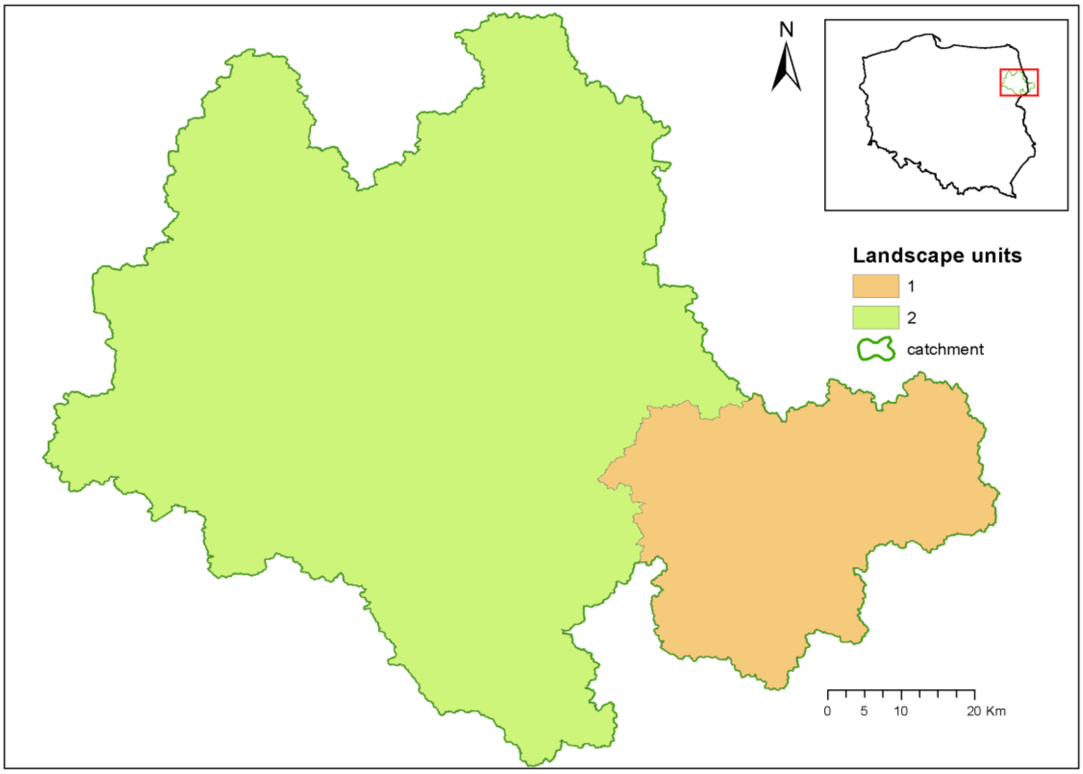


Figure 3.4 Delineated landscape units.

Table 3.1 Preliminary characterisation of the elevation, geology and land cover of the landscape units of the Narew.

	Landscape Units	
	1	**2**
Area (km^2)	1368	5288
Mean Elevation (m)	165	145
Dominant Geology	Siliceous	Siliceous
Land Cover	Forest	Agricultural
Mean soil erosion rate (tons/ha/year)	0.03	0.03

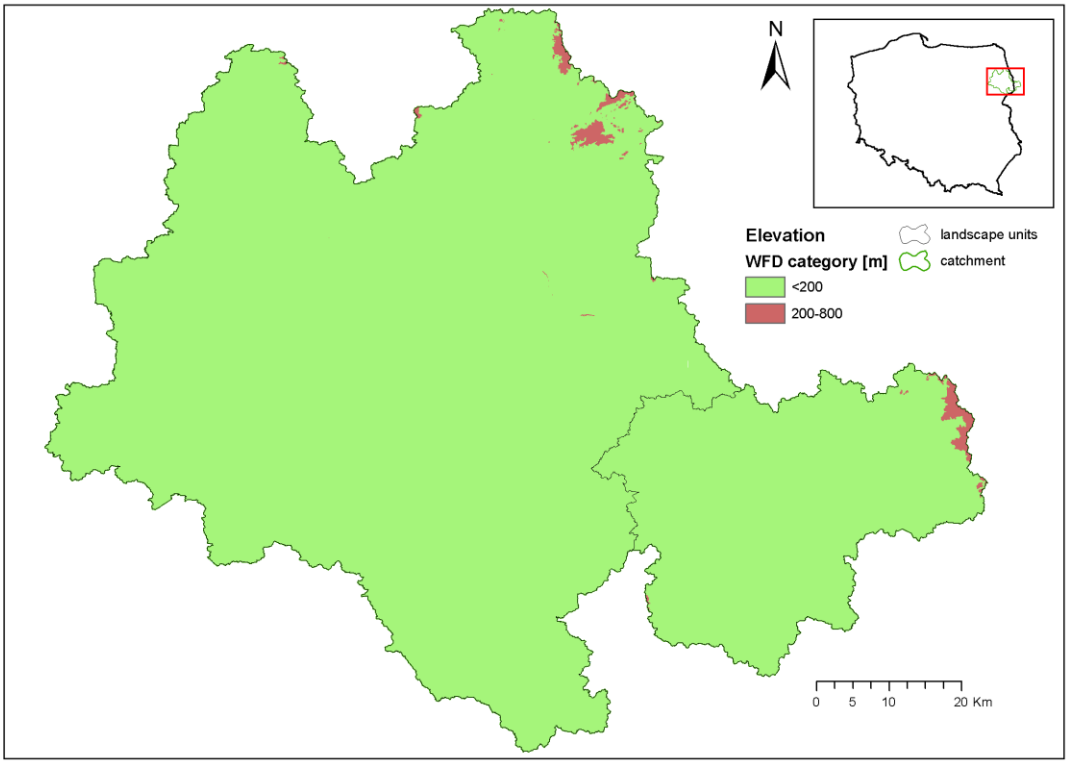


Figure 3.5 Elevation classes of the Narew catchment according to the WFD typology.

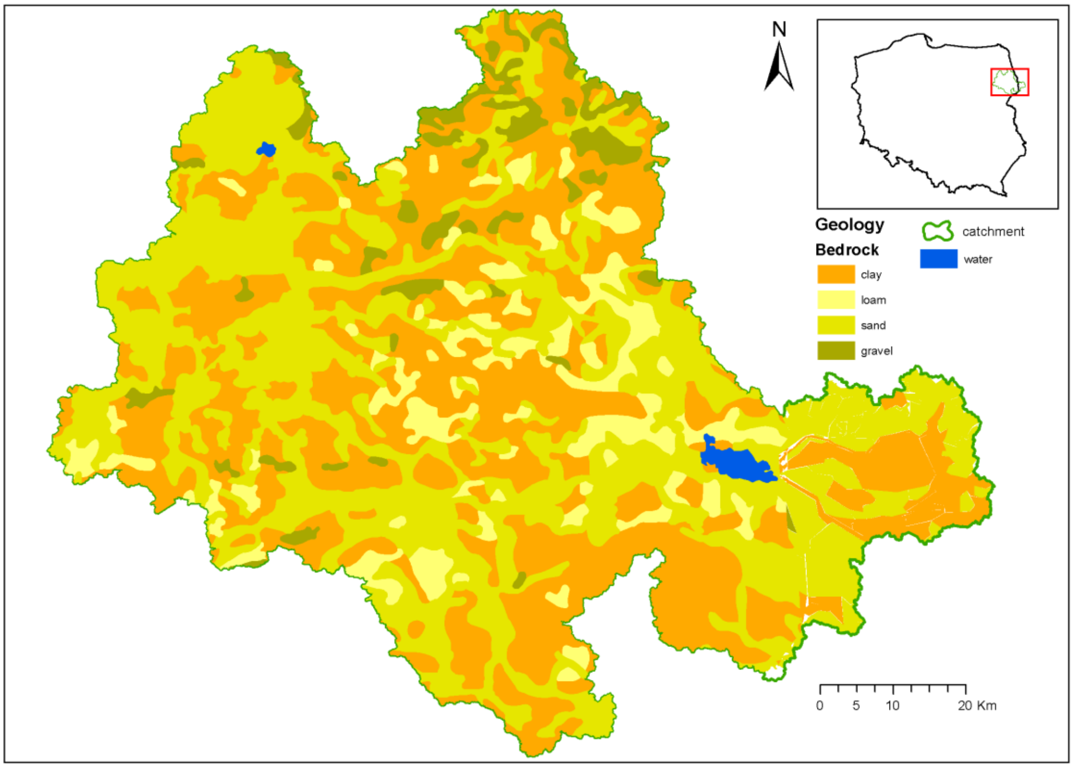


Figure 3.6 Geology of the Narew catchment.

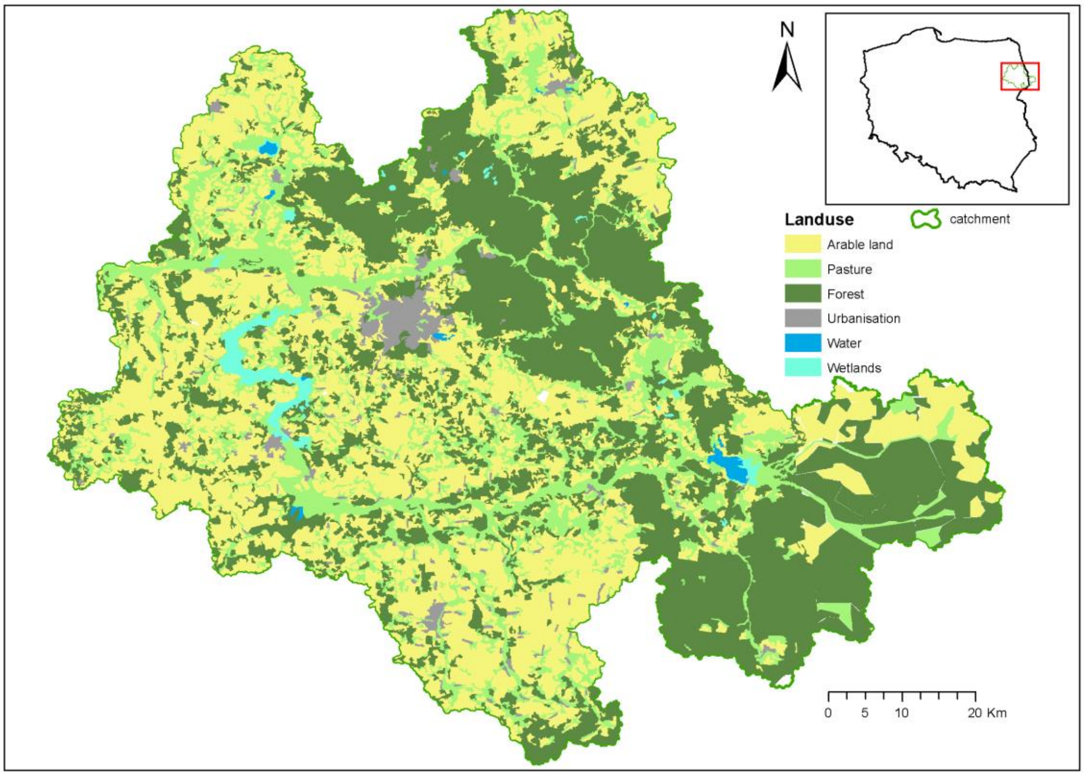


Figure 3.7 Land use map in the Narew catchment.

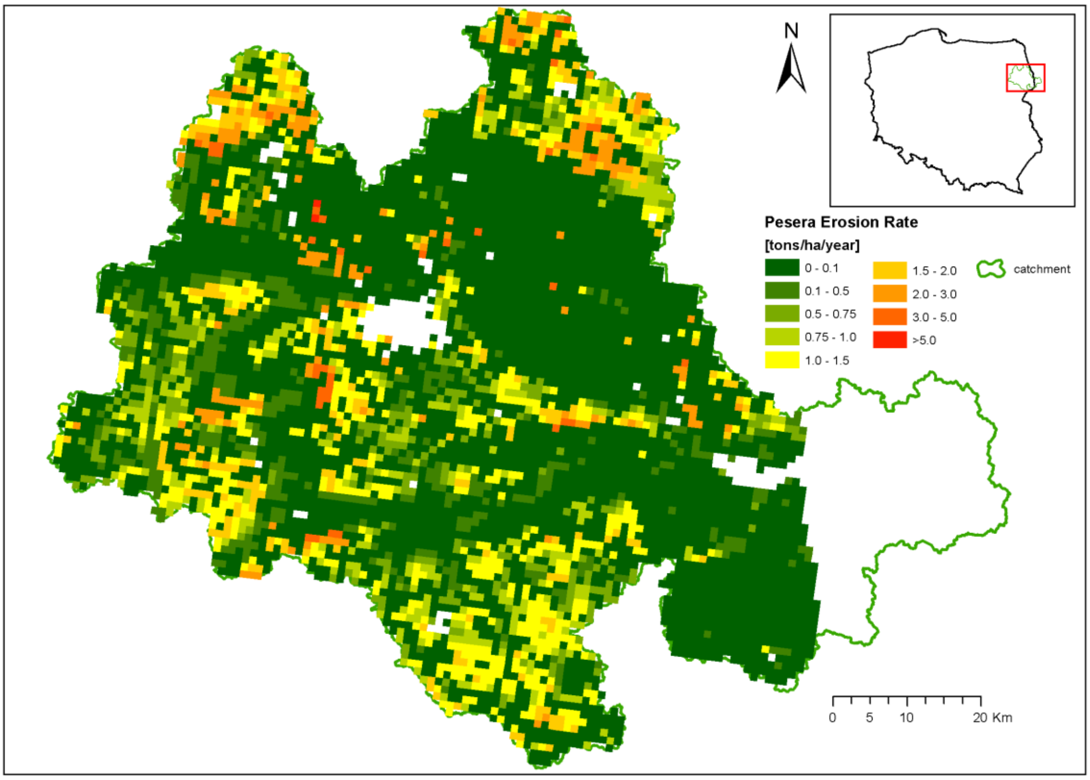


Figure 3.8 Rate of erosion in the Narew catchment (Pesera model).

3.4 River segments

The River Narew was delineated into 7 segments primarily based on the significant increase in catchment area at major tributary confluences (Figures 3.9, 3.10). A confluence was deemed significant when the sub-catchment area drained by the tributary was greater than 20% of the main stem catchment area immediately upstream of the junction. The longitudinal profile of the river indicated a very low and relatively constant gradient (Table 3.2). An additional segment was delineated for the large Siemianówka reservoir (32.5 km^2 surface area at maximum impoundment level, 11 km or river length), which, due to its major influence on the flow regime, was considered as a separate river segment.

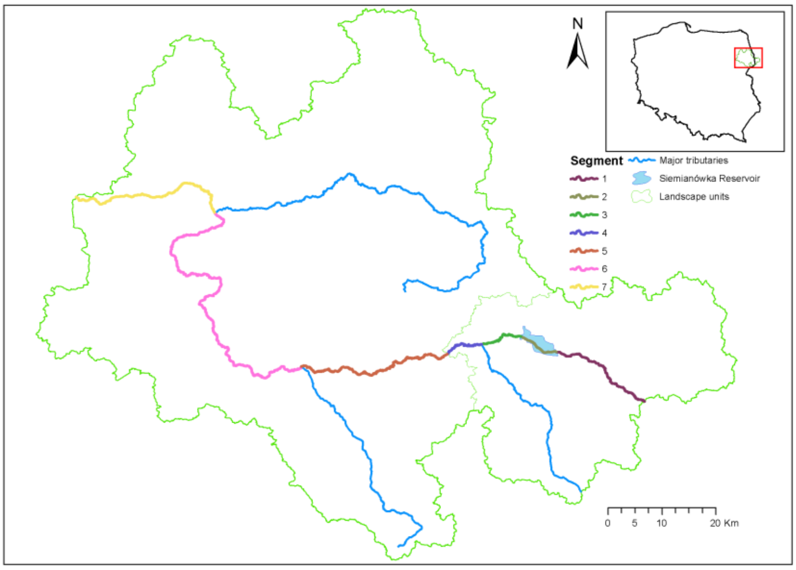


Figure 3.9 The River Narew segments delineation map.

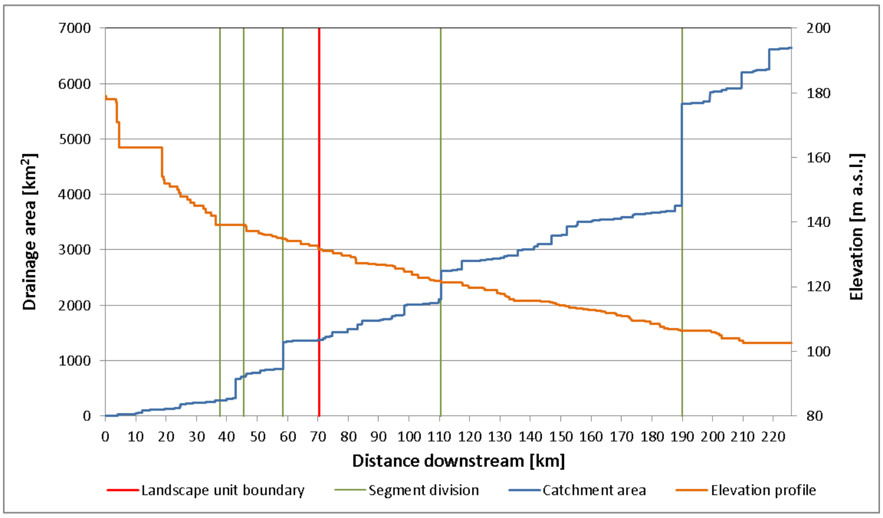


Figure 3.10 Longitudinal profile across the River Narew with division units.

Table 3.2 Characteristics used in the segment delineation process.

Segment	Increase in catchment area due to tributary area (km^2)	% increase	Gradient (channel)	Gradient (segment)	Valley confinement
1			0.00093	0.00143	Unconfined
2	Reservoir		0	0	Unconfined
3			0.00027	0.00070	Unconfined
4	487.8	58	0.00026	0.00031	Unconfined
5	LU2		0.00024	0.00055	Unconfined
6	511	24	0.00019	0.00045	Unconfined
7	1838.1	48	0.00011	0.00019	Unconfined

3.5 River reaches

River reaches are sections of a river with relatively uniform boundary conditions in terms of hydromorphological characterisation.

The River Narew was delineated into 35 reaches (Figure 3.11 and Table 3.3). Further characterisation focused on the 5 anastomosing reaches within the Narew National Park (reaches 26-30) due to their unique and complex geomorphological structure.

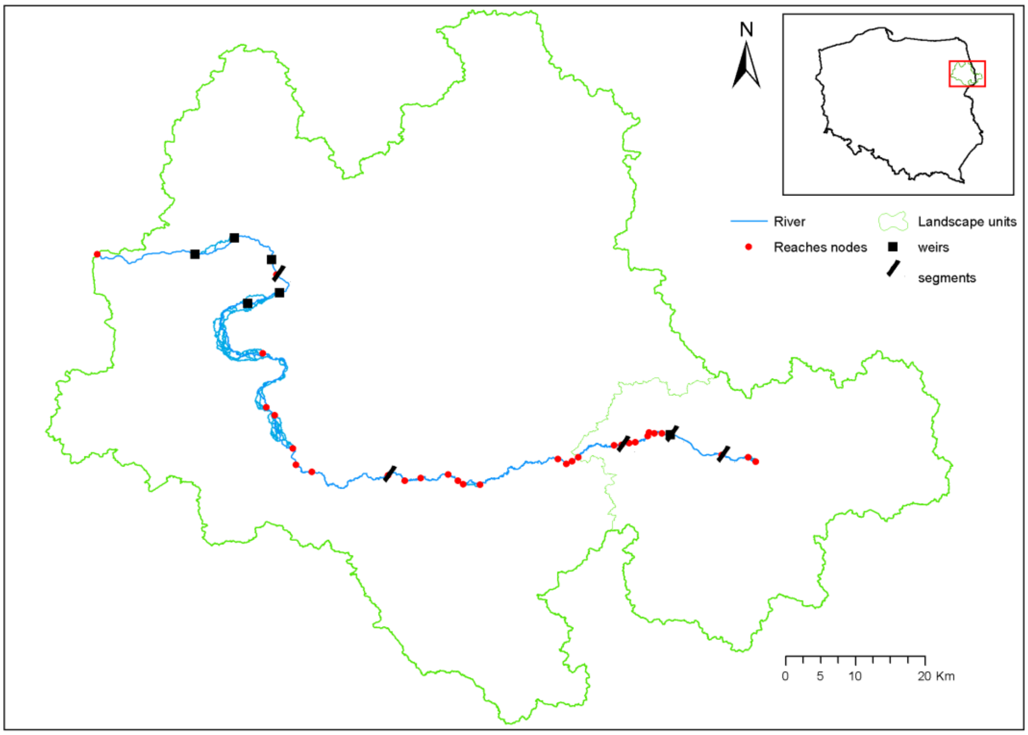


Figure 3.11 River reaches in the Narew catchment.

Table 3.3 Characteristics used in the reach delineation process.

LU	Segment	Reach	River confinement	Threads	Planform	Structure at downstream end
1	1	1	Unconfined	Multi-thread	Anabranching	
		2	Unconfined	Single	Meandering	
	2	3	Unconfined	Reservoir		dam
	3	4	Unconfined	Single	Sinuous	
		5	Unconfined	Single	Meandering	
		6	Unconfined	Single	Sinuous	
		7	Unconfined	Single	Straight	
		8	Unconfined	Single	Meandering	
		9	Unconfined	Single	Sinuous	
		10	Unconfined	Single	Meandering	
	4	11	Unconfined	Single	Sinuous	
		12	Unconfined	Single	Meandering	
2	5	13	Unconfined	Single	Sinuous	
		14	Unconfined	Single	Meandering	
		15	Unconfined	Single	Sinuous	
		16	Unconfined	Single	Meandering	
		17	Unconfined	Multi-thread	Anabranching	
		18	Unconfined	Single	Sinuous	
		19	Unconfined	Single	Meandering	
		20	Unconfined	Single	Sinuous	
		21	Unconfined	Single	Meandering	
		22	Unconfined	Single	Sinuous	
	6	23	Unconfined	Single	Sinuous	
		24	Unconfined	Single	Meandring	
		25	Unconfined	Single	Sinuous	
		26	Unconfined	Multi-thread	Anabranching	
		27	Unconfined	Multi-thread	Anabranching	
		28	Unconfined	Multi-thread	Anabranching	
		29	Unconfined	Multi-thread	Anabranching	weir
		30	Unconfined	Multi-thread	Anabranching	weir
		31	Unconfined	Single	Sinuous	
	7	32	Unconfined	Single	Sinuous	weir
		33	Unconfined	Single	Sinuous	weir
		34	Unconfined	Multi-thread	Anabranching	weir
		35	Unconfined	Single	Sinuous	

4. Characterisation of the spatial units

4.1 Region

The River Narew lies within the Continental biogeographic region (Figure 3.1), which is characterised by significant annual variations in temperature and moderate precipitation.

4.2 Catchment

4.2.1 Size and morphology

The River Narew catchment is a large-sized, lowland, siliceous catchment according to the Water Framework Directive typology (catchment area = 6656 km2, mean elevation = 149.5 m a.s.l.) (Table 4.1).

Table 4.1 Characteristics of the size and morphology of the catchment.

Attribute	Value
Catchment area (km^2)	6656
Elevation (m)	
Mean	149.5
Minimum	102.5
Maximum	260
Elevation – WFD Classes	
<200 m	99.25%
200 – 800 m	0.75%
> 800 m	0%
Relative Relief (m)	157.5
Relative Relief / Longest distance	0.000601

4.2.2 Geology and soils

The River Narew catchment is entirely underlain by siliceous bedrock (Figure 3.6). The surficial geology is dominated by glacial till, sand and loam soils (Figure 4.1). The loamy soils are typically sandy loams, and very heavy impermeable soils (clay, clay loam, silt loam) are rare in the landscape. The main valley bottoms are filled with Holocene peat deposits.

4.2.3 Land cover

The land cover in the River Narew catchment is predominantly agriculture (53%) with arable lands composing 39% and pastures the remaining 14.4%. The second most important land use by area is forests (39.5%). Urban areas cover less than 3% of the catchment (Table 4.2).

Table 4.2 Land cover for the Narew catchment from the CORINE land cover database.

Land use type	Cover [%]
Agriculture: arable lands	39.00
Agriculture: pasture	14.40
Forests	39.50
Urbanisation	2.35
Water	0.30
Wetlands	1.15

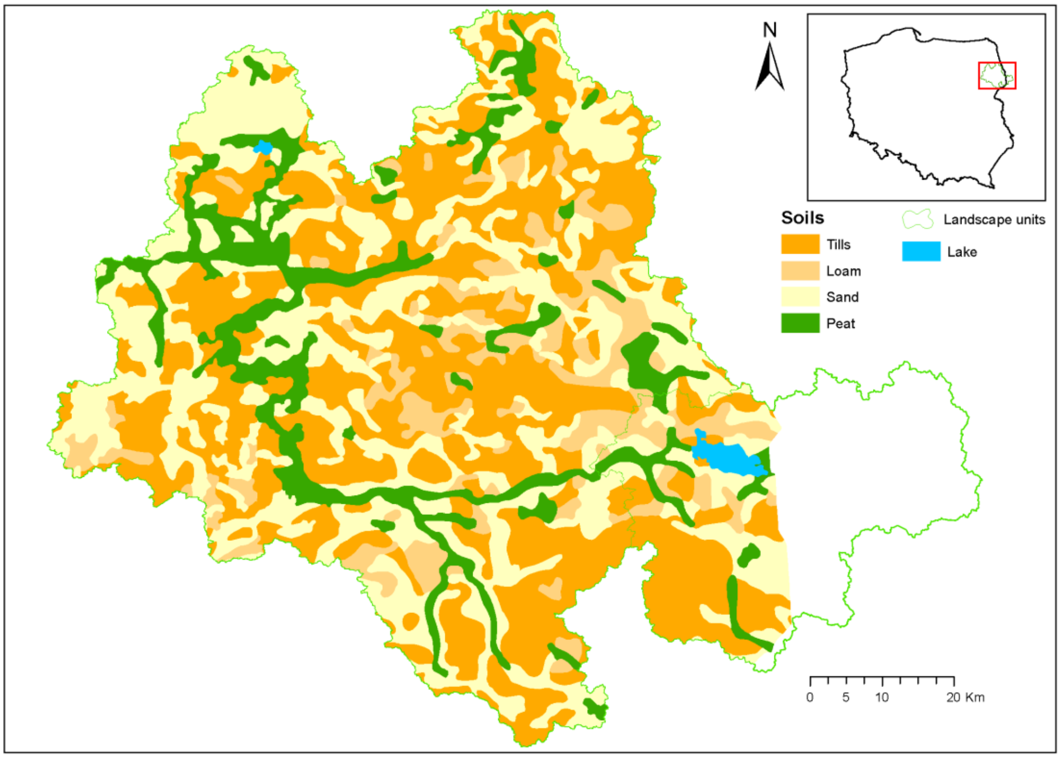


Figure 4.1 Soil map of the Narew catchment.

4.3 Landscape units

4.3.1 Water delivery potential

(i) Rainfall

Historical precipitation records where acquired from the Institute of Meteorology and Water Management – National Research Institute. Rainfall statistics (Table 4.3) were based on the time period 1951-2012 from 20 rainfall gauging stations. Most of gauges were located in Landscape unit 2 (19 stations) and only one station was situated within Landscape unit 1 (Figure 4.2). Average monthly min, mean and max rainfall for the landscape units is presented in Figures 4.3 and 4.4.

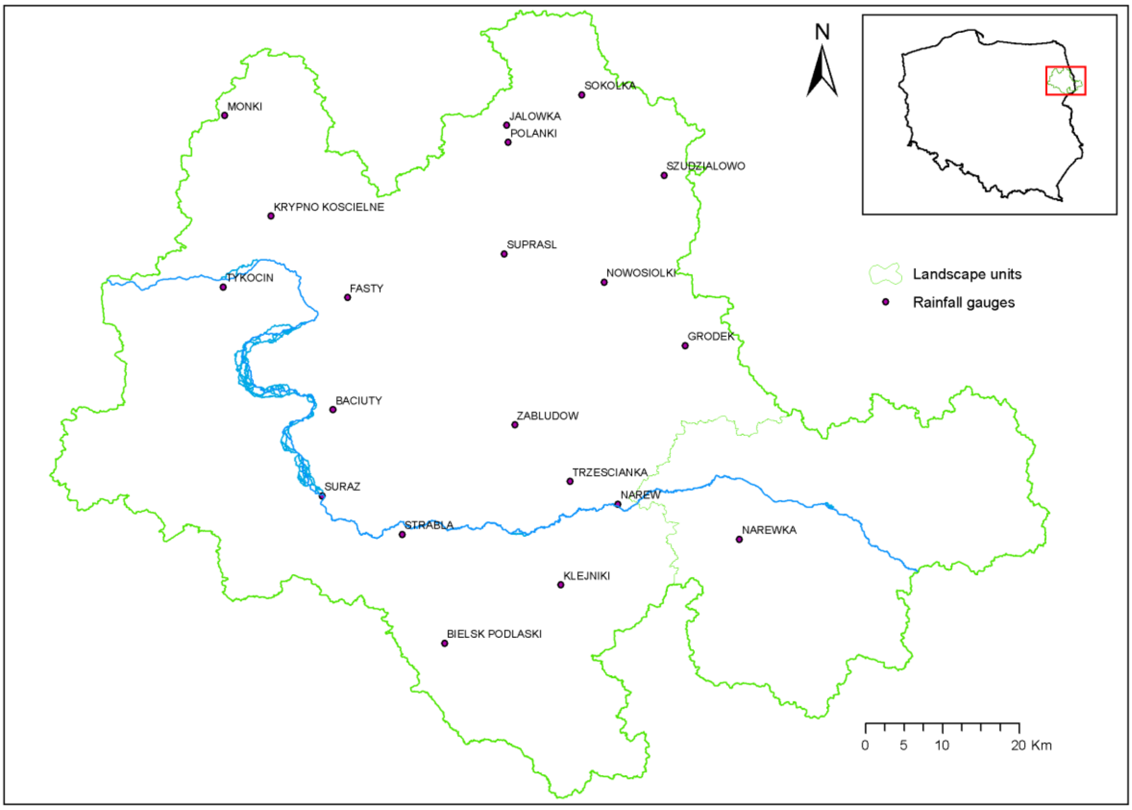


Figure 4.2 Location of Rainfall gauging stations in the Narew catchment.

Table 4.3 Average monthly rainfall statistics in the Narew catchment (1951-2012).

Landscape unit 1	Precipitation [mm]			Landscape unit 2	Precipitation [mm]		
Month	min	mean	max	Month	min	mean	max
Jan	4.0	39.6	119	Jan	6.1	34.2	98.5
Feb	8.0	33.1	70.8	Feb	3.7	30.3	63.2
Mar	10.5	37.2	70.5	Mar	6.0	32.7	72.5
Apr	2.3	39.9	101.3	Apr	4.3	36.4	88.7
May	4.0	64.5	165.1	May	11.4	58.8	133.1
Jun	17.0	65.5	153.8	Jun	22.7	70.1	164.0
Jul	3.3	77.2	183.9	Jul	8.8	80.5	207.7
Aug	5.0	73.6	184.5	Aug	11.2	72.5	221.5
Sep	11.7	58.3	128.5	Sep	12.8	53.7	140.0
Oct	2.4	41.2	117.2	Oct	2.7	43.4	168.6
Nov	11.4	41.9	85.1	Nov	12.6	43.2	84.9
Dec	11.4	44.5	81.7	Dec	9.7	41.1	83.4

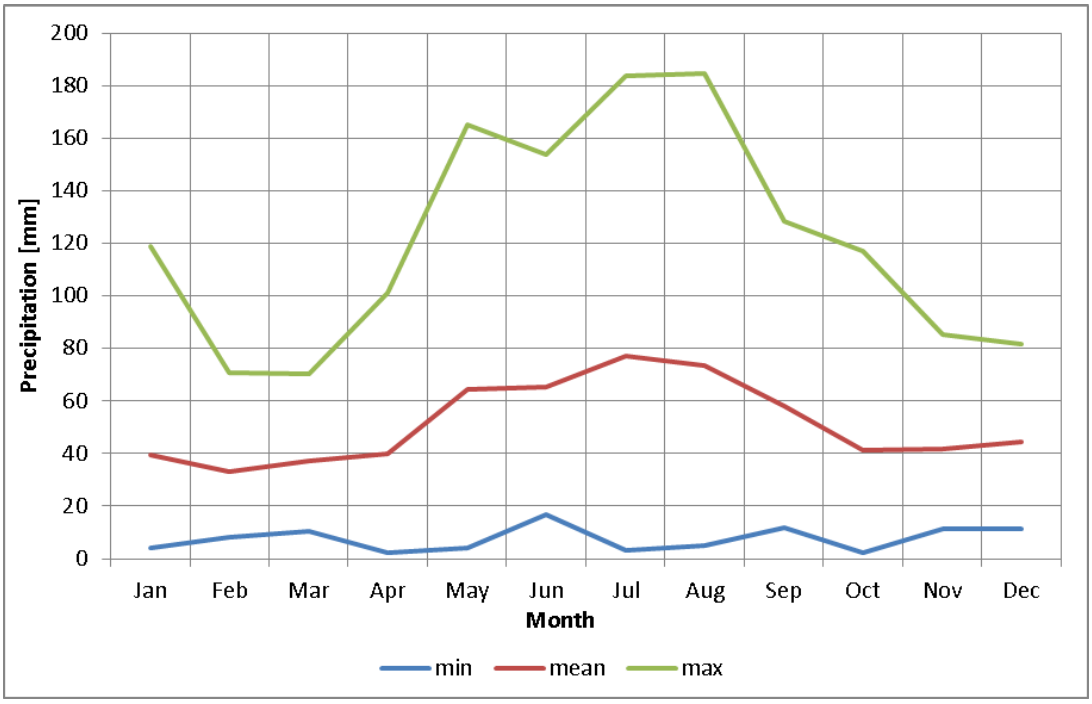


Figure 4.3 Average monthly rainfall statistics for Landscape unit 1 (1951-2012).

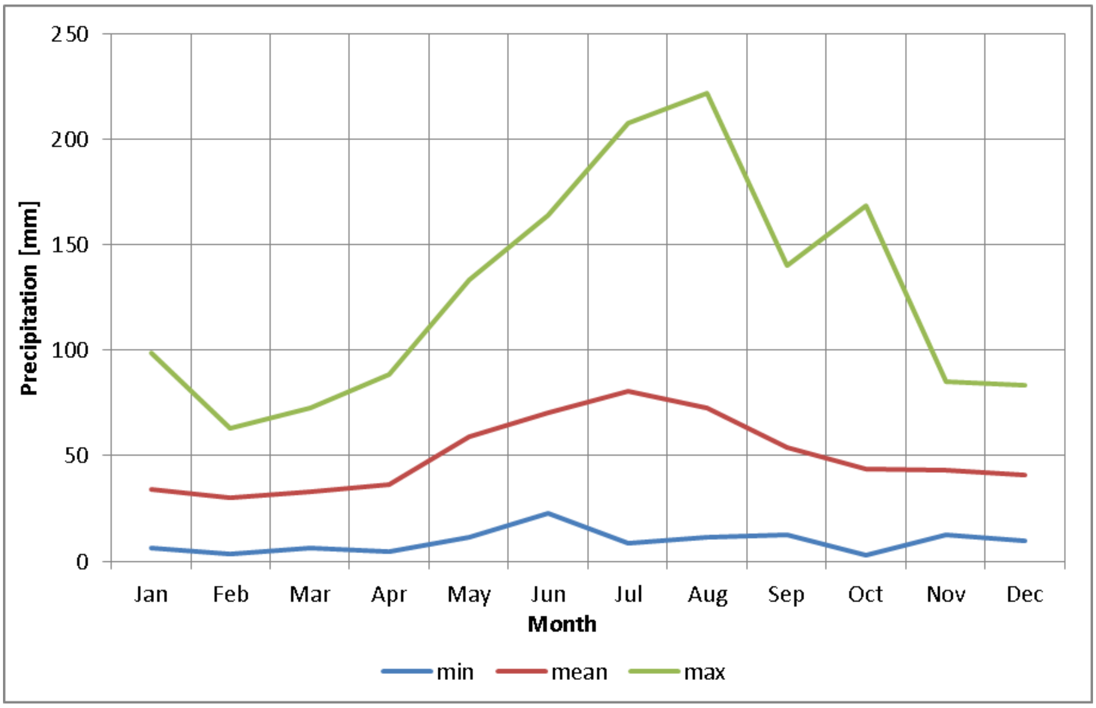


Figure 4.4 Average monthly rainfall statistics for Landscape unit 2 (1951-2012).

(ii) Relief/Topography

The drainage density based on perennial streams equals 0.25 and 0.38 km/km^2 for landscape units 1 and 2, respectively. The drainage density for the derived river streams based on the DTM is 1.04 and 1.07 km/km^2 for landscape units 1 and 2, respectively. A threshold value of 50 hectares was set as a minimum area of flow accumulation to define a stream.

(iii) Surface: groundwater

The description of groundwater in the Narew Catchment was based on the *Geological and hydrogeological characteristic of the verified groundwater bodies* (Polish Geological Institute – National Research Institute, 2009). The region was glaciated during the last two glacial periods: Riss (Oder) 300-230 thousand years ago; and Würm (Vistulian) 115-11.5 thousands years ago. Therefore the entire catchment is composed of alluvial deposits with a number of aquifers in the geological profile. The aquifer underling the upper Narew is unconfined across the entire studied sub-catchment (groundwater body no. 55) (Figure 4.5). The thickness of the water-bearing layer is varied (40 to 60m).

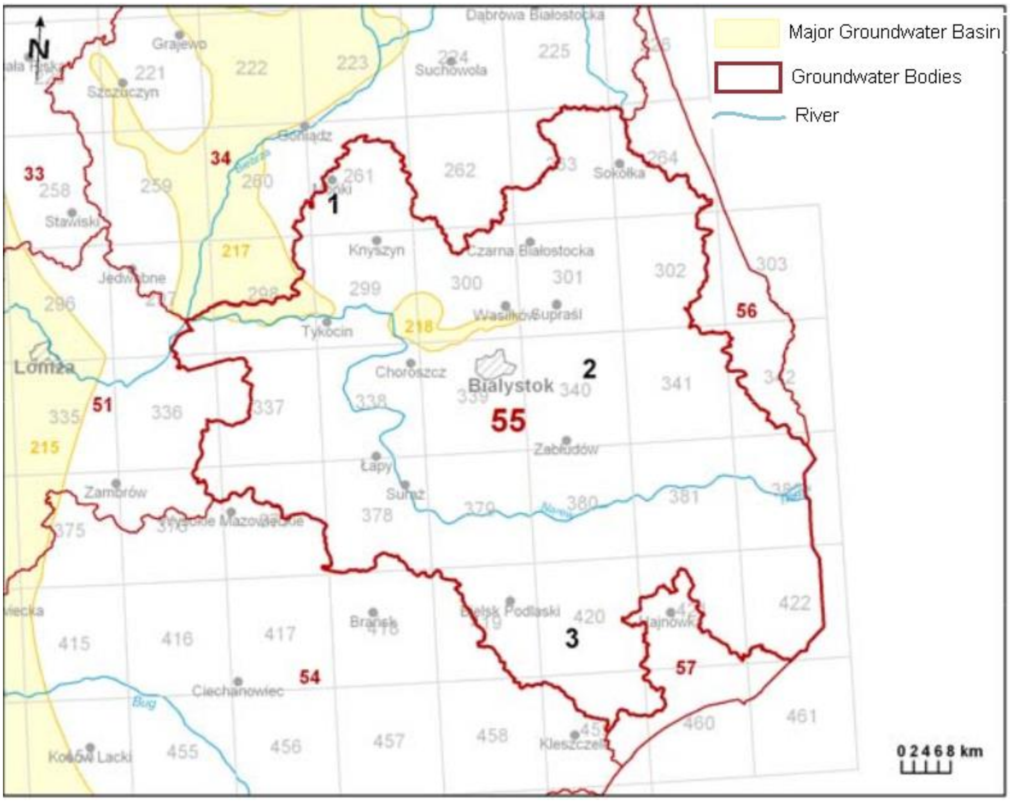


Figure 4.5 Map of groundwater body no. 55 (source: http://pgi.gov.pl).

(iv) Land cover

Land cover is predominantly agricultural (arable lands and pastures) in Landscape Unit 2, and forests in Landscape unit 1 (Table 4.4). Other types of land use (urban, wetlands and water) occupy less than 2% and 5% of the catchment area in LU1 and LU2, respectively.

Table 4.4 Land cover by landscape unit for the River Narew catchment from the CORINE land cover database.

	Landscape unit	
Class	**1**	**2**
Agricultural - Arable	21.1%	44.8%
Agricultural - Pasture	12.7%	17.7%
Forest	64.4%	33.2%
Artifical - Urbanisation	0.3%	2.9%
Water	0.9%	0.2%
Wetlands	0.6%	1.2%

4.3.2 Sediment delivery potential

(i) Potential fine sediment availability

Fine sediment erosion rates are very low for both landscape units in the catchment, as compared to the range across Europe (0 to >50 tons ha-1 year-1, PESERA). The highest erosion rate occurs in Landscape unit 2 (0.57 tons ha-1 year-1) and the average rate equals 0.03 (tons ha-1 year-1) for both LU1 and LU2 (Table 4.5).

Table 4.5 Estimated soil erosion rate by landscape unit (tons ha-1 year-1) (Pan-European Soil Erosion Risk Assessment-PESERA, European Commission, Joint Research Centre).

	Landscape unit	
	1	**2**
Minimum	0	0
Mean	0.03	0.03
Maximum	0.3	0.57

(ii) Potential coarse sediment availability

Visual assessment of aerial imagery of the Narew catchment indicated no coarse sediment sources.

4.4 Segments

In this report, detailed characterisation of the segments focuses on Segment 6 where the anastomosing reaches of Narew National Park are located and the segment immediately upstream (Segment 5) (Figure 4.6).

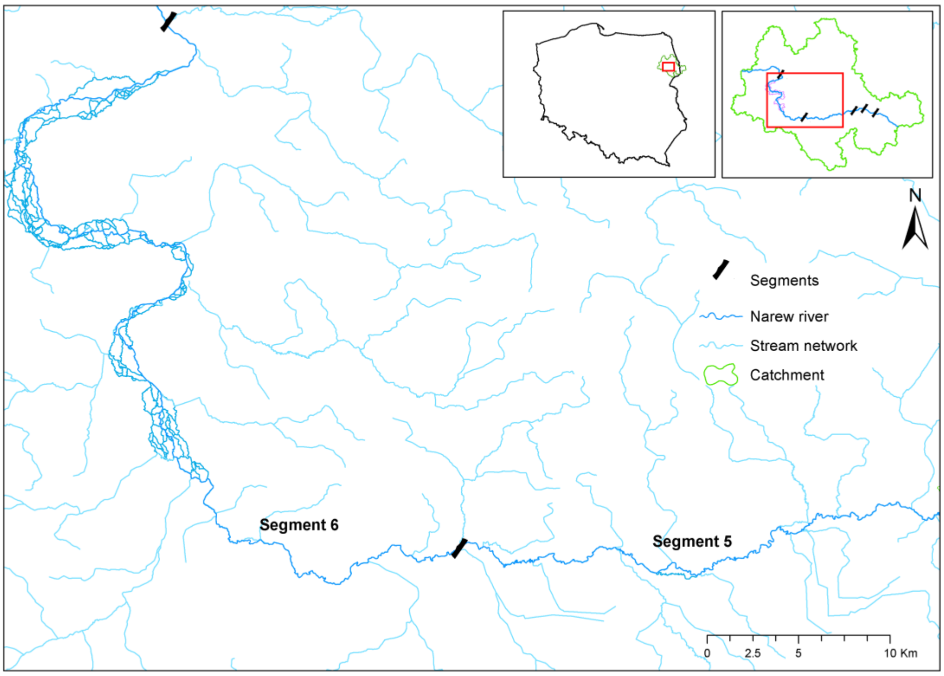


Figure 4.6 Location of the investigated segments in the Narew catchment.

4.4.1 Flow regime

Flow regime analysis was based on the daily flow data record from two gauging stations, the Narew gauge (segment 5) and the Suraż gauge (segment 6). The time period covered by the datasets spanned 1951 to 2012. The most significant structure that currently affects river flows is a dam located at 367km from the source of the River Narew that creates Siemianówka reservoir. The construction was finished in 1991 and from 1992 its impact on the flow regime is noticeable as a reduction in the frequency and magnitude of floods (Figures 4.7 and 4.8) and an increase in baseflow (Table 4.6). Therefore, flow regime analysis was conducted separately for two time periods 1951-1991 (pre-dam) and 1992-2012 (post-dam).

(i) Flow regime classification

The River Narew is currently classified as a perennial stable river. Flow records show that it has a moderate baseflow index (0.5 ≥ BFI ≥ 0.30) for both gauging stations (Table 4.6). Detailed information from the Suraż gauging station indicates that floods occur mainly in spring after snow melt and the duration of the flood varies depending on the external conditions in the catchment (Figures 4.9, 4.10). Prior to the construction of the dam in 1991, the river was classified as having a perennial runoff regime. The increase in baseflow and decrease in flow variability caused by dam operations has shifted the river to a stable flow regime that is characteristic of a groundwater dominated river (Table 4.6), and has reduced the average number of days of floodplain inundation from 31 to 29 (Figure 4.9).

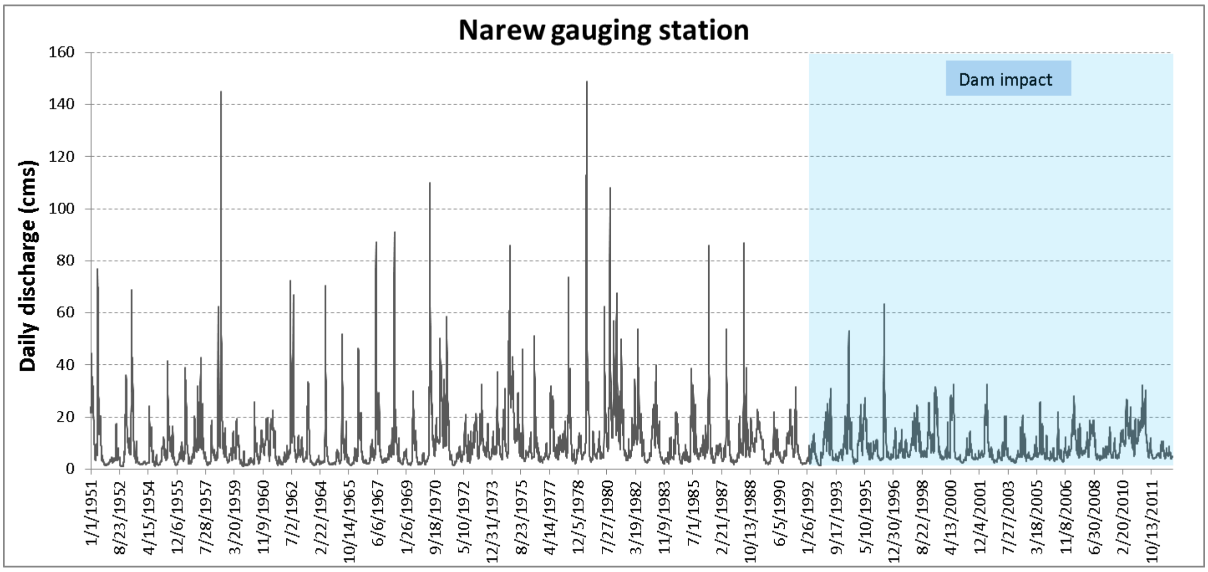


Figure 4.7 Daily discharge in Narew gauging station 1951-2012 (Institute of Meteorology and Water Management – National Research Institute).

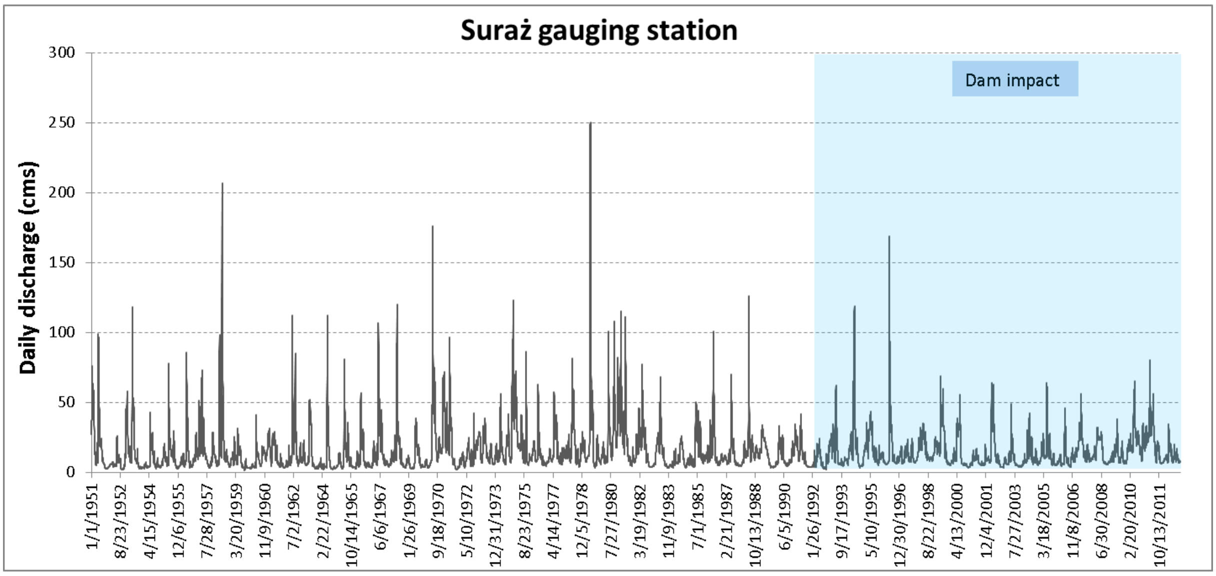


Figure 4.8 Daily discharge in Suraż gauging station 1951-2012 (Institute of Meteorology and Water Management – National Research Institute).

Table 4.6 Hydrological indicators for the 2 gauging stations within the River Narew.

	Segment 5 Narew gauge		Segment 6 Suraż gauge	
	1951-1991	**1992-2012**	**1951-1991**	**1992-2012**
BFI – Baseflow index	0.25	0.41	0.26	0.39
ZERODAYS	0	0	0	0
FLDFREQ *Number of days per year when flow exceeds flood threshold*	0.46	0.57	0.56	0.57
FLDPRED *Maximum proportion of floods (days when flow exceeds flood threshold) that falls in one of six 60-day seasonal windows*	0.63	0.83	0.65	0.92
FLDTIME *First Julian day within the seasonal window with FLDPRED is highest*	60	60	60	60
DAYCV *Standard deviation of daily discharge divided by annual mean discharge (x 100)*	99.28	61.1	94.39	67.92
Regime	Perennial Runoff	Perennial stable (groundwater)	Perennial Runoff	Perennial stable (groundwater)

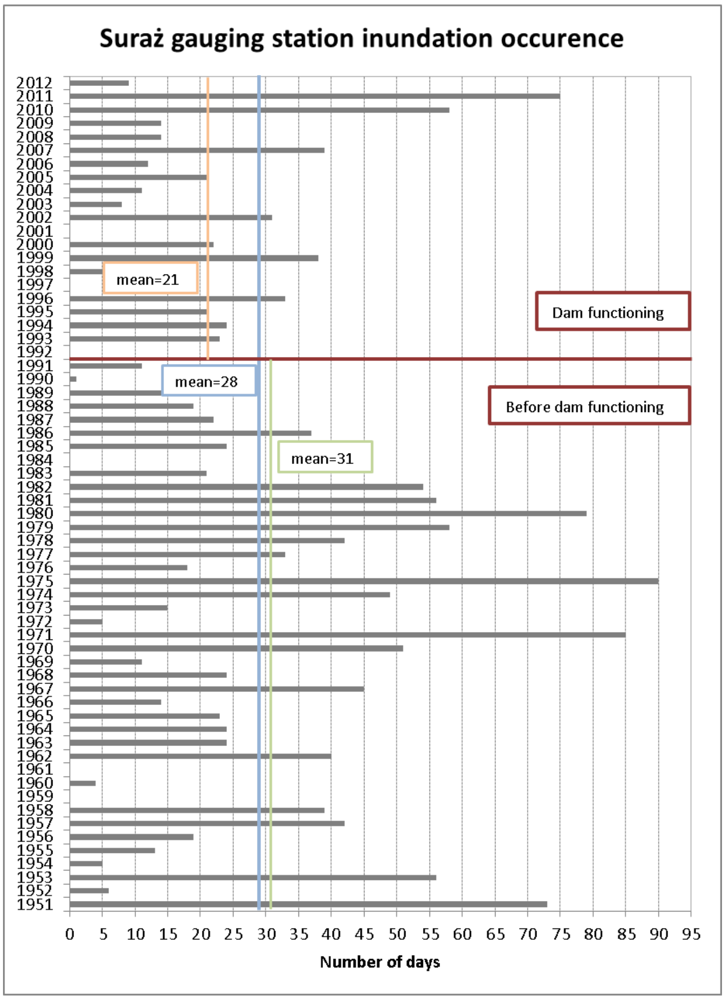


Figure 4.9 Duration of inundation within Narew National Park based on a dataset from the Suraż gauging station.

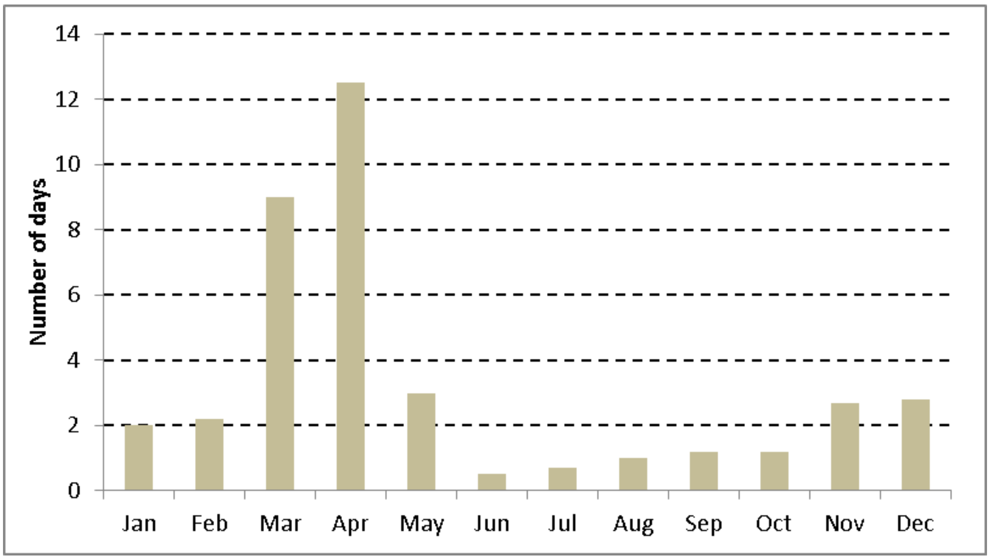


Figure 4.10 Mean monthly distribution of flood duration at the Suraż gauging station (1951-2012).

(ii) Channel forming discharge

Channel forming discharge was estimated at the outlet of each segment based on the relationship between discharge and catchment area for the gauging stations (Tables 4.7 and 4.8). Construction of the dam for the Siemianówka reservoir has caused a significant reduction in channel forming discharge: the current Qp_2 is half of the pre-dam value, and Qp_{10} is approximately a third of the pre-dam value.

Table 4.7 Channel forming discharge by landscape unit based on gauging station records. Qp_{median} – median peak flood, Qp_2 – 2-year return period flood, Qp_{10} – 10-year return period flood.

Segment	Gauging station	Catchment area (km^2)	Discharge (m^3/s)					
			Qp_{median}		Qp_2		Qp_{10}	
			1951-1991	1992-2012	1951-1991	1992-2012	1951-1991	1992-2012
5	Narew	1434	51.0	25.1	51.2	25.8	90.9	32.6
6	Suraż	2892	77.4	49.3	77.4	49.3	123.0	80.1

Table 4.8 Estimated channel forming discharge at the outlet for each segment, based on the sub-catchment area drained by each segment.

Segment	Gauging station	Catchment area (km^2)	Discharge (m^3/s)					
			Qp_{median}		Qp_2		Qp_{10}	
			1951-1991	1992-2012	1951-1991	1992-2012	1951-1991	1992-2012
5	Narew	2101	60.0	30.1	60.4	30.4	107.3	38.5
6	Suraż	3795	101.4	64.6	101.4	64.6	161.1	104.9

(iii) Short term (1 day) and prolonged (30 day) extreme flow conditions and their timing

Extreme flow conditions were calculated using the 61 year-long flow records (in two periods of 40 and 21 years length, representing pre- and post-dam functioning, respectively) and were analysed using the Indicators of Hydrologic Alteration software (v. 7) (Table 4.9, 4.10). Minimum flows in the catchment most commonly occur in early summer (June) and maximum flows in spring (April).

Table 4.9 Discharge (m^3/s) for the short term (1 day) and prolonged extreme flow conditions (30 day) for the gauging stations in the River Narew catchment. Time period before dam construction (1951-1991). 1Q – Lower quartile (25%), Median (50%), 3Q – Upper quartile (75%).

	Segment 5			Segment 6		
	1Q	**Median**	**3Q**	**1Q**	**Median**	**3Q**
Min						
1-day	1.7	2.2	2.8	3.4	4.2	5.7
30-day	2.0	2.6	3.4	3.5	4.3	5.7
Max						
1-day	36.3	54.6	89.0	55.0	95.6	144.1
30-day	24.9	33.9	47.3	41.3	59.4	82.0
Mean annual		9.86			15.56	

Table 4.10 Discharge (m^3/s) for the short term (1 day) and prolonged extreme flow conditions (30 day) for the gauging stations in the River Narew catchment. Time period during which the dam was functioning (1991 – 2012). 1Q – Lower quartile (25%), Median (50%), 3Q – Upper quartile (75%).

	Segment 5			Segment 6		
	1Q	**Median**	**3Q**	**1Q**	**Median**	**3Q**
Min						
1-day	2.9	4.1	4.6	4.7	6.7	8.1
30-day	3.6	4.5	5.3	5.5	7.6	9.4
Max						
1-day	18.9	29.7	37.4	44.5	62.6	84.3
30-day	15.7	22.7	29.1	34.3	45.7	56.3
Mean annual		8.43			14.23	

(iv) Annual pattern of monthly flows

The annual hydrographs for the 2 gauging stations demonstrate the characteristic temporal patterns in flow for Polish Plain, low energy rivers (Figures 4.11 and 4.12). Discharge is lowest in summer and winter months (June-January) and begins to increase in spring to reach the maximum flows in April due to snow melt.

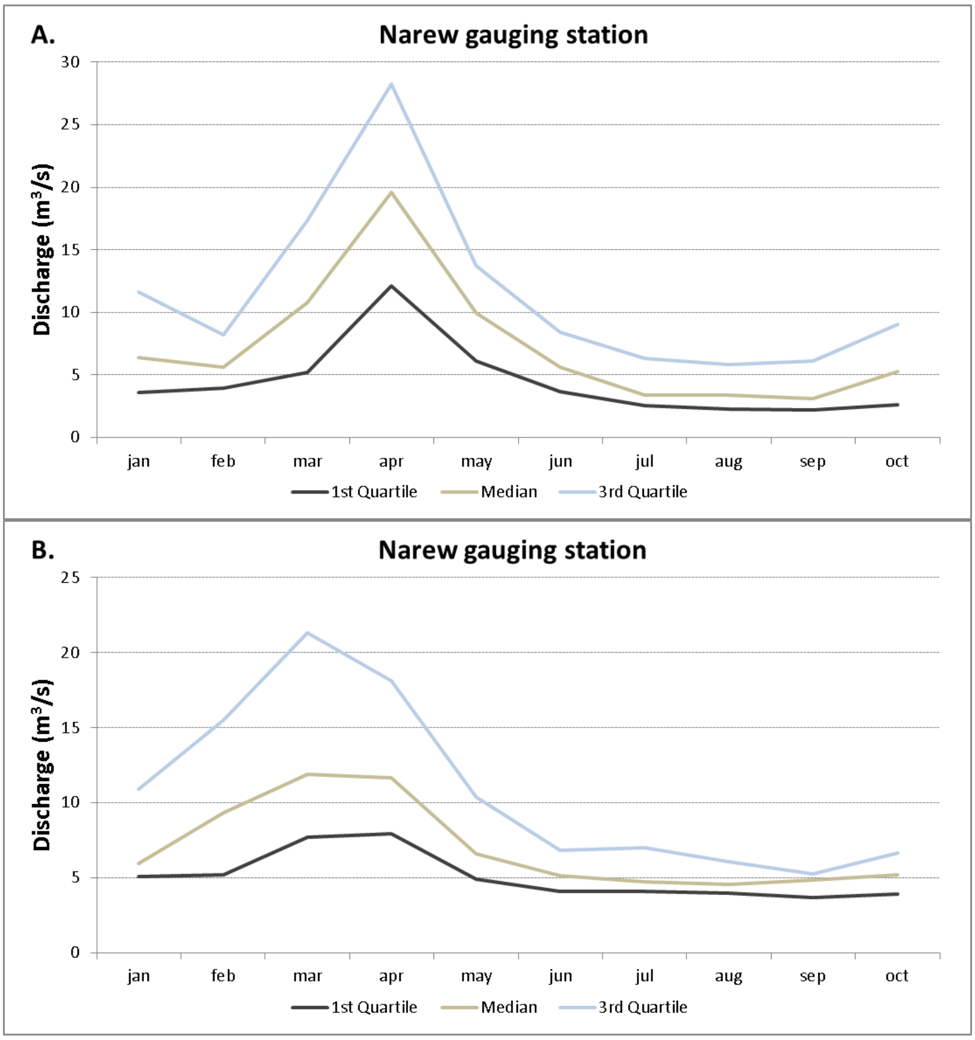


Figure 4.11 Mean annual month discharge at Narew gauging station (A) – before dam functioning, (B) – after dam construction.

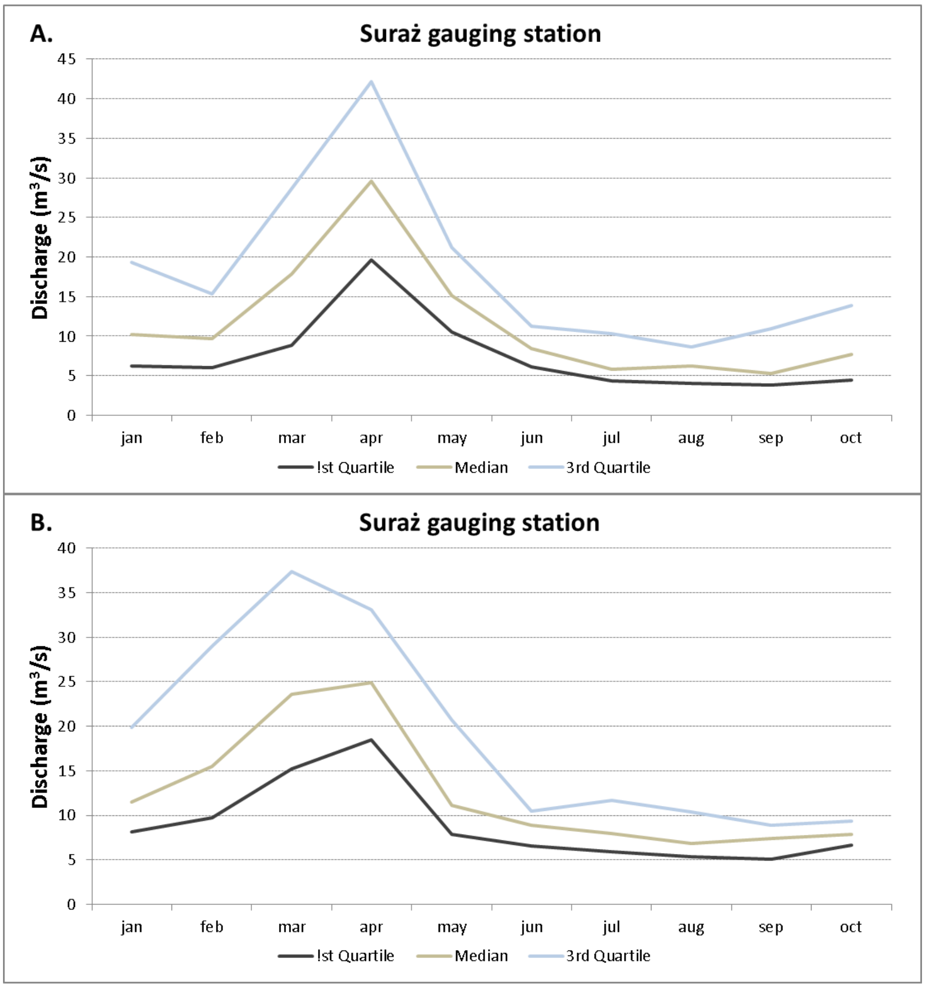


Figure 4.12 Mean annual month discharge at Suraż gauging station (A) – before dam functioning, (B) – after dam constructing.

4.4.2 Valley characteristics

The River Narew is a low gradient, unconfined river in both Segment 5 and 6 (Table 4.11). There is no valley or river channel confinement in either segment; the valley is 86-101 times greater than the channel width.

Table 4.11 Valley characteristics for the segments of the River Narew. River confinement index was calculated using the channel width (sum of all channels widths in a cross section).

Segment	Gradient	Valley Confinement	River Confinement Index
5	0.00024	Unconfined	101
6	0.00019	Unconfined	86

4.4.3 Sediment

The dominant bed material is fine and coarse sand for all segments in the River Narew (Banaszuk 2004, Gradziński 2003).

4.4.4 Riparian corridor features

(i) Presence of a riparian corridor

The River Narew is a lowland, low energy river with minimal floodplain topographical variation and no artificial embankments, and thus is potentially subject to inundation over nearly its entire length and the area of the valley. Therefore riparian corridor is synonymous with the non-developed portions of the floodplain, where riparian vegetation has the potential to grow. Table 4.12 lists the width and area of the riparian corridor and functioning riparian vegetation in two segments of the Upper Narew Catchment. The riparian corridor in segment 6 is over two times wider than in segment 5 and occupies and area that is almost four times larger. The only human activity recorded in the valley is grass mowing in patches concentrated near villages. The areas of naturally growing native grasses where seasonal mowing is performed were included in the riparian vegetation area despite the human activities and management. Harvesting frequency is usually two to three times a year in this region of Poland. The mowing operation will significantly impact on biodiversity and the response of the environment is complex and depends on the timing of the harvest (Humbert et al. 2012). The most important influence on the meadow ecosystem is the prevention of the natural succession of shrubs and further forestation of the valley. The proportion of the riparian corridor under riparian vegetation and the riparian corridor continuity are 100% in both segments.

Table 4.12 Characteristics of the riparian corridor: average width, average area, proportion of riparian corridor with vegetation.

Segment	Riparian corridor		Riparian vegetation		Proportion of corridor under riparian vegetation	
	Width (m)	Area (km^2)	Width (m)	Area (km^2)	Width	Area
5	730	26.4	730	26.4	100%	100%
6	1700	96.9	1700	96.9	100%	100%

(ii) Structure of the riparian corridor

The prevailing vegetation type recorded in the riparian corridor in both segments is sedge communities, which occupy 41% of the riparian corridor. In segment 5 the second most frequently occurring vegetation is grass communities (34%) and the third is reed communities (16%). Trees cover only 8% of the corridor area in Segment 5. Segment 6 has a similar proportion of the corridor under early and mature vegetation types as Segment 5, but reeds are more abundant than grasses (28% and 19%, respectively) (Table 4.13).

Table 4.13 Proportion of vegetation by type in segment 5 and 6.

Vegetation Type	segment 5	segment 6
Sedge	41%	41%
Reed	16%	28%
Grass	34%	19%
Trees	8%	10%
Other	0%	1%

(iii) Wood delivery potential

Analyses of satellite imagery indicate that the proportion of the active river channel edge (bank top and island margins) covered by mature (living or dead) trees is zero. No trees were observed along the banks of the Narew in the study segments, therefore there is no potential for wood delivery within this stretch of the river.

4.4.5 Physical pressures

Human-made artificial constructions have a minor impact on river continuity and sediment flow in segment 5 (5 spanning structures inventoried and no weirs and dams). In segment 6 two large weirs were identified. Considering the very low gradient of the river, the weirs significantly affect water level causing impoundment effects for hundreds of meters upstream and constituting a barrier to sediment transport (Figure 4.13).

Other structures present in the anastomosing part of segment 6, in both the main and side channels, are minor (less than 1 m crest height), and are typically old wooden dams built by local residents in the past and submerged during normal flows (Figures 4.14 and 4.15). The most likely function of the dams was for watermills and to create access to the water for cattle. The result of these structures was the permanent or temporary alteration of discharge distribution between particular channels. Currently none of the dams are functioning due to damage caused by floods. In most cases the only visible evidence of a former dam are pieces of wood and stones remaining in the channel, noticeable during low flows or as a result of their effects on surface flow characteristics. These relict dams have very low to no impact on the flow of water and sediment in the channels.

Figure 4.13 One of the two significant blocking structures found in Segment 6.

Figure 4.14 Example of visible effect of relict dam now entirely underwater.

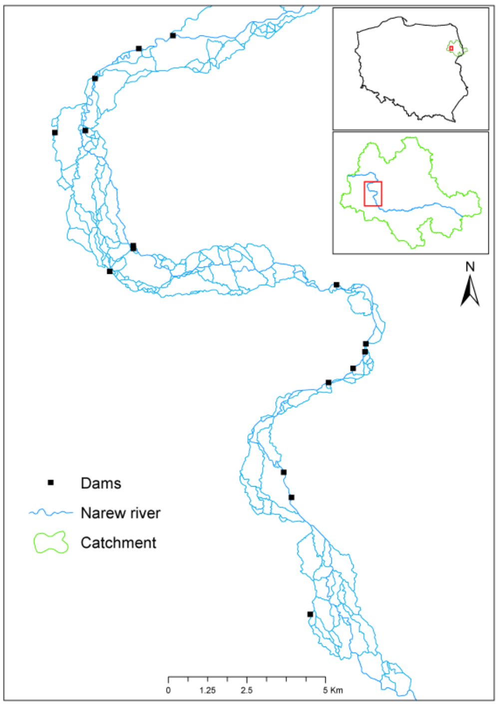


Figure 4.15 Locations of old wooden dams within Narew National Park.

4.5 Reach

Reach-level characterisation focuses on the anastomosing section of the river located within Narew National Park, which comprises 5 reaches in segment 6 (Figure 4.16).

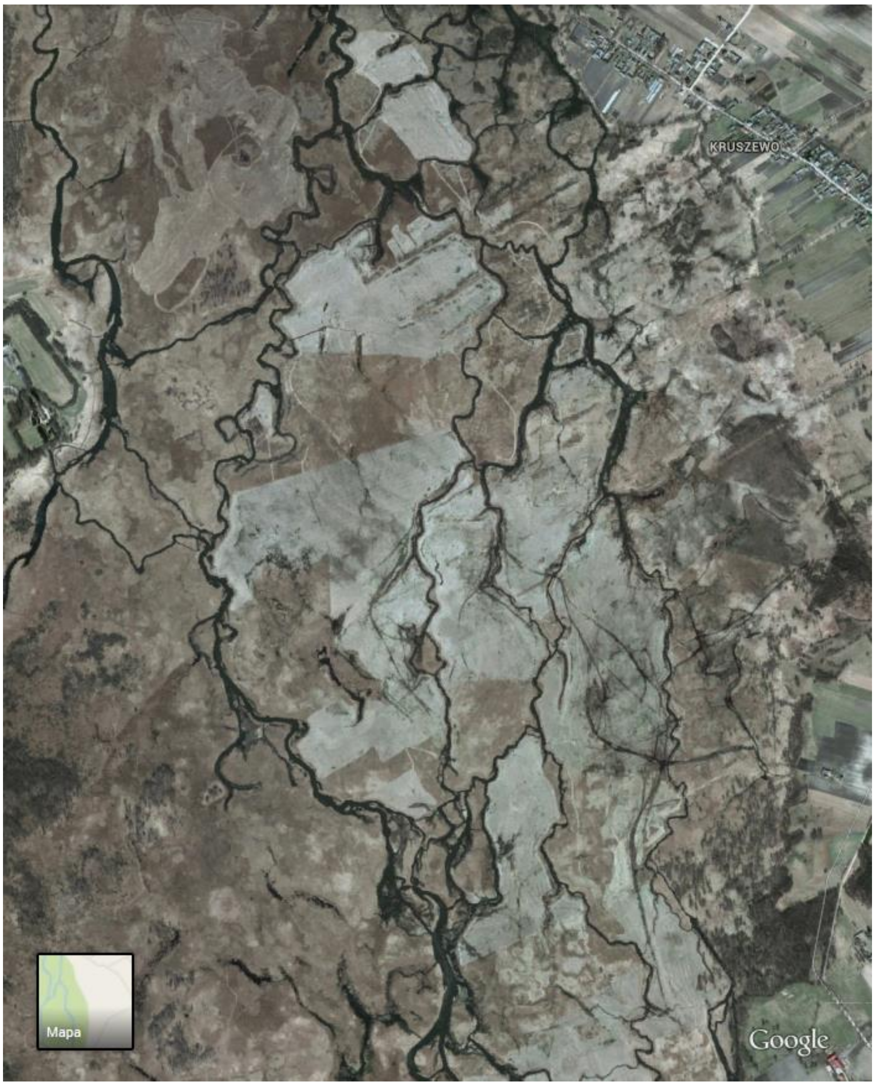


Figure 4.16 The multi-thread character of the River Narew (a part of the Reach 29) (source: http:\\google.maps.pl).

4.5.1 Channel dimensions

The anastomosing reaches are multi-thread, unconfined river stretches with very high anabranching indices (from 2.7 in reach 27 to 5.4 in reach 29). The sinuosity index for the main channel varies from 1.03 (reach 27) to 1.48 (reach 28) and the braiding index is equal to the anastomosing index for all reaches as all bars are completely vegetated (Table 4.14). Channel dimensions (Table 4.15) for the reaches were derived from satellite imagery and field measurements. Total channel width includes all major side channels and the main channel.

Table 4.14 Gradient and planform indices for the River Narew anastomosing reaches.

Reach	River confinement	Threads	Planform	Sinuosity	Braiding index	Anabranching index
26	Unconfined	Multi-thread	Anabranching	1.30	5.3	5.3
27	Unconfined	Multi-thread	Anabranching	1.03	2.7	2.7
28	Unconfined	Multi-thread	Anabranching	1.48	3.3	3.3
29	Unconfined	Multi-thread	Anabranching	1.27	5.4	5.4
30	Unconfined	Multi-thread	Anabranching	1.11	3.8	3.8

Table 4.15 Average channel dimensions for the anastomosing reaches in the River Narew.

Reach	All channels Width (m)	Main Channel		
		Width (m)	Depth (m)	W:D
26	26.5	20.0	1.7	11.8
27	27.6	24.2	1.8	13.4
28	26.4	21.1	2.2	9.6
29	25.9	17.5	2.1	8.3
30	28.6	22.7	1.8	12.6

4.5.2 River energy

Total stream power is the lowest in Reach 27 and highest in Reach 30 (Tables 4.16, 4.17, 4.18). Specific stream power reflects a similar trend of increase from upstream to downstream reaches (with the exception of Reach 27 which has the lowest value). Although similar trends in stream power exist for both time periods (pre- and post-dam), total and specific stream power are substantially lower post-dam construction.

The River Narew over-tops its banks for a period of weeks every year in the NNP, and the average water stage in the channels is close to bankfull. Therefore estimates of morphologically-relevant discharge based on the max annual flow likely overestimate total and specific stream power. Gradzinski et al. (2003) suggest a specific stream power of 2-3 W m^{-2}, which is similar to but less than our estimates based on $Q_{pmedian}$ and Q_{p2} during the post-dam period.

Table 4.16 Average total stream power and specific stream power of the river Narew for the studied anastomosing reaches (based on Qp_{median}).

Reach	Total power (1951-1991) (W m $^{-1}$)	Total power (1992-2012) (W m $^{-1}$)	Specific power (1951-1991) (W m $^{-2}$)	Specific power (1992-2012) (W m $^{-2}$)
26	129.8	82.7	4.9	3.1
27	81.1	51.7	2.9	1.9
28	138.1	88.0	5.2	3.3
29	134.5	85.6	5.1	3.2
30	194.2	123.7	6.8	4.3

Table 4.17 Average total stream power and specific stream power of the river Narew for the studied anastomosing reaches (based on Qp_2).

Reach	Total power (1951-1991) (W m $^{-1}$)	Total power (1992-2012) (W m $^{-1}$)	Specific power (1951-1991) (W m $^{-2}$)	Specific power (1992-2012) (W m $^{-2}$)
26	129.8	82.7	4.9	3.1
27	81.1	51.7	2.9	1.9
28	138.1	88.0	5.2	3.3
29	134.5	85.6	5.1	3.2
30	194.2	123.7	6.8	4.3

Table 4.18 Average total stream power and specific stream power of the river Narew for the studied anastomosing reaches (based on Qp_{10}).

Reach	Total power (1951-1991) (W m $^{-1}$)	Total power (1992-2012) (W m $^{-1}$)	Specific power (1951-1991) (W m $^{-2}$)	Specific power (1992-2012) (W m $^{-2}$)
26	207.7	132.3	7.8	5.0
27	129.8	82.7	4.7	3.0
28	220.9	140.7	8.4	5.3
29	215.1	137.0	8.3	5.3
30	310.7	197.9	10.9	6.9

4.5.3 Bed and bank sediment

(i) Sediment size

Channel bed sediment is predominantly medium to coarse-grained sand (Gradzinski et al. 2003). Fine sediment can be found along with plant detritus as laminae within the sand, but it also forms thick deposits in slow-moving or abandoned channels. The area between the channels (i.e. islands), and thus the channel banks as well, are composed of peat derived primarily from sedge and reed organic material, but also contain between 9% and 50% mineral material (sand).

(ii) Lateral sediment delivery

Fine sediment delivery to the River Narew (within segment 5 and 6) is estimated at 103 tons $year^{-1}$ (0.85 tons km^{-1} $year^{-1}$), based on the PESERA dataset and a river valley shape as an active buffer zone from which sediment has easy access to the river. At the reach scale, the valley surrounding reaches 26-30 is completely filled with organic soils and peat (which is resistant to erosion), and sediment delivery is predicted to be negligible (calculation based on the PESERA model).

4.5.4 Riparian and aquatic vegetation

(i) Riparian vegetation and large wood

Within the Narew National Park, detailed maps inventorying plant communities and prevailing species in each community are available (Banaszuk et al. 2004). Based on the maps, a generalized structure of vegetation type within the anastomosing reaches is presented in Figures 4.17 and 4.18. As shown, the dominant vegetation type, covering from 38 to 58% of the valley area in each reach, is sedge, whilst the second most frequently identified is reed (up to 46% in reach 29). In this system sedges and reeds would be considered pioneer vegetation types that would be succeeded by trees and shrubs over time. Mature trees and scrub cover only 10 to 19% of the area mostly at the edges of the valley. Grass constitutes 6% (reach 29) to 16% (reach 26) of the riparian corridor area. Reaches in the Narew National Park predominantly consists of large areas of similar vegetation structure. However, patches of trees and other vegetation are visible particularly along the edges of the riparian corridor (Figures 4.17, 4.18). Table 4.19 lists the plant species that commonly occur in the anastomosing part of the Narew valley. Plant diversity is high in the system, and over 600 species have been recorded within the NNP (Banaszuk et al. 2004).

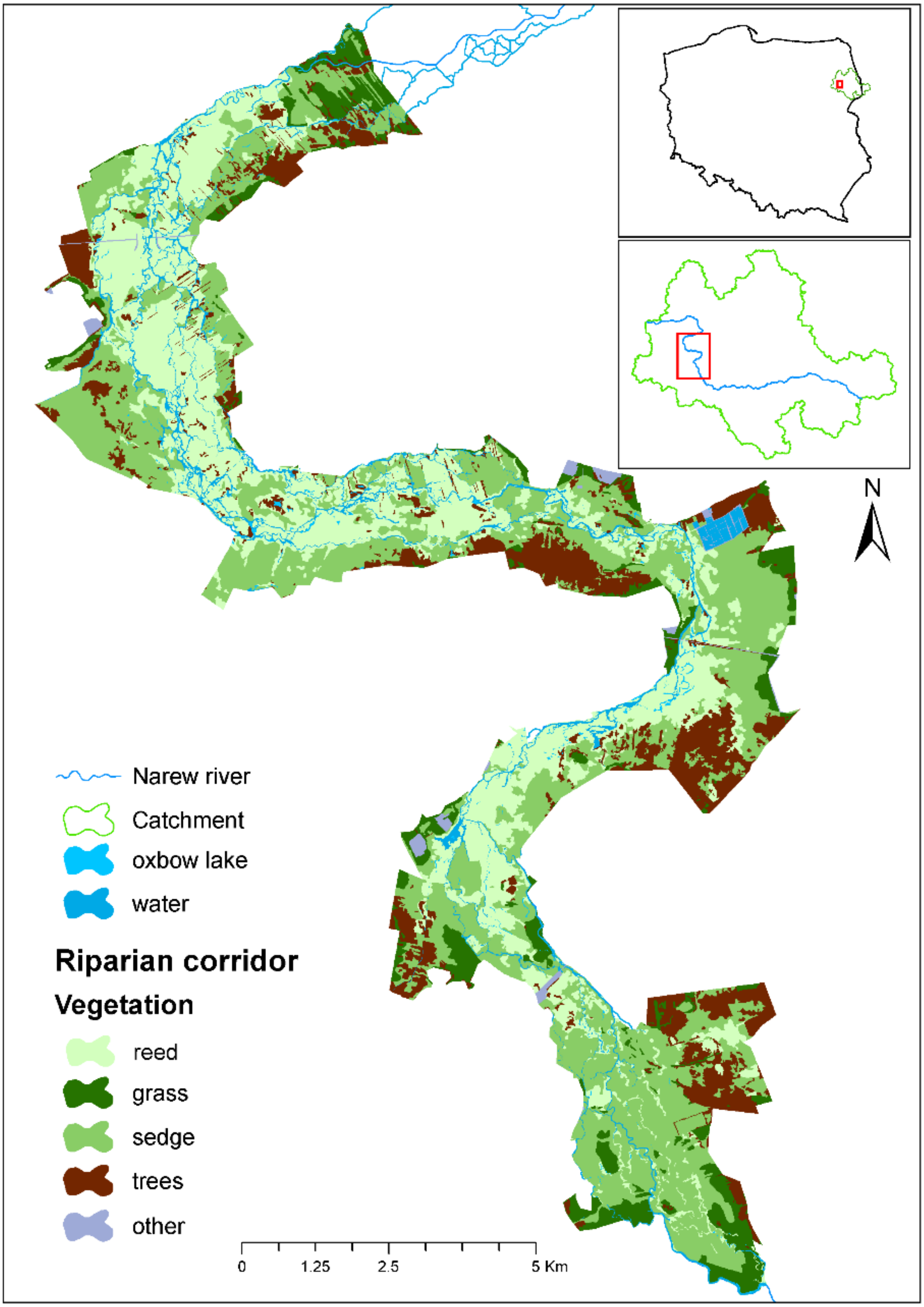


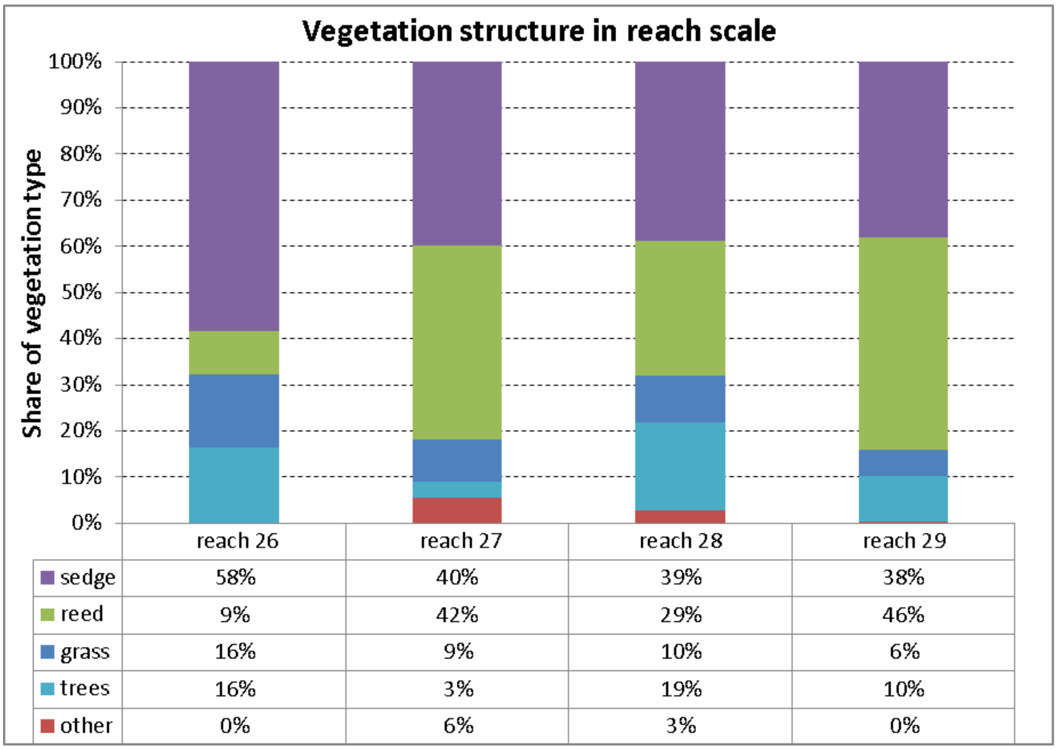
Figure 4.17 Map of the riparian corridor vegetation within the NNP.

Table 4.19 Most commonly inventoried plants within NNP (Banaszuk et al. 2004).

Species	Type	Species	Type
Acorus calamus	monocot	*Lysimachia vulgaris*	herb
Agrostis stolonifera	graminoid	*Phalaridetum arundinaceae*	rushes
Alopecurus geniculatus	graminoid	*Phalaris arundinacea*	bunchgrass
Barbarea stricta	herb	*Phragmites australis*	reed
Betula pubescens	woody	*Pinus silvestris*	woody
Bidens cernua	herb	*Poa palustris*	graminoid
Bidens tripartita	herb	*Polygonum hydropiper*	herb
Calamagrostis canescens	graminoid	*Polygonum mite*	herb
Calamagrostis stricta	bunchgrass	*Polytrichum strictum*	moss
Calystegia sepium	herb	*Ranunculus flammula*	herb
Carex acutiformis	sedge	*Ranunculus repens*	herb
Carex appropinquata	sedge	*Rorippa amphibia*	herb
Carex nigra	sedge	*Rorippa palustris*	herb
Carex vulpina	sedge	*Salix cinerea*	woody
Cirsium arvense	herb	*Sphagnum fimbriatum*	moss
Comarum palustre	herb	*Sphagnum nemoreum*	moss
Drepanocladus revolvens	moss	*Sphagnum palustre*	moss
Eriphorum angustifolium	sedge	*Stachys palustris*	herb
Filipendula ulmaria	herb	*Symphytum officinale*	herb
Galium aparine	herb	*Typha angustifolia*	herb
Glyceria fluitans	graminoid	*Urtica dioica*	herb
Glycerietum maximae	rushes	*Veronica beccabunga*	herb
Lathyrus palustris	herb		

(ii) Aquatic vegetation

The abundance of aquatic vegetation in river channels depends on the water depth and current velocity. Active channels deeper than 2 m are free of vegetation (Figure 4.19) but shallower stretches are promptly colonized (Gradziński et al. 2003) (Figures 4.20, 4.21). The first species which appears is arrowhead (*Sagittaria sagittifolia*), an emergent herbaceous perennial plant, commonly growing in standing, or slow-moving water, from 10–50 cm deep) followed by perennial Yellow Water-lily (*Nuphar lutea*), which grows in shallow water and wetlands, with its roots in the sediment and its leaves floating on the water surface: it can grow in water up to 5 metres deep. Sluggish-water and inactive channels are rather densely covered with numerous species of aquatic plants. Especially abundant is water soldier (*Stratiotes aloides*), a submerged aquatic perennial plant, accompanied by common frogbit (*Hydrocharis morsusranae*), which can be a submerged or floating aquatic perennial plant, and common duckweed (*Spirodela polyrhiza*), a perennial aquatic plant usually growing in dense colonies that form a mat on the water surface.



	reach 26	reach 27	reach 28	reach 29
sedge	58%	40%	39%	38%
reed	9%	42%	29%	46%
grass	16%	9%	10%	6%
trees	16%	3%	19%	10%
other	0%	6%	3%	0%

Figure 4.18 Proportion of the riparian corridor covered by different types of riparian vegetation.

Figure 4.19 An example of typical wide main channel in Reach 29. The channel is 4 m deep, free of aquatic vegetation, and bordered with common reed.

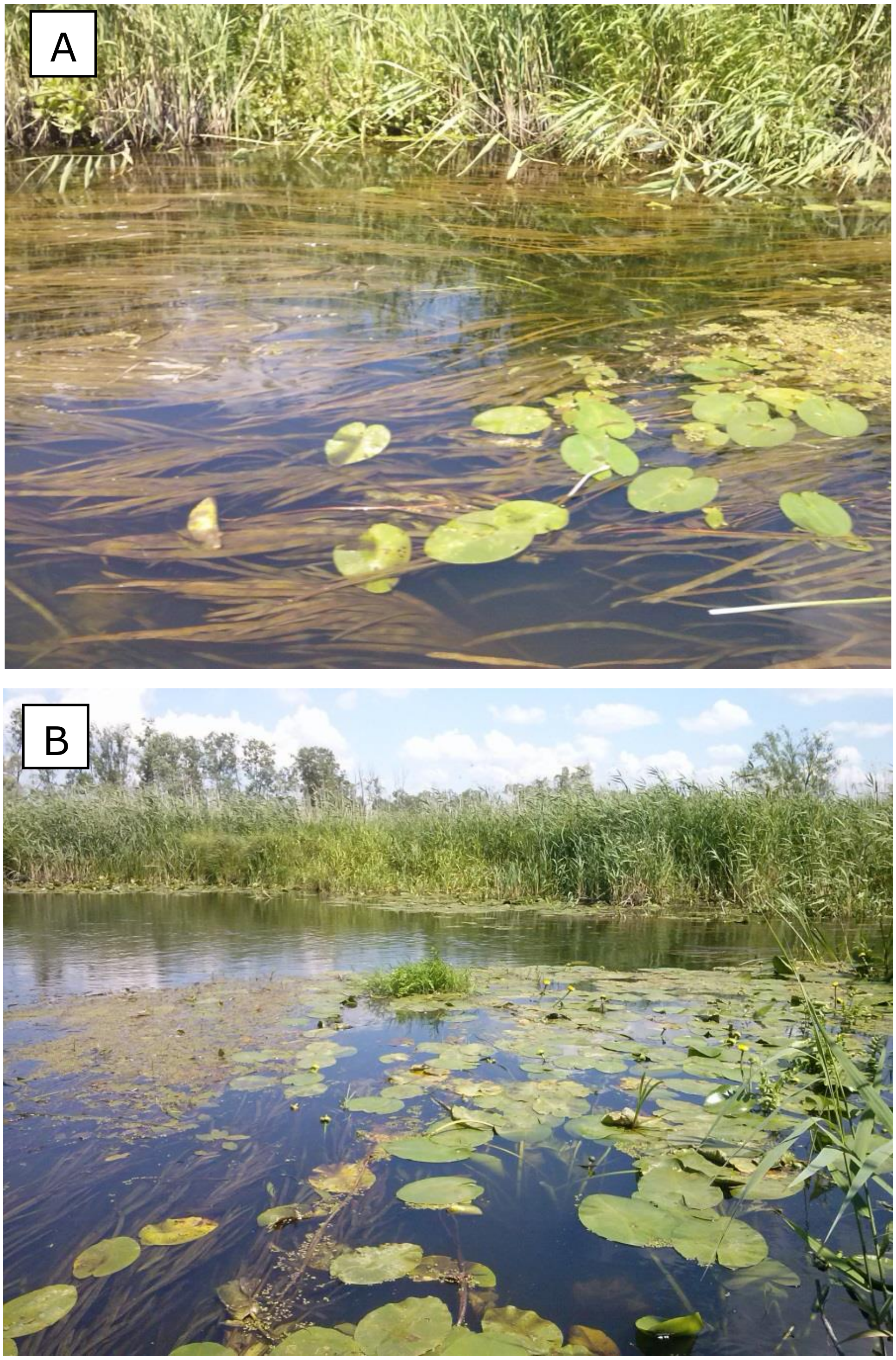


Figure 4.20 Examples of shallow stretches of Reach 29 colonised by vegetation.

Figure 4.21 An example of a shallow side channel completely colonized by water soldier (*Stratiotes aloides*). (In the active channel, water depth reaches 0.5m).

4.5.5 Physical pressures

(i) River Bed condition

The bed of the River Narew is entirely composed of natural material. No data is available on the removal of sediment, wood or aquatic vegetation from the active river channel. Since the valley has formal protection (National Park 1996), activities that are permitted are very restricted and must not cause a negative impact on the habitat.

(ii) River Bank condition and processes

Banks of the anastomosing reaches are usually very steep or nearly vertical and extremely resistant to erosion because of the stabilizing force of peat layer and plant roots (Figure 4.22). Steepness of the banks was supported by 190 cross-sections made in reach 28 and 29 (Figures 4.23, 4.24). Where it does occur, bank erosion is identified by the presence of peat blocks within the channel, however it occurs only exceptionally within the anastomosing reaches in few short sections along the banks (Figure 4.25). It indicates that the protective nature of riparian vegetation, erosion resistance of the peat layer, and low specific stream power result in the negligible lateral erosion of the Narew River channels and lateral stability of the internode reaches of the river. Due to the legal provisions within the borders of the Narew National Park (the major and most restricted form of environmental protection in Polish law), management in the Park is strictly controlled and activities potentially harmful to the environment are forbidden. On the entire length of the river (reaches 26 to 29) there were no stretches where the bed or banks were altered or regulated by human activities.

Figure 4.22 Examples of entirely vegetated river banks stabilized by roots of common reed and sedge.

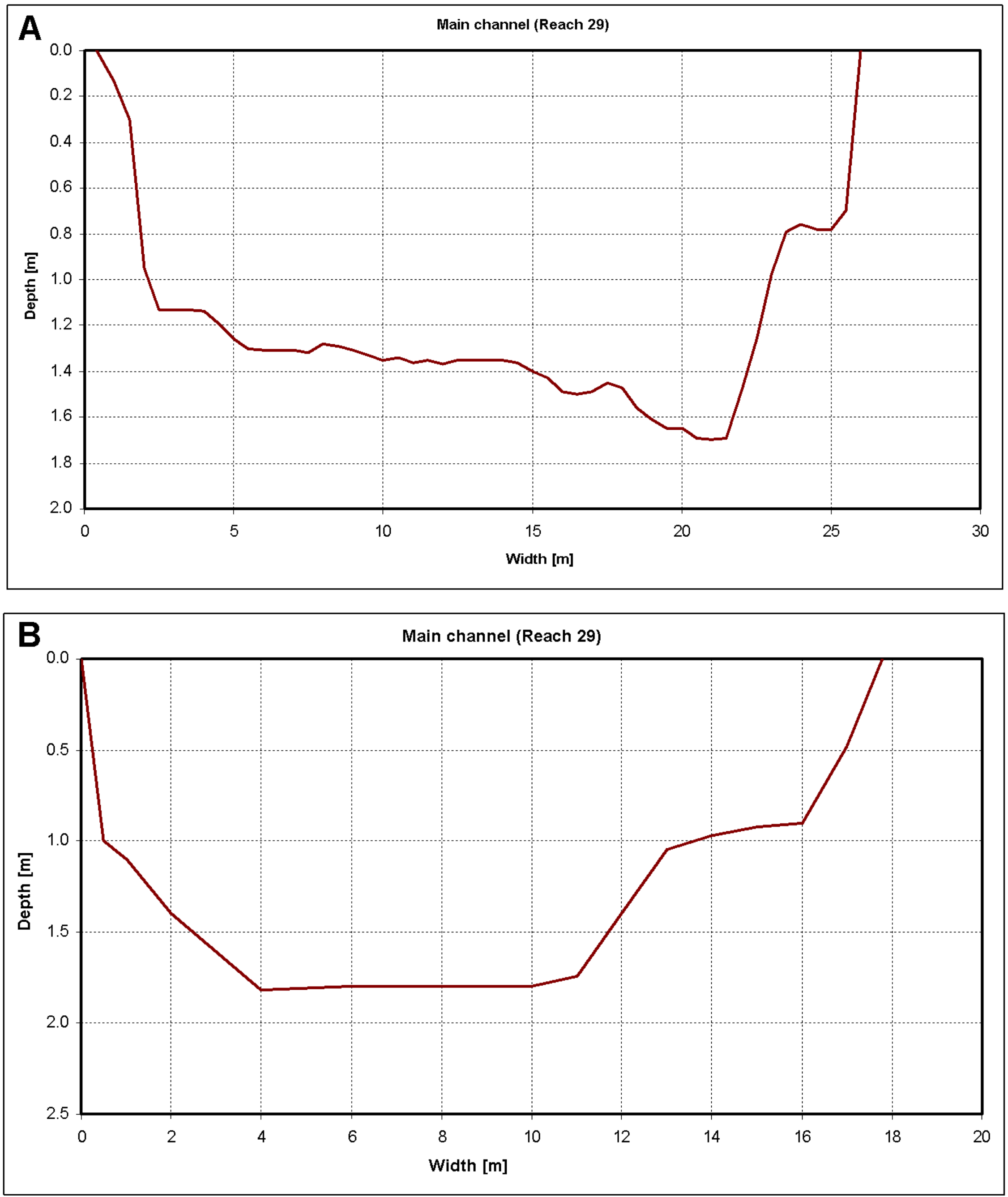


Figure 4.23 Example cross-sections of the main channel (Reach 29): A. downstream part of the reach; B. upstream part of the reach.

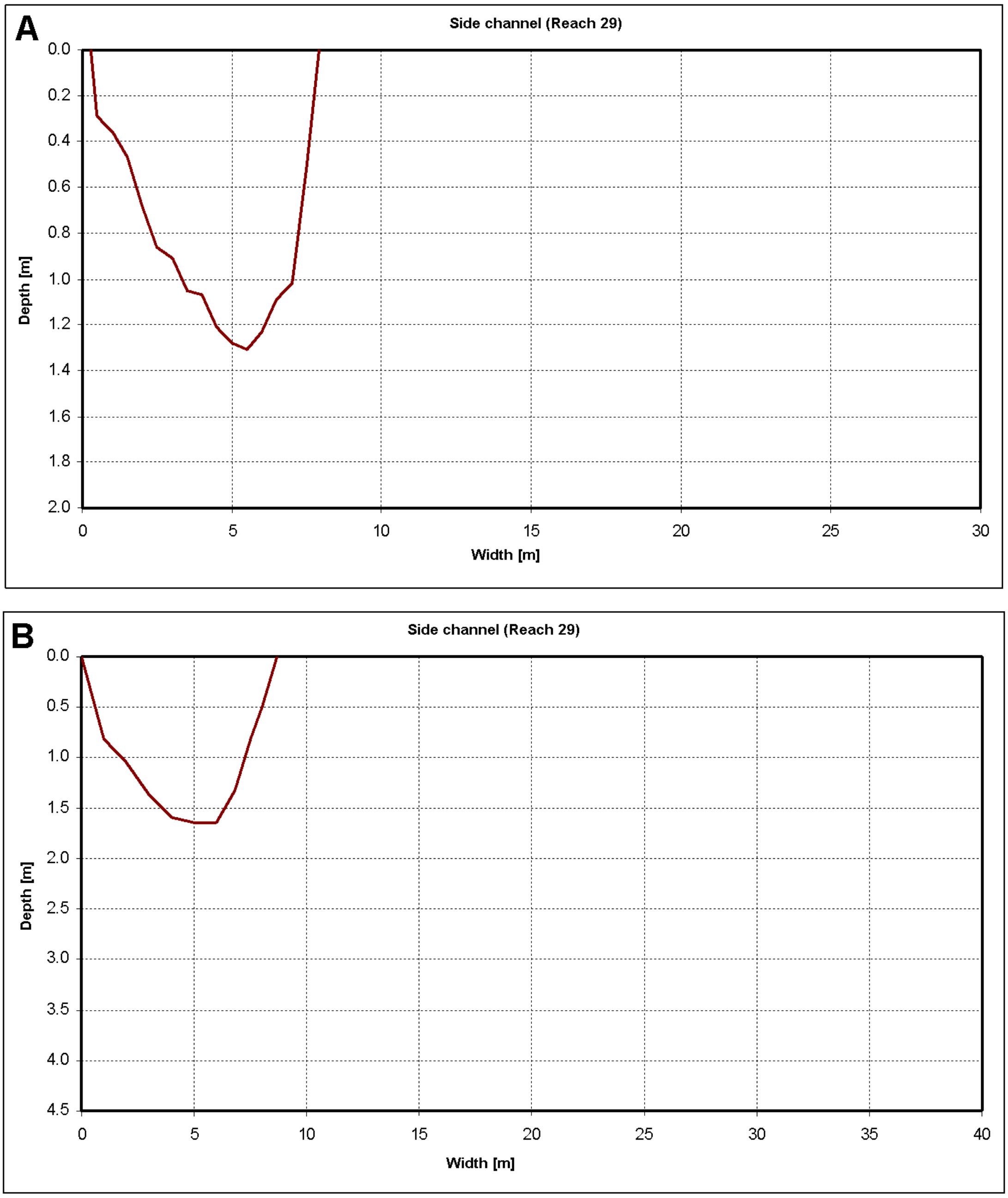


Figure 4.24 Example of cross-sections of side channels (Reach 29): A. downstream part of the reach; B. upstream part of the reach.

Figure 4.25 Examples of local erosion of the peat banks (evidenced by overhanging grass roots).

(iii) Riparian corridor connectivity and condition

In the anastomosing part of the River Narew within the NNP, all areas of the potential riparian corridor are accessible by floodwater. The floodplain was delineated based on the flood extent of the 1 in 100 year flood (source: *mapy.isok.gov.pl*). The riparian corridor was defined as the maximum extent of naturally functioning riparian vegetation within this floodable area and due to the lack of any artificial constructions within NNP (railways, embankments etc.) that could potentially affect and disturb the flow of water, no portion of the potential floodplain was excluded.

From the literature (Banaszuk et al. 2004), 20% of all species occurring in the NNP are alien plant species (125 of 630 plant species), including: Forking larkspur (*Consolida regalis*), Long pricklyhead poppy (*Papaver argemone*), Dwarf nettle (*Urtica urens*), Rye brome (*Bromus secalinus*), Canadian waterweed (*Elodea canadensis*), Wild cucumber (*Echinocystis lobata)*, and Himalayan balsam (*Impatiens glandulifera*).

Impervious surfaces such as buildings, roads or other man-made surfaces do not occur in the River Narew floodplain area. The part of the valley within the NNP is not urbanised, and is nearly pristine and unaltered by human.

4.6 Channel and floodplain geomorphic units

An assessment of channel and geomorphic units was conducted using historical aerial photographs from Google Earth, available literature (Gradziński et al. 2003, Banaszuk et al. 2004) and field work conducted in the Narew National Park.

4.6.1 Geomorphic units within the bankfull channel

(i) The river bed

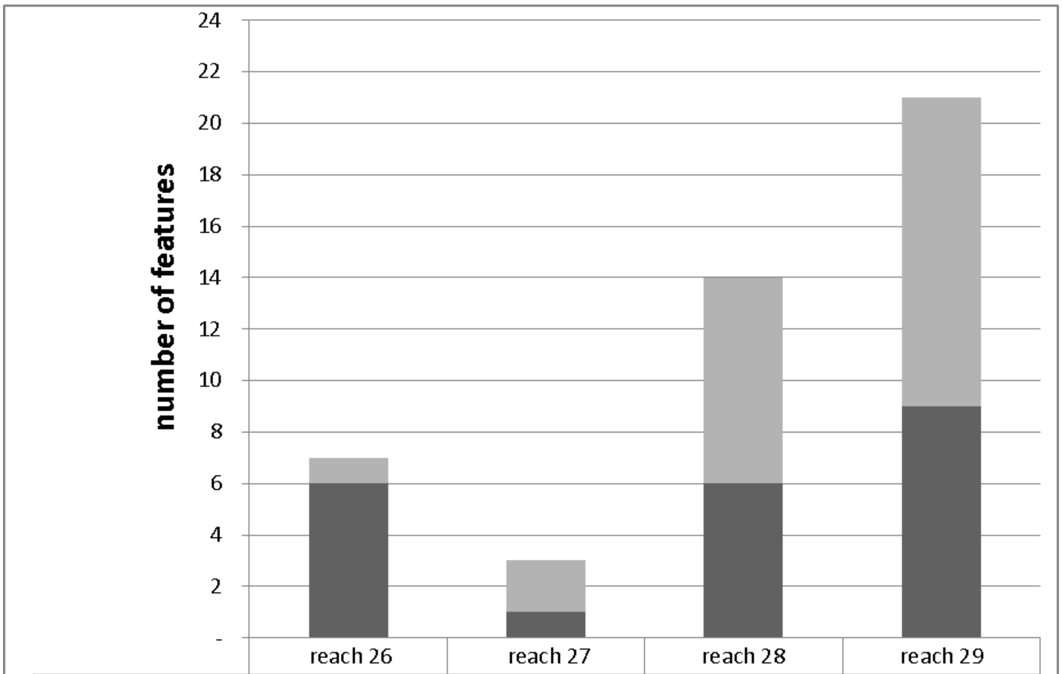
Characteristic geomorphic units in the studied reaches of the Narew were investigated from aerial imagery due to the lack of habitat surveys describing the forms along the river. The observation of the orthophotomaps did not indicate any significant alterations in surface flow characteristics to infer the presence of geomorphic units. However, more detailed and specific investigations such as habitat surveys and field morphological and fluvial audit surveys would provide a better description of the morphology and are required to identify bed geomorphic units in this case.

(ii) Depositional emergent sediment features

The analysis of emergent sediment features was conducted using aerial imagery. The total number of inventoried geomorphic features per reach is presented in Figure 4.26. The average numbers of any reported feature in analysed reaches were calculated and scaled to km to yield the number of features per km (Figure 4.27). Figure 4.28 illustrates a completely vegetated mid channel island.

Due to the resolution of the imagery only the main channel was investigated. Side channels were not taken into account, but field work conducted during low water stages indicated very low numbers of geomorphic features in side channels. Most of the side branches are shallow and narrow with low flow energy and sediment supply and thus a low potential for the creation of any geomorphic units. The aerial imagery and the field observations indicated no unvegetated mid-channel bars along the river reaches.

Gradzinski et al. (2003) identified 5 different types of plant-stabilised depositional features in an anastomosing section of the River Narew: (1) mid channel bars, (2) linguoid bars, (3) side bars, (4) plug bars, (5) concave-bank bars and (6) point bars. They state that only the first 2 types are normally visible at average water stages, so the present analysis based on aerial imagery may underestimate the number and diversity of depositional features.



	reach 26	reach 27	reach 28	reach 29
mid-channel island	1	2	8	12
side bar	6	1	6	9

Figure 4.26 The total number of geomorphic features inventoried in the studied anastomosing reaches.

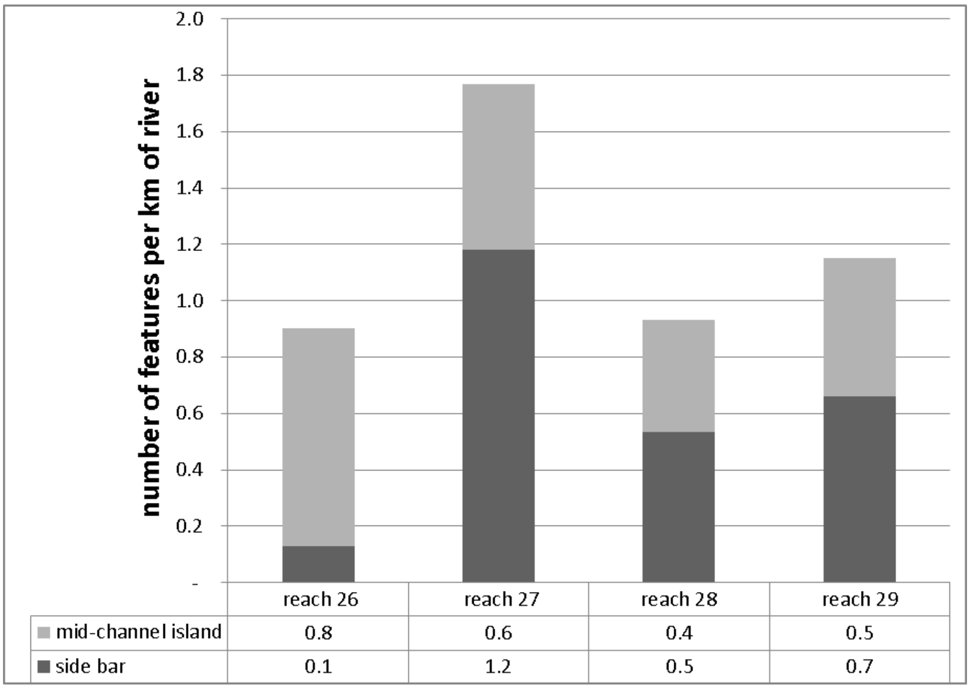


Figure 4.27 The number of side bars and vegetated islands identified in aerial imagery per kilometre of river.

Figure 4.28 An example of a mid-channel vegetated bar in reach 29.

4.6.2 Floodplain units

Floodplain geomorphic units were investigated using aerial imagery from Google Earth and field observations. The research indicates that the most common geomorphic features in the floodplain area in the studied anastomosing reaches are abandoned channels (AC) functioning as wetlands (Figure 4.29). The greatest number of such units was identified in reach 29 where the area of the units occupied 22 ha and in reach 28 – 180 units (19.8 ha). In reaches 26 and 27 the number of AC wetlands was lower (38 – occupying 3.6 ha and 10 – 0.4 ha, respectively). Oxbow lakes were much less frequently identified features and did not exceed 10 occurrences per reach.

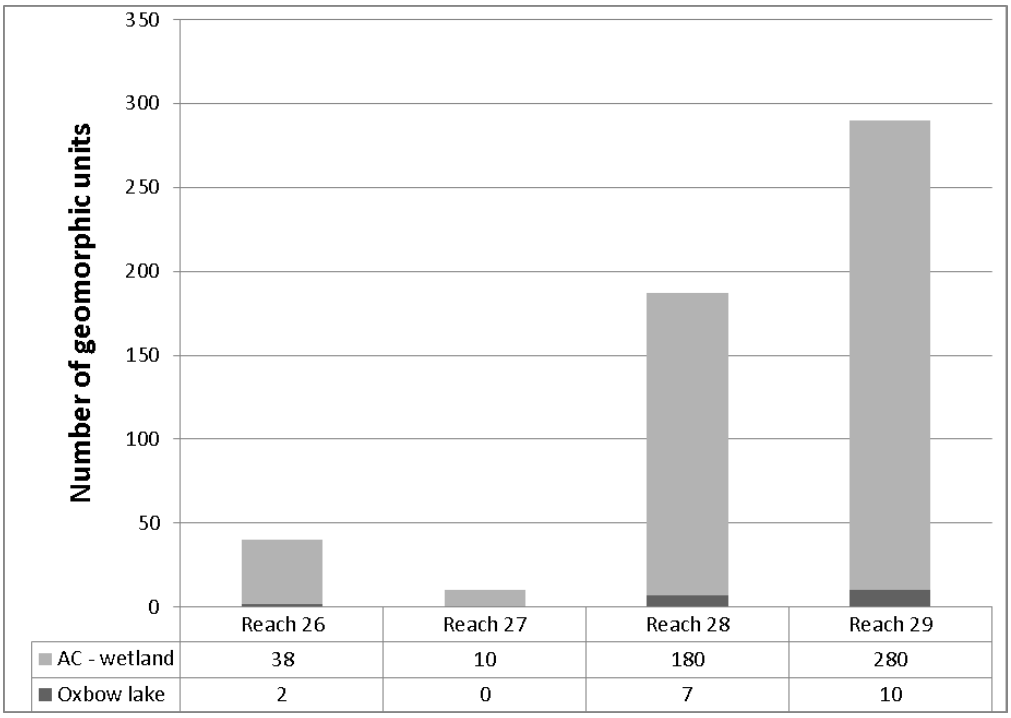


Figure 4.29 The number of floodplain geomorphic features per reach identified using aerial imagery, including abandoned channels (AC) and oxbow lakes.

5. Characterising temporal change in spatial units

5.1 Introduction

This section provides an overview of changes that have occurred in the hydromorphology of the River Narew over approximately the last century.

5.2 Catchment and landscape unit

5.2.1 Topography and coarse sediment production

The River Narew is a lowland, low energy river draining a very flat catchment. The region was glaciated during the last two glacial periods (Riss (Oder) 300-230 thousands years ago and Würm (Vistulian) 115-11.5 thousands years ago, using Alpine glaciation nomenclature). As a result there is little topographical variation or vertical relief. Sediments of glacial origin (i.e. till) are found throughout the catchment (Figure 4.1) and are a potential source of coarse sediment. However, investigation of current and historical aerial imagery of the Narew catchment and previous studies (Banaszuk et al. 2004) did not reveal any major coarse sediment sources.

5.2.2 Land use

Large storages of surface water have a very strong influence on the river flow regime by greatly delaying runoff. In Landscape unit 1 a major increase in % surface water bodies was noted in 1991 after construction of a large artificial reservoir on the River Narew (Siemianówka). The dam increases the catchment area covered by permanent water bodies from 0.1 to 0.9% and considerably affected the downstream water flow regime in both landscape units. Land cover has remained largely unchanged over the last 90 years, although there has been a loss of wetlands and a slight increase in pasture and forest (Table 5.1).

Table 5.1 Land use changes in the Narew landscape units during the 20th and 21st centuries (after: Nasiłowska 2008).

Class	Landscape unit			
	1		2	
	1923-1937	1999-2006	1923-1937	1999-2006
Agricultural - Arable	22%	21%	46%	44%
Agricultural - Pasture	9%	11%	15%	17%
Forest	63%	67%	32%	35%
Artificial - Urbanisation	0%	0%	1%	3%
Wetlands	6%	1%	6%	1%

More detailed characteristics of major shifts and alteration trends in agriculture are available for the time period 1995-2009 (based on the NNP Protection Plan, 2014) (Table 5.2). The data indicate a decrease in agriculture area but also a slight increase in crop yields which can be explained by more intensive production and increased use of fertilizers in recent years. What is noteworthy is the major increase in livestock numbers, particularly cattle.

5.2.3 Rainfall and groundwater abstraction

Rainfall statistics, based on 21 rain gauges within the Narew Catchment, demonstrate a slight increasing trend over the last 60 years and also some wetter and drier periods. Total annual precipitation is higher from 1970 to 1980 than from either 1951 to 1969 or 1981 to 2012. This pattern was broken in 2010 by an extremely wet year with flooding across Poland, but the pattern appears to be continuing at the present time (Figure 5.1). A similar trend is noticeable in terms of average yearly runoff volume and average runoff ratio, which were calculated for the outlet of Upper Narew Catchment in Strękowa Góra gauging station (Figures 5.2 and 5.3). No significant groundwater abstraction occurs within the catchment.

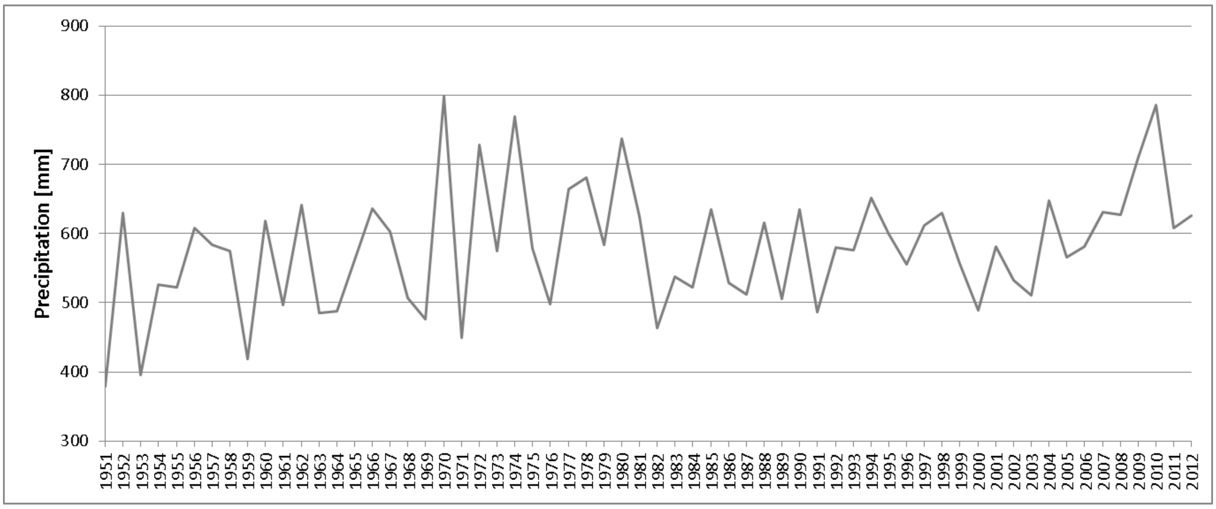


Figure 5.1 Average yearly sum of precipitation for time period 1951-2012 based on observations from 21 gauging stations in the Narew catchment.

Table 5.2 Characterisation of changes in agriculture in Narew Catchment (NNP Protection Plan 2013).

Characteristic	Years												
	1995	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Number of residents	1221877	1223802	1222709	1210688	1209439	1207704	1205117	1202425	1199689	1196101	1192660	1191470	1189730
in cities	696765	710992	713444	709976	710394	711300	710759	710828	709950	711597	710098	710073	715761
in the country side	525112	512810	509265	500712	499045	496404	494358	491597	489739	484504	482562	481397	473970
Agriculture area (thousands of hectares)	1208.9	1201.5	1201.1	1188.7	1182.5	1142.1	1038.4	1106.6	1089.3	1094.7	1116.6	1126.2	1147
Crop yields (dt/ha):													
cereals	-	24.8	23.6	14.8	26	24.1	24.1	26.9	26.8	21.4	25.8	26.7	27
potatos	172	199	161	194	177	185	169	186	172	147	196	190	161
Livestock (cattle) in thousands of heads	-	691.2	685.5	667.5	636.7	688.4	690.9	683.4	737.8	759.1	793.9	835.1	900.7
Fertilisation usage (dry weight per 1 ha)	72.5	79.2	78.5	75.1	78.5	79.8	80.1	86.2	87.1	91.5	89.3	94.5	93.3

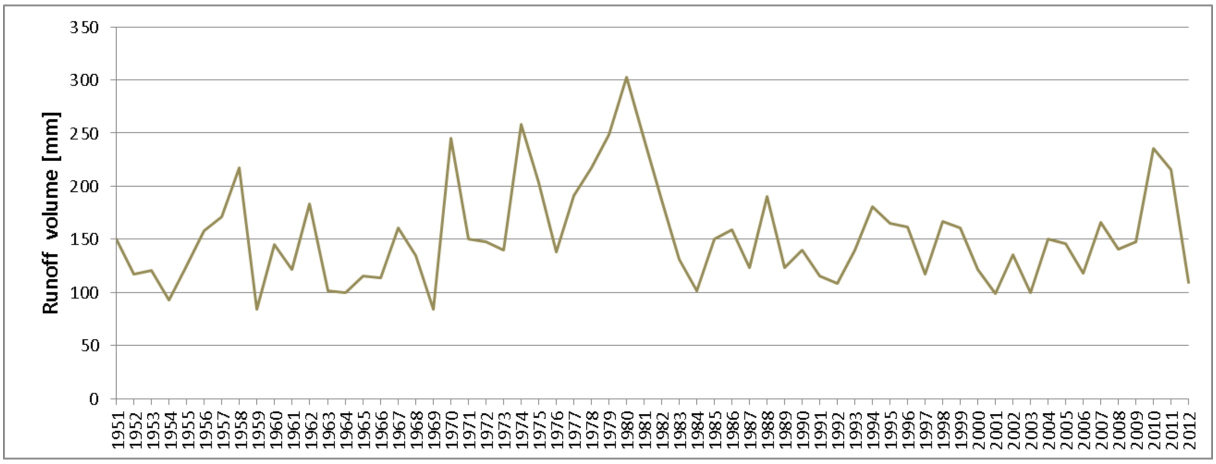


Figure 5.2 Average yearly runoff volume for Strękowa Góra gauge (1951-2012).

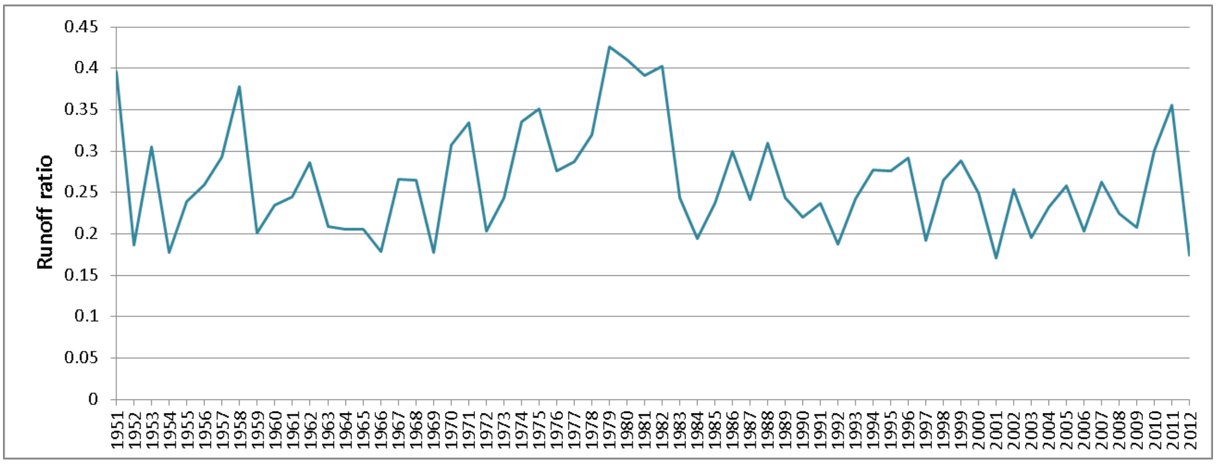


Figure 5.3 Average yearly runoff ratio for Strękowa Góra gauging station (1951-2012).

5.3 Segment

5.3.1 Water flow

Selected hydrological characteristics have been calculated with respect to four continuous time periods between 1951 and 2012. Separation of the time periods reflects the impact of Siemianówka Reservoir and encompasses nearly equal intervals of observed years. Characteristics of the record are presented in Table 5.3 and Figures 5.4 and 5.5.

Table 5.3 Variations in flow characteristics through time for two segments in the Narew catchment.

Flow characteristics	Segment 5 1951-1963	1964-1980	1981-1991	1992-2012	Segment 6 1951-1963	1964-1980	1981-1991	1992-2012
Mean annual	8.0	11.0	9.7	8.8	14.2	17.6	15.0	14.9
Baseflow index	0.2	0.3	0.2	0.4	0.2	0.2	0.3	0.4
Qp_{median}	40.3	58.0	39.0	26.2	74.0	86.3	59.1	52.0
Qp_2	40.4	58.5	39.3	26.3	74.6	86.4	59.2	52.4
Qp_{10}	75.6	108.8	82.7	34.6	116.2	144.2	110.0	84.0
1-day Min	1.3	1.7	1.9	2.6	2.4	2.8	3.1	3.9
30-day Min	1.6	1.9	2.2	3.1	2.8	3.4	3.7	4.5
1-day Max	70.7	89.0	53.9	32.1	102.4	115.7	95.1	64.9
30-day Max	38.9	49.4	37.0	25.2	59.2	67.6	60.5	43.1

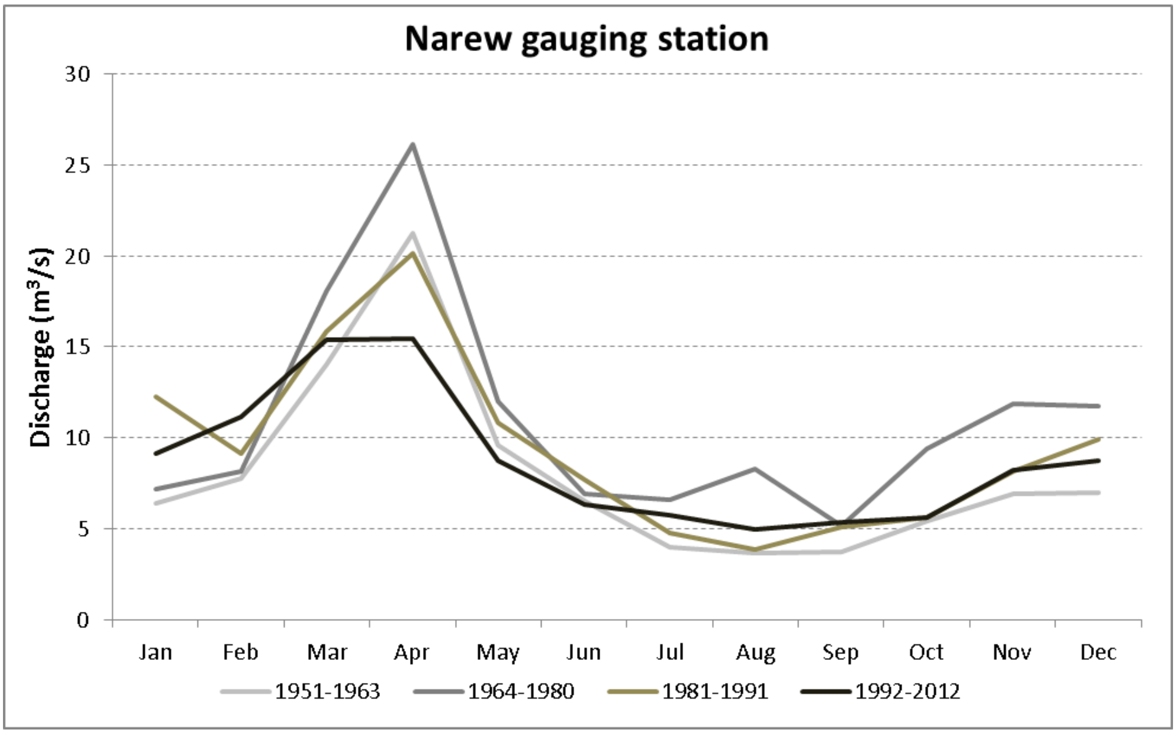


Figure 5.4 Average monthly flow changes for four time periods in Narew gauging station.

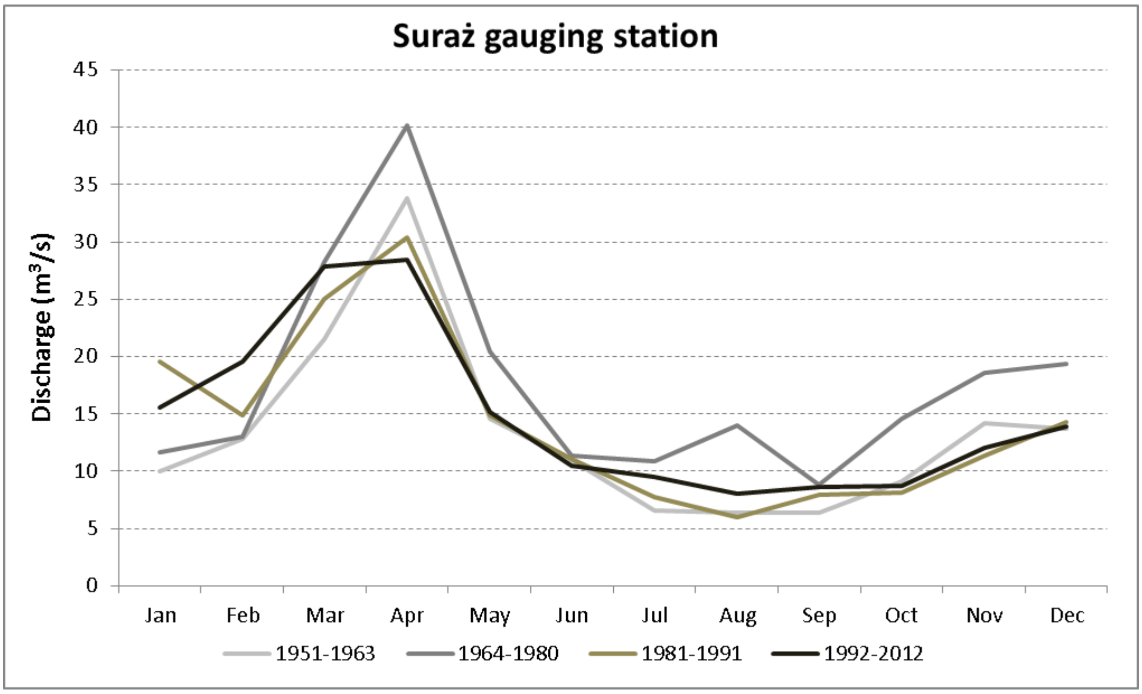


Figure 5.5 Average monthly flow changes for four time periods in Suraż gauging station.

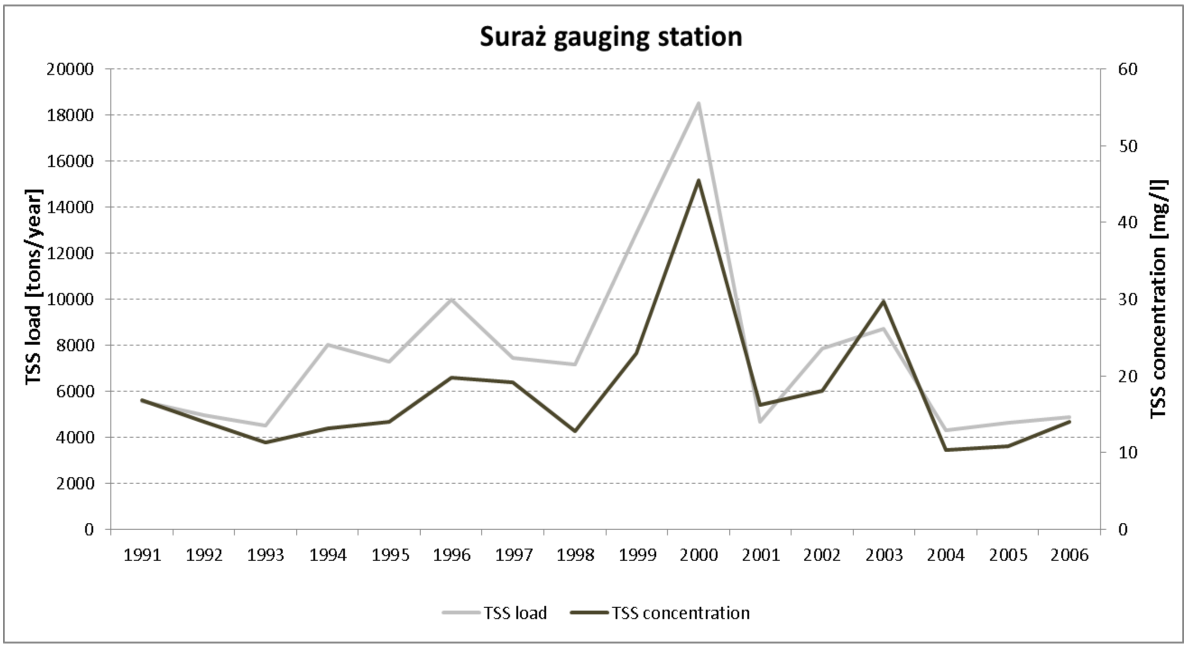


Figure 5.6 Mean total suspended sediment (TSS) loads and concentration in Suraż gauging station.

5.3.2 Sediment delivery

Estimation of sediment flow in river Narew at segment scale was based on monthly measurements of total suspended sediment (TSS) at the Suraż gauging station which is a part of the State Environmental Monitoring programme led by the Province Inspectorate of Environmental Protection in Białystok. The dataset includes observations for the time period 1991-2006. Figure 5.6 presents the yearly sum of TSS (tons/year) calculated using mean annual TSS concentration (mg/l) and annual discharge for a given year (m^3/year). With the exception of 2000, suspended sediment loads are low.

5.3.3 Valley setting

There have been no significant changes in the valley gradient or width in the last decades in the Narew catchment. The only processes that the valley is subject to are natural environmental processes without any significant human changes caused by urbanisation or flood control measures. The only alteration which affects the valley shape and its continuity are 2 spanning structures in segment 5, and 4 spanning structures in segment 6 which may impact longitudinal continuity of the river.

5.3.4 Channel gradient

Bed levels are not monitored in the River Narew. Therefore, direct evidence of changes in channel gradients could not be provided.

5.3.5 Riparian corridor and wood

There is no evidence of substantial changes in the size, type or location of naturally functioning riparian vegetation at the segment-scale. No information on historical wood production or delivery to the catchment was found.

5.4 Reach

5.4.1 Channel planform, migration and features

A detailed investigation of river planform changes was conducted using aerial imagery and orthophotomaps from 1966 and 1997 (Tobiasz, 2012). Table 5.4 presents the direction of changes in the area of active channels and cutoffs. The analysis conducted in the cited research pertained to a part of the river within the borders of NNP which corresponds with reaches 26 – 29. Therefore the calculation of parameters separately for each reach was not possible. According to that study, over 75% of the river channels remained unchanged over a 30-year period. Channel creation accounted for 7.9% of the total channel area, but this was matched by channel abandonment / deactivation (8%). The results suggest a slight decrease in the active channel area attributed to cut-offs (3.7%)

Table 5.4 Changes in river channel area by type for the time period 1966–1997; current channel types – column headings, previous types – row headings (Tobiasz 2012).

	Current planform		
Past planform	Active channel	Cutoff	No channel
Active channel	3.93 (75%)	0.2 (3.7%)	0.42 (8%)
Cutoff	<0.01 (0%)	0.08 (1.5%)	0.12 (2.4%)
No channel	0.41 (7.9%)	0.08 (1.5%)	0 (0.0%)

Anastomosing rivers are characterised by their high bank stability and minimal lateral channel migration (Gradziński et al. 2003, Makaske 2000). Planform change is a slow process in the Narew, and is believed to operate primarily by avulsions triggered by local increases in water levels caused by bed aggradation and channel blocking by aquatic and riparian plants Gradziński et al. 2003).

5.4.2 Channel geometry

No specific data is available on channel geometry changes in past decades.

5.4.3 Bed sediment calibre

No data is available on long-term changes in bed sediment calibre.

6. Extended river typology

River reaches in the Narew catchment are classified as one of three types, and are all entirely unconfined and have sand-bed material. The planforms of the reaches present in the catchment are sinuous, straight, meandering and low-energy anabranching (anastomosing) (Table 5.5). The bed material is sand, which is intermediate between the fine gravel-sand and fine sand-silt-clay bed materials of the extended typology classes. However, because there is no gravel in the bed material and there are local silt-clay deposits, the straight, meandering and low-energy anastomosing channels have been allocated to types 20, 21, 22, respectively, rather than to types 17, 18,19.

Table 5.5 Extended river typology of the reaches in the river Narew catchment.

LU	Segment	Reach	Morphological type	Threads	Planform	Floodplain type
1	1	1	22	Multi-thread	Anabranching	J
		2	21	Single	Meandering	G
	2	3	Reservoir			
	3	4	20	Single	Sinuous	G
		5	21	Single	Meandering	G
		6	20	Single	Sinuous	G
		7	20	Single	Straight	G
		8	21	Single	Meandering	G
		9	20	Single	Sinuous	G
		10	21	Single	Meandering	G
	4	11	20	Single	Sinuous	G
		12	21	Single	Meandering	G
2	5	13	20	Single	Sinuous	G
		14	21	Single	Meandering	G
		15	20	Single	Sinuous	G
		16	21	Single	Meandering	G
		17	22	Multi-thread	Anabranching	J
		18	20	Single	Sinuous	G
		19	21	Single	Meandering	G
		20	20	Single	Sinuous	G
		21	21	Single	Meandering	G
		22	20	Single	Sinuous	G
	6	23	20	Single	Sinuous	G
		24	21	Single	Meandering	G
		25	20	Single	Sinuous	G
		26	22	Multi-thread	Anabranching	J
		27	22	Multi-thread	Anabranching	J
		28	22	Multi-thread	Anabranching	J
		29	22	Multi-thread	Anabranching	J
		30	22	Multi-thread	Anabranching	J
		31	20	Single	Sinuous	G
	7	32	20	Single	Sinuous	G
		33	20	Single	Sinuous	G
		34	22	Multi-thread	Anabranching	J

35	20	Single	Sinuous	G

7. Indicators of present and past condition.

7.1 Catchment

At the catchment scale, indicators aim to identify broad properties of runoff production by the catchment and, in some cases, how these have changed over time.

7.1.1 Catchment area

In the River Narew catchment the loss or gain of water as a result of inter-basin transfer does not occur, therefore the actual catchment area (6,656 km^2) can be considered to the same as the functioning catchment area (for details see Table 5).

7.1.2 Water Yield and Runoff Coefficient

Water yield (mm) and the runoff coefficient are catchment indicators of the effectiveness with which the catchment converts rainfall to runoff. Flow records from Strękowa Góra gauging station (at the outlet of investigated Upper Narew catchment) were used to calculate these parameters in four, 15-year time windows from 1951 to 2012 (Table 7.1). These are a major control on river channel dimensions and dynamics. Water yield was calculated based on mean annual flow (and subcatchment area) and the runoff coefficient used average yearly precipitation from 21 stations.

Table 7.1 Average Water Yield and Runoff Coefficient changes in Narew Catchment.

Time period	Q [m^3/s]	Precipitation [mm]	Water yield [mm]	Runoff coefficient
1951-1965	31.55	535	149	0.28
1966-1980	35.85	628	170	0.27
1981-1991	33.70	568	160	0.28
1992-2012	31.41	610	149	0.24

7.1.3 Geology and Land Cover

The River Narew catchment is entirely occupied by siliceous bedrock. The surficial geology is dominated by glacial till, sand and loam soils (Figure 4.1). The loamy soils are typically sandy loams; very heavy impermeable soils (clay, clay loam, silt loam) are rare in the landscape. The main valley bottoms are filled with peat deposits from the Holocene.

Land cover changes in the Narew catchment were based on analyses of historical maps acquired from the Polish Military Institute of Geography. Maps of various scales (1:100 000 and 1:300 000) were assembled and digitised. Land use was classified and the area of each land use type was calculated for 3 time periods between 1885 and 2001 (Nasiłowska 2008). Overall land cover has remained largely unchanged over the last 130 years, and is dominated by agricultural land (Table 7.2). However, results indicate an increase in artificial surfaces (i.e. urban development; from 0.8 to 2.3%) and a decrease in wetland areas (from 4.2 to 1.2%). Moreover a minor reduction of arable land and a slight increase in forest is noticeable in recent few decades.

Table 7.2 Land cover in Narew catchment from the 19th to 21st centuries (after: Nasiłowska 2008).

Land use class	1885-1923 [%]	1923-1937 [%]	1999-2001 [%]
Agriculture: arable lands	46.6	44.6	39.0
Agriculture: pasture	3.5	5.0	14.4
Forests	34.8	34.1	39.5
Urbanisation	0.8	1.2	2.3
Water	0.1	0.1	0.3
Wetlands	14.1	14.2	1.2
Other	0.1	0.8	2.8

7.2 Landscape Unit

At the landscape unit scale, indicators focus on water and sediment production so that locations of high production within the catchment can be recognised to aid spatial (and temporal) interpretation of likely impacts on river form and dynamics.

7.2.1 Exposed Aquifers and Soil / Bedrock Permeability

An unconfined aquifer extends over the entire catchment area. The % area of exposed aquifers is 100% for both landscape units. The % area of (soil and rock) permeability classes was not assessed directly, but is likely to be predominantly permeable because of the dominance of highly permeable bedrock and surficial geology types (e.g. glacial till and sandy loam soil) under both landscape units.

7.2.2 Land cover

The land cover proportion in the landscape units was presented in Table 5.1, and is summarised here in terms of potential runoff production.

% area of delayed runoff production is attributable to forest cover and is 67.4% and 35.2% for Landscape units 1 and 2, respectively.

% area of rapid runoff production is attributable to urban, industrial, commercial and transport and is 0.3% and 2.9% for Landscape units 1 and 2, respectively.

% area of intermediate runoff production is attributable to arable land, pasture and open spaces and is 32.3% and 52.1% for Landscape units 1 and 2, respectively.

Over the last few decades there have been no major shifts in land use. Minor changes such as an increase in forest cover and a decrease in the area covered by agriculture were detected. Extension of impermeable surfaces related to urbanization is minor (less than 3 % of total catchment area).

7.2.3 Sediment production

In the Narew catchment sediment delivery potential is very low (section 4.3.2 Table 4.5), where a low mean soil erosion rate of 0.03 tons ha^{-1} $year^{-1}$ is estimated for both landscape units. There have been no significant changes in land cover over the last 130 years which would affect fine sediment production (Table 5.1), however changes in land use and agricultural practices, such as the increase in cattle numbers in recent years (Table 5.2), may have an impact on sediment production and delivery to the channel.

The % area with potential sources of coarse sediment is 0 for both landscape units.

7.3 Segment

At the segment scale, indicators highlight the properties of the river and its floodplain rather than the surrounding areas of the catchment, notably indicators of flows of water, sediment and wood, and indicators of space for and constraints upon river adjustments within the river corridor.

7.3.1 Water Flow

Indicators of water flow, including the flow regime type, average annual flow, average monthly flows, baseflow index, morphologically meaningful discharges and extreme flows, were presented in Section 4.4.1 (Tables 4.6 to 4.10, Figures 4.7 to 4.12).

Detailed flow parameters calculated separately for four time periods were presented in Table 26. Due to the operation of the dam, peak flows have decreased, baseflows have increased and the flow regime has changed from perennial runoff to perennial groundwater. These changes to the flow regime mean that morphologically meaningful flows (Qp_{median}, Qp_2 and Qp_{10}) are now substantially lower than they were during the pre-dam period (Table 5.3). Another interesting characteristic is the difference in flow parameters between periods 1964-1980 and 1981-1991 where the former had substantially higher flows. This is strongly correlated with rainfall records which indicate higher precipitation in the 1970s. The daily water volume released from the reservoir fluctuates throughout the year with little seasonal correlation. The evidence of this diversity is reflected by the flow records from Bondary gauging station, located immediately downstream of the reservoir (Figure 7.1). This may indicate hydropeaking, however higher resolution time series data (e.g. instantaneous or 15-min flow) or records of dam operations would be needed for confirmation.

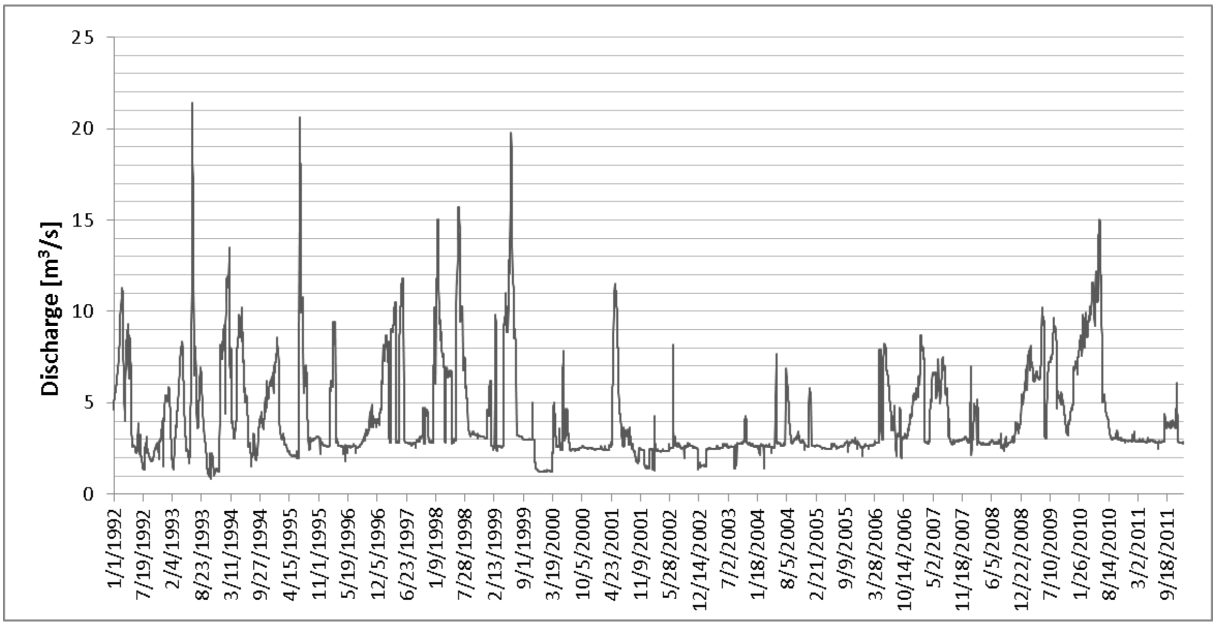


Figure 7.1 Daily flow records from Bondary gauging station (post-dam period 1992-2011).

7.3.2 Sediment flow

At the segment scale no continuous measurements of sediment transport were available to allow for a comparison between segments or over time. Suspended sediment monitoring for one location from 1991 to 2006 was presented in Figure 5.6, and shows that the river has low sediment loads. Additional evidence of the low sediment flow comes from field work conducted in April 2014 (high water stages). Samples taken at different points within each segment indicated low sediment concentrations (16 mg/l and 14 mg/l for segments 5 and 6, respectively).

There are no land surface instabilities connected to channel as the river banks are composed of stable organic soil with high resistance to erosion.

Number of high blocking structures – none

Number of medium blocking structures – 1 in segment 6

Number of high (impact) spanning structures – 1 in segment 5, 2 in segment 6

Number of medium (impact) spanning structures – 1 in segment 5, 3 in segment 6

7.3.3 River morphology adjustments

Segments 5 and 6 are characterised by very low gradients (0.0002 m m^{-1}) and are entirely unconfined (Table 4.11).

Riparian corridor width and the proportion of riparian corridor under functioning riparian vegetation are presented in Table 4.12. The grasses, reeds and sedges in the anastomosing reaches are native species growing naturally, but are subject to mowing.

For the purposes of this assessment, they were considered to be naturally-functioning, because the low level of human intervention maintains the grassland ecosystem that provides habitat to a range of plant and animal species.

Riparian corridor vegetation cover / structure is presented in (Figures 4.17 and 4.18) and is classified as predominantly early growth.

7.3.4 Wood production

Analyses of historical topographic maps from the Military Institute of Geography including four time periods (1915, 1935, 1980 and 2010) indicate that wood production is negligible along River Narew. The proportion of the active river channel edge (bank top and island margins) covered by mature (living or dead) trees is zero as a result of the complete absence of individual trees or forests along the banks. Therefore potential wood delivery in the segment is 0.

7.4 Reach

At the reach scale, indicators provide evidence of the current form and functioning of the river channel and its margins and how these may be changing. In this section, only indicators for reach 29 are reported because it has been the subject of targeted desk-based and field work. However many of the indicators were presented earlier in the spatial characterisation section (Section 4.5).

7.4.1 Flooding

Reach 29 is deemed to be a nearly pristine stretch of the river without any direct human induced changes or structures along its length that could affect the area of natural floodplain. The only artificial concrete structure is a weir at the downstream end of the reach which causes an impoundment effect for a few hundred metres upstream.

% floodplain accessible by floodwater – is 100% of the reach floodplain area.

7.4.2 Channel self-maintenance / reshaping

Flow energy represented by the specific stream power was calculated on the basis of Qp_{median}, Qp_2 and Qp_{10} (presented in Tables 4.16, 4.17,4.18) and equals to 5.1, 5.1, 8.3 W m^{-2} respectively, for reach 29.

Channel bed sediment is predominantly medium to coarse-grained sand (Gradzinski et al. 2003). Fine sediment can be found along with plant detritus as laminae within the sand, but forms thick deposits in slow-moving or abandoned channels. The area between the channels (i.e. islands), and thus the channel banks as well, are composed of peat derived primarily from sedge and reed organic material, but also contain between 9% and 50% mineral material (sand).

Reach 29 is characterised, like other anastomosing reaches in Narew catchment, by a very low gradient (0.00014). The main channel averages 17.5 m wide, and the total channel width of the main and side channels is 25.9 m. Mean bankfull reach depth is 3m which makes the width/depth ratio equal to 8.63 (Table 4.15). Other characteristics are as follows: sinuosity index (1.27), braiding index (5.34), and anabranching index (5.34) (Table 4.14).

Several types of modern accretionary bedforms can be distinguished along reach 29: mid-channel bars, side bars and point bars (Figures 4.26, 4.27). However, the % area of the bankfull channel occupied by bars is less than 2%.

7.4.3 Channel Change / Adjustments

To estimate changes in channel planform of the reach, historical maps (1:100000) were investigated. Indicators such as the sinuosity index, braiding index and anabranching index were calculated separately for various points in time (1915, 1980, 2010) (Table 7.3).

Table 7.3 Alteration of planform parameters of reach 29.

Year	Sinuosity index	Braiding index	Anabranching index
1915	1.33	5.18	5.18
1980	1.32	5.30	5.30
2010	1.27	5.34	5.34

The analysis of historical maps shows little to no change in planform over time, which provides evidence of the stability of the anastomosing character of the river. A slight change in sinuosity and anabranching indices between the periods may result from different scales of analysed historical maps and the accuracy of the presented objects (e.g. channels). Consultations with NNP authorities indicated that there are local changes visible within the reach over the last few decades, but these are complex and do not indicate a clear direction of change. According to the authorities and rangers there are river stretches where side channels are slowly being overgrown by plants and other stretches where avulsion processes are ongoing and new channels are forming.

In the investigated reach 29, field work allowed the following indicators to be estimated:

Eroding banks – 0%

Laterally aggrading bank – 0%

In-channel retention of sediment – 0%

Change in sinuosity – negligible change between 1915 and 2010 (Table 7.3)

Change in braiding index – little or no change over a time (Table 7.3)

Change in anabranching index – little to no change over a time (Table 7.3)

Change in active channel width – no changes were observed, perhaps due to the stable character of the river banks composed of peat

Changes in active channel depth – not analysed due to lack of the data

Changes in active channel width:depth ratio – not analysed due to lack of the data

Presence of geomorphic units / features indicative of narrowing: none

Presence of geomorphic units / features indicative of widening: none

Changes in bed sediment structure indicating incision: Not analysed due to lack of the data

Changes in bed sediment structure indicating shallowing / bed aggradation: Not analysed due to lack of the data

Vegetation encroachment is believed to play a crucial role in planform dynamics for the anastomosing sections of the River Narew (Gradzinski et al 2003), however data is not available to assess this indicator

Width of the erodible corridor – 'wide' over the entire length of the River Narew (> 10 bankfull width)

Proportion of potentially erodible channel margin – due to no artificial reinforcements of the river bank, 100% of the channel margin is potentially erodible

Proportion of river bed that is artificially reinforced – 0%

Number of high blocking structures - 0

Number of medium blocking structures - 1

Number of low blocking structures - 6

Number of high spanning/crossing structures - 0

Number of medium spanning/crossing structures - 0

Number of low spanning/crossing structures – 0

7.4.4 Vegetation succession

The Narew catchment is located in a biogeographic region for which forests are the last stage of natural vegetation succession. However, the proportion of the riparian corridor covered by forests is 10% (Figure 4.18). The dominant vegetation types in reach 29 are reed and sedge (46% and 38% respectively), which can be classified as pioneer or early growth. The maintenance of such an early stage of vegetation succession is an effect of human land management preventing the expansion of shrubs and forests through reed cutting and more recently by regular mowing. However the dynamics of vegetation expansion and succession are influenced by the extent, frequency and duration of inundation and groundwater levels and flows (Banaszuk et al. 2004).

Gradually from the 1960s an expansion of reed has taken place in the NNP due to a reduction in regular cutting. A decrease in the number and duration of spring inundations since 1980 has contributed to this increase in the spatial cover of reed. The area covered by reed increased by 7% between 1981-1987 and 16% between 1987-1997 (Banaszuk et al. 2004).

Among other parameters evaluated for reach 29 based on both analysis of aerial imagery and field survey are:

Aquatic vegetation extent – absent in the middle sections of deep, wide main channels; abundant along the channel margins in the main and side channels; abundant in the entire cross-section of shallow side channels (Figures 4.19, 4.20, 4.21)

Aquatic vegetation patchiness – limited data to asses this indicator, believed to be quasi-continuous patches

Aquatic vegetation species – no detailed investigation was conducted and no information was available for sufficient description of this parameter

Proportion of the riparian corridor under mature trees, shrubs and shorter vegetation, and bare soil – mature trees occupy only 10% of the area of reach 29 and are located in patches at the edge of the valley. The most abundant is short vegetation covering the remaining 90% of the area where the proportions are as follows: sedge (38%), reed (46%), grass (6%) (Figure 4.18).

Lateral gradient in riparian vegetation cover classes – a moderate correlation is visible between the type of vegetation and the distance from the stream. Figure 4.17 shows that the most common vegetation present near the channels is reed. With the increasing distance from the stream edge, sedge increases in area and becomes dominant and mature trees are most abundant near the valley edge.

Patchiness in riparian vegetation cover types – some patchiness is visible in Figure 4.17

The dominant riparian tree species – *Salix cinerea, Pinus silvestris, Betula pubescens*

Presence of wood- or riparian tree- dependent geomorphic units / features – absent

7.4.5 Wood delivery

Analyses of historical maps and satellite imagery indicate that the proportion of the active river channel edge (bank top and island margins) covered by mature (living or dead) trees is zero. Fieldwork conducted in Narew National Park (Reaches 28, 29) noted the presence of only a few individual trees near the channel (Figure 7.2).

Other parameters relevant to wood delivery and evaluated for the reach 29 based on both, aerial imagery analysis and field work are:

Abundance of isolated large wood pieces in the active channel – negligible

Abundance of accumulations of large wood pieces in the active channel – negligible

Abundance of channel-blocking jams of wood in the active channel – negligible

Abundance of large wood in the riparian corridor – negligible

Figure 7.2 Examples of presence of single trees near the channels (Reaches 28, 29).

8. Interpreting condition and trajectories of change

8.1 Stage 1: Synthesis of current reach condition

An assessment of current reach condition is presented in Table 8.1, whereas Tables 8.2 to 8.6 present the elements that contribute to the overall assessment in Table 8.1. In most cases the evaluation of the parameters follows the methods suggested in section 9 of the D2.1 main report. Where information and data were lacking a new approach was proposed.

(i) Due to the large catchment area and the river length of the case study it was unmanageable to carry out the field work on the entire investigated segment. Therefore, much of the information was gathered from aerial imagery and assessment of parameters in the field was conducted only on the low energy anabranching (anastomosing) part within NNP borders.

(ii) Presence of aquatic plant dependent geomorphic features was assessed entirely using aerial imagery.

The reaches of the River Narew within the national park are assessed as having predominantly good hydromorphological function, with the exception of reach 27, a short reach located adjacent to a town and affected by a series of road and rail embankments. All reaches have a low level of hydromphological artificiality; channel banks and beds are entirely natural, the floodplain is wide and largely unaffected by direct human intervention, and few blocking structures are present within the channel, none of which have a significant effect on water or sediment transport. Hydromorphological adjustment is low to negligible, which is appropriate for low energy anabranching systems with erosion-resistant channel banks and mobile sand beds like the Narew. Riparian function and artificiality are both classified as moderate. Whilst the entire riparian corridor is covered by functioning riparian vegetation, the dominance of reed/sedge and the lack of woody riparian vegetation and wood is a consequence of past and current management practices.

Table 8.1 Current reach condition (for anastomosing type reaches).

Reach	Type	Hydromorphological Function	Hydromorphological alteration/artificiality	hydromorphological Adjustment	Riparian vegetation		Wood budget	
					Function	Artificiality	Function	Artificiality
26	19	Good	Low artificiality	Small changes in the number of channels	Moderate	Moderate	Poor	negligible
27	19	Intermediate*	Low artificiality	None	Moderate	Moderate	Poor	negligible
28	19	Good	Low artificiality	Small changes in the number of channels	Moderate	Moderate	Poor	negligible
29	19	Good	Low artificiality	Small changes in the number of channels	Moderate	Moderate	Poor	negligible

* reflects the presence of a large bridge and adjacent town on this relatively short reach

Table 8.2 Control and descriptor indicators used to assess the reach type.

Reach	Specific stream power	Bed sediment	Bank sediment	Channel gradient	Width	Depth	W:D	Threads	Planform	Reach Type
26	3.1	Sand and finer	Organic	0.00016	20.0	1.7	11.8	Multi-thread	Anabranching	22
27	1.9	Sand and finer	Organic	0.00010	24.2	1.8	13.4	Multi-thread	Anabranching	22
28	3.3	Sand and finer	Organic	0.00015	21.1	2.2	9.6	Multi-thread	Anabranching	22
29	3.2	Sand and finer	Organic	0.00014	17.5	2.1	8.3	Multi-thread	Anabranching	22

Table 8.3 Indicators used to assess hydromorphological function.

Reach	Hydromorphology function assessment	Channel / floodplain geomorphic features typical of type^	% area of bankfull channel occupied by bars, benches, islands	Eroding + aggrading banks	Aquatic-plant dependent geomorphic units^	Wood / tree dependent geomorphic units^
26	Good	Some	<1%	Stable organic banks*	None	Absent
27	Intermediate	Some	<1%	Stable organic banks*	None	Absent
28	Good	Many	<1%	Stable organic banks*	None	Absent
29	Good	Many	<1%	Stable organic banks*	None	Absent

^ Indicators assessed using aerial imagery

* Stable banks are characteristic of low-energy anastomosing rivers.

Table 8.4 Hydromorphological adjustment.

Reach	Artificiality Assessment and Score	Longitudinal continuity - Blocking structures					Lateral continuity			Adjustment potential			
		Class Score	Total	Low	Int	High	Class Score	Floodplain accessible	Erodible corridor	Class Score	Adjustment potential	Reinforced banks	Reinforced bed
26	Low Artificiality 3	Good 1	1	1	0	0	Good 1	100%	>10 bankfull widths	High 1	high	0	0
27	Low Artificiality 3	Good 1	1	1	0	0	Good 1	100%	>10 bankfull widths	High 1	high	0	0
28	Low Artificiality 3	Good 1	6	6	0	0	Good 1	100%	>10 bankfull widths	High 1	high	0	0
29	Low Artificiality 3	Good 1	7	6	1	0	Good 1	100%	>10 bankfull widths	High 1	high	0	0

Table 8.5 Riparian corridor function.

Reach	Adjustment assessment	Channel narrowing	In-channel retention of sediment	Channel widening	Channel incision	Main channel W:D	% bed covered by sand and finer
26	None	N	N	N	N	11.8	100
27	None	N	N	N	N	13.4	100
28	None	N	N	N	N	9.6	100
29	None	N	N	N	N	8.3	100

Table 8.6 Riparian corridor alteration, artificiality.

Reach	Riparian corridor artificiality	Riparian corridor function	Functioning riparian vegetation class	Lateral gradient in riparian vegetation cover classes	Patchiness in riparian vegetation cover classes	Proportion (%) functioning riparian corridor under mature riparian vegetation	Proportion (%) functioning riparian corridor under early riparian vegetation	Proportion (%) riparian corridor under riparian vegetation
26	Natural	Good	Early growth	Negligible	Some	16	84	100
27	Natural	Good	Early growth	Clear lateral change	Some	3	97	100
28	Natural	Good	Early growth	Clear lateral change	Some	19	81	100
29	Natural	Good	Early growth	Clear lateral change	Some	10	90	100

8.2 Stage 2: Controls on change

8.2.1 Catchment

The River Narew lies in a large agricultural catchment where slight changes through time were noticed (Table 8.7).

Table 8.7 Catchment scale indicators of hydromorphology and evidence of change over time.

Indicators	Value	Change
Drainage area (km^2)	6656	No
Geology (WFD types)		
Siliceous	100%	No
Land cover		
% Forest	39.5	slight increase
% Wetlands	1.2	slight decrease
% Agriculture	53.4	slight decrease
% Artificial areas	2.3	slight increace
Water yield	149	decrease
Annual runoff ratio (coefficient)	0.24	decrease

8.2.2 Landscape units

At the landscape unit scale small changes in characteristics over a time were noticed. The most significant change is an increase in % large water bodies in landscape unit 1. Although the relative change is slight (2.3%) the overall impact on surface water flow is significant, aswas reported in the analysis of water flows at the segment scale. A slight increase was noted in the land cover types associated with rapid runoff in landscape unit 2 due to urbanisation (2% increase). The area of intermediate runoff experienced a slight decrease which relates to the declining trend in agricultural areas, and the % area of delayed runoff slightly increased as a result of the gradual afforestation of the land (Table 8.8).

8.2.3 Segments

The River Narew is a low gradient, unconfined river over its entire length with a perennial stable flow regime type (estimation based on flow records from two gauging stations). Average monthly discharges are greatest in the spring (March, April) due to snow melt and lowest in the summer due to low precipitation and high evapotranspiration. The most significant alteration in the flow regime is related to dam construction which has resulted in a reduction of high flows, an increase of baseflow and a decrease in the occurrence of floods downstream of the Siemianówka reservoir. Along the investigated river segments no high impact structures were inventoried and only one intermediate impact dam is present in segment 6 (Table 8.9).

Table 8.8 Hydromorphological characteristics and evidence of change over time at the landscape unit scale.

Indicators	LU1	LU2	Change
% area of permeable soil substratum	100	100	No
% glaciers and perpetual snow	0	0	No
% large surface water bodies	2.3	0	increase
Land cover / Runoff production			
% area of rapid	0.3	2.9	slight increase
% area of intermediate	32.3	52.1	slight decrease
% area of delayed	67.4	35.2	slight increase
Soil erosion rate	0.03	0.03	No
% area with potential sources of coarse sediment	0	0	No

8.2.4 Space-time inventory

The inventory for the River Narew covers predominantely the last few decades due to the limited availability of historical date. Given the available datasets a synthesised description is as follows:

(i) Whilst the River Narew has retained a near-natural low-energy anabranching river style within the national park, the vegetation that covers the riparian corridor and the wider landscape differs significantly from the natural forest cover that would be expected in this biogeographical region. These changes in land cover preceed the historical record covered in this study (*ca.* 130 years) and relate to land management practices adopted for economic and political reasons. Reed was historically harvested from the floodplain for use as roofing material. The establishment of woody riparian vegetation was supressed by this cutting as well as by direct removal to maintain line of site across the river, which historically served as a geopolitical boundary. Consequently the dominance of herbaceous wetland plants in the floodplain and the lack of riparian tree cover and wood delivery is an artefact of centuries of human intervention.

(ii) The Narew catchment is an agricultural and forested catchment with only a very small area covered by artificial surfaces. Based on an analysis of historical maps, no significant changes in land cover were detected over the last 130 years apart from a small increase in the area covered by water bodies, caused by the construction of the Siemianówka reservoir, and a small increase in the area covered by artificial surfaces in landscape unit 2, due to expansion of cities and towns. Agricultural practices have changed over the last 30 years and the catchment has experienced a noticeable increase in the number of cattle and the amounts of fertilizer used, which could have an impact on the amount of fine sediment and nutrients in the River Narew.

(iii) In the late 1970s, the River Narew was realigned downstream of the national park. To counteract the drop in water levels that would accompany realignment and which would negatively impact the reed and sedge wetland community, a large weir was constructed at the downstream end of the park. Additionally, a buffer zone was constructed around the park to transition water levels down to the low levels found in the neighboring drained grassland.

Table 8.9 Hydromorphological characteristics and evidence of change over time at the segment scale.

Indicators	LU5	LU6	Change
Valley gradient	0.00024	0.00019	No
Valley confinement	Unconfined	Unconfined	No
River confinement	101	86	No
Flow regime type	Perennial stable	Perennial stable	more stable
Baseflow index (BFI)	0.41	0.39	Increase
Average annual flow (m^3/s)	9.86	15.56	No
Average monthly flows	See Figure	See Figure	N/A
Morph. Meaningful discharges			
Qpmedian (m^3/s)	30.4	64.6	Decrease
Qp2 (m^3/s)	30.4	64.6	Decrease
Qp10 (m^3/s)	38.5	104.9	Decrease
Extremes: 1- and 30-day maximum and minimum flows			
1-day low (m^3/s)	2.2	4.2	Increase
30-day low (m^3/s)	2.6	4.3	Increase
1-day high (m^3/s)	54.6	95.6	Decrease
30-day high (m^3/s)	33.9	59.4	Decrease
Land surface instabilities	none	none	No
Estimated suspended sediment load (tons/ha/year)	103	103	No
Sediment budget	gain	gain	N/A
Number of channel blocking structures			
High impact	0	0	No
Intermediate impact	0	1	No
Riparian corridor			
Width (m)	730	1700	No
Continuity	100%	100%	No
Cover / structure	early growth	early growth	No
Active channel bordered by trees	0	0	No

(iv) The construction of the Siemianówka reservoir in the upper River Narew has been one of the most significant hydromorphological changes. The dam has caused a decrease in the magnitude, frequency and duration of peak flows; an increase in baseflows; and consequently a shift from a perennial flashy flow regime to a perennial baseflow regime. The reduction of spring inundations controlling and stimulating the development of aquatic ecosystems is one reason for the expansion of reed in the NNP.

8.3 Stage 3: Assess reach sensitivity

The anastomosing reaches of the River Narew in the Narew National Park are highly stable geomorphologically. The river is a lowland, low energy system, which, combined with the large number of channels, results in low specific stream power (*ca.* 3 W m^{-2}). Banks and inter-channel areas are composed of peat which is highly resistant to erosion, therefore limiting the lateral migration of channels. Geomorphic change is believed to be a slow process that is reliant on aquatic and riparian vegetation (Gradzinski et al. 2003). As the channel bed is composed predominantly of sand, depositional features are small and transient. However when colonised by submerged and emergent aquatic plants, the sand bars are stabilised by roots and rhizomes causing local bed aggradation and variation in the bed configuration. Vegetation within the channel also slows water flows and increases water levels which is hypothesised to trigger a slow avulsion process. Therefore, the river with its characteristic anastomosing planform has a low susceptibility to adjustment, is highly resilient to change, and thus is highly stable in space and time, as long as water levels remain high and sediment loads low.

Whilst the anastomosing section of the River Narew appears to be entirely natural, the vegetation community has been managed for centuries through cutting, and more recently mowing, of riparian vegetation to maintain the grassland environment. Therefore, few riparian trees and shrubs are found in the NNP, and there is little to no wood within the channel. Therefore, the vegetation-induced mechanisms proposed by Gradzinksi et al. (2002) are relevant only within this management context, but a low energy tree-dominated anastomosing river would also be expected to have a low susceptibility to adjustment an a high resilience to change.

8.4 Stage 4: Scenario based future changes

This section considers the consequences and the most probable direction of changes under proposed future scenarios. The previous sections have shown that over the last century Reach 29 has not experienced many direct or significant artificial human-made changes. Therefore, the hydromorphological functioning and environmental condition of the reach is deemed to be good. In order to maintain such a good state, in 1996 the anastomosing part of the River Narew, including Reach 29, was placed under formal protection (establishment of the National Park). To prevent the natural succession of the early growth vegetation stage surrounding Reach 29 (reed, sedge), which could entirely alter the conditions of the ecosystem, a regular mowing is scheduled within the borders of NNP.

The most significant influence on the water regime is the dam which has been constructed in LU1 and which has affected floods and the flow regime since 1992.

The above suggest two likely scenarios for the future:

(i) Modification of dam operation to increase flows in winter and spring
(ii) Cessation of mowing within the NNP

The likely consequences of each of these is considered below:

8.4.1 Scenario 1: Modification of dam operation to increase flows in winter and spring

Current management of water release from the dam causes a marked reduction in high flows, an increase of baseflow and a decrease in the number of floods. Seasonal inundations are one of the most important factors controlling vegetation growth and development and thereby the precious habitats protected within the NNP. Water-dependent ecosystems and wetlands need to be fed by regular inundations which in turn guarantee their proper functioning. A decrease in the number of spring floods results in deterioration of the state of the ecosystems and expansion of vegetation in channels according to the lowered water stages. Extensive growth and invasion of vegetation causes cutting-off and overgrowing of the channels and finally their permanent extinction, with a resulting gradual reduction in the number of anabranches of the system.

A modification of dam operations to increase flows in winter and spring would most likely result in an increased number of seasonal inundations to the level experienced in the pre-dam period. This would improve the condition of the flooded ecosystems and control the growth of vegetation across the anabranches, significantly restricting their invasion into the channels and preventing excessive blockages. This in turn would reduce the number of extinct anabranches and stop the gradual deterioration of this anastomosing fluvial system and could possibly reverse the tendency by creating new channels through the avulsion process.

8.4.2 Scenario 2: Cessation of mowing within NNP

Vegetation plays a significant role in the development and maintenance of the anastomosing system and its hydrological condition. For example, vegetation at early growth stages covers nearly 90% of the total area of Reach 29 allowing the maintenance of an appropriate evapotranspiration intensity and water use by the plants. Human activity in this matter is focused on preventing the natural succession towards afforestation of the floodplain area. One of the main operations to achieve this goal is regular mowing, usually conducted twice a year.

Cessation of mowing within the NNP would, in the long term, cause significant changes in the anastomosing fluvial system. Such situation occurred to a minor degree in the past when mowing was not conducted for a few years, and it resulted in uncontrolled expansion of common reed. Complete cessation of mowing could possibly cause an intensification of natural succession. In this scenario shorter vegetation would be repressed by shrubs and finally by trees. This in turn, due to increased water demands of this type of vegetation, would resulting intense water use and evapotranspiration. For anastomosing systems, water quantity is one of the most important factors necessary to their maintnenace. Such a reduction in water storage could lead to extinction of the anabranches, although an increased tree cover would shade out some of the aquatic plants and so might help to keep the anabranches open.

The complete cessation of mowing in the national park is unrealistic as a twin management goal to the maintenance of the anastomising planform is the preservation of the reed/sedge community which supports a diverse and unique wetland environment. Therefore a compromise could be the targeted cessation of riparian vegeration around anabranch confluences and divergences. This would allow natural succession to occur in these areas, which would lead to the establishment of riparian trees and eventually the delivery of large wood to the channel. Wood delivery and the formation of jams/dams would locally increase water levels and ensure that water is diverted into anabranches. This localised approach would minimise the impacts on the vegetation community in the remaining floodplain, leaving the reed/sedge dominated community, but also support it by increased water levels. In addition to the immediate benefits to water levels, log jams/dams also introduce hydraulic complexity, facilitate the formation of geomorphic units, and significantly slow the conveyance of flood waters thereby increasing inundation frequency and duration. Although the drivers of geomorphic change would switch from herbaceous riparian plants to woody trees and shrubs, the channel would still be expected to be stable because the erosion-resistant peat banks and low specific stream power limit the potential for bank erosion, channel migration and channel avulsion.

9. References

Banaszuk H. et al. 2004. Przyroda Podlasia : Narwiański Park Narodowy.[Nature of Podlasie: Narew National Park] Białystok : Narwiański Park Narodowy.

European Environment Agency (EEA). Biogeographic Regions in Europe. http://www.eea.europa.eu

General Inspectorate of Environmental Protection. The CORINE Land Cover 2006 clc.gios.gov.pl

Gradziński R, Baryła J, Doktor M, Gmur D, Gradziński M, Kędzior A, Paszkowski M, Soja R, Zieliński T, Żurek S. 2003. Vegetation-controlled modern anastomosing system of the upper Narew River (NE Poland) and its sediments. Sedimentary Geology 157, 253 – 276.

Humbert J, Pellet J, Buri P, Arlettaz R. 2012. Does delaying the first mowing date benefit biodiversity in meadowland? Environmental Evidence 2012, doi:10.1186/2047-2382-1-9

Institute of Meteorology and Water Management – National Research Institute. Flow records, Rainfall records (1951 -2012).

Joint Research Centre (EC). PESERA model. http://eusoils.jrc.ec.europa.eu

Main Geodetic and Cartographic Documentation Centre. LIDAR data. www.codgik.gov.pl

Nasiłowska S. 2008. Land use changes in the basin of upper Narew river, in XIX–XX century. Teledetekcja środowiska, Warszawa.

Polish Geological Institute – National Research Institute. 2009. Geological and hydrogeological characteristic of the verified groundwater bodies. http://www.pgi.gov.pl

Polish Geological Institute – National Research Institute. Polish Geological Map (1:500 000) http://www.pgi.gov.pl

Province Inspectorate of Environmental Protection in Białystok. Sediment concentration records (1991-2006). www.wios.bialystok.pl

Tobiasz M. 2012. River channel changes in the River Narew valley between Łapy and Żółtki in the second half of the twentieth century. Teledetekcja środowiska, Warszawa.

Catchment Case Study 4

Hydromorphological assessment of the Magra and Cecina rivers (Italy)

Barbara Belletti, Laura Nardi, Massimo Rinaldi
University of Florence (UNIFI)

1. Introduction

In this document we apply the hierarchical hydromorphological assessment framework to the Magra and Cecina river catchment, following the guidelines outlined in Deliverable D2.1 Part 1.

The Magra and Cecina rivers have been selected as case studies for a series of reasons, including: (i) they are representative of small to medium catchments (about 1600 km^2 and 900 km^2 respectively) located in the context of the Northern Apennines, Central-Northern Italy; (ii) they are predominantly gravel-bed rivers with medium to high energy conditions related to a relatively high basin relief (1039 m and 1018 m respectively), and consequently are characterized by an active channel dynamics (historically and in the current conditions); (iii) they have been impacted by multiple human disturbances, but gravel mining during the last decades was the main impact; the occurrence of different disturbances caused a sequence of channel adjustments which has been widely observed in many other rivers of Italy (Surian et al. 2009).

The Delineation of the spatial units (following Section 4 of Deliverable 2.1, Part 1) has been applied to the Magra river and its main tributary, the Vara river, as well as to the Cecina river. The characterization of the spatial units (Section 5 of Deliverable 2.1, Part 1) has been applied mainly to the Magra and Cecina rivers and, in case of available information it has been applied also to the Vara river. The characterization of the temporal changes (Section 6 of Deliverable 2.1, Part 1) has been applied to the Magra and Cecina rivers. Finally, the definition of the extended river typology and of the indicators of present and past conditions, as well as interpreting condition and trajectories of changes (Sections 7 to 9 of Deliverable 2.1, Part 1) have been applied only to the Magra river.

1.1 Delineation and characterisation

The methods for delineation and characterisation are based on the guidelines described in Sections 4 and 5 of the REFORM Deliverable 2.1. Delineation and characterisation are presented as separate phases of the framework; however, many aspects of the characterisation are actually conducted within the delineation phase because of the need to characterise the river system in order to delineate it into internally consistent spatial units. The delineation process is open-ended: boundaries are carried down through this phase, but a larger-scale delineation boundary often needs to be adjusted slightly to produce a more parsimonious delineation of the smaller-scale units.

Some general information concerning the methods for delineation and characterisation for each spatial scale are reported below.

2. Material and Methods

2.1 Datasets

The datasets used in the delineation and characterisation phases are summarised in Table 2.1.

Table 2.1 Primary datasets used in the delineation and characterisation of the Magra and Cecina catchments (n.a. = not available)

Property	Dataset	Format	Resolution	Version	Source
Aerial imagery	Satellite	Online	Variable	2000-2012	Google Earth
Aerial imagery	Photos and orthophotos	TIFF	Variable	Variable	IGM (IT); Regione Toscana (IT)
Elevation	CTR	Shapefile (polyline)	1:10,000	V3.5	Regione Toscana (IT)
	DEM	GRID	300 m	n.a.	Regione Toscana (IT)
Slope	Slopemap	GRID	200 m	n.a.	Previous works
Geology	Bedrock	Shapefile (polygon)	1:25,000 1:10,000	n.a.	Regione Toscana (IT)
Land Cover	Landuse	Shapefile (polygon)	1:200,000	1960	CNR-TCI (IT)
	CORINE CLC	Shapefile (polygon)	1:100,000	1990, 2000, 2006	EEA; ISPRA (IT)
Hydrological network, catchment and sub-catchment areas	GIS layers	Shapefile (polyline)		n.a.	Previous works
Artificial features census	GIS layer	Shapefile (point)		n.a.	Regione Toscana (IT)
River flows	Mean daily Mean daily Mean 1.5 discharge	Discharge Water level Discharge	2 stations 1 station Mean value per reach	Variable Variable Empirical equation	SIR Toscana (IT) Basin Authority
Catchment properties	General catchment characteristics	Reports and papers	Variable	Variable	Variable

2.2.1 Region

The regions are established at the European level (http://www.minambiente.it/pagina/le-regioni-biogeografiche).

2.2.2 Catchment

GIS data and general characteristics on the catchment were already available from previous work (published papers and unpublished technical reports and theses; e.g. for the Magra river: Nardi et al. 2012; Nardi and Rinaldi 2014; Rinaldi et al. 2009; e.g. for the Cecina river: Luppi et al. 2009; Nardi 2004, 2011; Rinaldi et al. 2008; Surian et al. 2009).

2.2.3 Landscape units

Landscape units have been delineated and characterised on the basis of GIS data (layers), i.e. mainly geology and physiographic characteristics, but also slope and land cover. Landscape units were delineated, by combining these layers, such that the dominant characteristics were broadly consistent internally.

2.2.4 Segments

Segments have been delineated from the intersection of the main river with the landscape units, and on the macro-characteristics of the valley setting.

2.2.5 Reach

Reaches have been delineated in 3 consecutive steps, on the basis of: (i) valley setting, in terms of confinement; (ii) channel morphology; (iii) presence of other discontinuities, e.g. presence of abrupt longitudinal profile changes, assemblages of existing geomorphic units, presence of main river tributaries, presence of major human impacts.

The characterisation at the reach level followed the reach delineation (e.g. calculation of indices of channel morphology, etc.). The 1.5 return interval discharge for the Magra river (and then the stream power) has been calculated by Nardi and Rinaldi (2014) using an empirical equation developed by the Basin Authority of the Magra River and obtained by a regionalisation of flow discharges at catchment scale.

2.3 Characterisation of historical changes

Information on historical changes has been taken or obtained from existing works, i.e. published papers and unpublished technical reports and thesis (e.g. for the Magra river: Rinaldi et al. 2009; Nardi et al. 2012; Nardi and Rinaldi 2014; e.g. for the Cecina river: Rinaldi et al. 2008; Surian et al. 2009).

3. Delineation of the Spatial Units

3.1 Region

The region is a large geographic area that contains characteristic assemblages of natural ecological communities that are the product of broad influences of climate patterns.

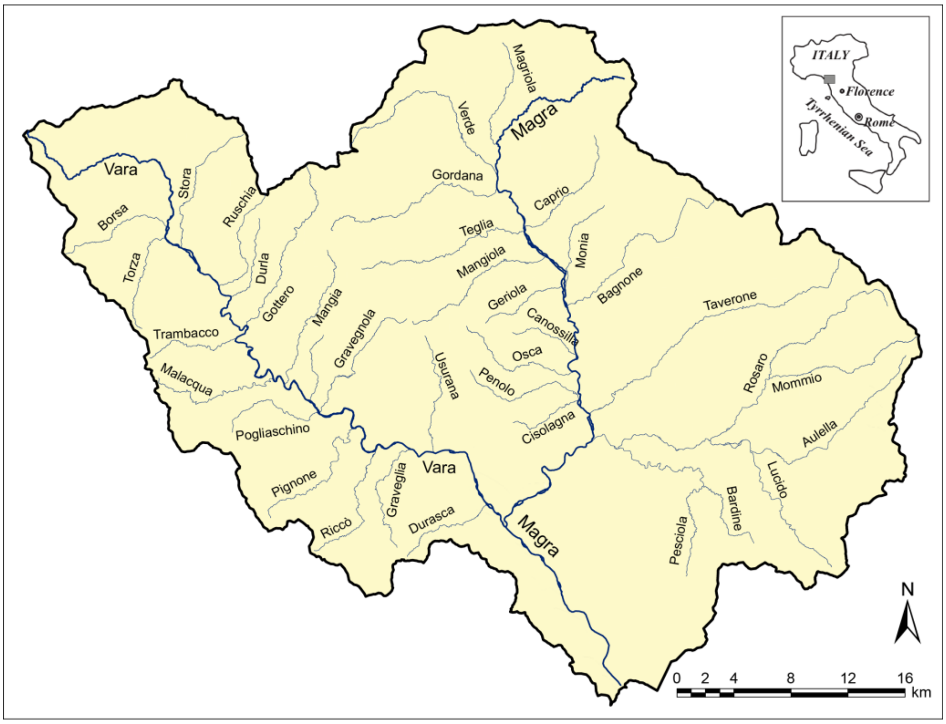
The Magra and the Cecina river catchments are located in the northern portion of the Mediterranean biogeographical region (Figure 3.1).

Figure 3.1 Italian biogeographic regions and localisation of the Magra and Cecina river catchments (modified from http://vnr.unipg.it/habitat/glossario.jsp).

3.2 Catchment area

The Magra river catchment (about 1700 km^2) is located in Northern Tuscany and Liguria (Central-Northern western Italy) (Figure 3.2a). The Cecina river catchment (905 km^2) is located in Central Tuscany (Central-Northern western Italy) (Figure 3.2b).

(a)



(b)

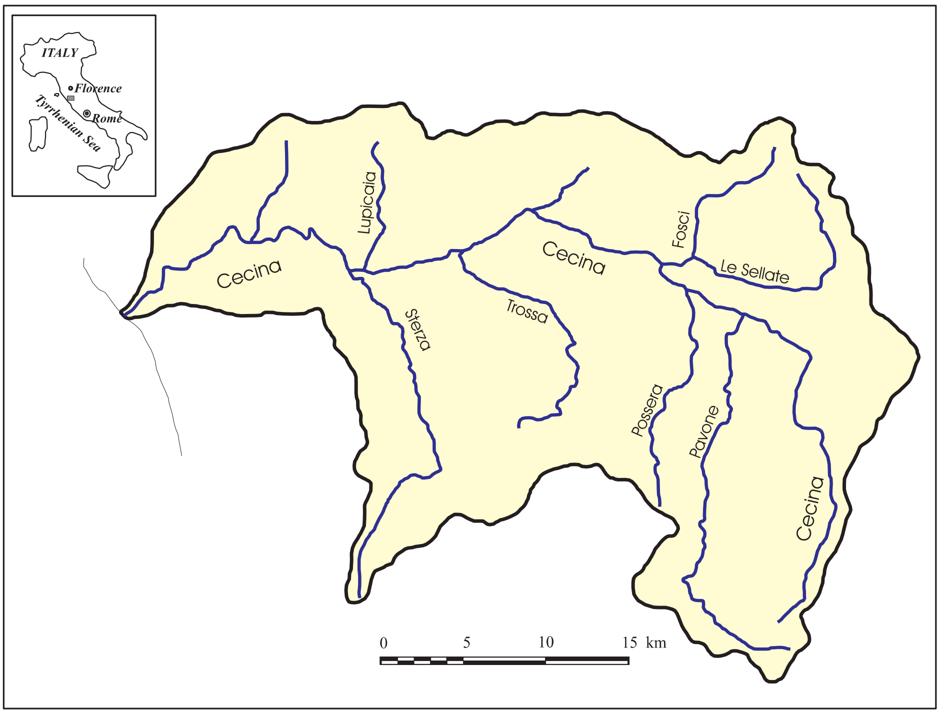


Figure 3.2 (a) The Magra river catchment; (b) the Cecina river catchment.

3.2.1 Physiography

The Magra river catchment is mainly dominated by hilly areas (from 200 to 600 m a.s.l.) (Figure 3.3a). The lower portion of the catchment, downstream of the confluence of the Vara and the Magra, is occupied by a large plain (3 km wide in average).

The Cecina river catchment is mainly dominated by hilly areas, except for the southern part of the catchment in which mountain areas reach about 1000 m a.s.l. and belong to the 'Inner reliefs' of Central Italy (Figure 3.3b).

(a)

(b)

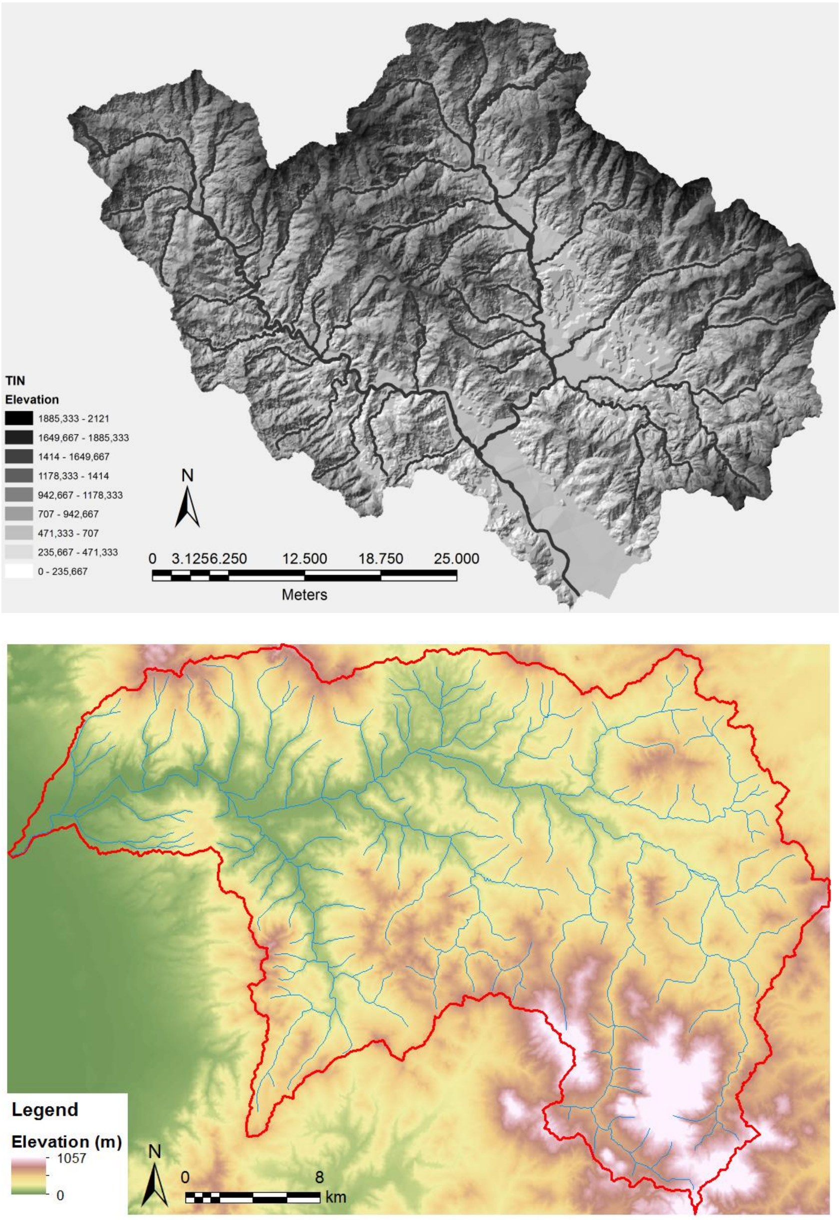


Figure 3.3 (a) Mean elevation of the Magra catchment; (b) relief of the Cecina catchment.

3.2.2 Geology

Magra river catchment

The catchment is predominantly composed of sedimentary rocks (limestone, sandstones, clays), with some minor outcrops of ophiolites and other crystalline rocks (Figure 3.4). A small part of the catchment, in the south-east, is dominated by metamorphic rocks (Apuan Alps). Most of the Magra valley floor is composed of erodible fluvio-lacustrine and marine sediments, dominated by relatively low relief.

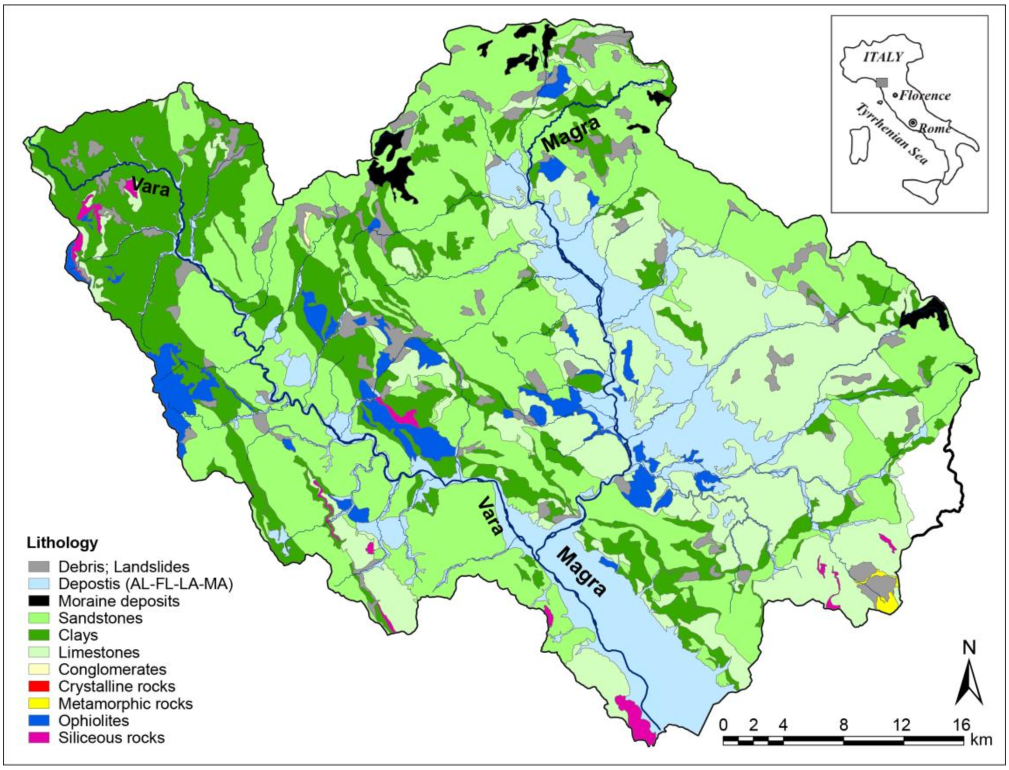


Figure 3.4 Geological sketch of the Magra catchment.

Cecina river catchment

The southern portion (hilly-mountain areas) and an area of the north-western portion of the catchment is dominated by sedimentary rocks (limestone, sandstones) and some outcrops of ophiolites. The remaining part is dominated by erodible fluvio-lacustrine and marine sediments (Upper Miocene, Plio-Pleistocene). A narrow alluvial plain is present on most of the valley floor of the Cecina river and some main tributaries, merging in a wide coastal plain only in the last part of the river course close to the mouth (Figure 3.5).

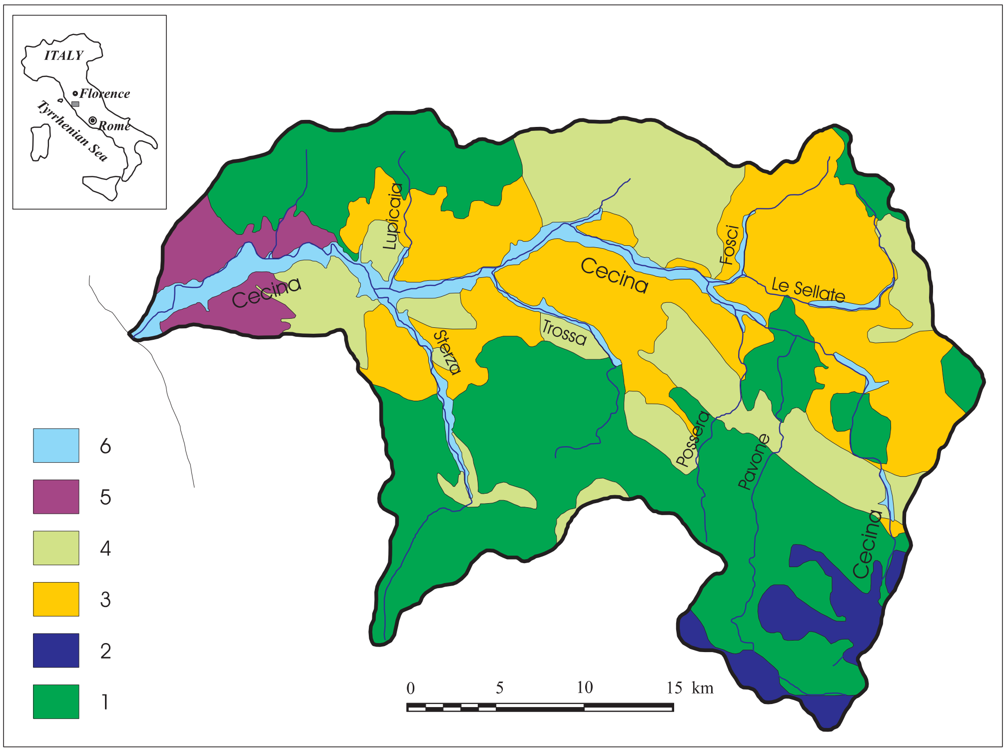


Figure 3.5 Geological sketch of the Cecina catchment. 1: limestones, sandstones, clays of the Tuscan sequence (pre – Miocene); 2: ophiolites; 3: lacustrine and marine deposits (upper Miocene); 4: marine deposits (Pliocene); 5: marine and fluvial deposits of the coastal belt (Quaternary); 6: present and terraced alluvial deposits (Quaternary).

3.3 Delineation of landscape units and segments

3.3.1 Landscape units

Based on the information on physiographic characteristics and geology of the catchment, a series of landscape units have been identified (Figures 3.6 and 3.7 for the Magra and the Cecina river catchments, respectively).

Magra river catchment

Landscape unit 1: Mountain areas (Apuan Alps): Mountain areas (up to 1550 m a.s.l. on the southern boundary) characterized by metamorphic rocks.

Landscape unit 2: Mountain areas: Mountain areas (up to 2000 m a.s.l. on the southern boundary) characterized by prevailing sandstones in the Magra catchment and clays in the Vara catchment.

Landscape unit 3: Hilly areas: Mountain areas (always <600 m a.s.l.) characterized by limestones in the Magra catchment prevailing on the left bank of the Magra river, and sandstones in the right side and in the lower portion of the Vara catchment; the upper part of the Vara catchment is characterized by clays.

Minor areas characterized by others types of rocks (i.e. ophiolites) are incorporated within this unit, because the relief was relatively low and the landscape was dominated by hills. Some areas of fluvial and lacustrine deposits are also included in this unit.

Landscape unit 4: High plain (intermountain): comprises a relatively high plain, including some low hilly portions, situated along the Magra main stem and characterized by recent and old alluvial deposits (terraces).

Landscape unit 5: Low plain: This unit coincides with the low plain of the Magra river, characterized by recent fluvial, lacustrine and marine deposits.

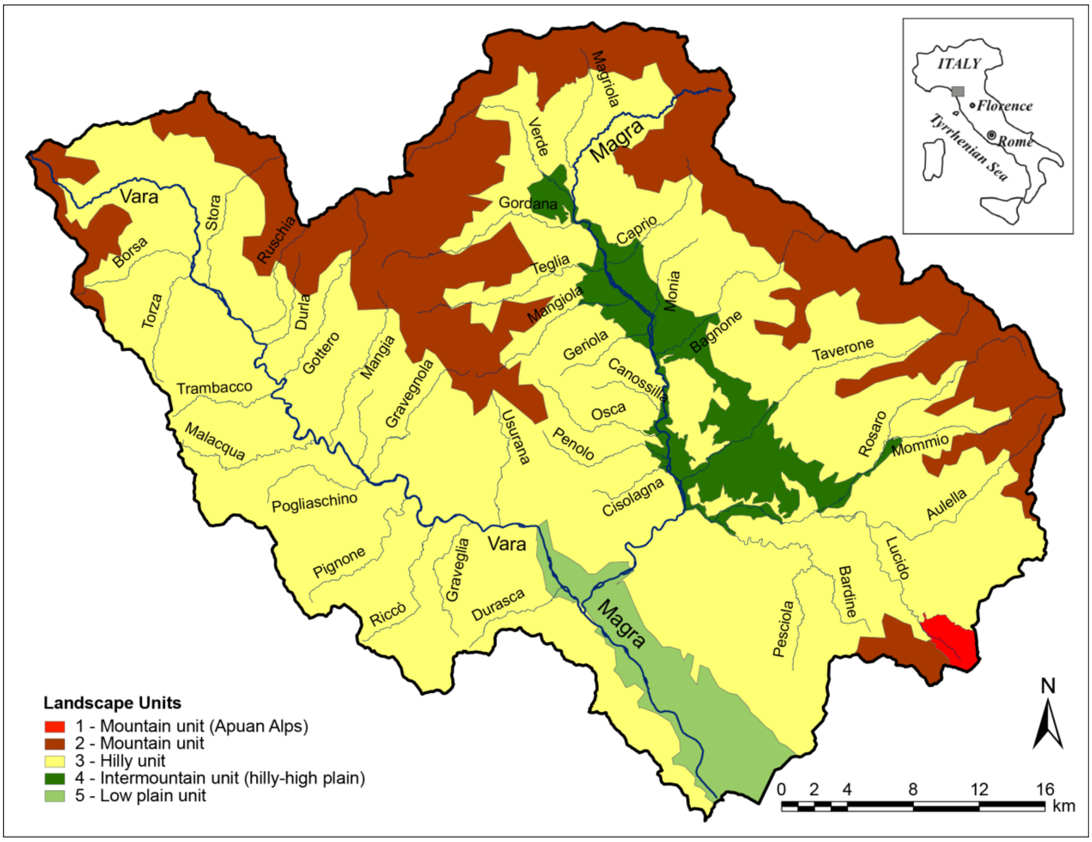


Figure 3.6 Landscape units of the Magra river catchment.

Cecina river catchment

Landscape unit 1: Hilly-mountain areas: Hilly and mountain areas (up to about 1000 m a.s.l. on the southern boundary) characterized by sedimentary and magmatic rocks of the Apenninic 'Inner relief'.

Landscape unit 2: Rounded hills: Hilly areas (always <600 m a.s.l.) characterized by prevailing soft lacustrine, marine or ancient fluvial deposits (clay, sand, conglomerate) (upper Miocene – Quaternary), including relatively narrow alluvial plains on the valley floor. Minor areas characterized by hard sedimentary / magmatic rocks are sometimes incorporated within this unit, because the relief is relatively low and the landscape is still dominated by hills.

Landscape unit 3: Coastal plain: It consists of a belt of alluvial and marine deposits, and is confined to the most downstream portion of the catchment near the river mouth.

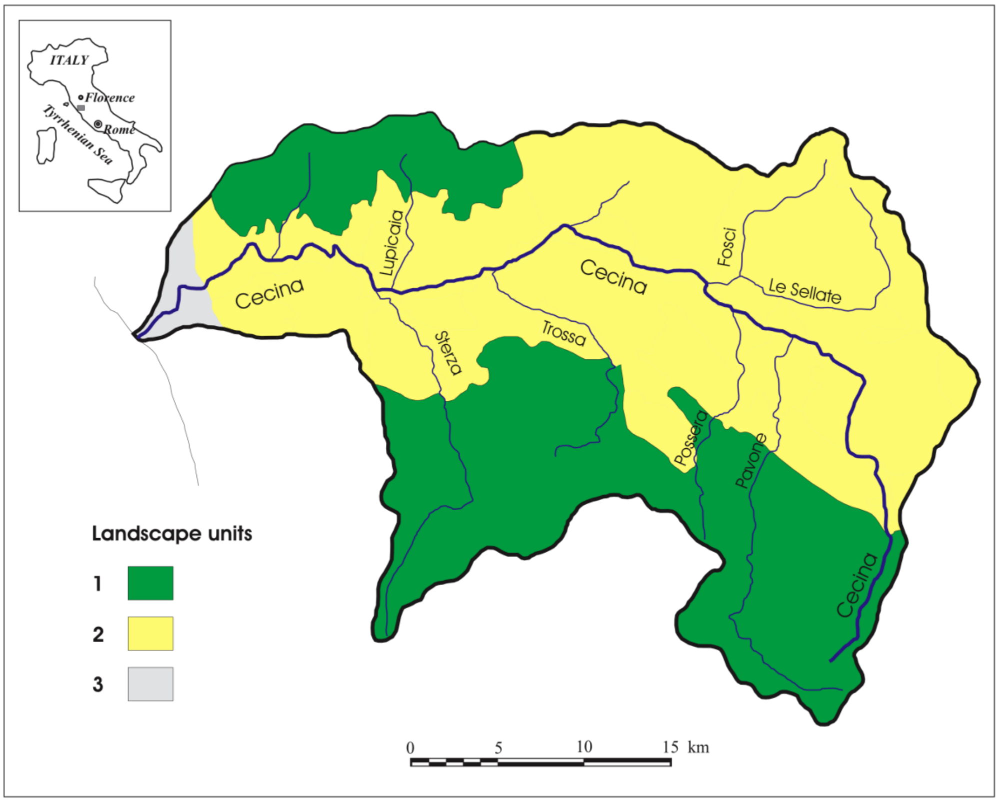


Figure 3.7 Landscape units of the Cecina River catchment: 1: Hilly - mountain areas; 2: rounded hills; 3: coastal plain.

3.3.2 River segments

Based on the intersection of the main streams with the landscape units, and on the macro-characteristics of the valley setting (i.e. presence and continuity of alluvial deposits), a series of segments have been identified (Magra river: Figures 3.8 and 3.9; Cecina river: Figure 3.10).

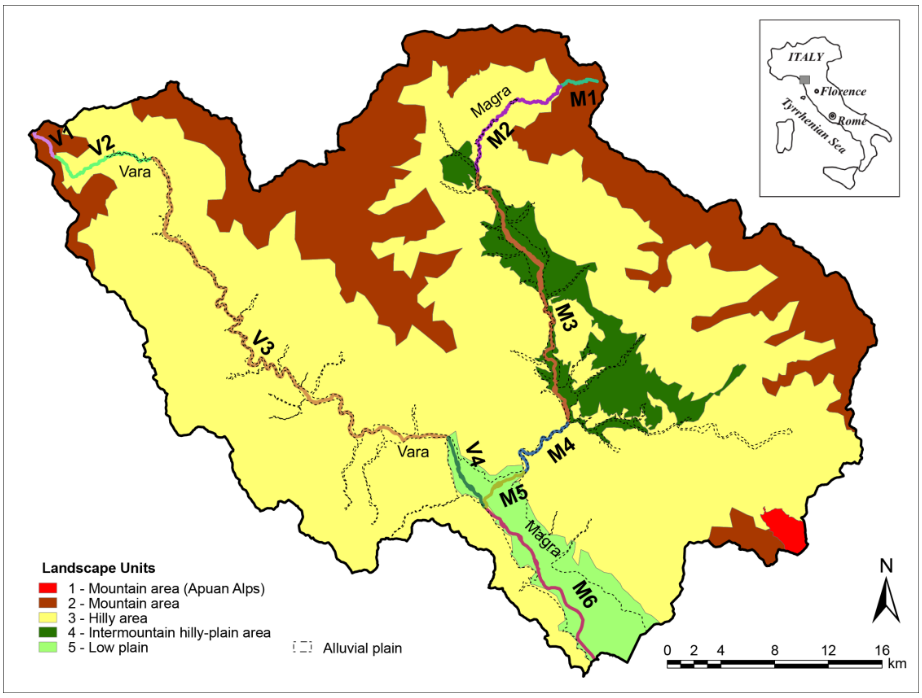


Figure 3.8 Identification of segments for the Magra and its main tributary, the Vara river. The extension of the alluvial deposits – dotted line – is useful in this phase to define the valley setting.

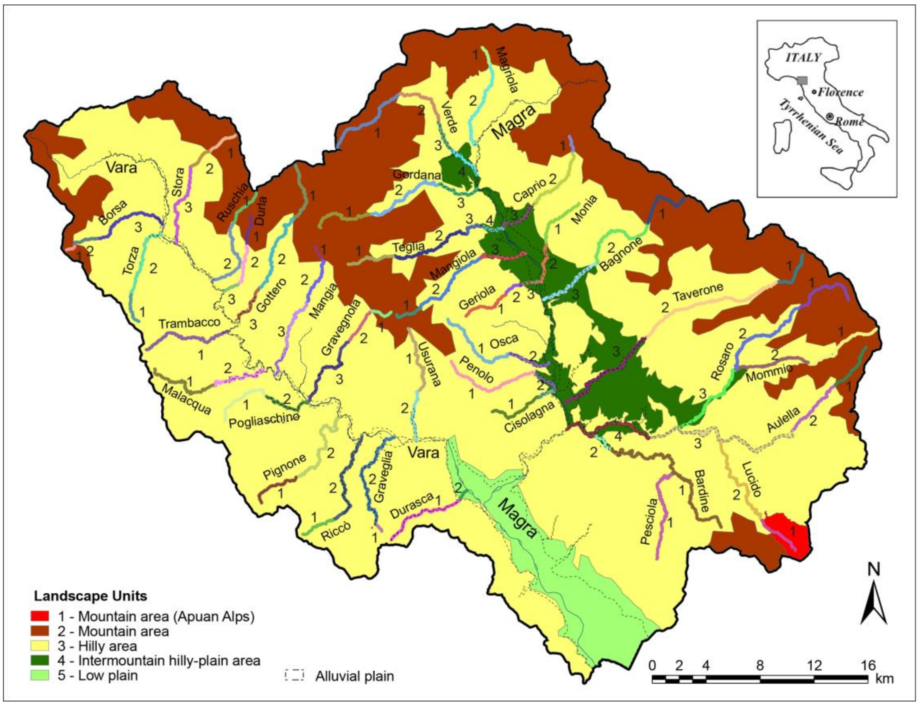


Figure 3.9 Identification of segments for the tributaries of the Magra and Vara rivers. The extension of the alluvial deposits is useful in this phase to define the valley setting.

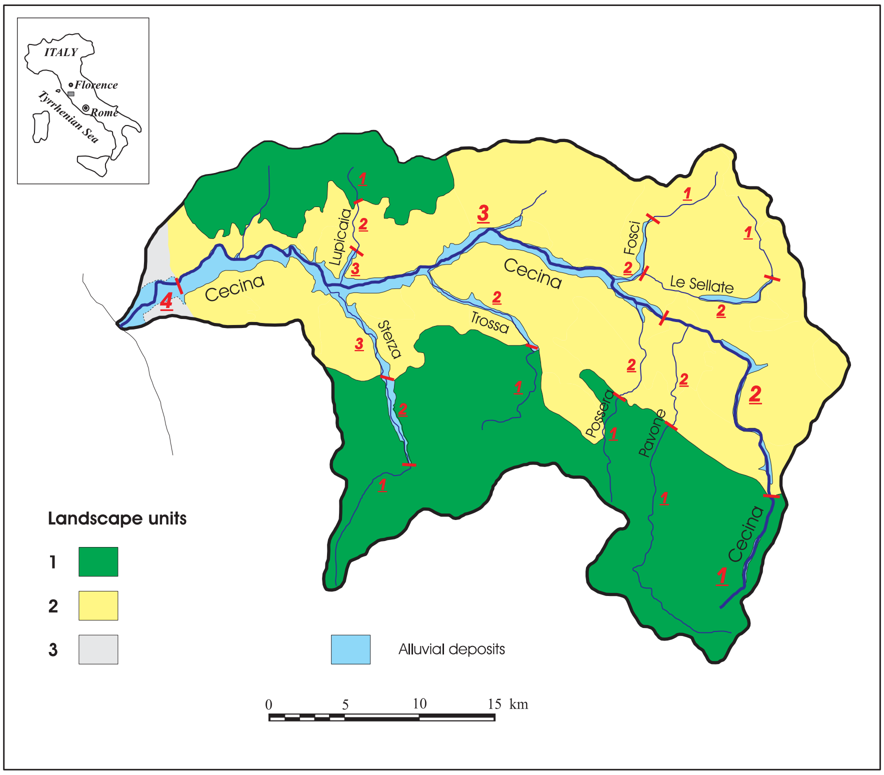


Figure 3.10 Identification of segments for the Cecina river (the extension of the alluvial deposits is useful in this phase to define the valley setting).

3.4 River reaches

3.4.1 Valley setting (confinement)

Analysing the confinement in more detail, a total of 7 preliminary macro-reaches have been identified for the Magra river, 7 for the Vara river, and 11 for the Cecina river (Figures 3.11 and 3.12).

3.4.2 Channel morphology

Magra and Vara rivers

Identification of planform pattern has been carried out by using the most recent available Google Earth© images:

- For the Magra river: 05/10/2011 for most of the river; 19/10/2003 for the upstream confined reaches.
- For the Vara river: 20/07/2011 for most part of the river; 06/02/2006 where images at that date were not available (approximately, the latest 17 km).

Based on channel morphology:

- Magra river: 10 preliminary reaches have been identified, associated with 5 river channel pattern typologies (Figure 3.13).

- Vara river: 8 preliminary reaches have been identified, associated with 4 river channel pattern typologies (Figure 3.13).

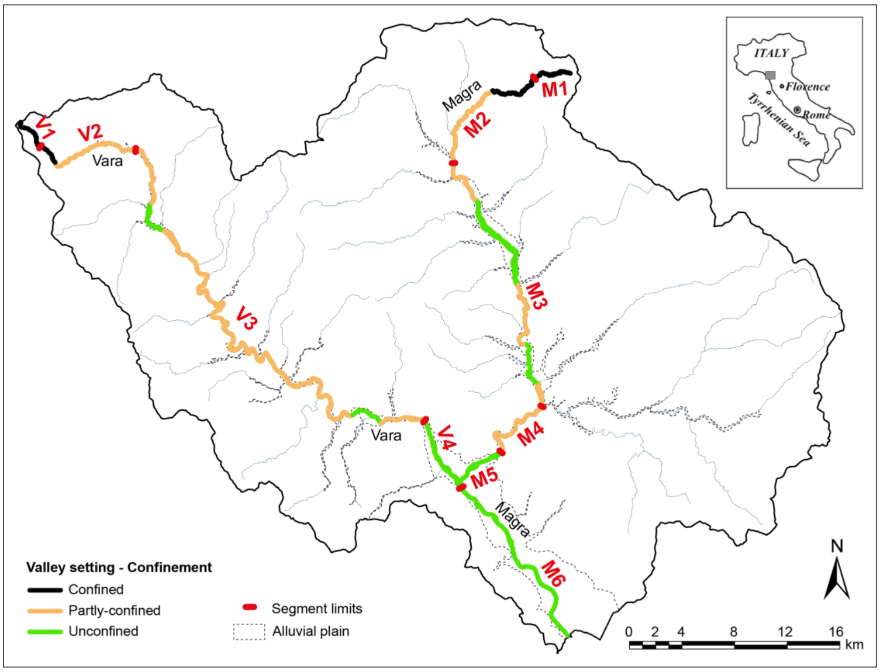


Figure 3.11 Confinement classes for the Magra and Vara rivers. Segment limits and names are also shown.

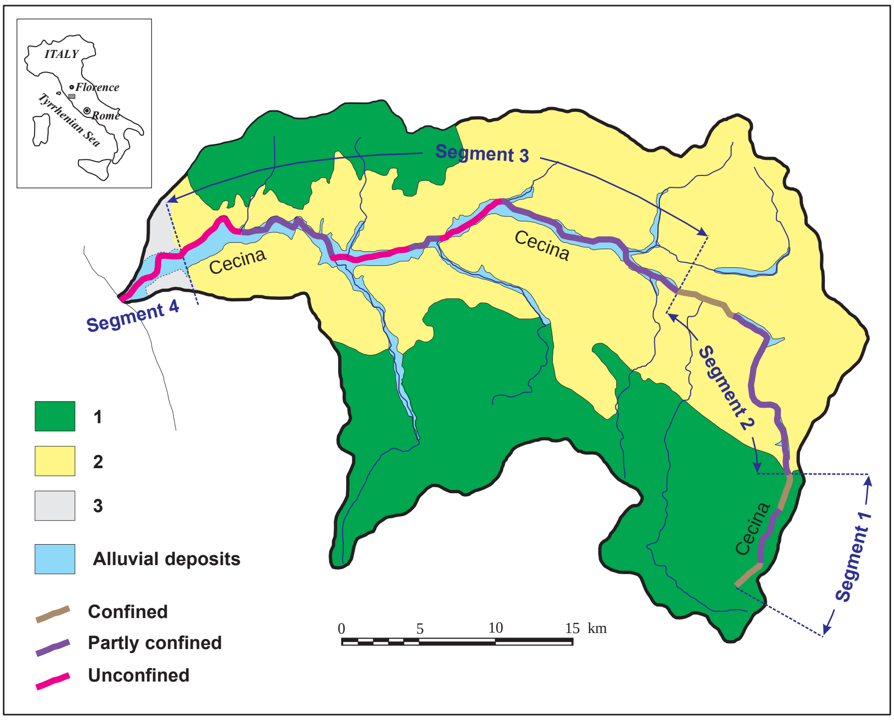


Figure 3.12 Confinement classes for the Cecina river.

By combining information obtained from the delineation of river segments, the valley setting (confinement classes) and channel morphology (planform pattern), 15 and 12 reaches have been identified for the Magra and the Vara rivers respectively (Figure 3.14).

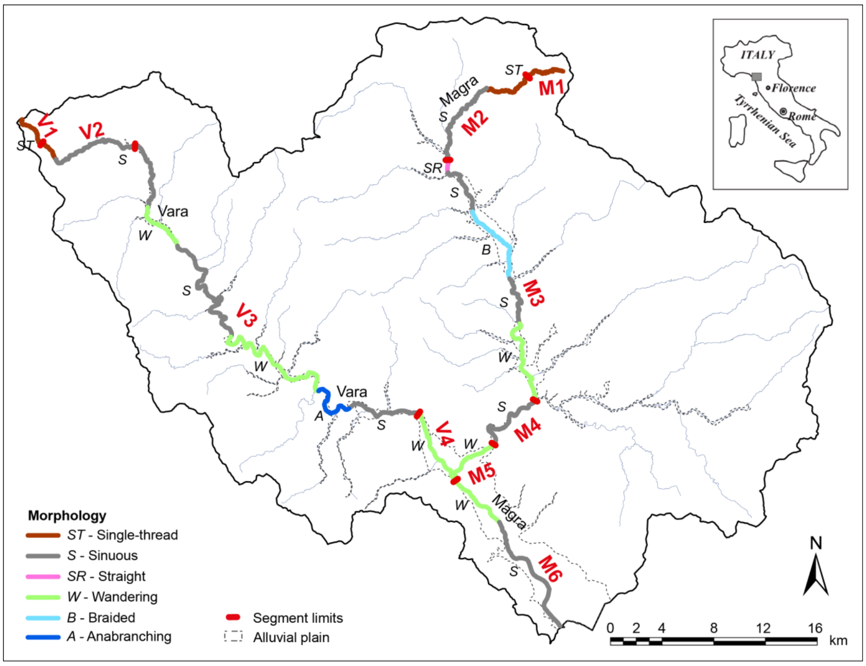


Figure 3.13 Identification of 10 reaches of 5 different morphological typologies for the Magra river, and 8 reaches of 4 different morphological typologies for the Vara river, based on planform pattern.

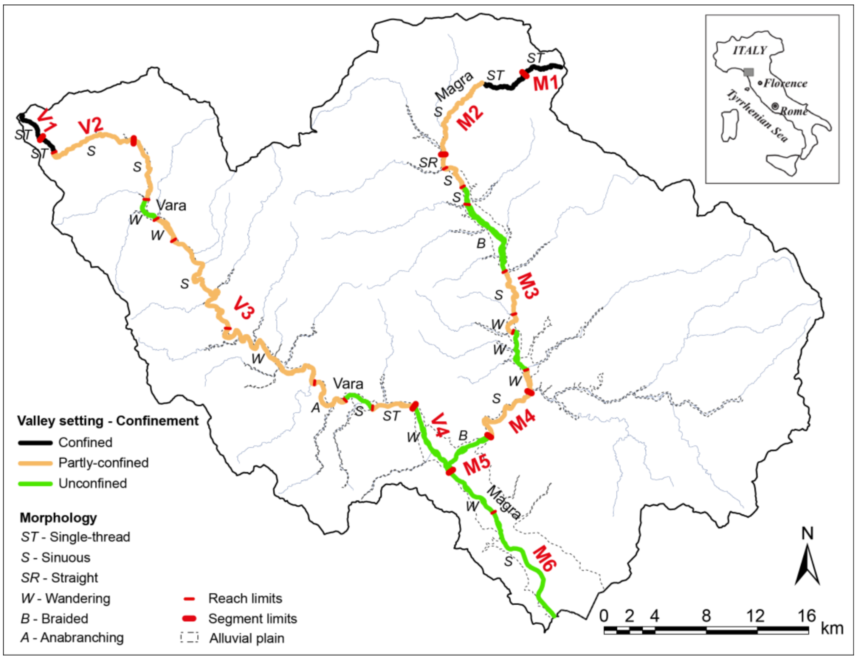


Figure 3.14 Identification of 15 (Magra) and 12 (Vara) reaches based on integration of segments, confinement classes and planform pattern.

Cecina river

Identification of planform pattern has been carried out by using the virtual observation tool Google Earth© dated 8/15/2009.

Based on channel morphology, 10 reaches have been identified, associated with 4 different planform patterns (Figure 3.15). Combining segments, confinement classes and planform patterns, 15 reaches have been identified (Figure 3.16).

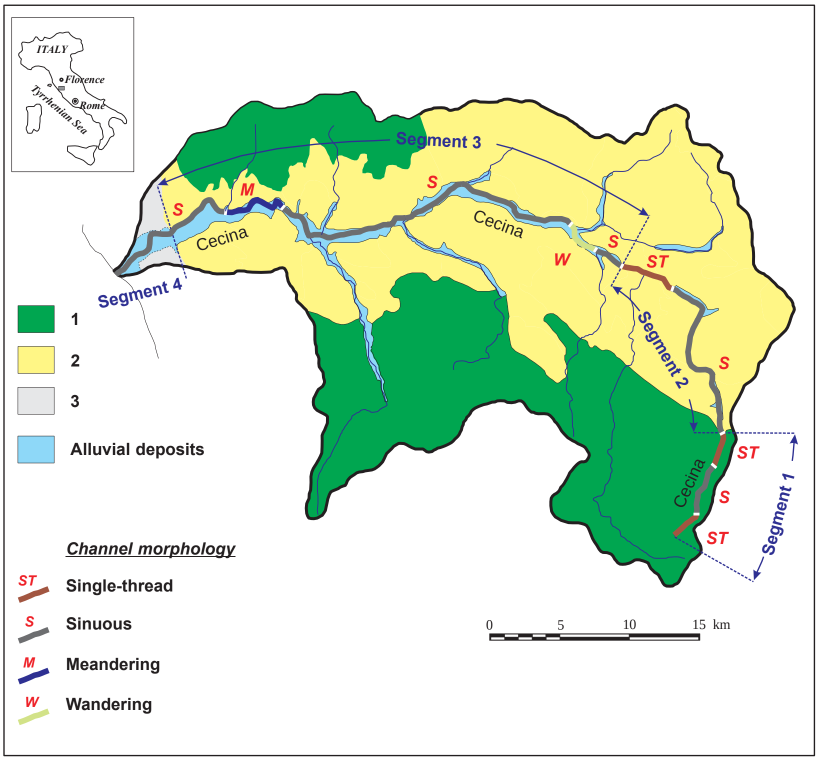


Figure 3.15 Identification of 10 reaches of 4 different morphological typologies based on planform pattern.

3.4.3 Other discontinuities

As a final step, additional discontinuities were considered, e.g. in terms of channel planform, morphological units and main river tributaries.

Magra and Vara rivers

For the Magra river, additional discontinuities have been identified in segments 2, 3 and 6.

In **segment 2**, the long partly confined sinuous reach was divided into four reaches because there is a clear transition between a discontinuous alluvial plain (2.2), continuous but narrow plain (2.3) and continuous but larger plain (2.4); finally the last portion of the segment 2 is influenced by the confluence of the Magriola torrent which allows identification of a further reach (2.5).

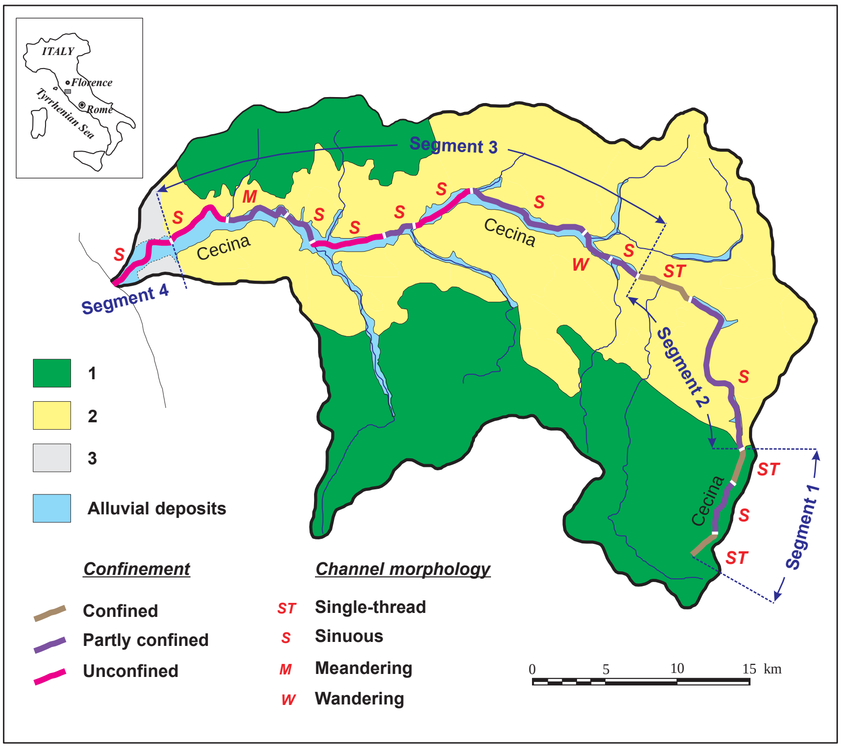


Figure 3.16 Identification of 15 reaches based on integration of confinement classes and planform pattern.

In **segment 3**, the long unconfined braided reach was divided into 2 separate reaches (3.4 and 3.5) because of a consistent difference in braiding pattern (the *Bi* changes from 1.6 to 2.1), and because of a distinctively different presence of morphological units: the presence of mid-channel bars and mid-channel islands becomes significantly important in the downstream reach (3.5).

In **segment 6**, the long unconfined sinuous downstream reach has been divided in two reaches because of the discontinuity in morphological units: the first part (6.2) is characterised by the presence of some depositional forms (i.e. lateral bars), whereas the last portion (6.3) is characterised by the absence of bars and other depositional forms.

For the Vara river, additional discontinuities have been identified in segments 2, and 3.

In **segment 2**, the long partly confined sinuous reach was divided into two reaches because the second part (reach 2.3) presents a wider and more continuous alluvial plain in comparison to the first one (reach 2.2).

The long **segment 3** shows numerous discontinuities:

(1) The partly confined sinuous reach at the beginning of the segment has been divided into two reaches because of a difference in morphological units: the upstream reach (3.1) shows a lower and discontinuous presence of bars compared to the downstream

reach (3.2), where bars are almost continuously present ('sinuous with alternate bar' morphology).

(2) The long partly confined sinuous reach, located in the mid-upstream part of the segment, has been divided into three reaches because of differences in morphological units: the reach shows, in its middle portion (3.6), a distinct passage to a 'sinuous with alternate bars' morphology.

(3) The long partly-confined wandering reach, located in the mid-downstream part of the segment, has been divided into two reaches because of differences in morphological units: the upstream reach (3.8) is characterised by a sequence of sinuous with no/few bars portions alternated by shorter portions in which braiding/anabranching phenomena occur; the downstream reach (3.9) is characterised by the more continuous presence of bars and/or islands.

After this step, the definitive map and list of reaches (20 and 17 for the Magra and Vara rivers respectively) was obtained (Figure 3.17).

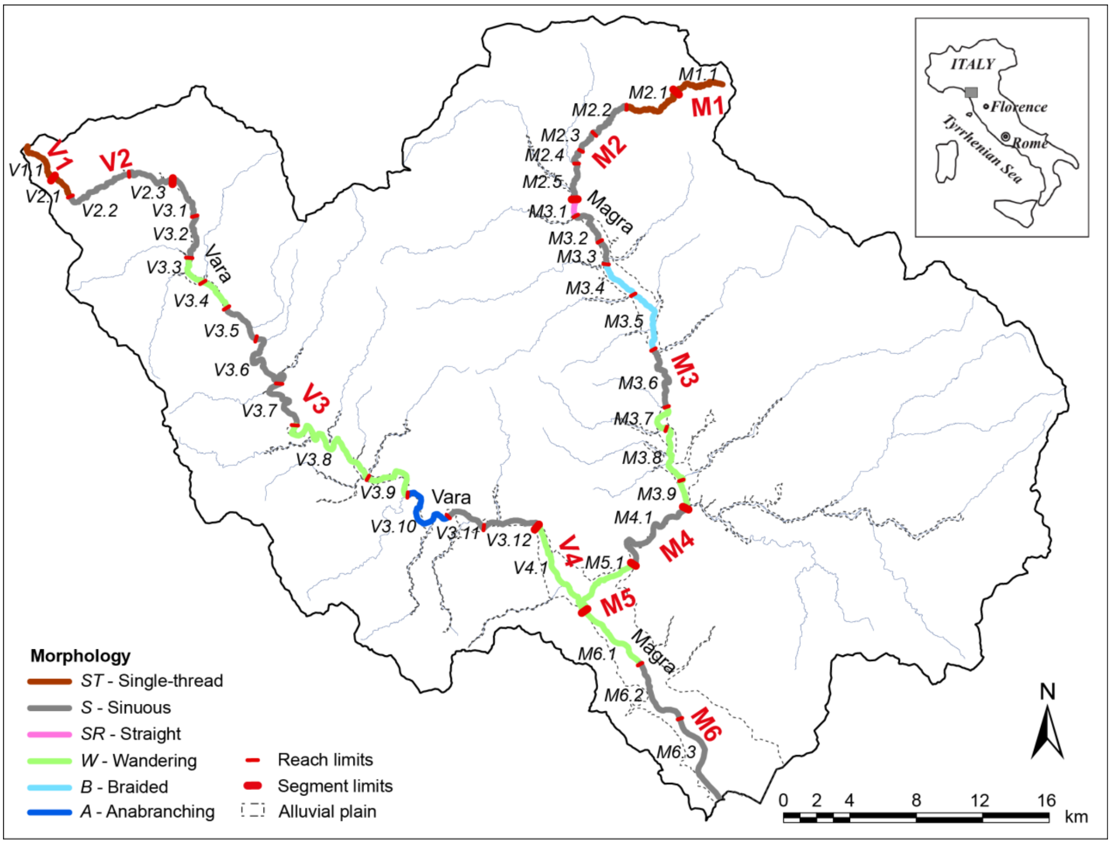


Figure 3.17 Final identification of 20 (Magra) and 17 (Vara) reaches.

Cecina river

Three cases of additional discontinuities have been identified for the Cecina river.

(1) In segment 2, a long partly confined sinuous reach was divided into three reaches because the intermediate portion (2.2) presented a significant reduction in the width of

the alluvial plain (and therefore in the confinement index), although still associated with the partly confined class. This has consequences in terms of lateral activity, because reach 2.2 is characterized by a much lower lateral mobility given that it is more confined.

(2) A second discontinuity was identified in segment 2 for a tributary of significant size (Pavone), based on which a reach was divided into two. Other major tributaries were already incorporated during the previous step, and this additional junction was associated with a change in channel morphology.

(3) In segment 3, a reach classified as 'sinuous' has been further divided into two reaches: reach 3.3 is characterized by few bars, and reach 3.4 is characterized by a distinct passage to a 'sinuous with alternate bars' morphology.

After this step, the definitive map and list of 19 reaches was obtained (Figure 3.18).

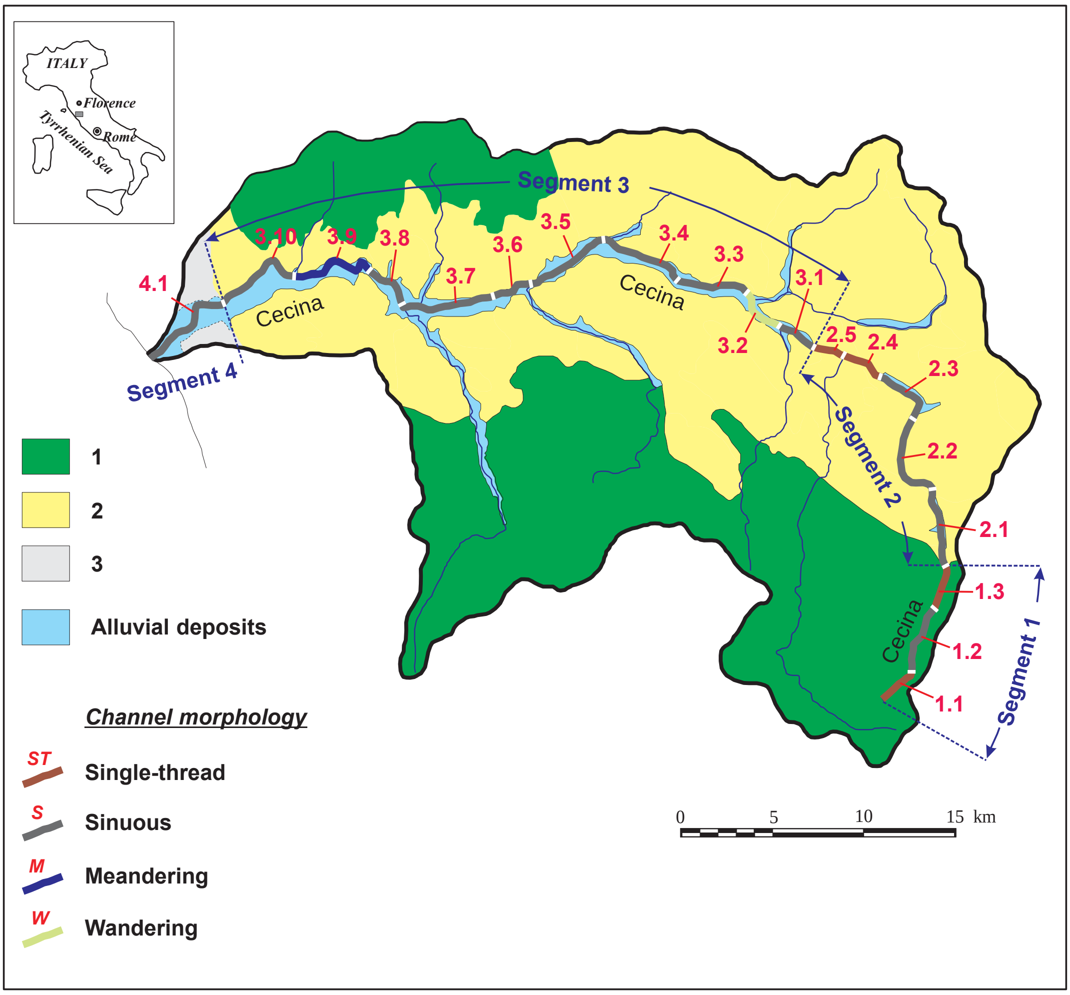


Figure 3.18 Final identification of 19 reaches.

4. Characterising the spatial units

This section mainly focuses on the Magra river and Cecina river; when available, some information on the Vara river is reported.

4.1 Region

The Magra river catchment is located in Northern Tuscany and Liguria (Central-Northern western Italy) (Figure 3.1a). The Cecina River catchment is located in Central Tuscany (Central-Northern western Italy) (Figures 3.1b). Both catchments are included within the Mediterranean biogeographical region.

4.2 Catchment

Magra river catchment

The Magra river catchment has an area of about 1700 km^2 and a perimeter of 238.1 km. The Magra river is about 69.5 km long, whereas the Vara river, its main tributary, is about 65 km long.

The general characteristics of the catchment are summarized in Table 4.1.

The physiography of the catchment is characterized by aligned ridges with a NW-SE trend, made up of Mesozoic and Tertiary units with folded structures, separated by two main basins with a similar trend: to the west is the valley of the Vara river, the main tributary of the Magra (catchment area of 572 km^2), and to the east is the middle-upper Magra valley. Mountain areas often reach 1300 and 1400 m a.s.l. and some isolated sectors reach 1800 m a.s.l. (Rinaldi et al. 2009). The mountains separating the Magra and the Vara catchment rarely reach 1100 m a.s.l.

The area falls within a temperate climatic zone but relatively humid (high rainfall). The catchment can be subdivided into 3 main climatic areas: the mountain area, the hilly area (colder for the Vara catchment) and the coast (temperate). The discharge regime is Apennine, with high flows during the autumn and low flows during the summer. The mean annual precipitation is greater than 1000 mm (Rinaldi et al. 2009).

Table 4.1 Physiographic and hydrological characteristics of the Magra river and its main tributary, the Vara river (from Rinaldi et al. 2009).

River	Drainage basin area (km^2)	Length (km)	Basin relief (m)	Precipitation (mm year^{-1})	Mean annual discharge (m^3 s^{-1})	Mean of maximum annual daily discharge (m^3 s^{-1})	Largest flood (m^3 s^{-1})
Magra	1699 (932*)	70	1639	1707	40	683	3480
Vara	572 (205*)	65	1603	1770	8.3	133.8	774

The dominant land cover is forests and semi-natural areas (79%), and then agriculture (18%) which dominates, together with artificial and urban areas (3% of the total cover), in the downstream part of the catchment (Figure 4.1).

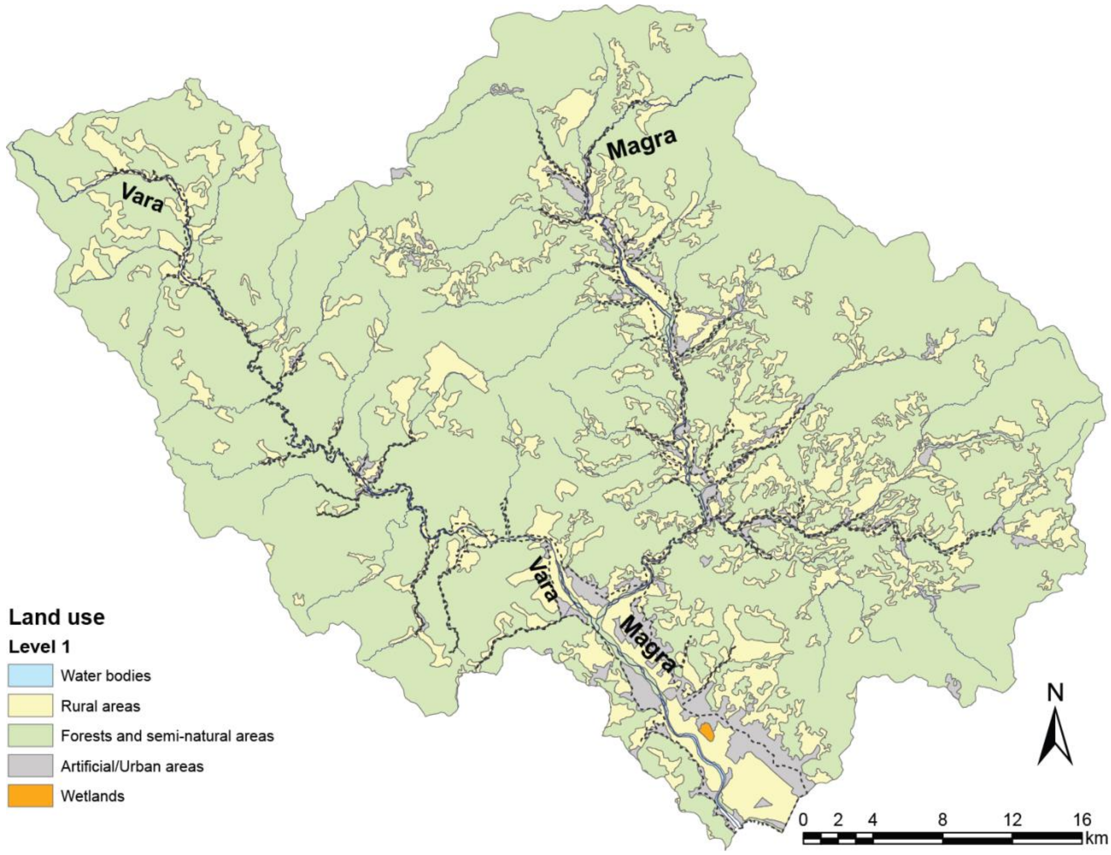


Figure 4.1 Corine Land Cover (land use) of level 1 (2006) for the Magra river catchment.

Cecina river catchment

The Cecina river has a total length of 53 km and its catchment area is about 905 km^2. The middle and lower portion of the watershed is dominated by hilly slopes constituted by erodible fluvio-lacustrine and marine sediments (Figure 3.5). The basin falls within a temperate climatic zone with a dry season and is characterized by high variability in flow discharges and flashy floods (Nardi 2011). The mean annual precipitation is about 944 mm (Table 4.2).

Table 4.2 Physiographic and hydrological characteristics of the Cecina River (extracted from Surian et al. 2009).

Drainage-basin area (km^2)	Length (km)	Basin relief (m)	Precipitation (mm yr^{-1})	Mean annual discharge (m^3 s^{-1})	Largest flood (m^3 s^{-1})
905	53	1018	944	8	1030

Concerning the land cover, only the upstream portions of the catchment is occupied by forests, whereas the remaining part of the catchment is mainly occupied by farm land (corns, cereals, olive trees and vineyards; Figure 4.2).

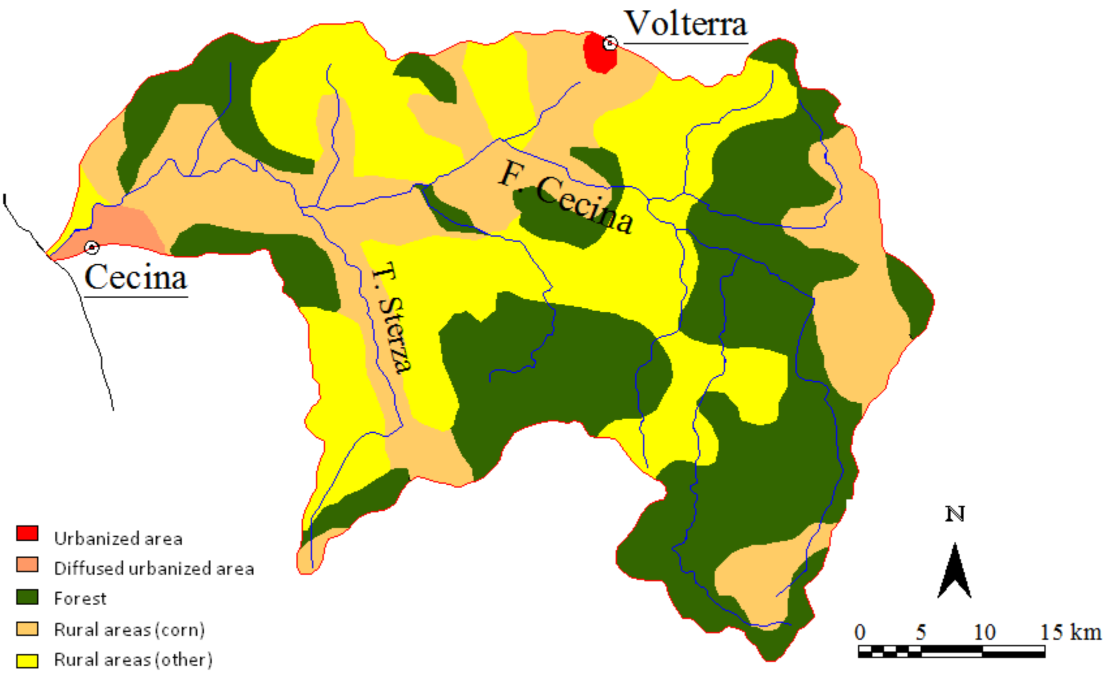


Figure 4.2 Land cover in the Cecina River catchment (modified from Nardi 2004).

4.3 Landscape units and river segments

Note that the characterisation of the flow and sediment regimes at the segment scale is provided only for the Magra river, since more data were available.

Table 4.3 synthetises the main characteristics of the landscape units and river segments for the Magra river and its main tributary, the Vara river.

Table 4.4 synthesises the main characteristics of identified landscape units and river segments for the Cecina river.

Table 4.3 Synthetic description of landscape units and segments for the Magra (M) and the Vara (V) river.

Landscape units		*Segment*	
Name	**Description**	**Number**	**Description**
Mountain areas (Apuan Apls)	Mountain areas (up to 1550 m a.s.l.) characterized by prevailing by metamorphic rocks	/	/
Mountain Areas	Mountain areas (up to 1800 m a.s.l.) characterized by sandstones (Magra) and clays (Vara)	M1; V1	Steep, mainly confined
Hilly areas	Hilly areas (<600 m a.s.l.) characterized by limestones and sandstones (Magra) and by sandstones and clays (Vara)	M2; M4; V2; V3	Prevailing alternation of partly confined and confined settings; M2 and V2 are mainly confined except some floodplain pockets
High plain (intermountain)	High plain, characterised by recent alluvial deposits (Magra catchment)	M3	Continuous alluvial plain but varying in width; presence of some hilly areas (ancient terraces)
Low plain	Low plain of the Magra river, characterised by recent fluvial lacustrine and marine Deposits	M5; V4	Low gradient, unconfined, wide alluvial plain

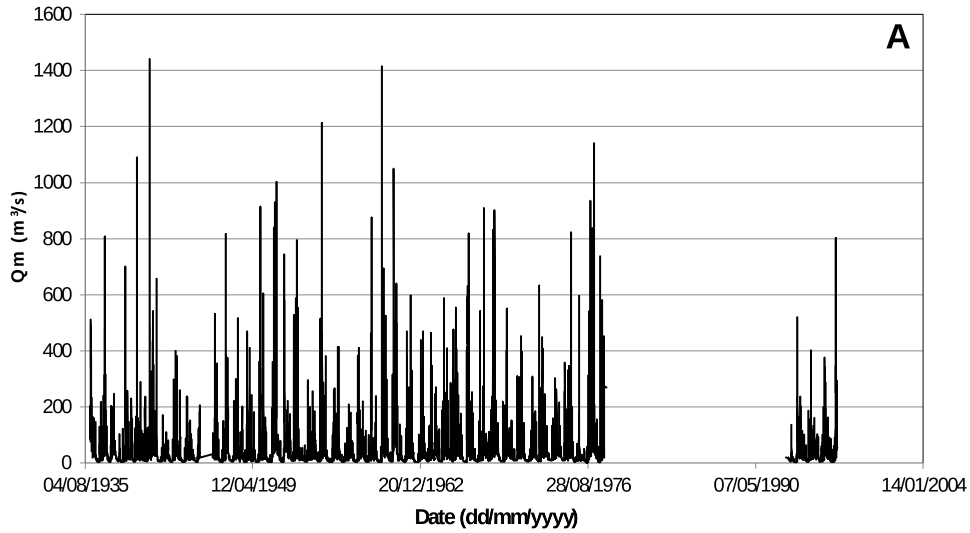
Table 4.4 Synthetic description of landscape units and segments for the Cecina river.

Landscape units		*Segments*	
Name	**Description**	**N**	**Description**
Hilly - mountain areas	Hilly and mountain areas (up to 1000 m a.s.l.) characterized by prevailing hard sedimentary and magmatic rocks	1	Steep, mostly confined except some floodplain pocket
Rounded hills	Hilly areas (always <600 m a.s.l.) characterized by prevailing soft lacustrine, marine or ancient fluvial deposits (clay, sand, conglomerate), including relatively narrow alluvial plains on the valley floor	2	Prevailing alternation of partly confined and confined settings
		3	Continuous presence of alluvial plain on the valley floor, with alternation of partly confined and unconfined
Coastal plain	Lowland plain	4	Low gradient, unconfined

4.3.1 Flow regime

Historical series of daily discharges are available at 2 gauging station within the Magra river within segments 2 and 4, named Piccatello and Calamazza, respectively (Figure 4.3). Data series cover a period of 30 years at Piccatello and 45 years at Calamazza. The various components of the flow regime analysis described in the Deliverable 2.1 Part 1 were applied to the aforementioned gauging stations and are reported in Table 4.5. The flow regime of the Magra River at Piccatello is classified as perennial flashy. Its annual hydrograph (averaged on the 30-years data series) is highly affected by flood events which are characterized by peak discharges values much greater than the mean flow discharge. Its 'flashy' behaviour is given by a high average number of flood events per year (FLDFREQ = 0.63).

The flow regime of the Magra River at Calamazza is classified as perennial runoff. Its impulsive behaviour is smoothed compared to that at Piccatello, having recorded 25 flood events in 45 year (FLDFREQ = 0.56). At this segment, floods commonly occur in late autumn (November-December).



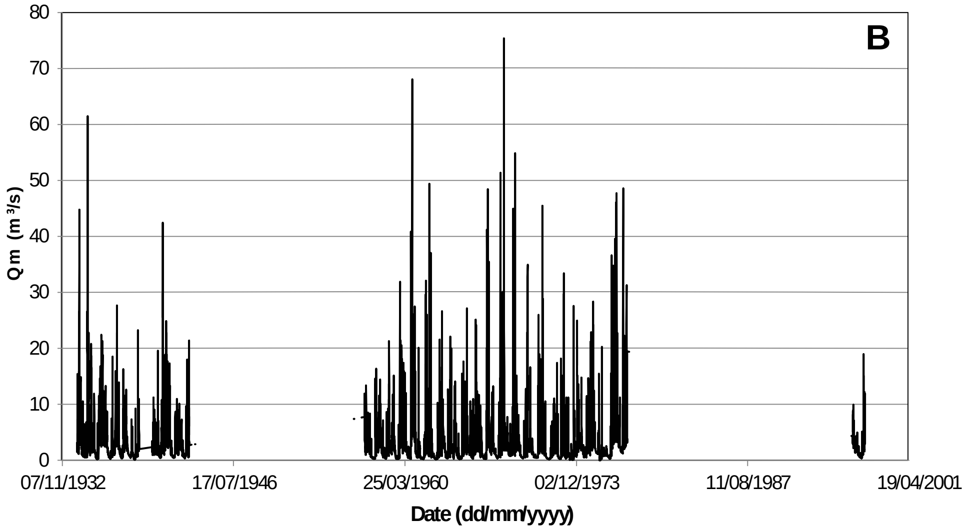


Figure 4.3 Historical series of mean daily discharges at Calamazza (A) and Piccatello (B) gauging stations.

Table 4.5 Hydrological indicators for 2 gauging stations within the River Magra catchment.

Hydrological indicators	Magra River Piccatello (segment 2)	Magra River Calamazza (segment 4)
BFI – Baseflow index *Annual mean of the monthly ratio between min month discharge and mean monthly discharge*	20.42	22.15
ZERODAYS *Number of days with no channel flow per year*	0	0
FLDFREQ *Average number of flood 'events' per year*	0.63	0.56
FLDPRED *Maximum proportion of floods that falls in one of six 60-day seasonal windows*	0.42	0.44
FLDTIME *First Julian day within the seasonal window when FLDPRED is highest*	274	305
DAYCV *Standard deviation of daily discharge divided by annual mean discharge (x 100)*	136.38	161.7
Regime	Perennial Flashy	Perennial Runoff

Minimum, maximum and mean annual flow recorded at the two gauging stations are reported in Table 4.6.

Table 4.6 Minimum, maximum and mean annul flow recorded at the two gauging stations in the recorded period.

Gauging station	Qmax	Qmean	Qmin
Piccatello	75.40	2.94	0.08
Calamazza	1440	39.7364	0.87

4.3.2 Sediment

Sediment size

The median particle diameter (D_{50}) varies approximately between 17 and 91 mm along the Magra River, and between 12 and 68 mm along the Vara River (Rinaldi et al. 2008).

Sediment production

Figure 4.4 shows the potential contribution of coarse sediment production for each segment. The analysis is based on the identification of landslides (active/suspended vs. quiescent/relict) at the catchment scale provided by the available geological map. Segment 2 has the greatest surface of active/suspended landslides compared to its drainage area (Fig. 4.4a). When these data are expressed per unit segment length, segments 2 and 3 make the the same contribution to sediment production from active/suspended landslides (Fig. 4.4b).

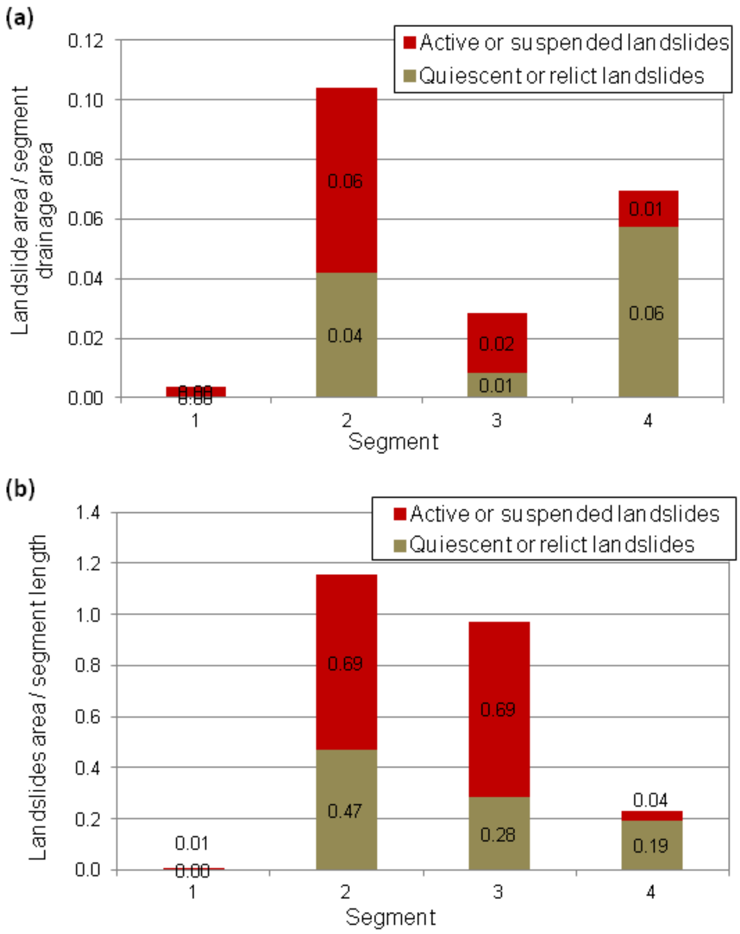


Figure 4.4 Potential contribution to sediment production per segment from catchment landslides in the Magra catchment: (a) landslide area per segment drainage area; (b) landslide area per segment length.

4.4 Reaches

Figures 4.5 and 4.6 show the final classification of the Magra and Vara reaches and the Cecina reaches, respectively, based on valley setting (confinement) and morphology (channel pattern). For each reach the characteristic valley setting and morphology are displayed.

Characteristics of each reach, in terms of landscape units, river segments, valley setting, channel morphology and the presence of further discontinuities, are summarised in Tables 4.7 and 4.8 for the Magra and Vara rivers and Table 4.9 for the Cecina river.

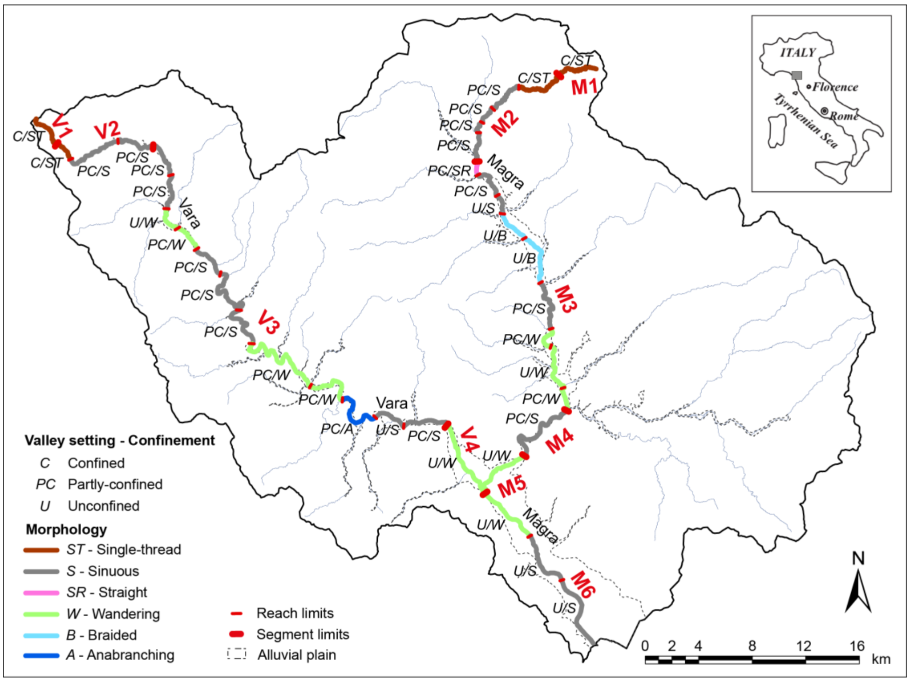


Figure 4.5 Final classification of the reaches (Magra and Vara) based on confinement and morphology.

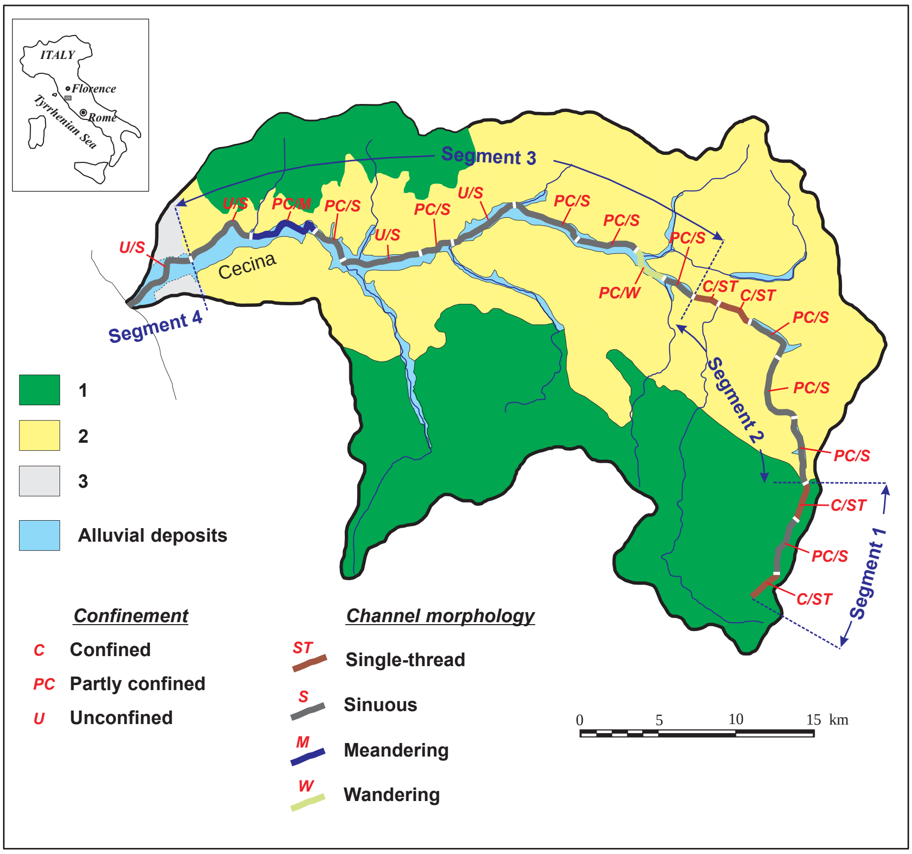


Figure 4.6 Classification and characterisation of the reaches of the Cecina river based on confinement and morphology.

Table 4.7 Summary table of reach characteristics used for the segmentation in reaches (M: Magra river; V: Vara river).

Landscape units	Segments	Confinement (valley setting)	Channel morphology	Other discontinuities	Reaches
Mountain	M1 - Confined	Confined	Single-thread		[M1.1]
unit (1)	V1 - Confined	Confined	Single-thread		[V1.1]
Hilly unit (3)	M2 - Confined/ Partly confined	Confined	Single-thread		[M2.1]
		Partly confined	Sinuous	Discontinuous plain	[M2.2]
		Partly confined	Sinuous	Narrow plain	[M2.3]
		Partly confined	Sinuous	Wider plain	[M2.4]
		Partly confined	Sinuous	Main tributary (Magriola T.)	[M2.5]
	M4 - Partly confined	Partly-confined	Sinuous		[M4.1]
	V2 - Confined/ Partly confined	Confined	Single-thread		[V2.1]
		Partly confined	Sinuous	Discontinuous plain	[V2.2]
		Partly confined	Sinuous	Continuous plain	[V2.2]
	V3 - Alternation partly confined –	Partly confined	Sinuous		[V3.1]
		Partly confined	Sinuous	'Sinuous with alternate bar' morphology	[V3.2]
	unconfined (continuous plain)	Unconfined	Wandering		[V3.3]
		Partly confined	Wandering		[V3.4]
		Partly confined	Sinuous		[V3.5]
		Partly confined	Sinuous	'Sinuous with alternate bar' morphology	[V3.6]
		Partly confined	Sinuous		[V3.7]
		Partly confined	Wandering	Discontinuous presence of bars and braiding/anabranching phenomena	[V3.8]
		Partly confined	Wandering	Continuous presence of bars/islands	[V3.9]

		Partly confined	Anabranching		[V3.10]
		Unconfined	Sinuous		[V3.11]
		Partly confined	Sinuous		[V3.12]
Intermountain unit (4)	M3 - Alternation partly confined – Unconfined (continuous plain)	Partly confined	Straight		[M3.1]
		Partly confined	Sinuous		[M3.2]
		Unconfined	Sinuous		[M3.3]
		Unconfined	Braided	‘bar braided’ morphology	[M3.4]
		Unconfined	Braided	higher braiding intensity; ‘island braided’ morphology	[M3.5]
		Partly confined	Sinuous		[M3.6]
		Partly confined	Wandering		[M3.7]
		Unconfined	Wandering		[M3.8]
		Partly confined	Wandering		[M3.9]
Low plain unit (5)	M5 - Lowland plain	Unconfined	Wandering	Upstream Vara catchment	[M5.1]
	M6 - Lowland plain	Unconfined	Wandering	Downstream Vara catchment	[M6.1]
		Unconfined	Sinuous	With bars	[M6.2]
		Unconfined	Sinuous	Absence of bars	[M6.3]
	V4 – Lowland plain	Unconfined	Wandering		[V4.1]

Table 4.8 Summary table of general reach characteristics (‘M’, Magra; ‘V’, Vara) (n. a., data not available). L: reach length (m); Cd: confinement degree (%); Ci: confinement index; C: confined; PC: partly confined; U: unconfined; ST: single-thread; S: sinuous; SR: straight; W: wandering; B: braided; A: anabranching.

Reach	L (m)	Cd (%)	Ci	Confinement	Morphology
M1.1	3685	>90	n. a.	C	ST
M2.1	4780	>90	n. a.	C	ST
M2.2	2977	70	4	PC	S
M2.3	1390	52	3	PC	S
M2.4	957	43	7	PC	S
M2.5	2603	47	4	PC	S
M3.1	1014	20	4	PC	SR
M3.2	3044	47	3	PC	S
M3.3	1248	0	5	U	S
M3.4	2562	<10	5	U	B
M3.5	4023	<10	4	U	B
M3.6	4115	33	2.5	PC	S
M3.7	1535	20	3.3	PC	W
M3.8	3693	<10	5.7	U	W
M3.9	1712	32	2.9	PC	W
M4.1	6616	39	3.2	PC	S
M5.1	4399	<10	5.8	U	W
M6.1	4820	<10	13.2	U	W
M6.2	4511	<10	15.6	U	S
M6.3	6201	<10	18.7	U	S
V1.1	3171	>90	n. a.	C	ST
V2.1	1782	>90	n. a.	C	ST
V2.2	4693	15	4.8	PC	S
V2.3	3181	19	7	PC	S
V3.1	2860	16	11.8	PC	S
V3.2	3086	16	5	PC	S
V3.3	2209	7	4.6	U	W
V3.4	2117	45	1.8	PC	W
V3.5	2922	17	4	PC	S
V3.6	5669	41	2.6	PC	S
V3.7	4480	28	3.4	PC	S
V3.8	8590	29	3.1	PC	W
V3.9	4200	29	4	PC	W
V3.10	4688	33	2.4	PC	A
V3.11	2667	0	9.1	U	S
V3.12	3593	18	5.2	PC	S
V4.1	6360	0	9.6	U	W

Table 4.9 Summary table of segmentation in reaches for the Cecina river.

Step 1 - Landscape units	Step 1 - Segments	Step 2 - Confinement	Step 3 – Channel morphology	Step 4 - Other discontinuities	Reaches
1. Hilly - mountain areas	1. Confined	Confined	Single-thread		[1.1]
		Partly confined	Sinuous		[1.2]
		Confined	Single-thread		[1.3]
2. Rounded hills	2. Alternation confined – partly confined	Partly confined	Sinuous		[2.1]
		Partly confined	Sinuous	Lower confinement index	[2.2]
		Partly confined	Sinuous		[2.3]
		Confined	Single-thread	Upstream tributary	[2.4]
		Confined	Single-thread	Downstream tributary	[2.5]
	3. Alternation partly confined – unconfined (continuous plain)	Partly confined	Sinuous		[3.1]
		Partly confined	Wandering		[3.2]
		Partly confined	Sinuous	Sinuous with sporadic bars	[3.3]
		Partly confined	Sinuous	Sinuous with alternate bars	[3.4]
		Unconfined	Sinuous		[3.5]
		Partly confined	Sinuous		[3.6]
		Unconfined	Sinuous		[3.7]
		Partly confined	Sinuous		[3.8]
		Partly confined	Meandering		[3.9]
		Unconfined	Sinuous		[3.10]
3. Coastal plain	4. Lowland plain	Unconfined	Sinuous		[4.1]

4.4.1 Channel dimensions (width, planform and gradient)

Reach characteristics in terms of channel width (both bankfull and active widths), planform and gradient are displayed in Table 4.10 and Figure 4.7 for the Magra and Vara rivers and Table 4.11 and Figure 4.8 for the Cecina river.

Table 4.10 Summary table of reach characteristics in terms of channel dimensions (n. a., data not available). Channel width: Wtot, total channel width (m) (i.e. including islands). Channel planform: Si, sinuosity index; Bi, braiding index; Ai, anabranching index; S, reach/channel gradient (%).

Reach	Wtot (m)	Si	Bi	Ai	S (%)
M1.1	8	n. a.	n. a.	n. a.	10.31
M2.1	8	n. a.	n. a.	n. a.	5.65
M2.2	12	1.11	1	1	2.45
M2.3	13	1.02	1	1	1.80
M2.4	18	1.08	1	1	1.78
M2.5	18	1.07	1	1	1.42
M3.1	30	1.03	1	1	1.58
M3.2	65	1.1	1.2	1	0.88
M3.3	96	1.07	1.2	1	1.11
M3.4	185	1.03	1.6	1.1	0.88
M3.5	226	1.04	2.15	1.6	0.85
M3.6	85	1.06	1.16	1	0.54
M3.7	172	1.31	1.14	1	0.48
M3.8	156	1.05	1.33	1	0.52
M3.9	192	1.008	1.33	1	0.37
M4.1	92	1.05	1	1	0.29
M5.1	206	1.07	1.6	1.2	0.29
M6.1	163	1.003	1.5	1.08	0.10
M6.2	145	1.11	1.3	1	0.11
M6.3	214	1.11	1	1	0.10
V1.1	n. a.	n.a.	n.a.	n.a.	19,49
V2.1	n. a.	n.a.	n.a.	n.a.	7,30
V2.2	15	1.2	1	1	2,66
V2.3	19	1.05	1	1	1,57
V3.1	16	1.06	1.03	1.03	1,57
V3.2	38	1.07	1.09	1.04	1,46
V3.3	61	1.05	1.1	1	0,45
V3.4	115	1.02	1.66	1.5	1,42
V3.5	39	1.03	1	1	0,34
V3.6	42	1.05	1.07	1	1,06
V3.7	39	1.04	1.02	1.02	0,67
V3.8	70	1.04	1.3	1.3	0,64
V3.9	64	1.08	1.3	1.15	0,12
V3.10	80	1.01	1.55	1.52	0,43
V3.11	59	1.05	1.38	1.23	0,56
V3.12	61	1.02	1.13	1	0,42
V4.1	101	1.03	1.43	1.15	0,39

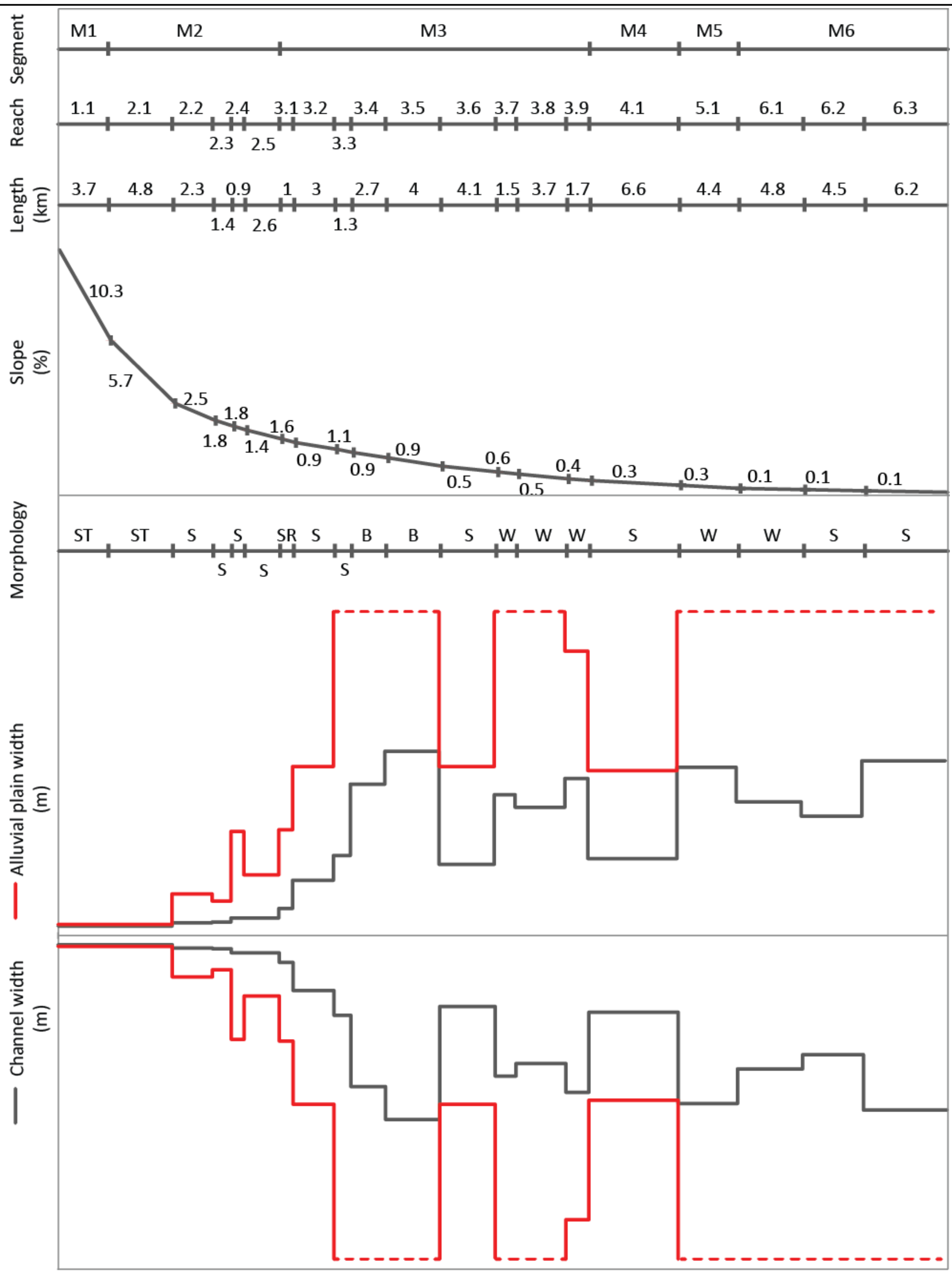


Figure 4.7 Summary of reach characteristics for the Magra river.

Table 4.11 Summary table of reach characteristics for the Cecina river. L: reach length (m); Cd: confinement degree (%); Ci: confinement index; C: confined; PC: partly confined; U: unconfined; ST: single-thread; S: sinuous; W: wandering; M: meandering; Si: sinuosity index; Bi: braiding index (anabranching index was not applicable); S: channel slope; W: channel width (m); D: dominant sediment type; B: boulders; C: cobble; G: gravel; D_{50}: median diameter of bed sediment (mm); n.a.: not applicable; n.av.: not available.

Reach	*L*	*Cd*	*Ci*	*Confinement*	*Morphology*	*Si*	*Bi*	*S*	*W*	*D*	*D_{50}*
1.1	4481	100	1	C	ST	n.a.	n.a.	0,070	5	B	n.av.
1.2	4775	48	6	PC	S	1,24	n.a.	0,016	8	C/G	n.av.
1.3	1122	100	1	C	ST	n.a.	n.a.	0,027	9	B/C	n.av.
2.1	4655	24	16	PC	S	1,1	n.a.	0,014	16	C/G	n.av.
2.2	4469	44	2	PC	S	1,1	n.a.	0,008	19	C/G	45,3
2.3	6980	34	20	PC	S	1,2	n.a.	0,006	28	G	n.av.
2.4	1400	>90	1	C	ST	n.a.	n.a.	0,0096	10	n.av.	n.av.
2.5	2300	>90	1	C	ST	n.a.	n.a.	0,0093	20	n.av.	n.av.
3.1	2200	52	10	PC	S	1,1	n.a.	0,0045	56	n.av.	34,4
3.2	3741	26	10	PC	W	1,1	1,2	0,004	74	C/G	27,3
3.3	2800	27	14	PC	S	1,1	1,2	0,0043	58	n.av.	17,6
3.4	6600	27	23	PC	S	1,2	1,1	0,003	41	n.av.	17,6
3.5	5462	6	17	U	S	1,2	1,1	0,0004	58	G	17,6
3.6	1873	31	9	PC	S	1,2	1,1	0,0059	49	G/C	n.av.
3.7	6425	0	20	U	S	1,1	1,2	0,003	73	G	16,5
3.8	3300	28	16	PC	S	1,1	1,1	0,0012	52	n.av.	11,6
3.9	5800	13	18	PC	M	1,51	1,1	0,0015	41	n.av.	12,9
3.10	5900	9	47	U	S	1,3	1,1	0,002	43	n.av..	13,7
4.1	5609	5	65	U	S	1,3	n.a.	0,0014	46	NC	n.av.

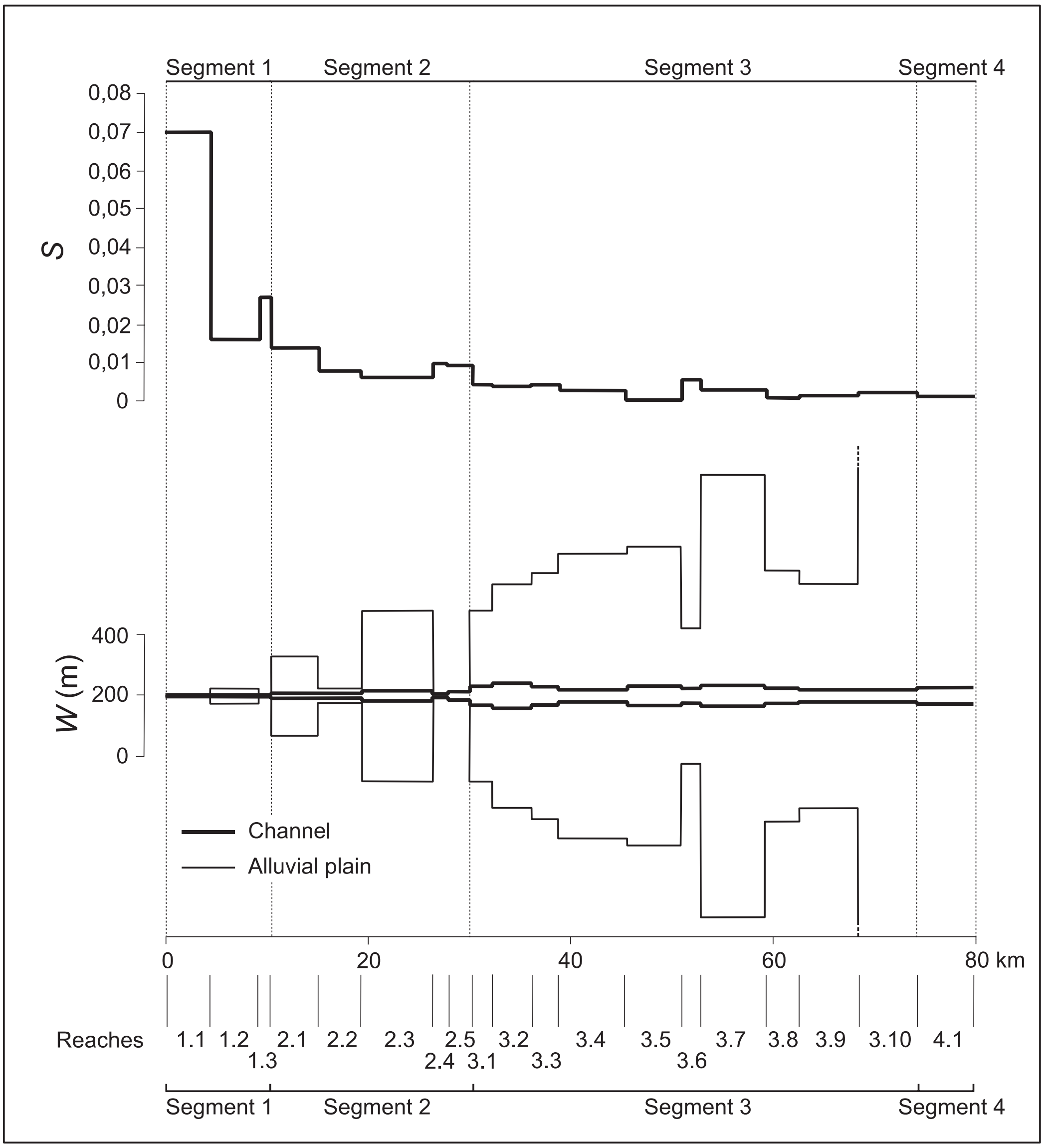


Figure 4.8 Summary of channel slope (S) and width (W) for the Cecina river.

4.4.2 River energy

Stream power (total and unit), as well as river discharge, for each reach of the Magra river, are shown in Figure 4.9.

The total stream power is lowest in the downstream reaches (segment M6) where the slope is lowest and reaches the maximum value in reach M3.5.

Specific stream power is greatest in reach 2.2 (mean = 6970 W m^{-2}) where the channel is narrowest and steepest. It decreases downstream reaching the lowest value in reach 6.3 which is characterised by the lowest slope and widest mean cross section.

Average bed shear stress and velocities computed with the 1D model HEC-RAS for three different discharges decrease with distance downstream (Figure 4.10), mirroring the longitudinal pattern in channel gradient.

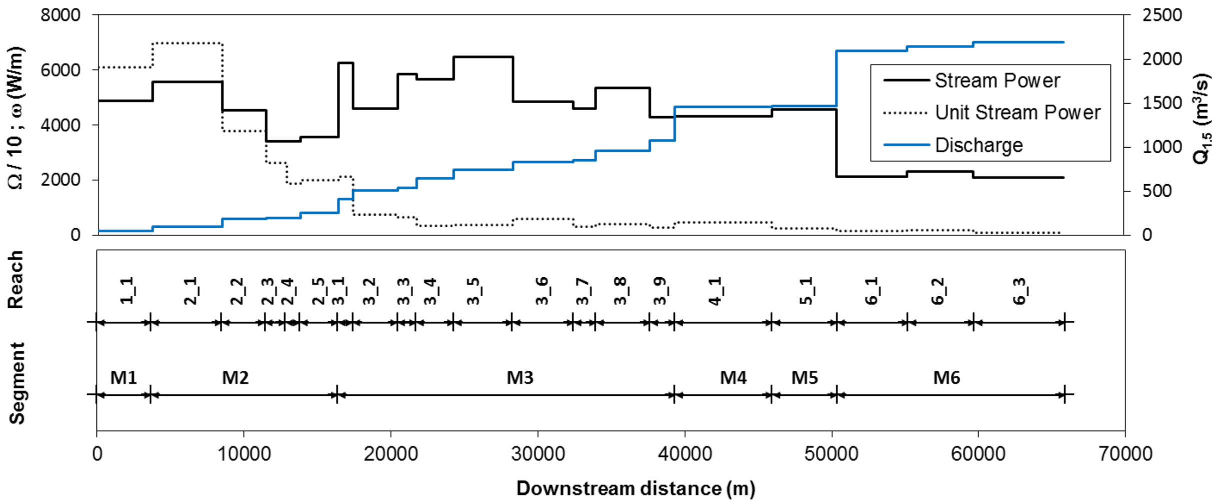


Figure 4.9 Distribution of $Q_{1.5}$, stream power and unit stream power for the Magra river.

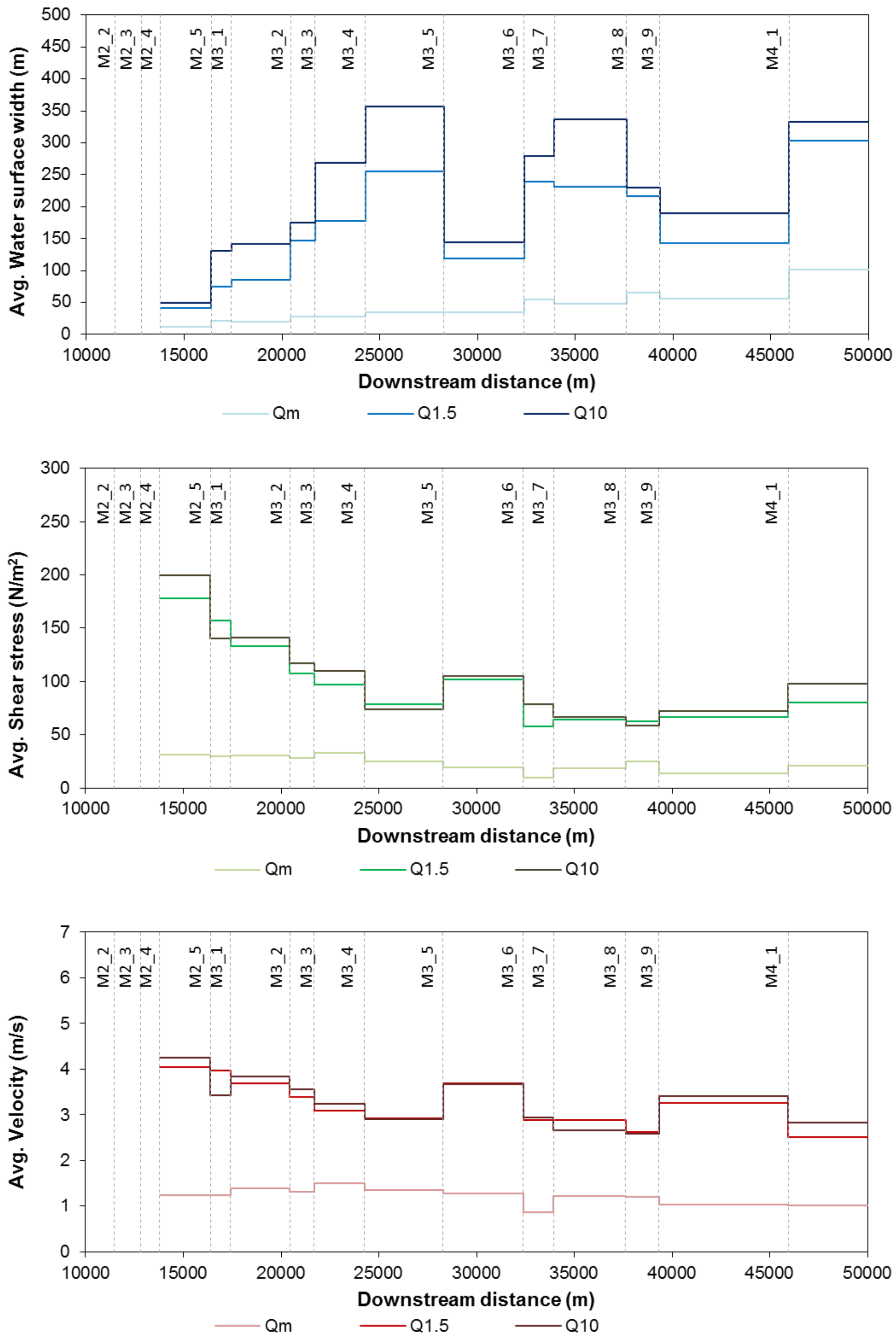


Figure 4.10 Distribution of the average water surface width (top), average shear stress (middle) and average velocity (bottom) for the mean annual discharge, the 1.5 and the 10-year return period discharges, for the Magra river.

4.4.3 Bed sediment

The dominant bed material calibre (bedrock, boulder, cobble, gravel, sand, silt, clay) of the Magra and Vara river reaches is listed in Table 4.12. For some reaches also the D50 is available from a survey undertaken in 2004 (Rinaldi 2005, 2007). The downstream distribution of median diameter of bed sediments (D50) along the Cecina river is shown in Figure 4.11.

Table 4.12 Bed sediment of the Magra river reaches (n. a., data not available). Dominant material calibre (D): C, cobble; G, gravel. D50, median particle diameter (mm).

Reach	L (m)	D	D50 (mm)	Reach	L (m)	D	D50 (mm)
M1.1	3685	n. a.	n. a.	*V1.1*	3171	n. a.	n. a.
M2.1	4780	C	n. a.	*V2.1*	1782	n. a.	n. a.
M2.2	2977	C	n. a.	*V2.2*	4693	C	n. a.
M2.3	1390	C	n. a.	*V2.3*	3181	C	n. a.
M2.4	957	C	n. a.	*V3.1*	2860	C	67.6
M2.5	2603	C	75.7	*V3.2*	3086	C	53.4
M3.1	1014	C	n. a.	*V3.3*	2209	C	n. a.
M3.2	3044	C	90.9	*V3.4*	2117	C/G	38.5
M3.3	1248	G/C	45.3	*V3.5*	2922	C/G	n. a.
M3.4	2562	C/G	50.6	*V3.6*	5669	G/C	64.0
M3.5	4023	C/G	n. a.	*V3.7*	4480	C/G	n. a.
M3.6	4115	C/G	57.6	*V3.8*	8590	C/G	38.9
M3.7	1535	C/G	n. a.	*V3.9*	4200	G	12.4
M3.8	3693	C/G	51.3	*V3.10*	4688	G	46.6
M3.9	1712	G	34.6	*V3.11*	2667	G	35.3
M4.1	6616	G	34.6	*V3.12*	3593	G	44.5
M5.1	4399	G	29.1	*V4.1*	6360	G	43.2
M6.1	4820	G	24.7				
M6.2	4511	n. a.	17.4				
M6.3	6201	n. a.	n. a.				

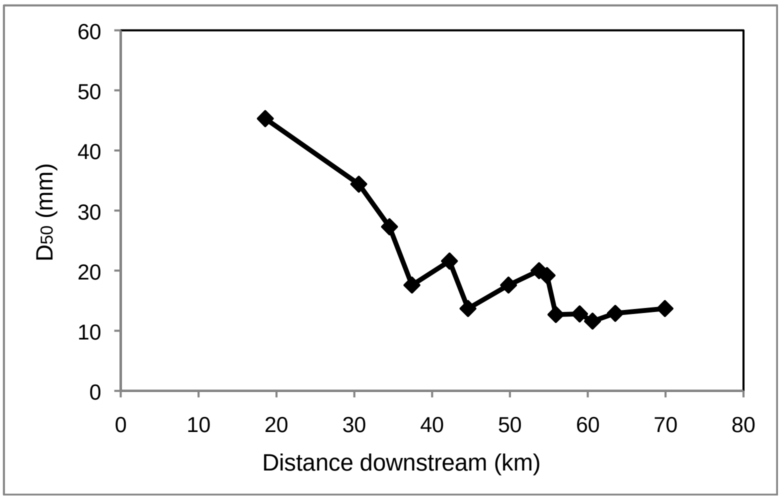


Figure 4.11 Downstream distribution of median diameter of bed sediments (D50) along the Cecina River.

4.4.3 Riparian vegetation

Figure 4.12 displays the distribution of islands along the Magra river from reach 3.2 to the mouth, in terms of island area per reach length and island number per reach, measured from aerial photos acquired in 2010 (Nardi and Rinaldi, 2014).

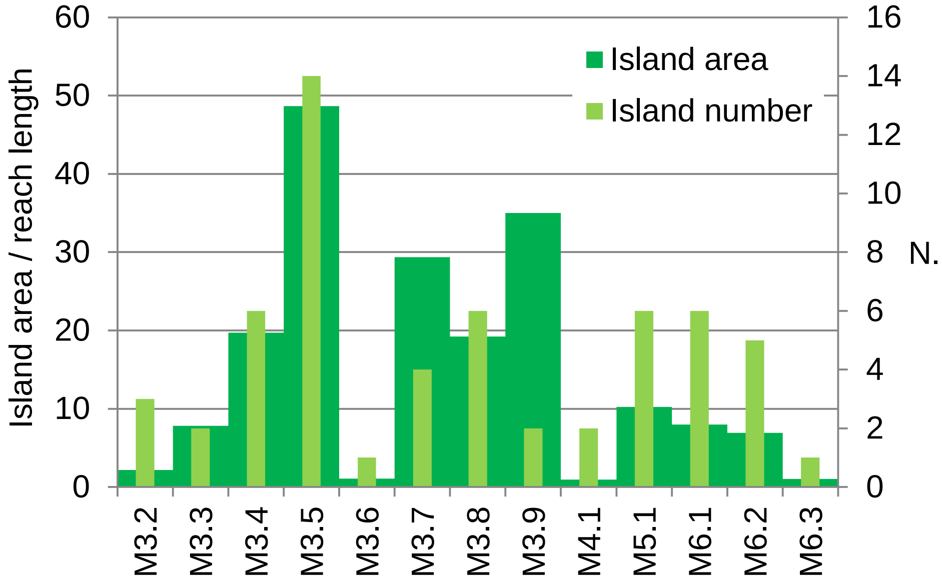


Figure 4.12 Island distribution along the Magra river from reach 3.2 to the mouth.

4.4.5 Physical pressures and impacts

A census of the main river human pressures is available for the Magra catchment from the River Basin Authority. Figure 4.13 summarises the main human pressures on the Magra catchment: barriers to sediment (i.e. dams and major weirs) and water (i.e. dams and other hydrological alteration structures, e.g. hydropower plants and diversions) longitudinal continuity; fixed and urban reaches (i.e. channelized reaches and reaches crossing urban areas).

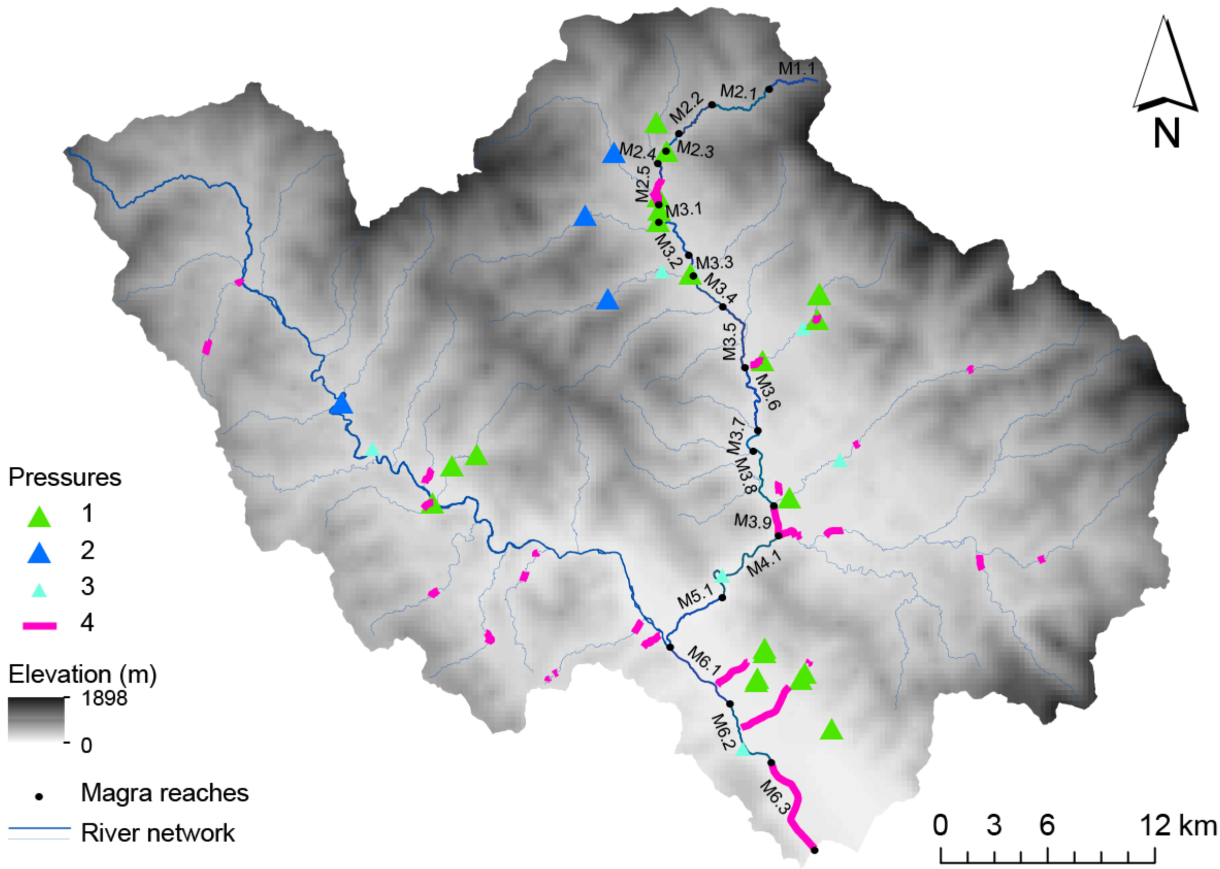


Figure 4.13 Human pressures in the Magra river catchment. 1, major weirs; 2, dams; 3, other hydrological alteration structures (i.e. hydropower plants, diversions); 4, highly fixed and urbanised reaches.

4.5 Geomorphic units

A preliminary assessment of morphological units associated to channel morphologies, based on remote sensing and field observations, is summarised in Table 4.13 for the Magra and Vara rivers, and Table 4.14 for the Cecina river.

Table 4.13 List of river typologies and associated geomorphic units for the Magra and the Vara river reaches.

Planform pattern	Characterisation of geomorphic units	Reaches
Single-thread	Not available	[M1.1]
		[V1.1; V2.1]
	Rapids, glides, cobbles	[M2.1]
Sinuous	Rapids, glides, cobbles	[M2.2]
	Rapids, glides, occasional lateral bars, cobbles	[M2.3; M2.4; M2.5]
	Riffles, pools, lateral bars, mid-channel bars, occasional braiding, cobbles	[M3.2; M3.3]
	Riffles, pools, lateral bars, mid-channel bars, occasional braiding, cobbles - gravel	[M3.6]
	Riffles, pools, lateral bars, gravel	[M4.1]
	Discontinuous lateral and mid-channel bars, occasional braiding, occasional secondary channels	[M6.2]
	No bars, laterally stable (partially controlled)	[M6.3]
	Rapids, glides, riffles, pools, occasional lateral bars, cobbles	[V2.2]
	Rapids, glides, occasional lateral bars, cobbles	[V2.3]
	Rapids, glides, occasional lateral bars and islands, occasional braiding, cobbles	[V3.1]
	Rapids, glides, lateral bars, occasional mid-channel bars and islands, occasional braiding, cobbles,	[V3.2]
	Rapids, glides, riffles, pools, discontinuous lateral bars, cobbles - gravel	[V3.5]
	Riffles, pools, rapids, glides, continuous lateral bars, occasional islands, gravel - cobbles	[V3.6]
	Riffles, pools, rapids, glides, occasional bars and islands, occasional braiding, cobbles - gravel	[V3.7]
	Riffles, pools, lateral bars, occasional mid-channel bars and islands, occasional braiding/anabranching, gravel	[V3.11; V3.12]
Straight	Rapids, glides, occasional lateral bars, cobbles	[M3.1]
Wandering	Riffles, pools, lateral and mid-channel bars, occasional braiding, wide active channel, islands, cobbles - gravel	[M3.7; M3.8]
	Riffles, pools, lateral and mid-channel bars, occasional braiding, wide active channel, islands, gravel dominated	[M3.9; M6.1]
	Riffles, pools, lateral and mid-channel bars, frequent braiding, wide active channel, islands, gravel dominated	[M5.1] [M4.1]
	Rapids, glides, riffles, pools, lateral bars, occasional mid-channel bars and islands, occasional braiding/anabranching, cobbles	[V3.3]
	Rapids, glides, lateral bars, occasional mid-channel bars, islands, braiding/anabranching, cobbles – gravel	[V3.4]
	Riffles, pools, rapids, glides, occasional lateral bars, discontinuous islands, discontinuous braiding/anabranching, cobbles - gravel	[V3.8]
	Riffles, pools, lateral bars, occasional mid-channel bars and island, occasional braiding, gravel dominated	[V3.9]
Braiding	Riffles, pools, lateral and mid-channel bars, braiding morphology, islands, cobbles - gravel	[M3.4]
	Riffles, pools, lateral and mid-channel bars, intense braiding, frequent islands, cobbles - gravel	[M3.5]
Anabranching	Riffles, pools, lateral and mid-channel bars, large islands,	[V3.10]

	braiding and anabranching, gravel dominated

Table 4.14 List of river typologies and associated geomorphic units for the Cecina river reaches.

Planform pattern (step 3)	Characterization of geomorphic units	Reaches
Single-thread	Bedrock, cascades, steps, pools, boulders - cobbles	[1.1]
	Glides, rapids, pools, riffles, cobble – gravel	[1.3]
	Riffles, pools, glides, lateral bars, gravel dominated	[2.4, 2.5]
Sinuous	Riffles, pools, glides, lateral bars, cobble - gravel, limited lateral activity because of partial confinement	[1.2, 2.1]
	Riffles, pools, glides, lateral bars, cobble – gravel, laterally active	[2.2]
	Riffles, pools, lateral bars, occasional braiding, local islands, secondary channels, floodplain, laterally active, gravel - sand	[2.3]
	Riffles, pools, glides, occasional lateral bars, low lateral activity, gravel dominated	[3.1, 3.3, 3.6, 3.8]
	'Sinuous with alternate bars': riffles, pools, glides, lateral bars, occasional braiding, highly sinuous low-flow channel, secondary channels, floodplain, laterally active, gravel dominated	[3.4, 3.5, 3.7]
	Very occasional bars, laterally stable (partially controlled)	[3.10, 4.1]
Wandering	Riffles, pools, glides, lateral and mid-channel bars, frequent braiding, islands, secondary channels, floodplain, laterally active, gravel dominated	[3.2]
Meandering	Riffles, pools, lateral and point bars, medium lateral activity, gravel dominated	[3.9]

5. Characterising temporal changes (historical)

5.1 Introduction

This section provides an overview of hydromorphological changes that have occurred in the Magra and Cecina rivers over approximately the last century.

Many studies have analysed channel changes along a series of rivers of Central Italy, including the Magra river (e.g. Rinaldi et al. 2009; Nardi et al. 2012; Nardi and Rinaldi, 2014) as well as the Cecina river (e.g. Rinaldi, 2003; Rinaldi et al. 2008; Teruggi and Rinaldi 2009; Surian et al. 2009).

5.2 Catchment and landscape unit

Figure 5.1 shows the land use changes in the Magra river catchment since 1960. The 1960 data are from CNR-TCI, whereas data since 1990 are from the Corine Land Cover project.

The main changes occurred between 1960 and 1990, and mainly consisted of a reduction of agricultural surfaces and an increase of forested and semi-natural areas. Table 5.1 summarises the main human impacts in the Cecina river catchment.

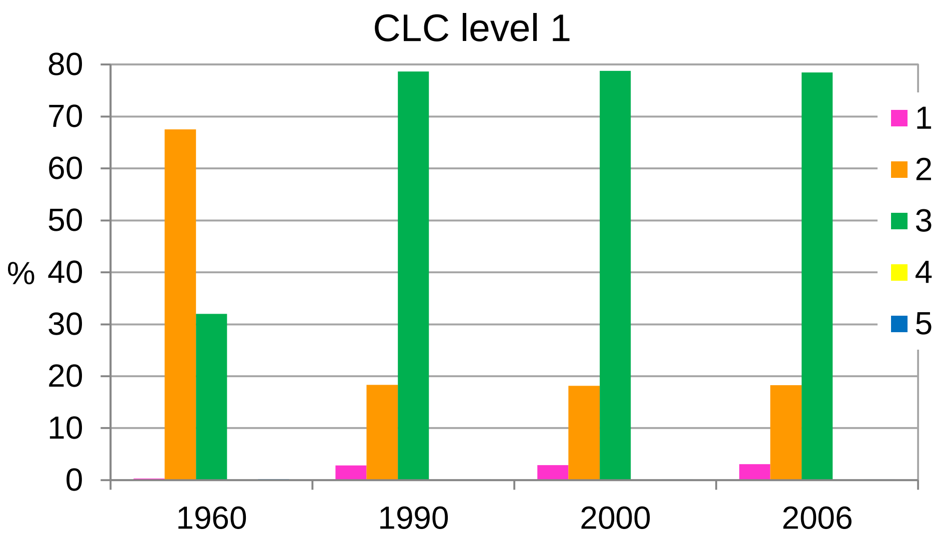


Figure 5.1 Land use changes in the Magra river catchment following the Corine Land Cover classification of level 1. 1, Artificial areas; 2, Agricultural areas; 3, Forested and semi-natural areas; 4, Wetlands; 5, Water bodies.

Table 5.1 Historical human impact in catchment of the Cecina river (from Surian et al. 2009).

Reforestation in the drainage basin	Construction of levees and other bank protection structures	Dates of intense sediment mining
Since 1920s-1930s	Locally, since 1920s-1930s	1970s

5.3 Segment

5.3.1 Water flow

There is no evidence of long-term changes in river flows along the Magra river, as can be seen in the mean, minimum and maximum daily flows recorded in each year at Piccatello and Calamazza river gauging station (Figures 5.2 and 5.3)

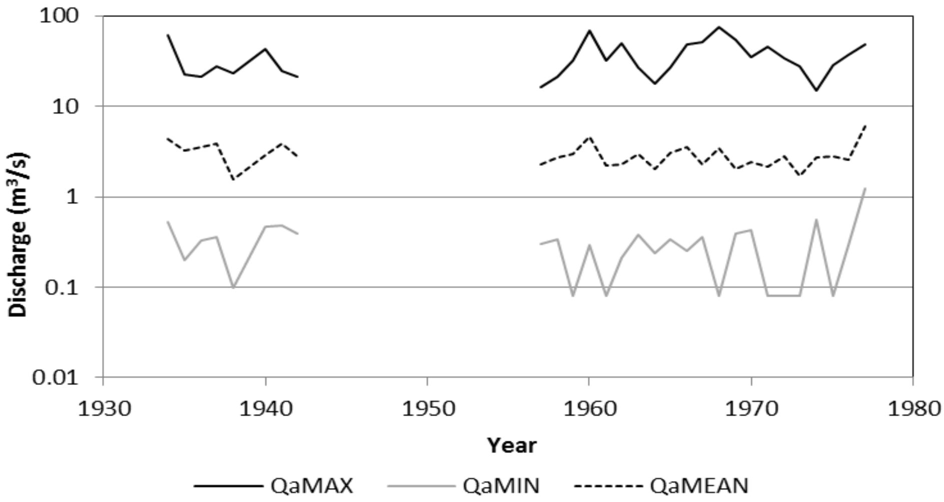


Figure 5.2 Minimum, maximum and mean annual flows from the Piccatello river gauging station.

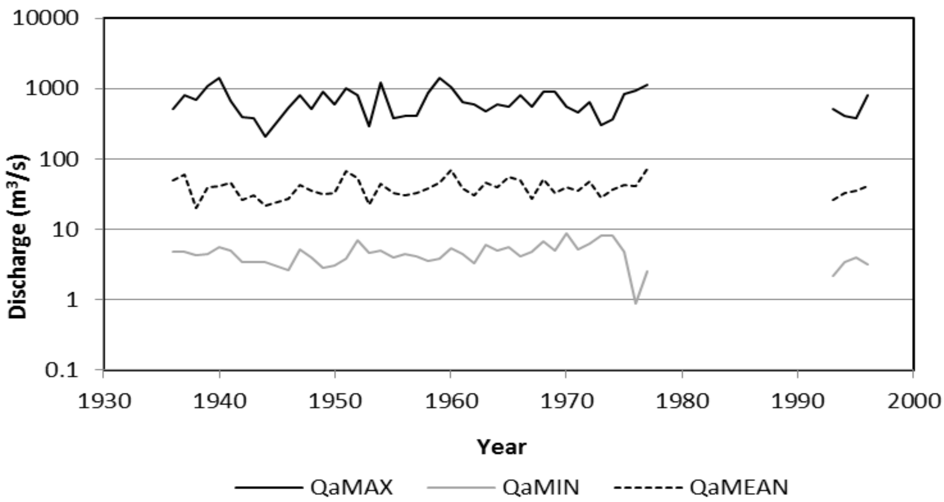


Figure 5.3 Minimum, maximum and mean annual flows from the Calamazza river gauging station.

Figure 5.4 shows the historical trend of maximum annual discharge for the Cecina river. The latter shows some decrease in maximum annual discharge even though there is no notable regulation along this river (Table 5.1).

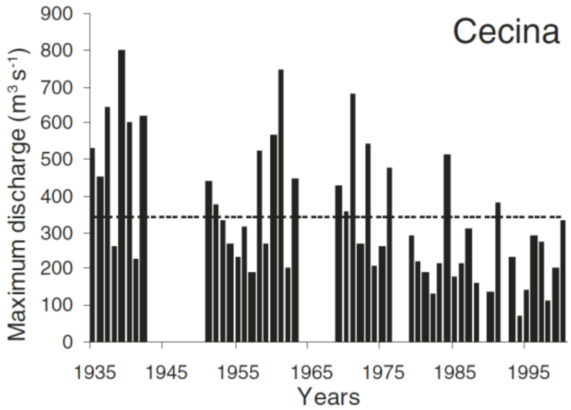


Figure 5.4 Historical trend of maximum annual discharge for the Cecina river. Dashed line represents the average maximum discharge for the examined period (from Surian et al. 2009).

5.4 Reach

5.4.1 Channel geometry

Magra river

The evolution of the Magra river during the last 200 years has been determined by several human impacts at the catchment, segment and reach scales.

In the XIX century the Magra was a large braided river, mainly in its downstream part. At that time there was high sediment supply because of lack of dense vegetation cover in the mountain parts (deforestation).

From the end of the XIX century to the middle of the XX century (1880s-1950s), the Magra catchment underwent several human impacts that caused severe morphological changes along the river channel, such as channel narrowing and bed incision, as well as changes of morphological pattern (Figures 5.5 and 5.6). The main human impacts were: land use changes at the catchment scale (e.g. reforestation); building of groynes (downstream reaches); dam constructions on the Vara river, as well as on some other upstream tributaries of the Magra river.

After the 1950s and until almost the end of the XX century with a peak in the 1960s-1970s, intense gravel mining of the river bed occurred, which caused severe bed incision (up to 8 m) in the most downstream alluvial reaches.

Then, during the last 20 years an inversion of the morphological trend has been observed, i.e. channel widening and in some reaches also aggradation. These processes are mainly observed in the unconfined and partly confined reaches of segment 3 (Figures 5.5 and 5.6). This has been related to an increase in sediment supply, mainly due to the reduction of the mining activity (Rinaldi et al. 2009).

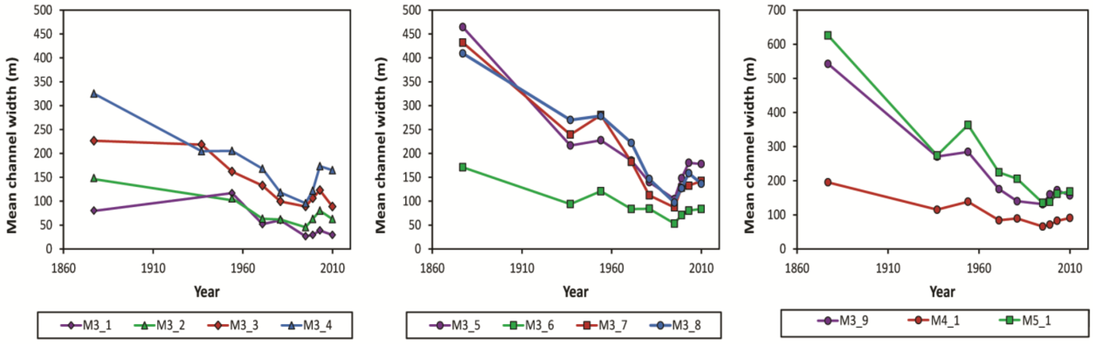


Figure 5.5 Trajectories of change in channel width along the Magra river from reach 3.1 to reach 4.1. Data from Nardi and Rinaldi (2014).

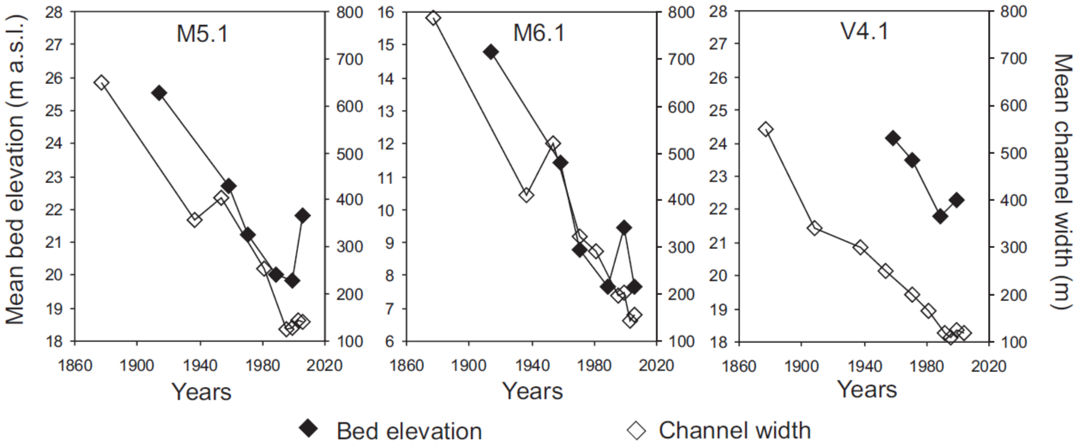


Figure 5.6 Temporal trends of bed elevation and channel width in two lowland reaches of the Magra river (M5.1 and M6.1) and one reach of the Vara river (V4.1) (from Rinaldi et al. 2009). M5.1 and M6.1 are respectively located upstream and downstream the confluence with the Vara river.

Based on the reconstruction of the trajectories of change previously described, Rinaldi et al. (2008) developed a conceptual model of channel evolution suited to the alluvial reaches of the Magra and Vara rivers (Figure 5.7). The model comprises four stages of channel evolution and three main phases of adjustment as follows: (1) stage I represents the initial predominantly braided morphology of the end of the XIX – beginning of the XX century; (2) stage II: the channel is partially incised and narrower in this first phase of adjustment; (3) stage III corresponds to the period of maximum narrowing and incision (end of 1990s); (4) stage IV reflects phase 3 of the inversion in the trend of channel width and, in some cases, of bed elevation.

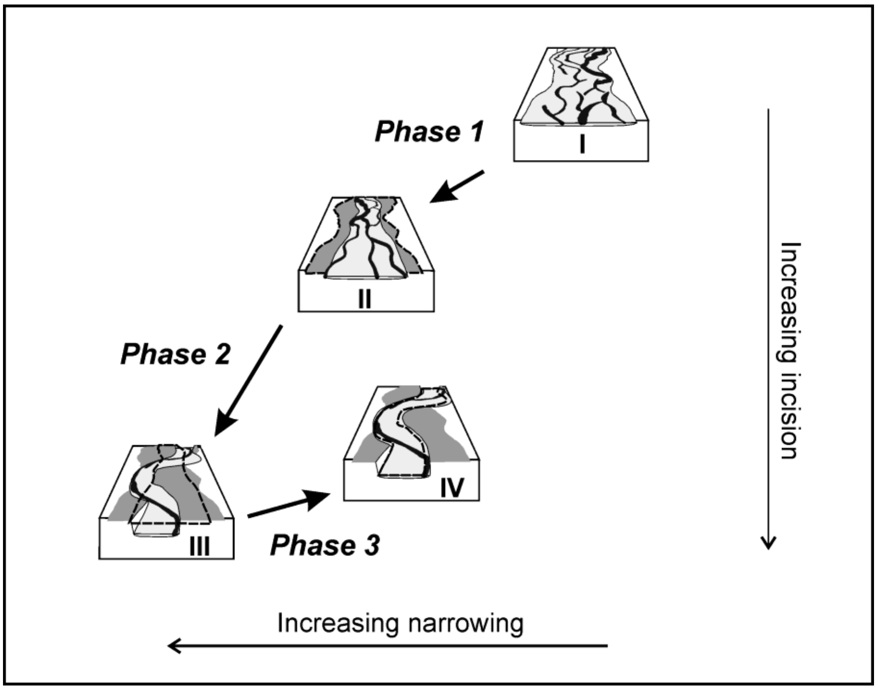


Figure 5.7 Model of channel evolution of the alluvial reaches of the Magra River (modified from Rinaldi et al. 2008, 2011).

Cecina river

The main data sources for the analysis of channel changes were historical maps and aerial photographs. The following maps and aerial photographs were analysed: 1883 (historical maps), 1938-40-48, 1954, 1976, 1986, 1994, 2000, 2004, 2006, 2009. The digital maps and aerial photographs have been georectified using GIS software, and measurements of channel width have been made along the reaches of segment 3. This analysis was carried out along the partly confined and unconfined segment 3, where planimetric changes were significant. Segment 4 was not included in this analysis because it is mostly fixed by human interventions. Long-term data on bed-level changes were not available, and a qualitative assessment along segment 3 was based on field evidence (Rinaldi et al. 2008).

Figure 5.8 shows the trajectory of change in channel width along segment 3. The trajectories of change in channel width estimated at reach scale show more variability, with some temporary inversion of change, but following the overall general trend of a progressive narrowing (Figure 5.9).

According to other studies on Italian rivers (e.g. Surian et al. 2009), the trajectory shows a progressive reduction in channel width through time. A first major phase of narrowing can be identified from historical times (1883) to the end of 1980s, followed by a second major phase of more intense narrowing, and then an inversion of this trend associated with a slight widening during recent years. Compared to other Italian rivers, the first phase of narrowing occurred over a longer period, while the second phase was restricted to less than 20 years. This could be associated with a minor degree of human impact compared to other Italian rivers, and to a delayed phase of intense sediment mining (in many other Italian cases the period of most intensive mining started in the 1950s).

Bed level change evaluated by field evidence comprised a moderate bed incision (1–3 m) over about the past 100 years, while the dominant situation during about the last 10 years is bed stability or, in some cases, a limited aggradation.

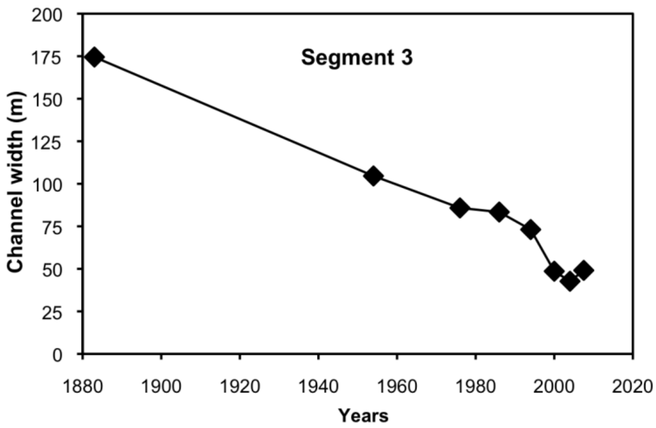


Figure 5.8 Trajectory of mean channel width along the segment 3.

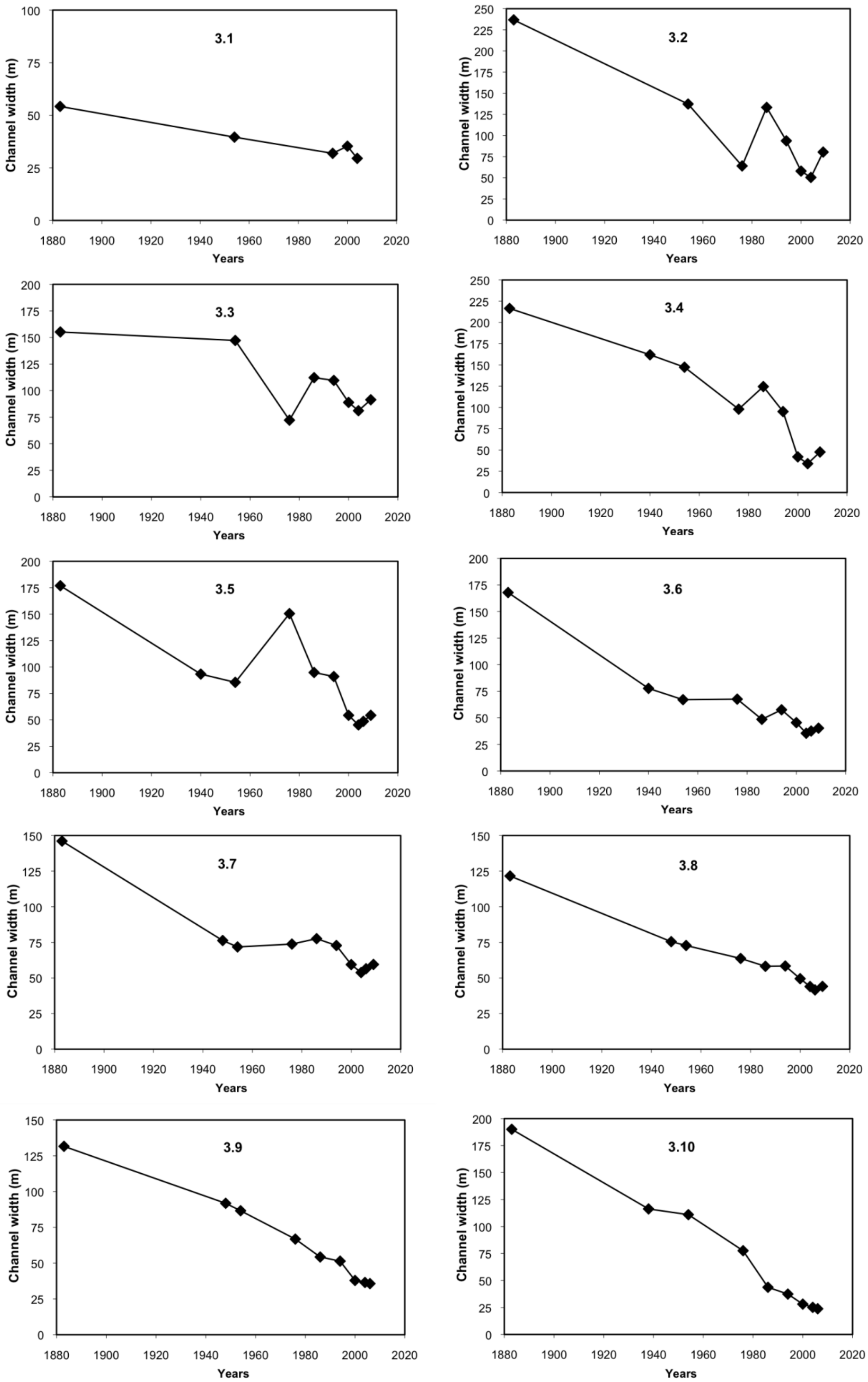


Figure 5.9 Trajectories of channel width changes along the reaches of segment 3.

5.4.2 Channel planform

Magra river

Similarly to the change in channel geometry, the Magra river also underwent changes in terms of channel planform. Figures 5.10 and 5.11 and Table 5.2 display these changes for reaches of segments 3 to 6, in terms of total channel sinuosity, percentage of channel area and channel pattern, respectively.

The evolution of the sinuosity index followed the overall narrowing trend showed in Figure 5.5: an overall increase in channel sinuosity since earliest observation (1887) mainly affecting downstream reaches (Figure 5.10).

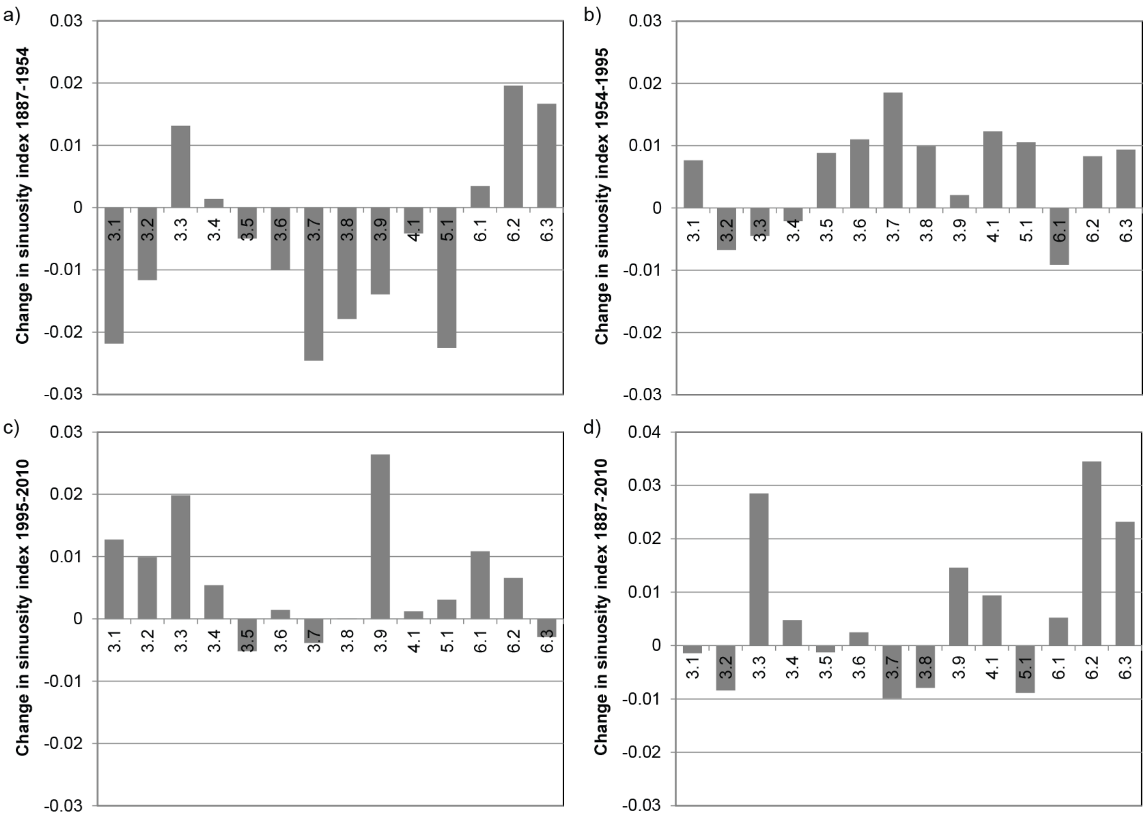


Figure 5.10 Changes in sinuosity index for Magra reaches of segment 3 to 6 between: (a) 1887 and 1954; (b) 1954 and 1995; (c) 1995 and 2010; (d) 1887 and 2010.

Figure 5.11 shows areas that changed in two different time periods since 1954 to 2010. The graphs provide a good indication of the total amount of adjustment that has occurred. In the figure 'no change' refers to areas that were identified as channel in both period; 'narrowing' corresponds to the areas that changed from channel to alluvial plain, whereas areas that were identified as alluvial plain in the first period and channel in the second are defined as 'widening'.

According to the width pattern, the first time period is characterised by an overall loss of channel areas, whereas the second time period is characterised by a generalised increase of channel areas.

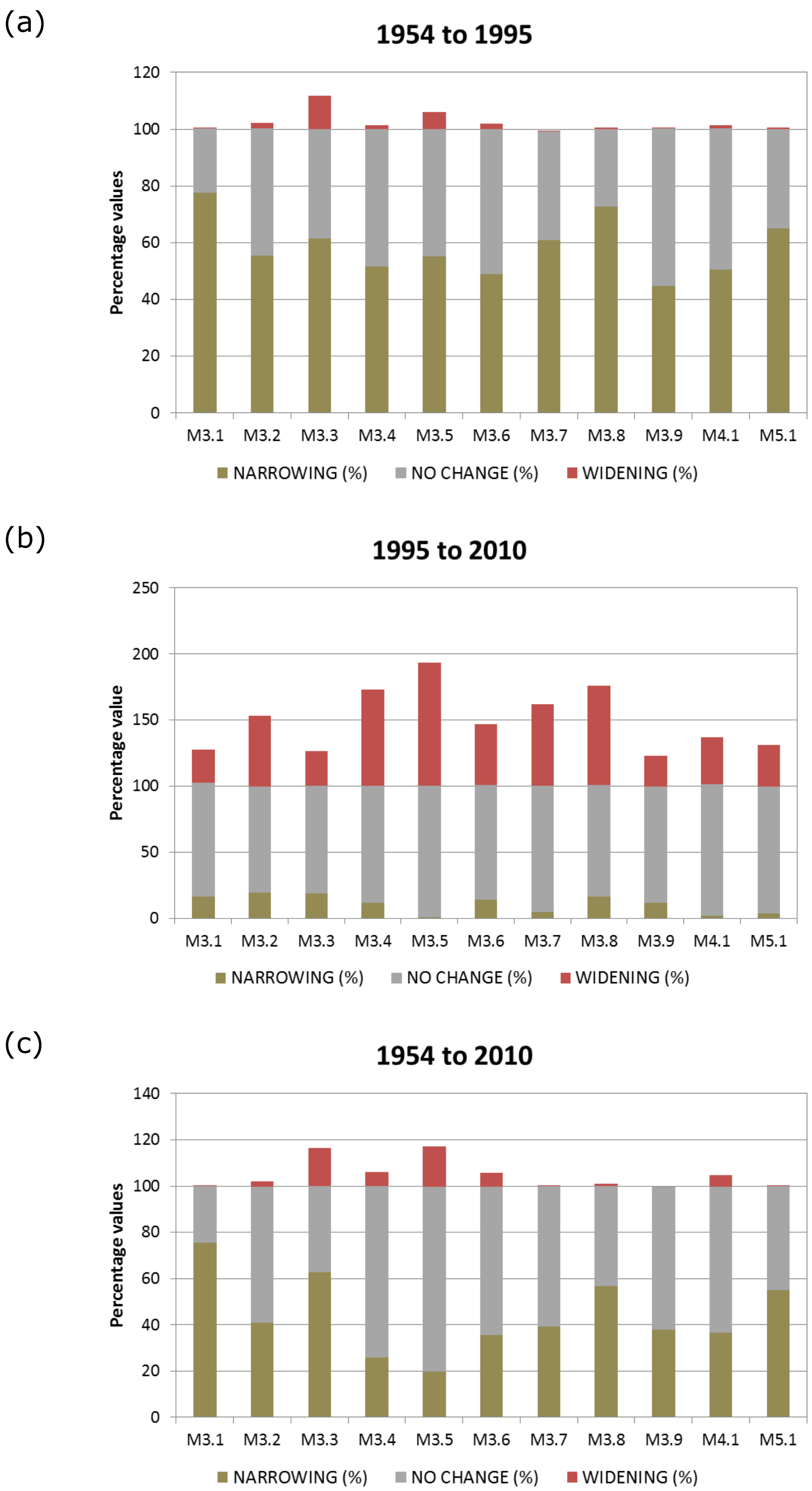


Figure 5.11 Change in channel area for reaches belonging to segments 3 to 6 between: (a) 1954 and 1995; (b) 1995 and 2010; (c) 1954 and 2010.

Finally, Table 5.2 displays the channel pattern changes between 1954 and 2010 for reaches of segments 3 to 5. In most cases the reaches changed their channel pattern from a multi-thread to a transitional channel pattern.

Table 5.2 Changes in channel pattern between 1954 and 2010 for reaches of segments 3 to 5.

Reach	Channel pattern 1954	Channel pattern 2010
M3_1	Wandering	Straight
M3_2	Wandering	Sinuous with alternate bars
M3_3	Braided	Sinuous with alternate bars
M3_4	Braided	Braided
M3_5	Braided	Braided
M3_6	Wandering	Sinuous with alternate bars
M3_7	Wandering	Wandering
M3_8	Braided	Wandering
M3_9	Braided	Wandering
M4_1	Sinuous with alternate bars	Sinuous with alternate bars
M5_1	Braided	Wandering

Cecina river

The channel morphology in the 1950s was wandering (locally braided), whereas in the following decades a significant narrowing occurred (Figure 5.12), with a change in morphology to a sinuous, single-thread channel with alternate bars (Surian et al. 2009).

A significant increase in sinuosity associated with channel narrowing was also observed in some reaches of segment 3 (a portion of reach 3.7 is shown in Figure 5.12).

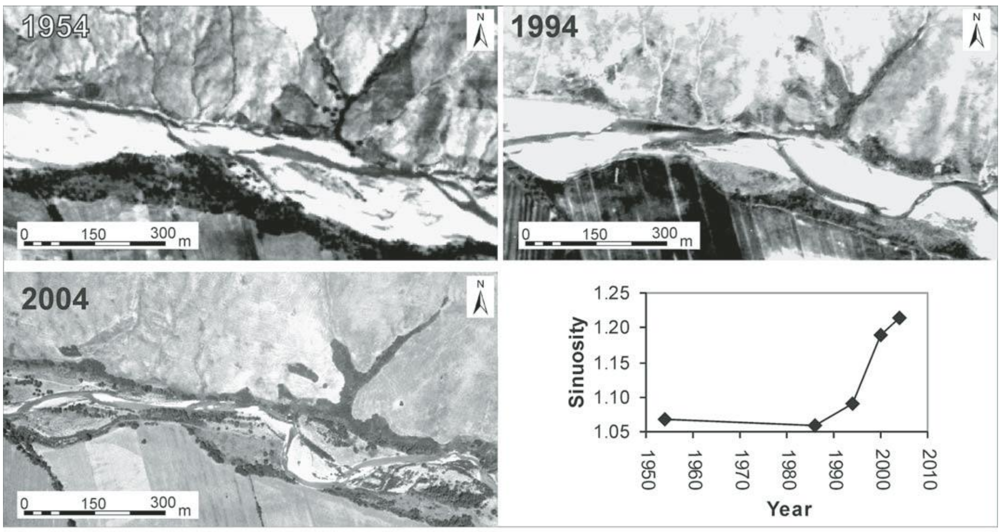


Figure 5.12 Channel adjustments in the Cecina river. Since 1954 a significant increase in sinuosity is observed, associated with channel narrowing (from Surian et al. 2009).

5.4.3 Bed sediment calibre

The mean bed sediment calibre has undergone a reduction since 1991, both for the Magra main stem and the surveyed tributaries (Figure 5.13). This could be related to flood events close to the 2004 survey, which contributed to an increase the bed sediment heterogeneity, as well as to the recent trend of sedimentation (Rinaldi 2005).

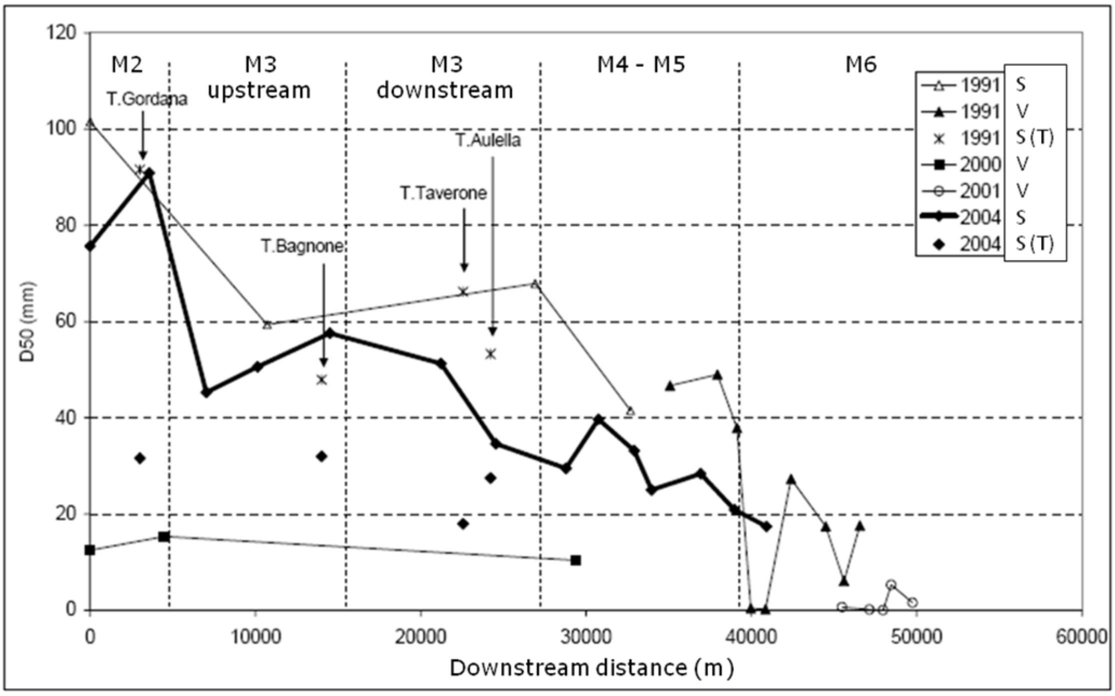


Figure 5.13 Decadal change in the D_{50} along the Magra river. S: surface surveys; V: volumetric surveys; T: surveys on tributaries. Modified from Rinaldi (2005).

6. Extended river typology

Table 6.1 summarises the river types for the reaches of the Magra river according to Section 7 of Deliverable 2.1 Part 1.

Table 6.1 River types by reach for the Magra river.

Segment	Reach	River type	Threads	Planform
1	1.1	/	Single	/
2	2.1	6	Single	/
	2.2	13	Single	Sinuous
	2.3	13	Single	Sinuous
	2.4	13	Single	Sinuous
	2.5	13	Single	Sinuous
3	3.1	13	Single	Straight
	3.2	12	Single	Sinuous
	3.3	12	Single	Sinuous
	3.4	9	Multi-thread	Island-braided
	3.5	9	Multi-thread	Island-braided
	3.6	12	Single	Sinuous
	3.7	11	Transitional	Wandering
	3.8	11	Transitional	Wandering
	3.9	11	Transitional	Wandering
4	4.1	12	Single	Sinuous
5	5.1	11	Transitional	Wandering
6	6.1	11	Transitional	Wandering
	6.2	13	Single	Sinuous
	6.3	13	Single	Sinuous

7. Indicators of Present and Past Condition

In this section some additional indicators are calculated for the Magra river, aiming at supporting the interpretation of current condition and trajectories of changes (Section 8).

7.1 Catchment and landscape unit

7.1.1 Land cover

Figure 7.1, based on the 2006 Corine dataset, summarises the proportion of different land cover types in each Landscape Unit (LU), leading to the following land cover contributions to likely runoff response:

- % area of delayed runoff production is attributable to forest cover and is 100%, 93%, 81%, 40% for Landscape Units from 1 to 5, respectively;
- % area of rapid runoff production is attributable to artificial areas, like urban, industrial, commercial and transport areas, and is 0%, 0.4%, 1.1%, 12%, 39% for Landscape Units from 1 to 5, respectively;
- % area of intermediate runoff production is attributable to arable land, agricultural and pasture areas and is 0%, 6.5%, 18%, 48%, 48% for Landscape Units from 1 to 5, respectively.

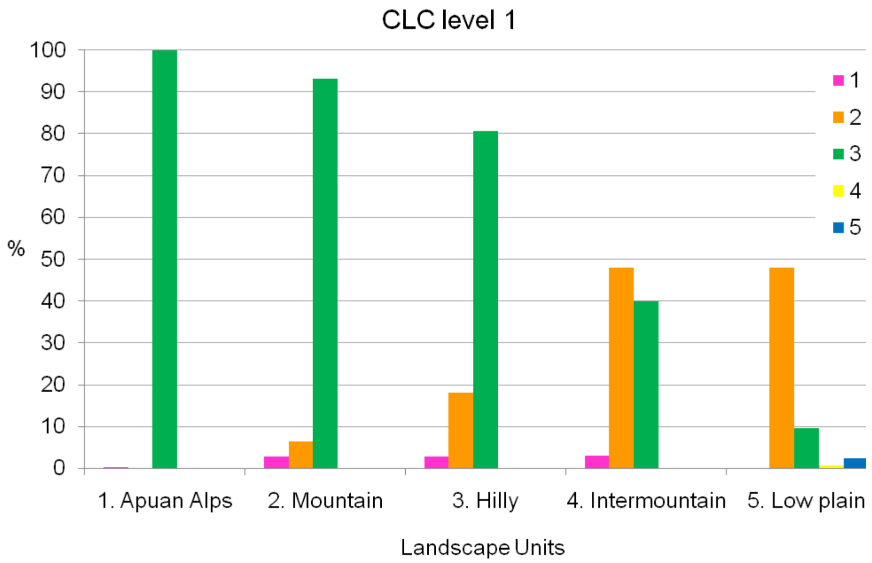


Figure 7.1 Proportion of the 2006 Corine Land Cover types of level 1 in each Landscape Unit. 1, Artificial areas; 2, Agricultural areas; 3, Forested and semi-natural areas; 4, Wetlands; 5, Water bodies.

Thus, the land cover in the catchment is predominantly associated with low and intermediate runoff production. There is a quite high variation in runoff potential between landscape units, mainly between mountain and hilly areas (LU 1 to 3) versus intermountain plains and low plains (LU 4 and 5), which are low and intermediate, respectively.

7.2 Segment

7.2.1 Water Flow

Water flow analysis was conducted in relation to two gauging stations, located in segments 2 and 4. A finer resolution was not possible because of insufficient gauging station data. Results of this analysis, reported in Table 7.1 showed that the flow regime type at the upstream segment is perennial flashy, whereas at the segment 4 is perennial runoff.

Besides this analysis, two morphologically representative discharges, $Qp_{1.5}$ and Qp_{10} (described in the Deliverable 2.1, Part 1, section 5.4.1(ii)) were estimated at the outlet of each reach. Channel-forming discharge for the Magra River is assumed to be the discharge with return interval of 1.5 years. To account for downstream variability of flows, discharge is usually scaled to the catchment area. In this study, we used an empirical equation developed by the Basin Authority of the Magra River and obtained by a regionalization of flow discharges at catchment scale.

Results of this analysis are illustrated in Table 7.1.

Table 7.1 Estimation of the $Q_{1.5}$ and Q_{10} discharges at the reach outlet.

REACH	Catchment area (km^2)	$Q_{1.5}$ (m^3/s)	Q_{10} (m^3/s)
M1.1	8.44	48.33828	69.0565
M2.1	20.91	100.7513	496.1029
M2.2	51.24	188.7197	769.7831
M2.3	53.01	193.2499	782.6719
M2.4	53.76	195.1676	788.1006
M2.5	79.73	257.1553	955.9453
M3.1	152.96	405.769	1315.502
M3.2	212.02	509.9566	1543.723
M3.3	225.80	532.9393	1592.101
M3.4	296.27	644.545	1818.752
M3.5	359.90	738.5894	2000.684
M3.6	427.86	833.648	2177.63
M3.7	437.96	847.372	2202.663
M3.8	522.01	958.1855	2400.551
M3.9	612.87	1072.084	2596.907
M4.1	952.41	1459.648	3223.071
M5.1	957.58	1465.19	3231.633
M6.1	1599.08	2097.887	4154.739
M6.2	1646.38	2141.133	4214.508
M6.3	1706.52	2195.587	4289.253

7.2.2 Sediment flow

Figure 7.2 displays the number of spanning (i.e. bridges and minor weirs, sills, ramps) and blocking (i.e. weirs and dams) structures along the Magra river and its main tributaries per segment. Blocking structures are mainly located upstream along the Magra river; blocking structures on tributaries of segment 6 belong to the Vara river and its catchment. The frequency of spanning structures along the Magra river increases downstream, except for segment 6. However, the frequency of spanning structures on tributaries flowing into segment 6 is the greatest.

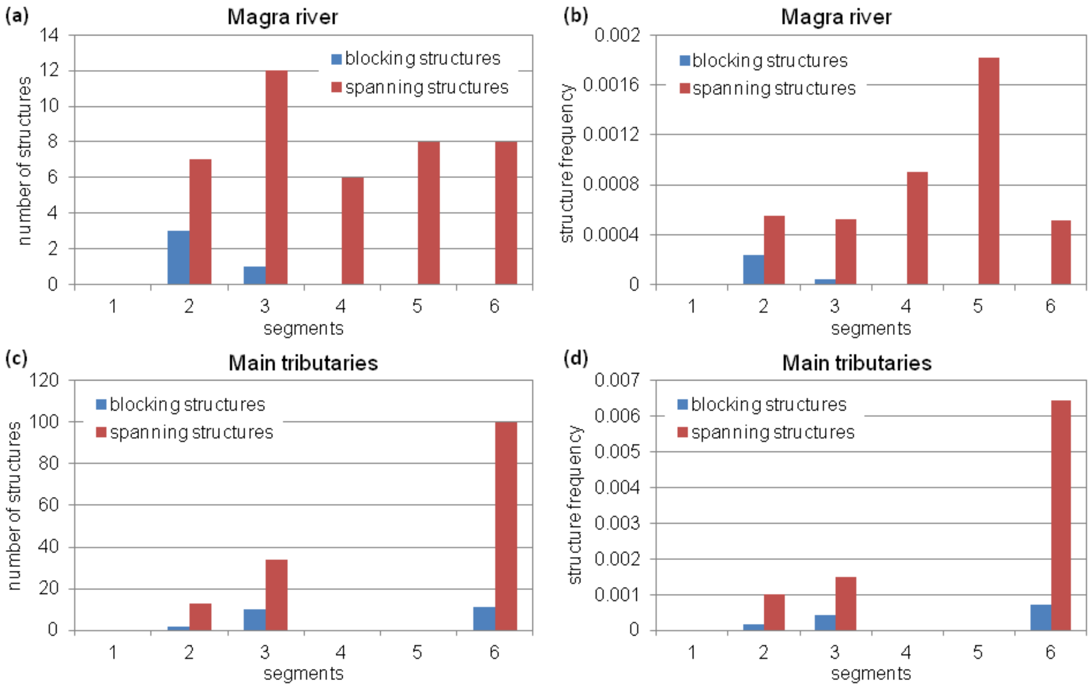


Figure 7.2 Count of spanning (bridges and minor weirs) and blocking (weirs and dams) structures for the Magra river and its main tributaries (a, b and c, d, respectively). The frequency is given by the number of structures divided by the segment length (b and d).

Table 7.2 summarises the number of bank protections per segment (bank-set levees are not included). Although the information on bank protection extent is not available for all the Magra river, the table gives an idea of the amount of sediment that is potentially available (or prevented by bank protection) from lateral dynamics. The density of bank protection increases downstream and reaches its maximum value at segment 5.

Table 7.2 Number and density of bank protections per segment along the Magra river.

Segment	Segment length (km)	Bank protection (N.)	Bank protection density (N/km)
1	3.7	/	/
2	12.7	3	0.2
3	22.9	15	0.7
4	6.6	5	0.8
5	4.4	18	4.1
6	15.5	36	2.3

Sediment budget

Rinaldi et al. (2009) described a procedure for diagnosis of sediment budget aiming at assessing the sediment transport and downstream delivery potential of the Magra and Vara river channel. For this, the two rivers were at first further subdivided into relatively homogeneous hydraulic and hydrological sub-reaches also accounting for their main tributaries. This generated 11 and 12 sub-reaches in the Magra and Vara rivers, respectively (Figure 7.3). The most downstream part of the Magra river was excluded from the analysis.

The mean annual bedload capacity was calculated using the following bedload formulae: (a) Shields (1936); (b) Schoklitsch (1950); (c) Parker (1990); (d) Meyer-Peter and Müller, in the form corrected by Wong and Parker (2006).

The mean annual sediment budget was obtained for each sub-reach by the difference between the estimated input of bedload from the upstream sub-reach (assuming that its transport capacity is completely saturated), plus the estimated input from any major tributaries, and estimated output from the given sub-reach.

The mean annual sediment budget ΔQ_s (m^3 $year^{-1}$) for a given sub-reach corresponds to the excess or deficit of mean annual total volume of sediment, and represents the tendency of the sub-reach to aggrade (positive values) or degrade (negative values) given its hydraulic and sedimentary characteristics.

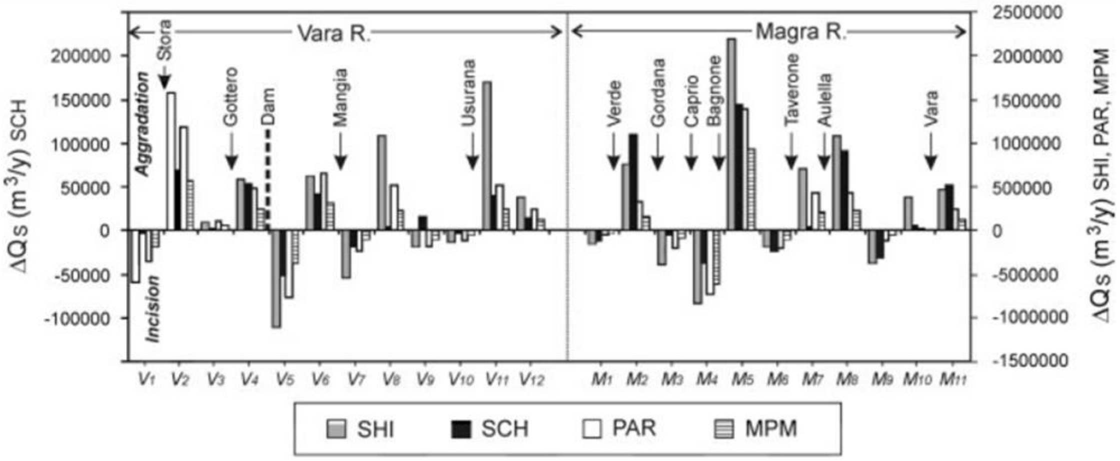


Figure 7.3 Sediment budget estimates for the Vara and Magra rivers (from Rinaldi et al. 2009): mean annual sediment budget (□Q_s) using the bedload eq uations of Shields (SHI), Schoklitsch (SCH), Parker (PAR) and Meyer-Peter and Müller (MPM). Rivers are segmented into homogeneous bedload transport subreaches (the main tributaries are included in the evaluations and reaches are classified according to their incision/aggradation tendency).

7.3.3 River morphology adjustment and wood production

Table 7.3 summarises indicators useful for understanding river morphological adjustments. Potential wood delivery is estimated on the basis of the segment drainage area occupied by forested and semi-natural areas coupled with the information about the condition of the vegetation in the riparian corridor (in terms of width and continuity; based on field surveys).

Table 7.3 Summary of information on potential river morphology adjustment based on the proportion of the natural vegetation over the segment drainage area and the presence and continuity of riparian vegetation along the Magra river channel.

Segment	Gradient (%)	Valley confinement	Potential wood delivery	Width riparian corridor	Riparian corridor continuity
1	10.3	Confined	High	Wide	Continuous
2	2.6	Confined/Partly-confined	High	Wide	Continuous
3	0.8	Partly-confined/Unconfined	Intermediate	Relatively wide	Relatively continuous
4	0.3	Partly-confined	High	Relatively wide	Relatively continuous
5	0.3	Unconfined	Low	Narrow	Discontinuous
6	0.1	Unconfined	Low	Relatively wide	Relatively continuous

7.4 Reach

7.4.1 Channel self maintenance / reshaping and channel changes / adjustments

Some qualitative information on bank erosion processes at the reach scale is provided in Table 7.4. The observed frequency is based on field observations and corresponds to the percentage of the eroding banks compared to the total bank length.

Reaches 1.1 and 2.1 have been excluded since they are confined reaches.

Concerning bank material, segments 3, 4 and 5 are mainly composed of non-cohesive material, whereas more cohesive material can be found in the downstream reaches (segment 6).

Detailed information on bank material at the reach scale is not available.

Additional information on reach self-maintenance/reshaping, channel changes and adjustments, sediment and wood delivery potential are provided in previous sections.

Table 7.4 Qualitative assessment of bank erosion processes based on field observations.

REACH	% of eroding banks	REACH	% of eroding banks
M2.2	< 10%	M3.6	> 10%
M2.3	< 10%	M3.7	> 10%
M2.4	< 10%	M3.8	> 10%
M2.5	< 10%	M3.9	< 2%
M3.1	< 2%	M4.1	< 10%
M3.2	< 10%	M5.1	< 10%
M3.3	> 10%	M6.1	< 10%
M3.4	> 10%	M6.2	< 10%
M3.5	> 10%	M6.3	< 2%

8. Interpreting condition and trajectories of change

This section is mainly focused on two representative reaches belonging to segment 3. These two reaches were selected on the basis of the evaluation of the current segment conditions summarised in Table 8.1, which were obtained from the results of previous Sections.

In particular, compared to other segments, the reaches of segment 3 show quite good functionality and low artificiality. Despite the fact that the reaches display a range of artificial elements and they have undergone some adjustments (Table 8.1).

Concerning the upstream reaches (segments 1 and 2), they show high hydromorphological function and low human impact, but in these cases data availability is scarce.

On the other hand, downstream reaches are more altered by human impact, the hydromorphological function is lower and they have undergone more significant adjustments. The human impact here dates back over a longer time, reaches are prevailingly fixed and thus less interesting in terms of future trajectories of change.

For these reasons, two reaches belonging to segment 3 have been selected for the present analysis (i.e. reaches 3.4 and 3.9), since they allow for a good comparison between the effects of different human impacts in a quite homogeneous hydromorphological context (valley setting, channel pattern, geomorphic function).

Table 8.1 Current segment condition: reach types included in each segment (see section 6 for details) and hydromorphological condition: function, alteration / artificiality / adjustments

Segment	Reach types	Functionality	Artificiality	Adjustments
1	/	Good	Low	/
2	6, 13	Good	Low	/
3	9, 11, 12, 13	Good	Low	Intermediate
4	12	Moderate	Low	High
5	11	Moderate	Intermediate	High
6	11, 13	Moderate	Intermediate	High

8.1 Stage 1: Synthesis of current reach condition

Current conditions of the two selected reaches, deduced by the results shown in previous sections, are summarised in Table 8.2.

Table 8.2 Current reach condition: reach type (see Section 6 for details), hydromorphological condition(function/artificiality/adjustment), and riparian vegetation condition (function/artificiality).

Reach	Type	Hydromorphology			Riparian vegetation	
		Function	Artificiality	Adjustment	Function	Artificiality
3.4	9	Good	Low	Narrowing & incision	Good	Low
3.9	11	Moderate	Intermediate	Narrowing & incision change in channel pattern	Good	Low

The good functionality of reach 3.4 is mainly due to the variability of the cross-sections, the presence of eroding banks and expected geomorphic units, as well as the absence of significant interception related to transversal and crossing structures which interrupt the continuity of sediment and wood along the reach. These elements, combined with the scarce presence of artificial elements, ensure the occurrence of processes and the development of related forms responsible for the correct functioning of the reach.

The presence of two minor transversal structures (i.e. bridge piles) and the presence of extended bank protections and artificial levees to prevent flooding at the municipality of Aulla lead to a reduction of the functionality of reach 3.9 compared to reach 3.4.

Both reaches have undergone significant channel narrowing and incision since the 1950s, but narrowing was stronger in reach 3.9 which also changed its channel pattern from a truly braided to a transitional form (i.e. wandering).

Concerning riparian vegetation, good functionality is guaranteed by the presence of a continuous and sufficiently wide riparian vegetated corridor in both cases (but it is more developed in reach 3.4).

8.2 Stage 2: Controls on change

8.2.1 Catchment and segment scales

Figure 8.1 illustrates the temporal trend of main human impacts that have occurred in the Magra river catchment, as identified in Section 5.

Figure 8.2 synthesises the main changes that have occurred in the Magra catchment since the middle of the XIX century at each relevant scale (i.e. from catchment to segment and reach scales), as the consequences of human impacts (alteration pressures) summarised in Figure 8.1. Changes are represented in terms of hydromorphological processes affected by the pressures and related indicators. The figure emphasises how pressures and thus processes at one scale may influence processes and related indicators at smaller spatial scales.

The list of pressures, processes and indicators is based on Deliverable 2.1, Part 1, Table 8.1.

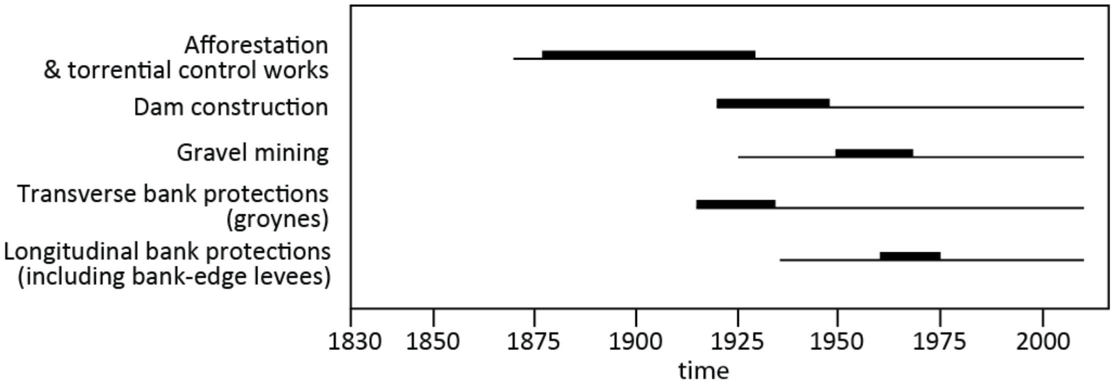


Figure 8.1 Synthesis of human impacts occurred in the Magra river catchment since the middle of the XIX century. Thick lines identify the main period of construction or activity, whereas thin lines identify the temporal magnitude of the impact. Concerning longitudinal bank protections, the thick line refers to the construction of the extended bank-edge levees on the left bank of the reach 3.9.

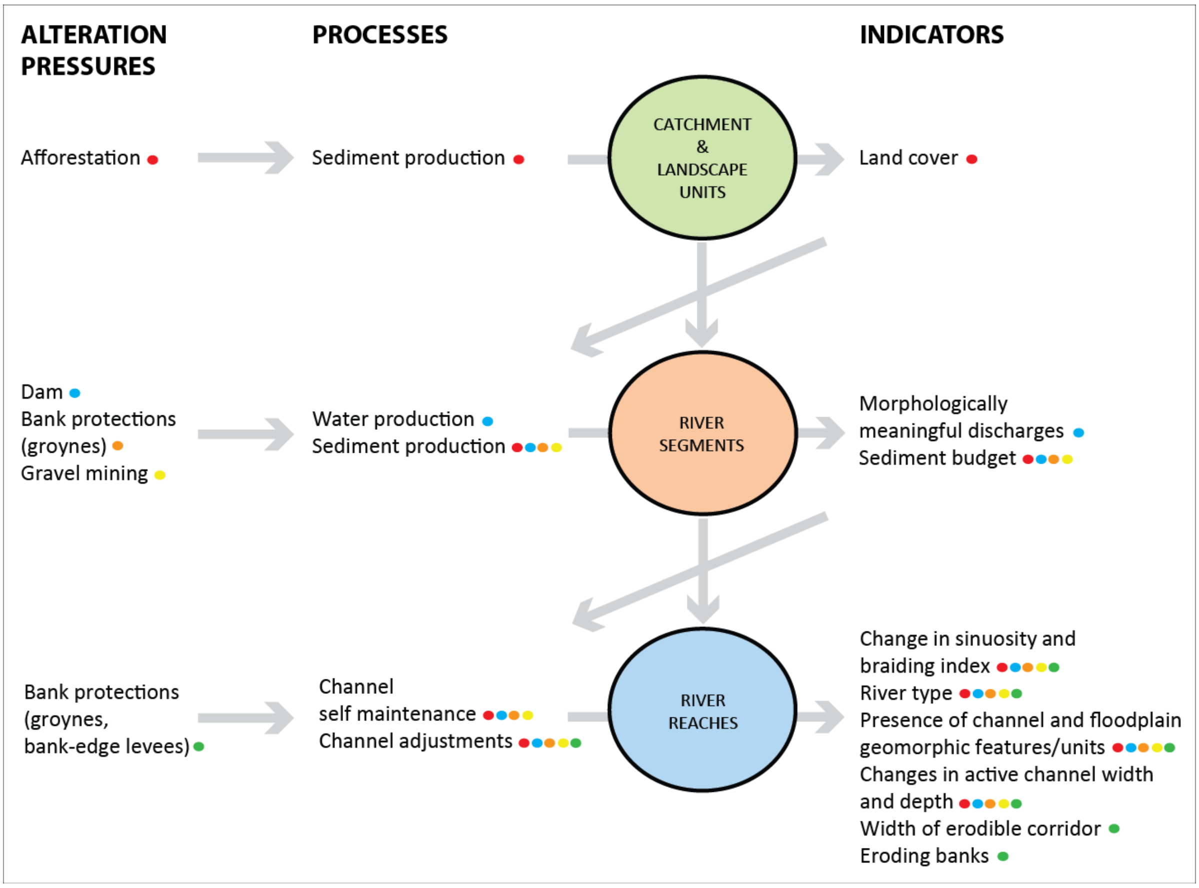


Figure 8.2 Synthesis of catchment to reach scale processes and indicators affected by human pressures in the Magra river catchment over time. Human pressure effects over spatial scales, for both processes and indicators, are displayed by coloured dots.

8.3 Stage 3: Assess reach sensitivity

Channel morphology, confinement, river energy, bedload as well as bank material provide important information on the inherent tendency of a given river typology to change.

Table 8.3 summarizes the main reach characteristics derived from previous sections, which are useful to assess reach sensitivity.

Table 8.3 Summary of the main reach characteristics derived from previous sections. Qualitative assessment of river energy and bedload potential are derived from sections 4.4.2 and 4.3.2-7.2.2 respectively.

Reach	Upstream catchment (km^2)	Reach type	Valley confinement	Bedload potential	River energy	Bank material
3.4	326	9	Unconfined	Moderate	High	Non-cohesive
3.9	615	11	Partly-confined	High	Moderate	Non-cohesive

Reach 3.4 is an unconfined, island-braided reach with alluvial bed and erodible banks, despite 600 m of bank protection on the right bank at its upstream end (see Section 7.4.1). The reach inherent energy is quite high (see Section 4.4.2); it belongs to a segment with a quite high bedload potential, although lower than reach 3.9.

Reach 3.9 is a partly-confined, wandering reach with alluvial bed material. Potentially it has erodible banks but at present bank erosion is completely prevented by the extended bank protection on the unconfined left bank (see Section 7.4.1). The reach has moderate energy; as well as reach 3.4 it belongs to a segment with a quite high bedload potential.

In addition to the elements above, investigation of channel adjustments that have occurred in the past in response to some disturbance allows identification of river reaches with a tendency to change, where past channel instability is used as evidence of sensitivity. According to previous studies (Rinaldi et al. 2008, 2009; see also Figure 5.7), the evolution of the Magra river is analysed by considering a conceptual model of channel changes consisting of three phases of river evolution: (1) 1880s-1950s, (2) 1950s-1990s, (3) 1990s-2010s. In figures 8.3 and 8.4 the magnitude of human impacts is attributed to an entire time period. For instance, the effect of dam construction has been attributed to the entire phase 1, even if the dam was built starting from the 1910s. Thus, in order to check the effective temporal succession and extent of each human pressure refer to Figure 8.1.

Figures 8.3 and 8.4 display the reach evolution in terms of channel width, bed elevation and channel pattern since the middle of the XIX century in response to the main human impacts, previously summarized in section 8.2, and their effect on hydromorphological processes.

Figure 8.3 shows that, over a century, reach 3.4 progressively narrowed up to 35% of the original width and incised more than 3 m. This mainly occurred as consequence of:

- At the catchment scale: land use changes (i.e. afforestation) and dam construction, mainly that on the Teglia torrent, a right-bank tributary located at the reach upstream end;
- At the segment scale: gravel mining.

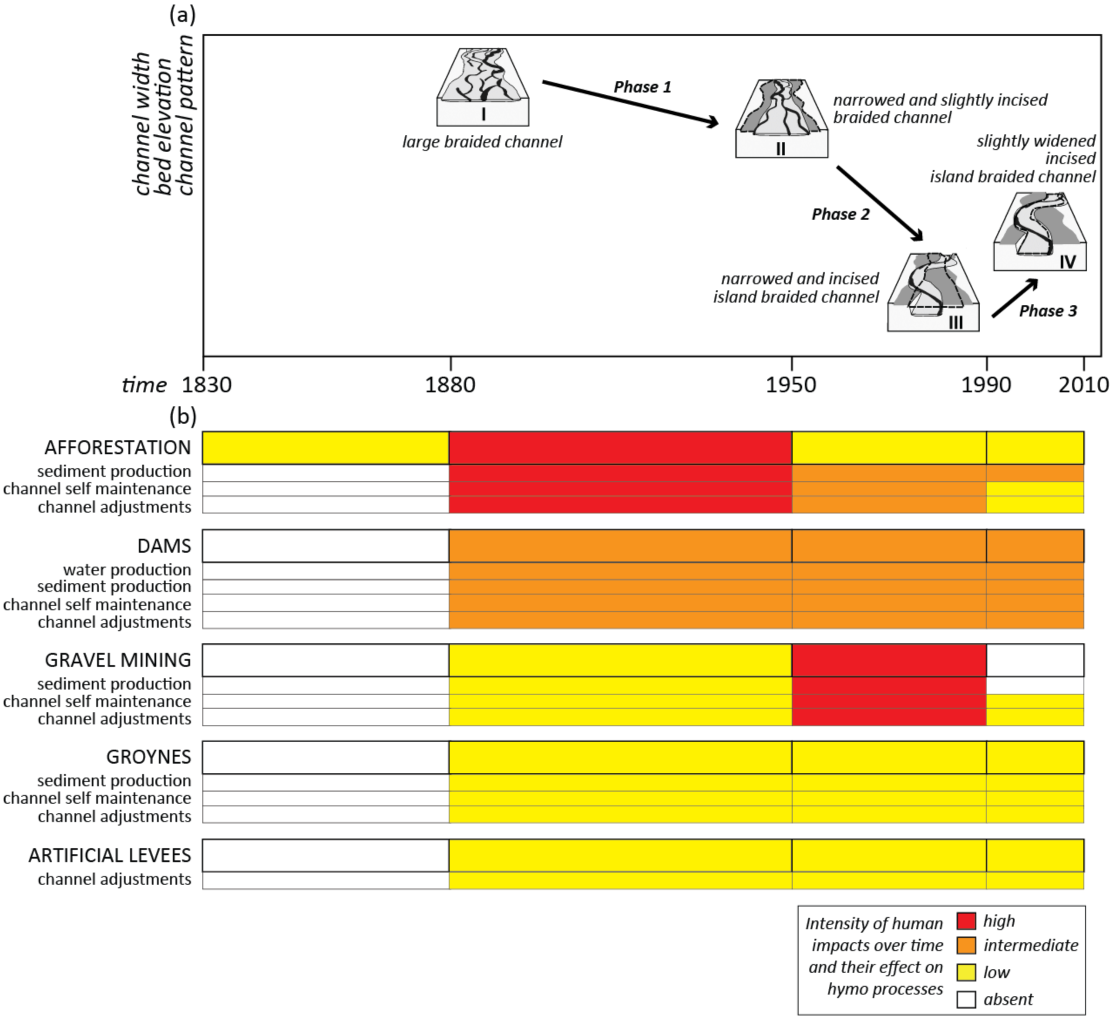


Figure 8.3 (a) Synthesis of the evolution of reach 3.4 in terms of channel width, bed elevation and channel pattern since the middle of the XIX century in response to (b) the intensity of the main human impacts (in capital) and their intensity effect on hydromorphological processes.

Note that the extent of bank protection in this reach is about 600 m which represents a small proportion of the entire river length.

No great change occurred in channel pattern which remained multi-thread braided (island braided at present).

Reach 3.9 (Figure 8.4) also underwent a progressive narrowing and channel incision, which started at the end of the XIX century according to the progressive afforestation of mountains and hills. But the narrowing pattern strengthened as a consequence of the gravel mining and the construction of artificial levees on the left bank during the 1960s-

70s, together with the urban development of the city of Aulla and aiming at preventing floods. These led to the change in channel pattern from braided to wandering and moderate channel incision.

Note that the groynes in Figure 8.4 refer to the entire segment 3, but they are not present in reach 3.9.

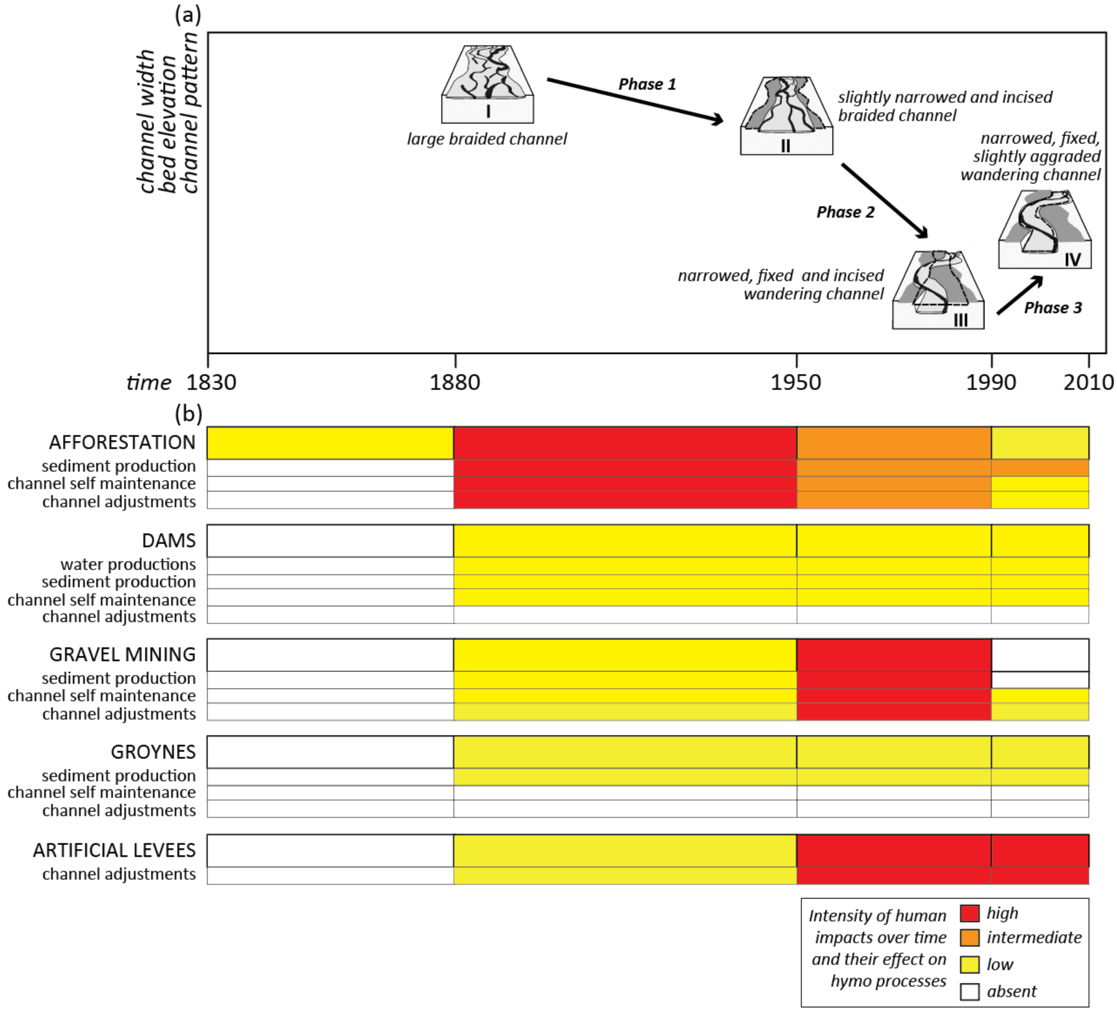


Figure 8.4 (a) Synthesis of the evolution of reach 3.9 in terms of channel width, bed elevation and channel pattern since the middle of the XIX century in response to (b) the intensity of the main human impacts (in capital) and their intensity effect on hydromorphological processes.

From the above analysis, it can be stated that both reaches are quite sensitive.

8.4 Stage 4: Assess scenario-based future changes

Three different scenarios have been considered for both reaches:

1. No changes
2. Bank protection removal
3. Dam removal

For each of these scenarios, some general, qualitative consideration on possible future trends of adjustment is provided, based on the knowledge of past changes and current conditions.

8.4.1 Scenario 1: No changes

Reach 3.4

Because of the dam on the Teglia river (the main tributary entering at the upstream end of the reach), and the high transport capacity of the reach, the sediment load from the upstream area will remain quite low, probably contributing to the observed narrowing process.

Anyway, the presence of erodible banks and the low density of structures which constrain the lateral dynamic will likely promote a continuation of the recovery pattern (i.e. widening and possible aggradation), that started during the last decade. The widening can be promoted by extreme flood events (lateral erosion and high sediment transport during floods).

Reach 3.9

The reach has a low lateral dynamic because it is partly–confined, with the right bank in contact with the hillslopes. Additionally, lateral dynamics are prevented by the presence of artificial levees on the left bank. As showed by Rinaldi et al. (2009), this reach has a higher sediment load potential from upstream, being far from the blocking structures (dams) (see also 7.2.2). Additionally, compared to upstream reaches, it has lower energy and lower shear stress values for significant discharges (i.e. bankfull discharge and Q10 year flood) (see Figure 4.7). These elements suggest that leaving the reach in its present condition may promote sediment deposition and aggradation. Similar findings have also been estimated by Rinaldi et al. (2009), by estimating the sediment budget using different bedload equations. No evidence suggests any change in the channel pattern.

8.4.2 Scenario 2: Bank protection removal

Reach 3.4

Within reach 3.4 there is some bank protection and bank-edge levees for a low percentage of the total length at the upstream part of the reach. Their removal would increase locally the channel width and thus, but not significantly, the mean channel width of the reach. No channel pattern changes are expected or changes in the bed elevation. Bank erosion would occur promoting the natural variability of the cross section.

Reach 3.9

Within reach 3.9, the lateral mobility of the right bank is naturally constrained by the presence of the hills, whereas the extent of artificial protection (bank-edge levee) concerns the total length of the left bank. Thus, the removal of such structures would significantly improve the overall reach functionality. A significant effect of this measure would involve lateral channel adjustments, increasing the mean channel width of the reach. Additionally, channel widening would decrease the aggrading trend observed in the last two decades and it is likely to recover a braided pattern.

Bank protection removal would benefit the reach functionality, but it would have to entail the reallocation of the Aulla settlements, which represents a very expensive management option and therefore not easily feasible.

8.4.3 Scenario 3: Dam removal

Reach 3.4

The upstream limit of reach 3.4 is located at the confluence with the Teglia torrent, a tributary of the Magra river on the right bank. Along the Teglia torrent there is a hydropower dam. Another two dams with minor dimensions can be found along the Verde and Gordana torrents joining the Magra river at reaches 3.1 and 3.3, respectively. The total catchment area drained by the three structures represents 38% of the reach drainage area. Such dams induce a significant effect on channel-forming discharge and impact sediment discharge, and they have largely contributed to channel narrowing and bed incision.

Based on the aforementioned considerations, dam removal would entail an increase in flow and sediment discharge. Given the high sensitivity of the reach, channel widening and bed aggradation would be expected. These processes would very likely cause significantly greater changes than for the scenario 1. Minor changes in channel pattern could occur with, for instance, a higher percentage of gravel bars compared to islands.

Reach 3.9

The reach 3.9 is located about 15 km downstream of reach 3.4 and there is no other dam in between the two reaches. Specifically, the total catchment area drained by the three above-mentioned structures represents 20% of the reach drainage area. For this reason over the last century the impact of the three dams has been less severe. Keeping in mind that in the current conditions this reach is laterally constrained by the presence of the bank-edge levee and the hills on the left and right sides, respectively, it is likely that dam removal would not have significant effects in terms of channel adjustments.

9 References

Autorità del Bacino del Fiume Magra (2006). Piano stralcio "Assetto Idrogeologico" del bacino del Fiume Magra e del Torrente Parmignola. Relazione generale. Unpublished report, 209 pp.

Luppi L., Rinaldi M., Teruggi L.B., Darby S.E., Nardi L. (2009). Monitoring and numerical modelling of riverbank erosion processes: a case study along the Cecina River (Central Italy). Earth Surface Processes and Landforms 34(4):530-546. DOI: 10.1002/esp.1754.

Nardi L. (2004). Monitoraggio e modellazione dell'erosione e della stabilità di una sponda del Fiume Cecina. University of Florence. Unpublished thesis, 211 pp.

Nardi L. (2011). Numerical and physical modelling of bank retreat in gravel-bed rivers. University of Florence and University of Braunschweig. Unpublished PhD thesis. 222 pp.

Nardi L., Rinaldi M. (2014). Spatio-temporal patterns of channel changes in response to a major flood event: the case of the Magra River (central – northern Italy). Accepted by ESPL.

Nardi L., Rinaldi M., Scozzafava R. (2012). Studio del F. Magra e degli affluenti principali dal punto di vista geomorfologico a seguito dell'evento alluvionale del 25/10/2011 e definizione delle azioni e degli interventi di messa in sicurezza Relazione Magra. Relazione fluviale. Unpublsihed report, 65 pp.

Rinaldi M. (2005). Studio geomorfologico dei principali alvei fluviali nel bacino del Fiume Magra finalizzato alla definizione di linee guida di gestione dei sedimenti e della fascia di mobilità funzionale. Relazione finale. Unpublished report, 172 pp.

Rinaldi M. (2003). Recent channel adjustments in alluvial rivers of Tuscany, Central Italy. Earth Surface Processes and Landforms, 28 (6), 587-608.

Rinaldi M. (2007). Approfondimenti dello studio geomorfologico dei principali alvei fluviali nel bacino del Fiume Magra finalizzato alla definizione di linee guida di gestione dei sedimenti e della fascia di mobilità funzionale. Relazione finale. Unpublished report, 157 pp.

Rinaldi M., Teruggi L.B., Simoncini C., Nardi L. (2008). Dinamica recente ed attuale di alvei fluviali: alcuni casi di studio appenninici (Italia Centro-Settentrionale). Il Quaternario 21(1B): 291–302.

Rinaldi M., Simoncini C., Piégay H. (2009). Scientific design strategy for promoting sustainable sediment management: the case of the Magra river (Central-Northern Italy). River Research and Applications 25:607-625. DOI:10.1002/rra.1243

Rinaldi M., Piégay H., Surian N. (2011). Geomorphological approaches for river management and restoration in Italian and French rivers. In: Simon A., Bennett S.E., Castro J.M. (eds.). Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses and Tools. Geophysical Monograph Series 194, American Geophysical Union, Washington D.C., USA, 95-113.

Surian N., Rinaldi M., Pellegrini L., Audisio C., Maraga F., Teruggi L., Turitto O., Ziliani L. (2009). Channel adjustments in northern and central Italy over the last 200 years. Geological Society of America Special Papers 451:83-95. DOI: 10.1130/2009.2451(05).

Teruggi L.B., Rinaldi M. (2009). Analysis of planimetric channel changes along the Cecina River (Central Italy). In: Amorosi A. (Ed), International Proceedings 27th IAS Meeting of Sedimentologists, Alghero, Italy, September 20-23, 2009, Medimond, 27-30.

Catchment Case Study 5:
Hydromorphological assessment of the River Drau (Austria)

Helmut Habersack, Bernadette Blamauer, Mario Klösch

1. Introduction

The Drau or Drava River is a high-energy, alpine, gravel bed river and a right bank tributary to the Danube (Figure 1.1). The focus of this investigation is on the upstream part of the Austrian Drau catchment, the Upper Drau River. It is one of the last stretches of large river in the Alps unaffected by hydropower development. Many rare and protected plant and animal species inhabit this river segment. In 1998, the Upper Drau River was designated as a Natura 2000 area, which gives great importance to the protection and improvement of the state of natural processes, plant and animal species, and habitats.

Figure 1.1 The Drau catchment is part of the Danube River Basin (based on data from HAÖ (2007), www.eea.europa.eu and www.waterbase.org)

Until approximately 140 years ago, the Upper Drau was a free flowing, sinuous to meandering mountain river with numerous braided stretches due to presence of the alluvial cones of its tributaries. In this dynamic river system with its annual floods and high bed load transport, the river course frequently changed. A braided river - floodplain system with large gravel banks, grey alder, willow wetlands, and wetland meadows characterized the valley bottom (cp. Amt der Kärntner Landesregierung, 2004).

The first substantial human changes began with the building of the railway line through the Upper Drau valley in 1868. In the following years, river-engineering channelized the river to reduce flood risk, and to allow intensive agricultural land use and the expansion of settlements. After flood events in 1965 and 1966, bank protection was intensified and additional regulation measures were set (Nachtnebel et al., 1992). The narrowing of the river channel and the prohibition of bank erosion led to a loss of habitats for fauna and flora and to a significant change in sediment transport capacity. Flow velocities and water depths increased due to this channelization.

At the same time sediment load was reduced as a result of retention in the upper catchment (e.g. by torrent controls and/or hydropower plants at tributaries) and sediment removal (gravel excavation), so that river bed incision started to become a problem (Nachtnebel and Habersack, 1996). To stop river degradation, several river restoration measures were implemented within the Upper Drau River as part of EU-LIFE projects "Auenverbund Obere Drau" and "Lebensader Obere Drau". However, without re-establishing the sediment continuity in and from the tributaries to the Drau River, the success of the restoration measures in stopping river degradation is uncertain.

The application of the multi-scale framework should give an insight into the effects of measures at different scales and help to understand the current status and predict future trajectories of the hydromorphological condition of the Upper Drau River. Additionally, a decision tree applied within this case study provides a tool for catchment-based evaluation of the sediment regime and continuity of a river reach. By following a strict hierarchical procedure, the connectivity of the reach to sediment production and the transfer of the sediment to the reach are considered as preconditions for sustainable morphodynamics.

2. Materials and Methods

The delineation and characterisation method is based on the multi-scale framework described in Deliverable 2.1 Part 1.

2.1 Delineation of spatial units

The delineation follows a top-down procedure from the region down to the smallest entities (Figure 2.1). The boundaries of the higher levels have to be congruent with boundaries at lower levels. The delineation was carried out according to the description given in Deliverable 2.1 Part 1. Where deviations from the given procedures are applied, these are indicated in the relevant parts of the text.

In Table 2.1 summarises the data sources used in the delineation.

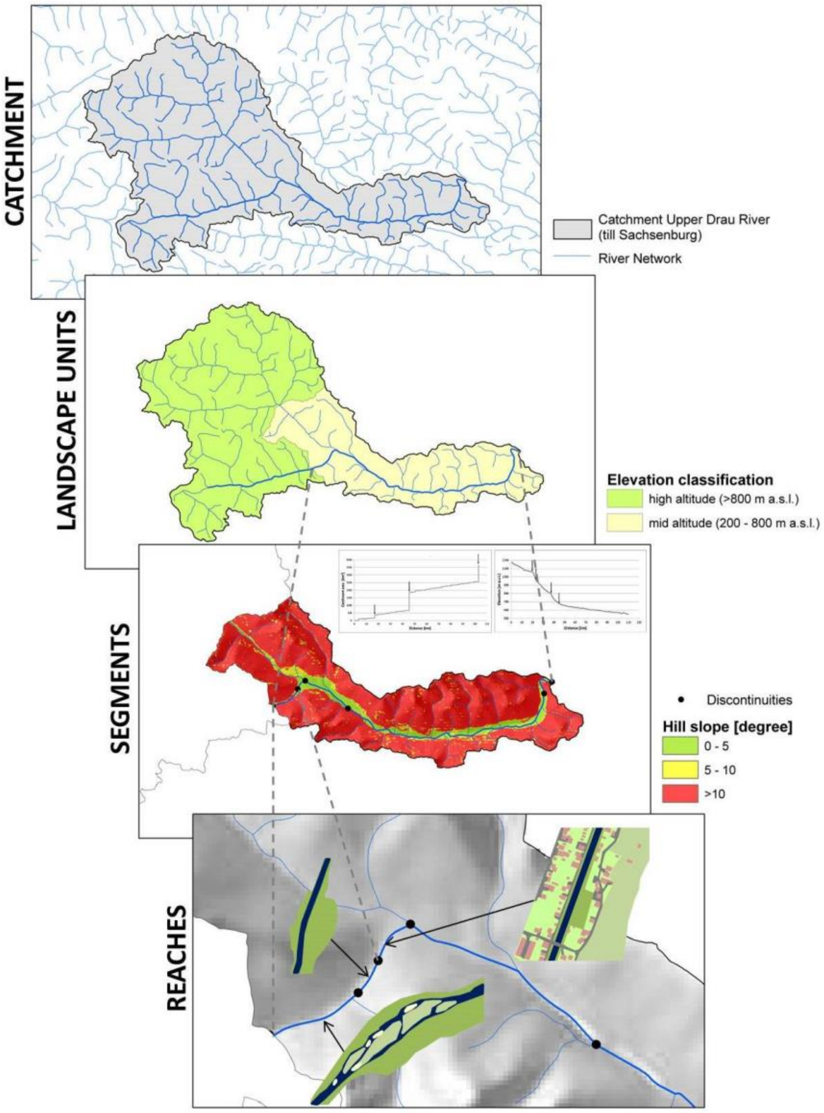


Figure 2.1 Delineation as a top-down procedure from catchment scale to reach scale.

Table 2.1 Data used for delineation of spatial units.

Spatial unit	Parameter	Data sources
Region	Biogeographical regions	Biogeographical regions (http://www.eea.europa.eu)
	Bioclimate	Bioclimatic map of Europe (Rivas-Martínez et al., 2004)
Catchment	Catchment and sub-catchments	digHAO (HAÖ, 2007)
Landscape Unit	Elevation	Processed SRTM data (Jarvis et al., 2008; http://srtm.csi.cgiar.org)
		90 m resolution, 10 m vertical accuracy
	Land cover 2006	Corine Land Cover 2006 (CLC 06) (http://www.eea.europa.eu/)
	Geology	USGS, Geologic provinces of Europe https://www.sciencebase.gov/catalog/item/535e9ee2e4b08e65d60fa23e).
Segment	Valley gradient	Processed SRTM data (Jarvis et al., 2008)
	Catchment area	digHAO (HAÖ, 2007)
Segment / Reach	Confinement (mainly applied at the reach scale but in some cases also at the segment scale)	Google Earth
Reach	Channel planform	Google Earth
	Transverse structures	Transverse structures (BMLFUW, 2010)
	River restorations	Final report "Lebensader Obere Drau" (Habersack et al., 2011)

2.2 Characterisation spatial units

The aim of the characterisation is to describe the delineated units and thereby support understanding of the condition and functioning of the fluvial system. Overviews of the assessed parameters for each spatial unit are given in Table 2.2 and Table 2.3.

Table 2.2 Overview of evaluated characteristics and data sources used at the catchment scale.

Characteristic	Data source	Notes
Geology	USGS, Geologic provinces of Europe https://www.sciencebase.gov/catalog/item/535e9ee2e4b08e65d60fa23e).	
Altitude typology	Processed SRTM data (Jarvis et al., 2008; http://srtm.csi.cgiar.org)	The classification of the WFD was used to give a general overview; Min, max and mean elevations were also derived.
Catchment size	DigHAO (HAÖ, 2007)	The classification scheme of the WFD was used.
Soil type	DigHAO (HAÖ, 2007)	
Hydrogeology	DigHAO (HAÖ, 2007)	
Land cover	CLC 06 (http://www.eea.europa.eu/)	

Table 2.3 Overview of evaluated characteristics and data sources used at the landscape unit scale.

Characteristic	Data source	Notes
River network and drainage density	DigHAO (HAÖ, 2007)	
Mean annual precipitation	DigHAO (HAÖ, 2007)	The mean annual precipitation for the entire catchment and the sub-catchments are evaluated.
Heavy precipitation	DigHAO (HAÖ, 2007)	The spatial distribution of precipitation intensities (15 minutes; 2-years reoccurrence interval) is analysed for the entire catchment
Mean annual actual evapotranspiration	DigHAO (HAÖ, 2007)	Similar to mean annual precipitation, the spatial distribution and the mean over the entire catchment is analysed.
Mean annual runoff	DigHAO (HAÖ, 2007)	The mean annual runoff derived from water balance calculations is given for the entire catchment.
Land cover	CLC 06 (http://www.eea.europa.eu/)	
Relief/ hill slope	Processed SRTM data (Jarvis et al., 2008; http://srtm.csi.cgiar.org)	
Soil erodibility class	Soil data base (http://eusoils.jrc.ec.europa.eu)	
Estimated annual soil erosion	Soil data base (http://eusoils.jrc.ec.europa.eu)	
Floodplain and riparian vegetation	Potential floodplain vegetation map (Muhar et al., 2004)	
Physical pressures	Impacts on hydrology and on river morphology (BMLFUW, 2010)	Transverse structures which have impacts on longitudinal sediment continuity are identified.

Table 2.4 Overview of evaluated characteristics and data sources used at the segment scale.

Characteristic	Used data source	Notes
Hydrological parameters	Hydrological regime (Mader et al., 1996) characteristic values (Lebensministerium, 2012; and www.ehyd.at);	Several gauging stations are available. For each of them, the hydrological regime and characteristic values are identified.
Season / month of annual flood	DigHAO (HAÖ, 2007)	
Trends of mean annual discharge	DigHAO (HAÖ, 2007)	
Valley gradient	Processed SRTM data (Jarvis et al., 2008; http://srtm.csi.cgiar.org)	
Valley confinement (mean valley bottom extent, mean bankfull width)	Processed SRTM data (Jarvis et al., 2008) and Google Earth	
Outer limits and structure of riparian corridor	Actual riparian vegetation types are taken from Muhar et al. (2004), extents are analysed based on Google Earth	
Sediment delivery / continuity	Bed load monitoring (Habersack et al., 2013)	Load and grain size distribution
	Suspended load (Lebensministerium, 2012)	Load and concentrations

Table 2.5 Overview of evaluated characteristics and data sources used at the reach scale – only applied to the restored reach "Kleblach", and in case of data availability, also to the regulated reach "Berg".

Characteristic	Used data source	Notes
Bed and bank calibre	Grain size distributions (Habersack et al., 2011)	Only for Kleblach (restored site)
Channel dimensions	Cross sections/digital elevation models (Amt der Kärntner Landesregierung)	
Flow parameters	2D Hydrodynamic model	Only for Kleblach
River bed and bank condition – physical pressures	Impacts on river morphology (BMFLUW, 2010)	Here, physical pressures concerning lateral and vertical continuity of sediment, e.g. bank protection, bed reinforcements etc., are treated. Longitudinal discontinuities were already evaluated at higher spatial scales.
Riparian and aquatic vegetation	Vegetation map Kleblach - final report "Ripclima" (Angermann et al., 2011); Orthophotos (Amt der Kärntner Landesregierung)	

2.3 Characterising temporal change in spatial units

Similar to the characterisation, temporal changes were assessed at each spatial scale. The parameters that were used are listed in Table 2.6.

Table 2.6 Data used for characterising temporal change in spatial units.

Spatial unit	Parameter	Data sources
Catchment and landscape unit	Rainfall and groundwater	digHAO (HAÖ, 2007)
Segment	River flow and water levels	Hydrographs (www.ehyd.at); low flow analysis (Habersack et al., 2011)
	Sediment delivery and transport	Position of transverse structure (BMLFUW, 2010) and evaluation of sediment continuity
	Valley setting	Franziszeischer Kataster (http://gis.ktn.gv.at), Atlas Tyroliensis (http://www.tirisdienste.at/), Google Earth, Orthophotos (Amt der Kärntner Landesregierung)
	Riparian corridor and wood	3.Landesaufnahme (www.tirisdienste.at/), Franziszeischer Kataster (http://gis.ktn.gv.at), Google Earth
Reach	Channel planform, migration and features	Franziszeischer Kataster (http://gis.ktn.gv.at), Google Earth, Orthophotos (Amt der Kärntner Landesregierung)

2.4 Indicators of present and past condition

Based on the data used for delineation and characterisation, the indicators of present and past condition for each scale (see Table 8.1 in Deliverable 2.1 Part 1) are derived.

2.5 Decision tree for catchment-based evaluation of the sediment regime and continuity

2.5.1 Introduction

River engineering structures such as bank protection or bed sills act as constraints on river morphology and limit morphodynamic processes. Accordingly, the deviations of a river's morphology from a natural reference condition were attributed to the degree of artificiality in the observed river section and river restoration works mainly aimed at reducing artificial constrains within the river reach. Less attention was drawn to alterations of the sediment continuum between sediment production in the river's catchment and downstream river reaches. However, especially in gravel bed rivers, the sediment supply from upstream is strongly reflected by morphodynamics such as bar formation or reworking of the river bed. Any alteration of the quantity of sediment supply (i.e. sediment discharge) or sediment quality (e.g. grain size) may affect the morphological appearance of a reach and determine its deviation from an undisturbed condition.

The decision tree for the evaluation of sediment regime accounts for sediment supply and sediment transfer as preconditions for sustainable morphodynamics in river reaches. At the reach scale, artificiality and the sediment budget are assessed. In contrast to existing evaluation methods for assessing hydromorphological state, no reference condition is needed for determining hydro-morphological alterations. Here, with re-established sediment supply and reduced artificiality, a river reach is expected to develop the morphodynamics that approaches an undisturbed condition.

2.5.2 Evaluation concept

The application of the decision tree for reach evaluation follows a three-step process (Figure 2.2). First, the connectivity of the reach to sediment production in its catchment is evaluated. In the second step, the sediment transfer in the river network upstream from the reach is analysed. In the last step, the reach itself is investigated for its own sediment budget and for its artificiality. The evaluation procedure is performed from catchment to reach scale in an hierarchical manner: the score assigned to the reach's catchment with respect to sediment supply defines the maximum score that can be achieved by the river network score concerning sediment transfer. In turn, the river network score is the maximum possible score that can be achieved by the final reach score. In contrast to existing methods for assessing the morphological quality of rivers, by following the decision tree, the sediment supply is considered as a prerequisite for sustainable functioning of morphodynamics. The hierarchical procedure ensures causal analysis of morphodynamics rather than interpretation of symptoms observed in the investigated reach.

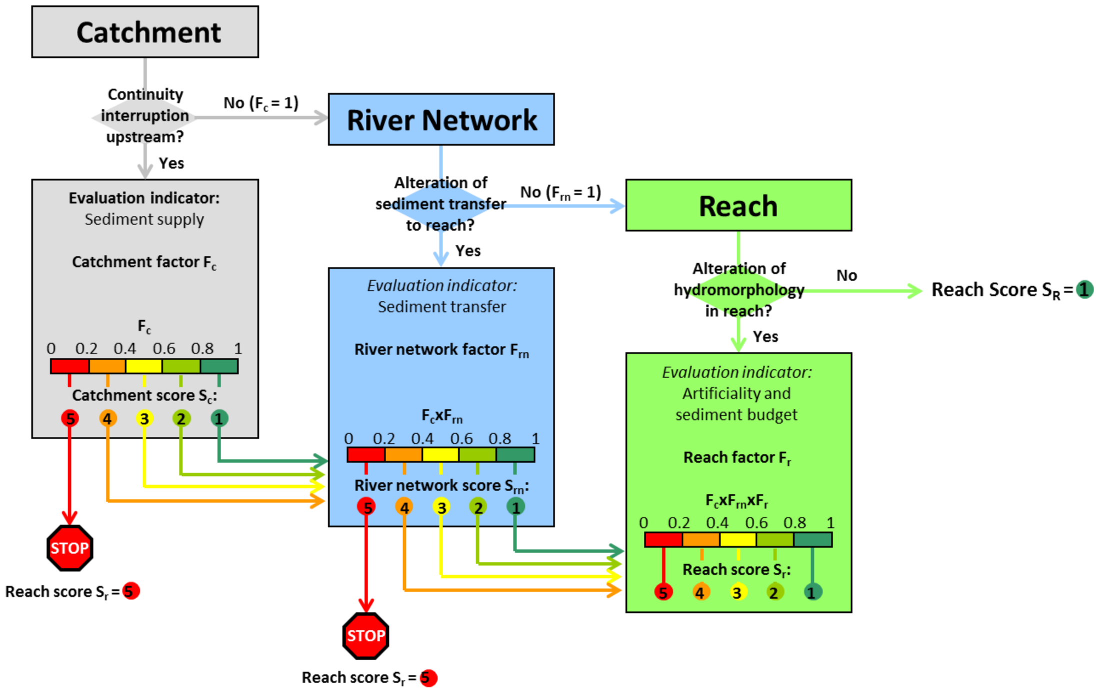


Figure 2.2 Decision tree for the evaluation of sediment regime.

(i) Catchment

In a first step, the catchment of the investigated reach is investigated for artificial sediment barriers such as torrent control structures or weirs from hydropower plants. By assigning throughput coefficients to the sediment barriers the proportion of the produced sediment which has access to the river network of the reach is calculated. Artificial compensation of the sediment deficit downstream from weirs may be acknowledged in the decision tree. However, its contribution may be reduced by a sustainability weighing factor, which lets the user define the sustainability of compensation measures.

The catchment condition is summarized in the catchment factor F_c. The reach's catchment score S_c is derived by classification of the catchment factor F_c into five intervals (Table 2.7).

Table 2.7 Scoring at the catchment level, which is solely based on the catchment factor F_c.

Catchment factor F_c	Score at catchment level	Connectivity of reach to sediment production in its catchment
0.0 - 0.2	5	very bad
0.2 - 0.4	4	bad
0.4 - 0.6	3	acceptable
0.6 - 0.8	2	good
0.8 - 1.0	1	very good

(ii) River network

The river network is investigated for alterations of the transfer of sediment from the catchment to the downstream, investigated reach. River engineering works in the upstream river network may alter the sediment budget by changing the sediment transport capacity. Training works such as channel narrowing may increase bed shear stress and hence sediment transport. Moreover, gravel mining or artificial sediment supply affects the sediment budget of the river network. Degradation (bed level lowering and/or channel widening) in upstream reaches would increase, and aggradation (bed level increase as well as channel narrowing) would decrease the amount of sediment which is transferred downstream. Mostly, aggradation, degradation and especially dredging activities and artificial sediment supply occur over a limited time. A reduction or increase of sediment supply to the investigated reach would therefore imply that the actual morphological condition of the reach, whether it resembles a natural or an altered condition, is temporary. By evaluating the sediment transfer within the river network, the sustainability of the morphological condition is considered in the evaluation.

For the properties of the river network the factor F_{rn} is calculated. The reach's score at the river network level, S_{rn}, characterises the condition of sediment supply to the reach and is derived by classification of the product F_c x F_{rn} into five intervals (Table 2.8).

Table 2.8 Scoring of sediment supply to the reach, performed at the river network level based on the product of the catchment factor Fc and river network factor Frn.

F_c x F_{rn}	Score at river network level	Sediment supply to reach
0.0 - 0.2	5	very bad
0.2 - 0.4	4	bad
0.4 - 0.6	3	acceptable
0.6 - 0.8	2	good

(iii) River reach

While morphodynamics evolve with local bed aggradation or degradation, within the length of the river reach the sediment budget has to be balanced to maintain the morphological condition. This is investigated based on repeated surveys of the channel geometry (cross section surveys or surveys including the entire channel). Second, the degree of artificiality is evaluated at the reach scale, since the sediment budget in a reach may be balanced just because of artificial interference in the channel processes. Non-erodible crossing structures or artificial sediment supply may prevent bed degradation, and a narrowed channel due to groynes or repeated dredging may prevent aggradation.

The final reach score, Sr, characterises the overall preconditions for sustainable morphodynamics in the reach and is derived by classification of the product F_c x F_{rn} x F_r into five intervals (Table 2.9).

Table 2.9 Marking of the preconditions for sustainable morphodynamics in the reach, performed at the reach level based on the product of the catchment factor Fc, river network factor F_{rn} and reach factor F_r.

F_c x F_{rn} x F_r	Score at reach level	Preconditions for sustainable morphodynamics in a reach
0.0 - 0.2	5	very bad
0.2 - 0.4	4	bad
0.4 - 0.6	3	acceptable
0.6 - 0.8	2	good
0.8 - 1.0	1	very good

2.6 Interpreting condition and trajectories of change

The evaluated indicators and characteristics, as well as the changes of these parameters are used to interpret the current condition of the river (stage 1), to investigate controls on changes (stage 2), to determine reach sensitivity (stage 3) and to derive future trajectories for the river (stage 4).

3. Delineation

3.1 Region

The Drau River and its major tributary the Mur River run through three different ecoregions (Figure 3.1).

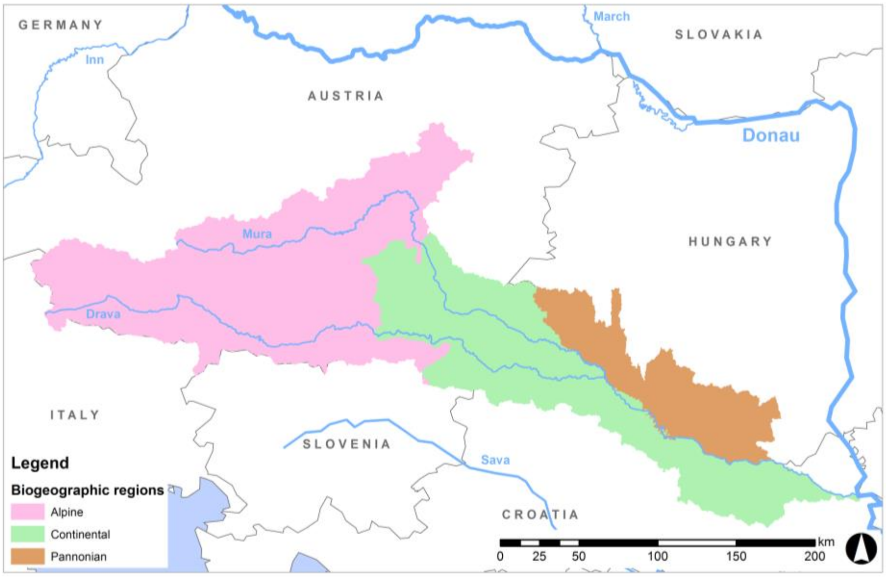


Figure 3.1 Biogeographic regions of the Drau catchment (data source: www.eea.europa.eu, European Environment Agency)

51% of the catchment can be classified as Alpine. Both the Drau and Mur rivers originate in this region, which is characterised by high elevations and a great variety of ecosystems and habitat types. The Alps (Alpine region) are characterized by a backbone of crystalline formations and external fringes of limestone, where the Upper Drau catchment is located, and schist formation (EEA, 2002). In this Alpine region, sufficient rainfall is available to support the establishment of forests. The rainfall is highly variable in space and time, and the mountain peaks may protect valleys from high levels of rain. The Alps represent, due to their geomorphology and the varying exposition to wind, sun, rain and other variables, a complex set of microclimates (EEA, 2002).

The middle section of the catchment (about 34% of the entire catchment) is located in the Continental biogeographical region. This region represents the connection between most other biogeographical regions of Europe. The landscape in this area is general hilly and the climate shows strong seasonal contrasts, (e.g. warm summers and cold winters, EEA, 2002).

In the downstream part of the catchment, the course of the Mur and then the Drau formthe border between the Pannonian region in the north-east and the Continental region in the south-west. About 15% of the catchment is located in the Pannonian region. This region is surrounded by mountains and dominated by the Great Hungarian Plain. It is characterised by alluvial plains in the interior and low mountain ranges along the boundaries. The climate in the Pannonian region can be assigned to the following types: the west-European climate (rich in precipitation), the continental climate (lower precipitation), the Mediterranean climate (warm summers and temperate winters) and the Atlantic-alpine climate (EEA, 2002).

The catchment of the Drau can be separated into three different bioclimatic regions: temperate oceanic, temperate continental and temperate continental steppic (Figure 3.2). A combination of the bioclimatic and the biogeographic regions is presented in Figure 3.3.

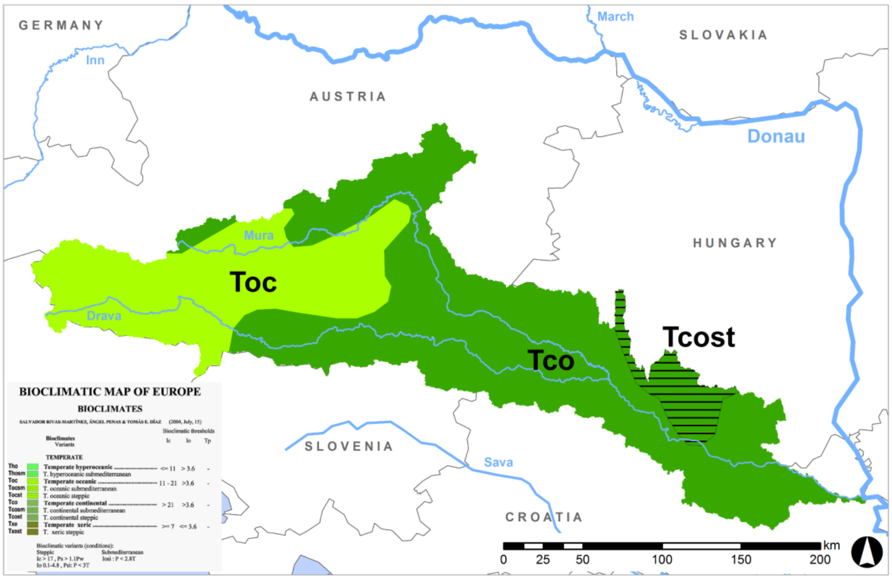


Figure 3.2 Bioclimatic regions of the Drau catchment (data source Rivas-Martínez et al., 2004). Toc stands for temperate oceanic, Tco denotes temperate continental and Tcost refers to a temperate continental steppic climate.

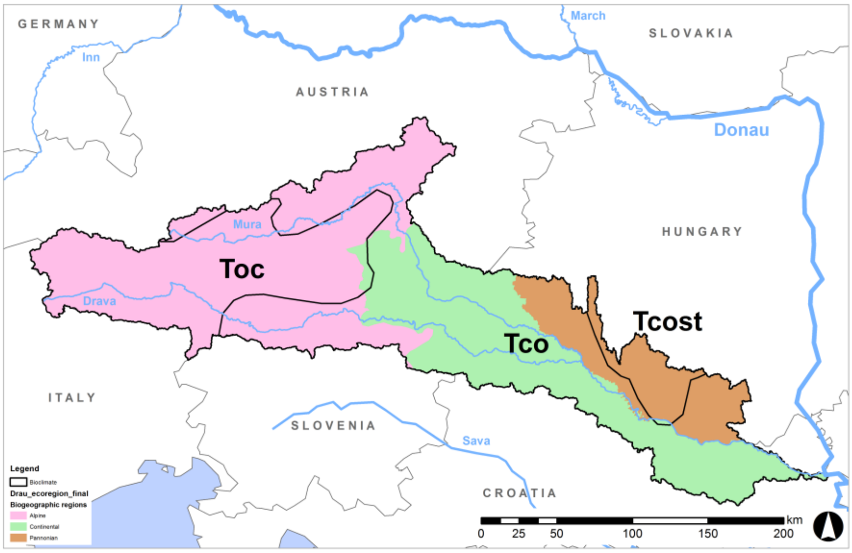


Figure 3.3 Overlay of biogeographic regions with bioclimatic regions (data source Rivas-Martínez et al., 2004; www.eea.europa.eu, European Environment Agency). Toc stands for temperate oceanic, Tco denotes temperate continental and Tcost refers to a temperate continental steppic climate.

3.2 Catchment

The Drau originates between Innichen and Döblach (South Tyrol, Italy) at 1192 m a.s.l.. It enters Austria at Erlach and runs through East Tyrol and Carinthia. It leaves Austria at Lavamünd, crosses Slovenia and merges with the Danube at Osijek (Croatia) (Figure 3.4). The main flow direction is from the west to the east, with a slight trend to the south. In Austria, the Drau follows predetermined geological structures (Alpine-Dinaric Transition Zone) with crystalline rocks in the north (e.g. Hohe Tauern, Kreuzeckgruppe,…) and carbonate rocks in the south (e.g. Karawanken,…).

Based on the WFD classification, the Drau catchment is very large (~39.676 km²). The Mur River, a major tributary to the Drau, drains 36,3% of the Drau catchment.

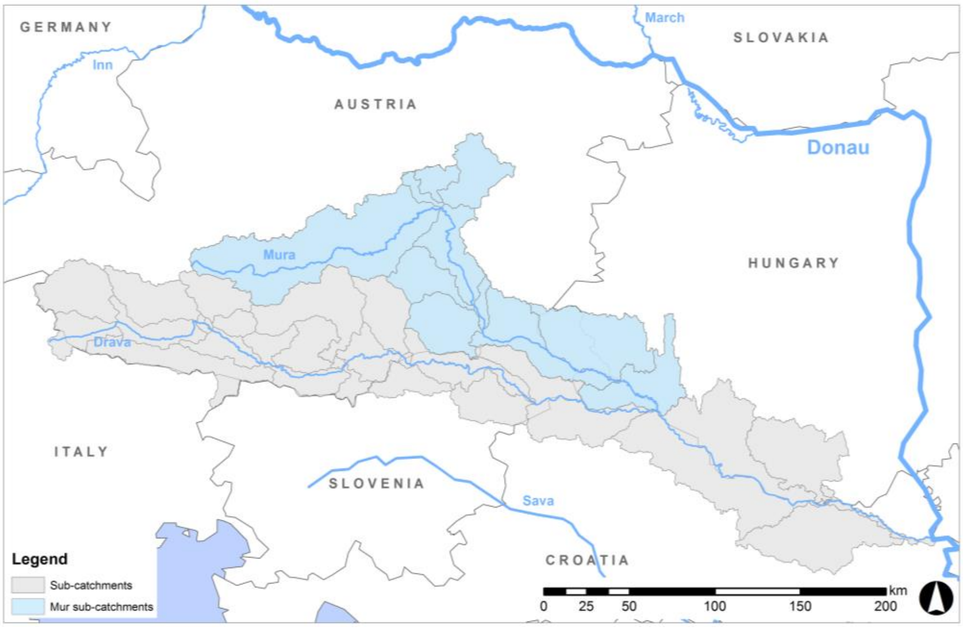


Figure 3.4 Sub-catchments of the Drau River Basin (based on data from HAÖ (2007) and www.eea.europa.eu). The catchment and sub-catchments of the River Mur (Mura), a major tributary to the Drau, are indicated by a blue color.

3.3 Landscape Unit

Seven landscape units were delineated for the entire Drau catchment (Figure 3.5). The delineation was based on the following characteristics: elevation, land cover and geology (Figures 3.6 and 3.7). The boundaries between the different landscape units were drawn along sub-catchment boundaries.

Tables 3.1 and 3.2 summarise the characteristics of the landscape units. Landscape units 1, 2, 3 and 5 are dominated by forest and semi natural areas on metamorphic rocks, whilst in landscape units 4, 6 and 7 agricultural areas dominate the land cover. In the latter landscape units, quaternary sediments dominate the geology.

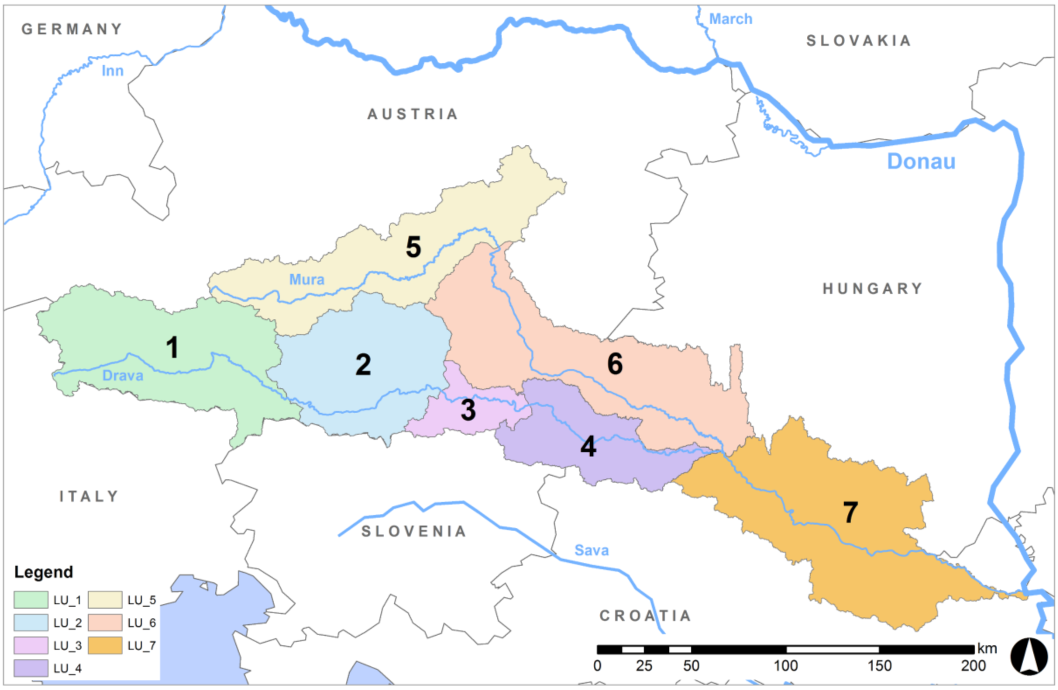


Figure 3.5 Delineated landscape units.

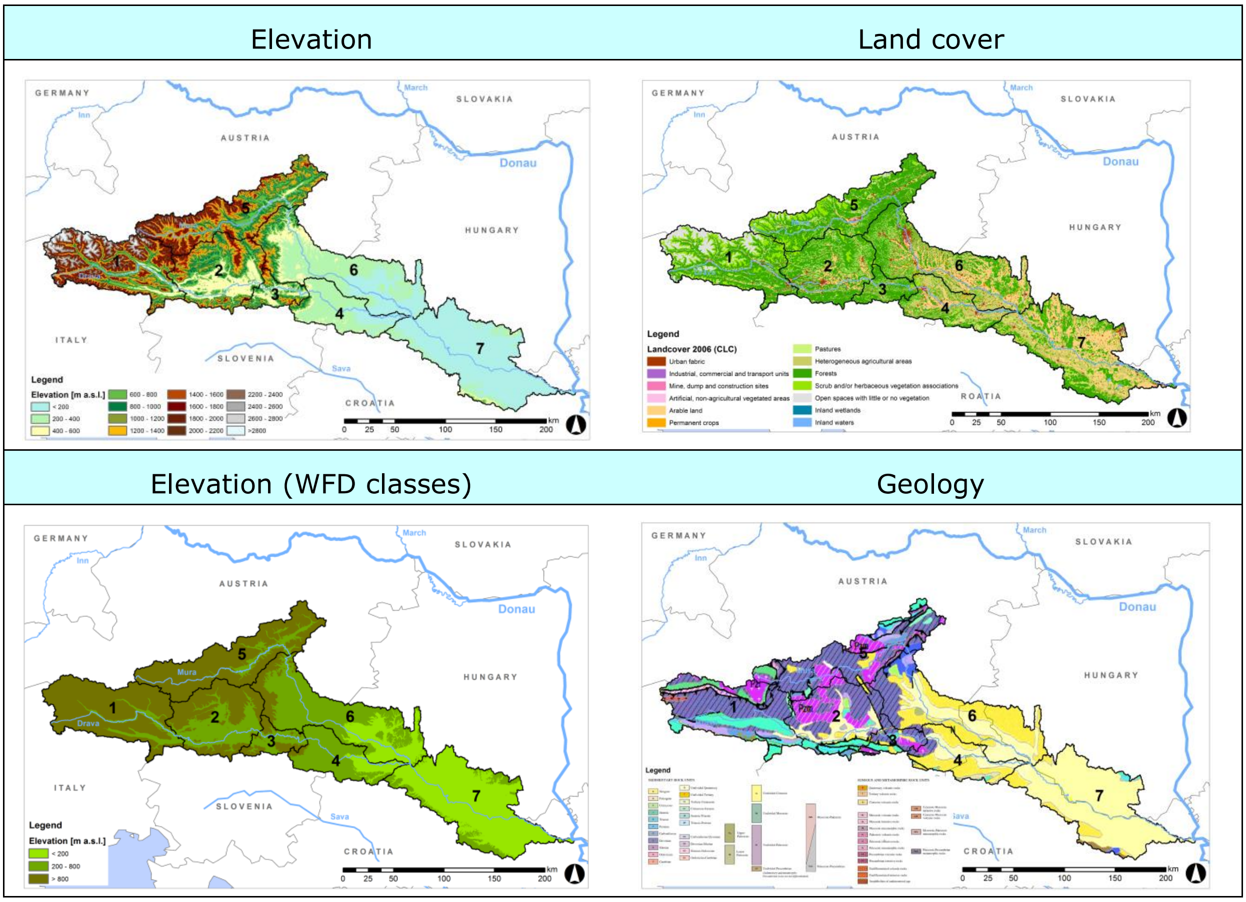


Figure 3.6 Overlay of Landscape Units on elevation, land cover, geology, biogeographic region, bio climate and sub-catchments.

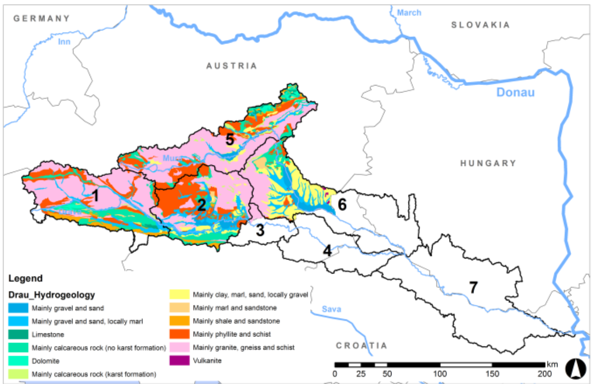
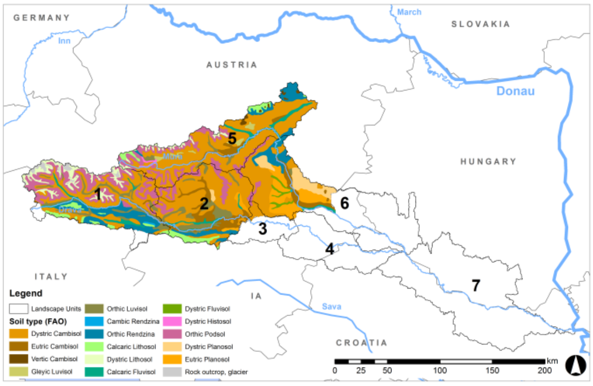
Soil	Hydrogeology
	

Figure 3.7 Soil types and hydrogeology of the Austrian part of the Drau catchment.

Table 3.1 Characteristics of the seven landscape units (LU) of the River Drau (part 1). "Scrub…" stand for scrubs and/or herbaceous vegetation associations, and "open spaces…" for open spaces with little or no vegetation.

LU	Elevation [m a.s.l.]				dominant Landcover (>=9%)	Geology (>=10%)	Biogeographic Region
	mean	min	max	WFD altitude			
1	1633	479	3736	High	Forests (46,64%) Scrub … (20,53%) Open spaces… (19,96%)	Metamorphic Rock (Palaeozoic - Precambrian: 47,25%) Sedimentary Rock (Triassic: 18,06%)	Alpine
2	926	337	2376	Mid-high	Forests (60,81%) Pastures (11,08%) Heterog. agricultural land (10,00%)	Metamorphic Rock (Palaeozoic - Precambrian: 33,70% Palaeozoic: 22,97%) Quaternary Sediments (17,30%)	Alpine
3	816	264	2110	Mid-high	Forests (71,22%) Heterog. agricultural land (12,24%) Pastures (9,35%)	Metamorphic Rock (Palaeozoic - Precambrian: 48,63%) Quaternary Sediments (18,33%) Igneous rock (Palaeozoic intrusive: 13,75%)	Alpine - Continental
4	308	124	1518	Low-mid	Heterog. agricultural land (37,77%) Forests (32,51%) Arable land (10,81%)	Sedimentary Rock (Neogene: 51,74%) Quaternary Sediments (29,06%)	Continental

Table 3.2 Characteristics of the 7 landscape units (LU) of the River Drau (part 2). "Scrub…" stand for scrubs and/or herbaceous vegetation associations.

LU	Elevation [m a.s.l.]				LU	Elevation [m a.s.l.]	LU
	mean	min	max	WFD altitude			
5	1294	438	3024	High	Forests (61,94%) Scrub … (17,18%) Pastures (9,35%)	Metamorphic Rock (Palaeozoic - Precambrian: 50,22% Palaeozoic: 20,27%)	Alpine
6	385	124	2110	Low-mid	Forests (40,61%) Arable land (22,99%) Heterog. agricultural land (17,97%)	Sedimentary Rock (Neogene: 46,65%) Quaternary Sediments (31,50%) Metamorphic Rock (Palaeozoic - Precambrian: 13,07%)	Continental (small parts alpine and Pannonia)
7	147	73	897	Low	Arable land (31,82%) Forests (29,77%) Heterog. agricultural land (22,51%)	Quaternary Sediments (87,89%)	Continental - Pannonia

3.4 Segment

Segments are delineated based on discontinuities in valley gradient and significant changes of drainage area due to major tributaries. A longitudinal profile of the River Drau is presented in Figure 3.8. In Figure 3.9, the position and extent of each segment is illustrated for landscape unit one.

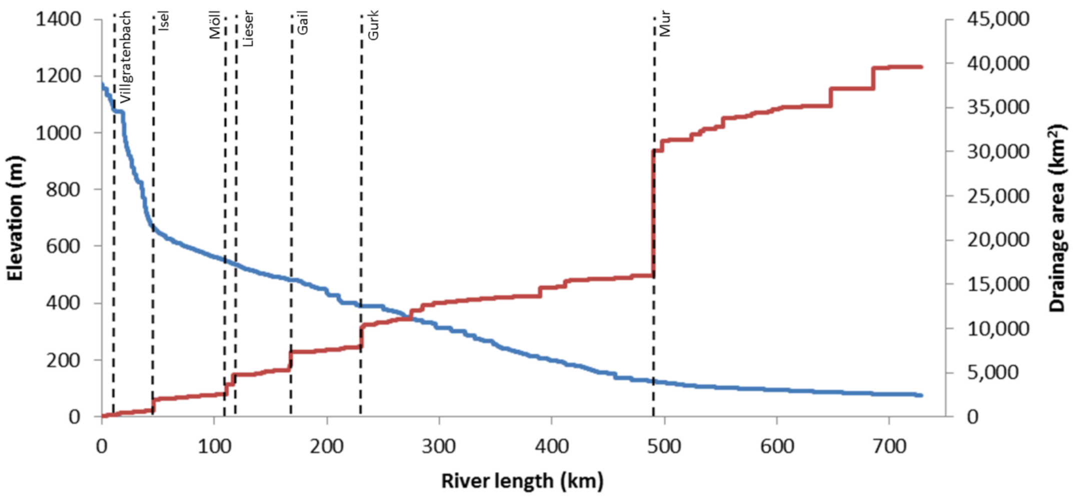


Figure 3.8 Longitudinal profile of the River Drau. The red line indicates the catchment area [km²] and the blue one represents the elevaion [m a.s.l.]. Major tributaries, and thus discontinuities in drainage area, are highlighted by the dashed lines.

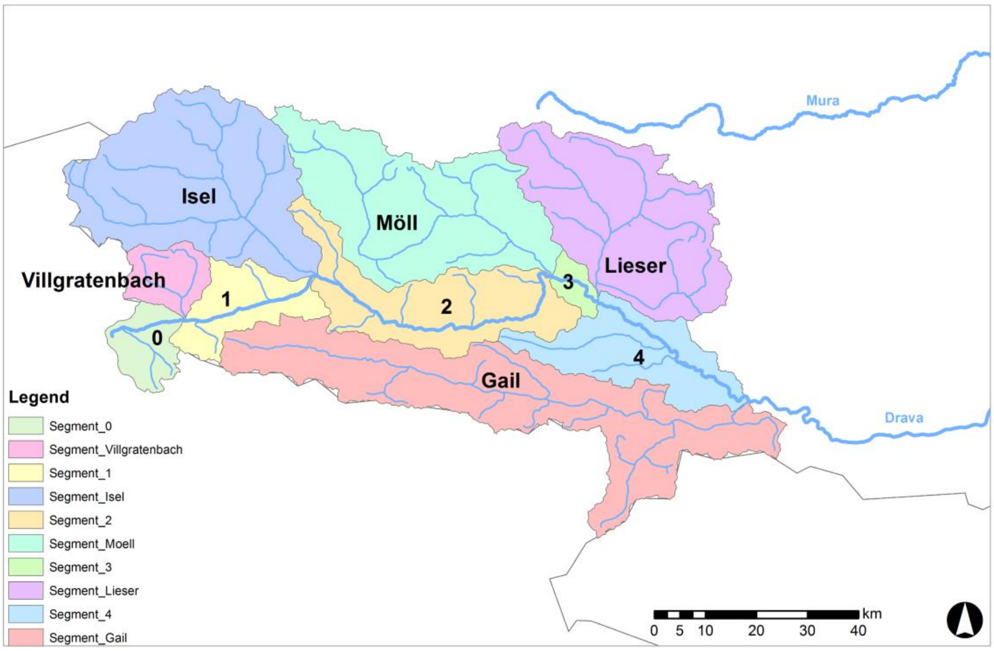


Figure 3.9 Segmentation of landscape unit 1.

Further characteristics are evaluated only for segments zero, one and two, respectively. In Figure 3.10 the longitudinal profile and the increase in catchment area for these segments is shown, and some characteristics of the segments are summarized in Table 3.3. In Figure 3.11 the confinement of this river stretch is depicted. In the first few kilometres, the Drau runs through a semi-confined valley where the river is sometimes in contact with the hill slopes. Then a confined, narrow valley section follows until the Drau River reaches the wide valley of Lienz (unconfined). There, it is joined by the Isel River and changes its main flow direction, which then is from North-West to South-East.

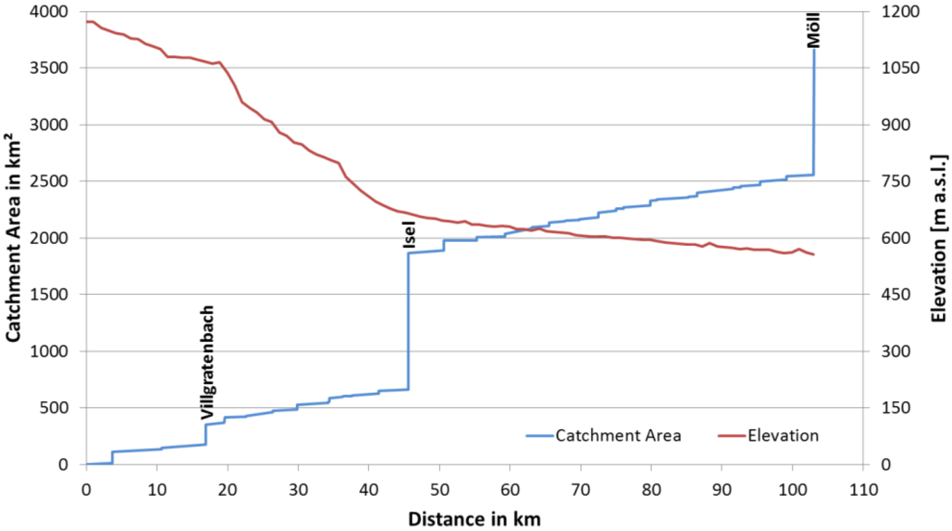


Figure 3.10 Increase in drainage area (HAÖ, 2007) and longitudinal profile of the Upper Drau River (height information is based on SRTM - Jarvis et al., 2008).

Table 3.3 Length, valley gradient and valley bottom extent of the Upper Drau River.

Segment	Length [km]	Mean valley gradient [‰]*	Valley bottom extent** (based on hillslope, raster width 80 m x 80 m)			Mean bankfull width***
			Min	Mean	Max	
0	16,9	5-10	160 m	375 m	630 m	<15 m
1	28,7	Till Gailbach 2,5-5 Till Isel 10-20	80 m	464 m	2960 m	~30 m
2	57,4	Mainly <2,5	440 m	1314 m	2480 m	~55 m
* based on Muhar et al., 2004, ** based on SRTM (Jarvis et al., 2008), *** based on Google Earth						

Downstream from Nikolsdorf, just before the Drau River enters Carinthia, the valley becomes narrower and the river oscillates from one side of the valley bottom to the other. This section is characterised as semi-confined, as there are still areas where the river is not in contact with the hill slopes. Before the Drau merges with the River Möll, the valley again becomes narrower, but it is still partially-confined. Figure 3.12 provides an impression of the valley width and confinement for several positions along the Drau River.

Figure 3.11 Major tributaries and confinement of the Drau River (segments 0-2) (Google Earth).

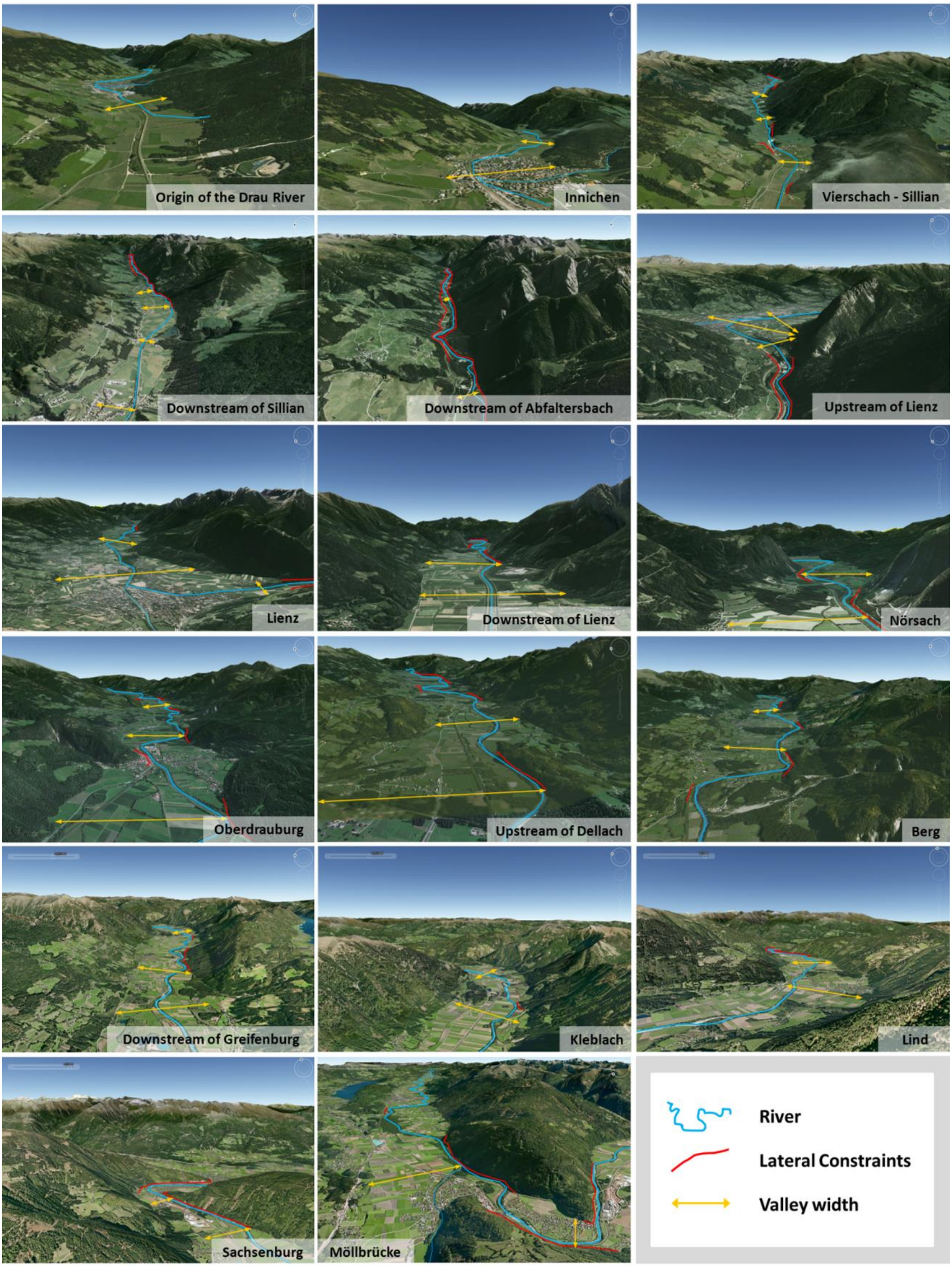


Figure 3.12 Visualisation of the confinement of the Upper Drau river (from source to Sachsenburg, where the Drau River confluences with the Möll River). Views are in the direction of flow (source: Google Earth).

3.5 Reach

The Upper Drau River as far as Sachsenburg (segments 0, 1 and 2) was delineated into 28 reaches based on channel planform, major transverse structures (e.g. weirs) and restored sections. The positions of the reaches are indicated in Figure 3.13 and additional information is given in Table 3.4.

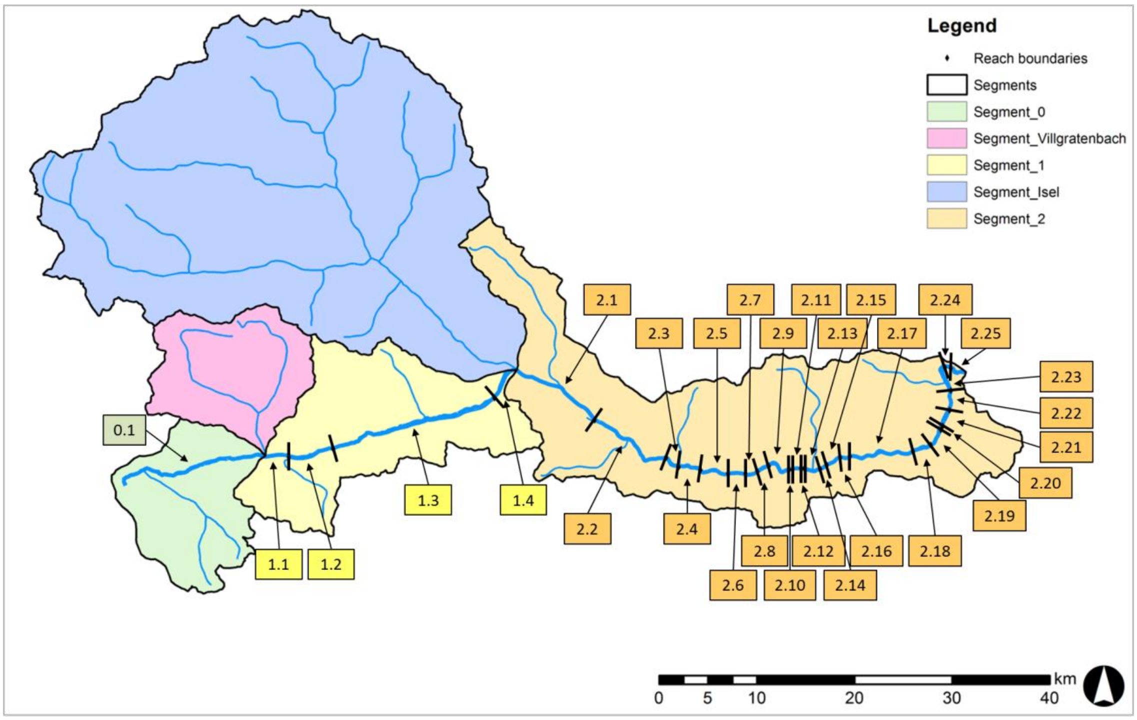


Figure 3.13 Delineated reaches for Segment 0, 1 and 2 of the Upper Drau River.

Table 3.4 Information about delineated reaches.

Segment	Reach	Length [km]	Confinement	Channel planform	Sinuosity index	Comment*
0	0.1	16,91	Semi-confined	Single thread, straight	1,02	-
1	1.1	2,42	Semi-confined	Single thread, straight	1,00	Upstream of diversion for hydropower plant (weir)
	1.2	4,87	Semi-confined	Single thread, straight	1,02	Downstream of diversion for hydropower plant; Residual flow stretch
	1.3	17,71	Confined	Single thread - transitional	1,04	Residual flow stretch
	1.4	3,66	Unconfined	Single thread, straight	1,03	Hydro-peaking
2	2.1	9,53	Unconfined	Single thread, straight	1,01	-
	2.2	8,72	Semi-confined	Single thread, sinuous	1,08	-

* the distance in brackets indicates the length of the restoration measures (data source: SEE River Project).

Table 3.5 Information about delineated reaches (continued).

Segment	Reach	Length [km]	Confinement	Channel planform	Sinuosity index	Comment*
	2.3	1,58	Semi-confined	Single thread, sinuous	1,06	River restoration "Oberdrauburg" (0,9 km)
	2.4	2,20	Semi-confined			-
	2.5	2,86	Semi-confined			River Restoration "Gröfelhof" (3,1 km)
	2.6	1,79	Semi-confined			-
	2.7	1,26	Semi-confined			River Restorration "Dellach" (1,7 km)
	2.8	1,28	Semi-confined			-
	2.9	2,42	Semi-confined			Downstream of "Feistritzbach"
	2.1	0,20	Semi-confined			Regulated reach WP4 "Berg" (0,2 km)
	2.11	0,88	Semi-confined			-
	2.12	0,39	Semi-confined			River restoration "Greifenburg" (0,9 km)
	2.13	1,69	Semi-confined			-
	2.14	0,77	Semi-confined			River restoration "Greifen-burg Bruggen" (1,15km)
	2.15	1,53	Semi-confined			-
	2.16	1,01	Semi-confined			River restoration "Radlach" (0,9 km)
	2.17	6,48	Semi-confined			-
	2.18	1,94	Unconfined	Single thread, straight	1,04	River restoration "Kleblach" (3,55 km)
	2.19	1,92	Unconfined			-
	2.2	0,46	Unconfined			River restoration "Kleblach II" (0,45 km)
	2.21	1,70	Unconfined			-
	2.22	2,00	Unconfined	Single thread, straight	1,01	River restoration "Obergottesfeld" (2,15 km)
	2.23	2,57	Semi-confined	Single thread, straight	1,00	-
	2.24	0,60	Semi-confined			River restoration "Sachsenburg" (0,88 km)
	2.25	1,55	Semi-confined	Single thread, sinuous	1,05	Hydro-peaking

* the distance in brackets indicates the length of the restoration measures (data source: SEE River Project).

Within the processed segments, the presence of river restoration measures was the delineation criterion that was mainly used. In total, eleven river restorations were present in the Upper Drau River in segment 2. Along the investigated river sections one major transverse structure is present, a weir for water extraction associated with a hydropower plant.

4. Characterisation of spatial units

4.1 Catchment

The upstream parts of the catchment are located in mountainous areas (Figures 4.1 and 4.2) with mainly metamorphic rocks (Figure 4.3), whereas the downstream section is located in hilly to lowland areas. The geology of the latter section is dominated by tertiary and quaternary sediments.

Similar to the geology and the relief, the land cover (Figure 4.4) in the upstream and downstream area are different. In the upstream catchment forests and scrub and/or herbaceous vegetation associations, at higher altitudes open spaces with little or no vegetation, are dominant. With decreasing hill slope and altitude, arable land and heterogeneous agricultural areas increase.

An overview of the soil types and the hydrogeology of the Austrian Drau catchment are given in Figures 4.5 amd 4.6.

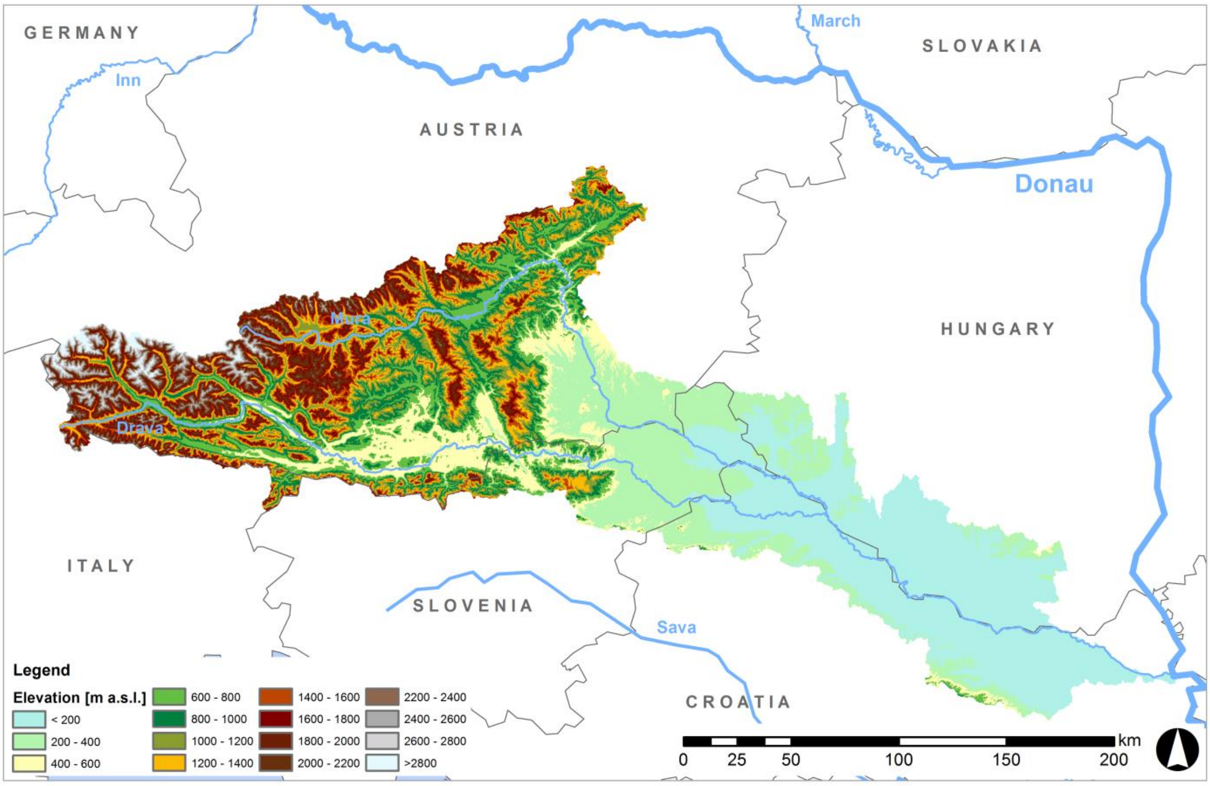


Figure 4.1 Elevation of the Drau catchment (based on data from digHAÖ, 2007; www.eea.europa.eu and Jarvis et al. (2008)).

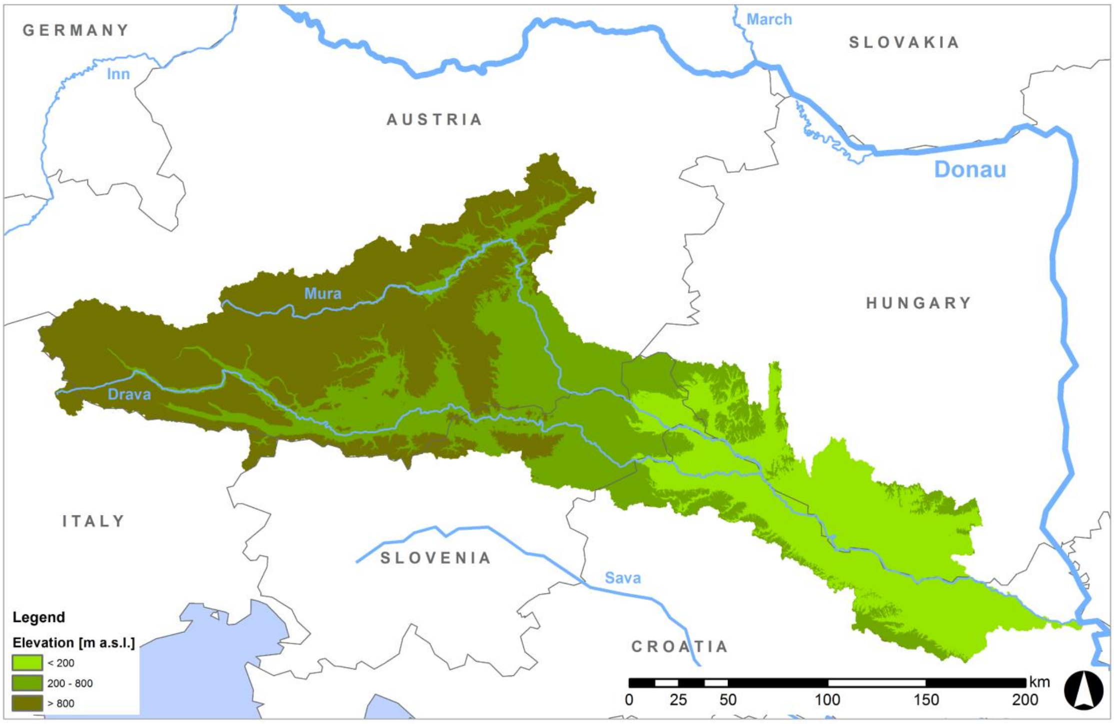


Figure 4.2 Elevation classes based on the WFD (based on data from digHAÖ, 2007; www.eea.europa.eu and Jarvis et al., 2008).

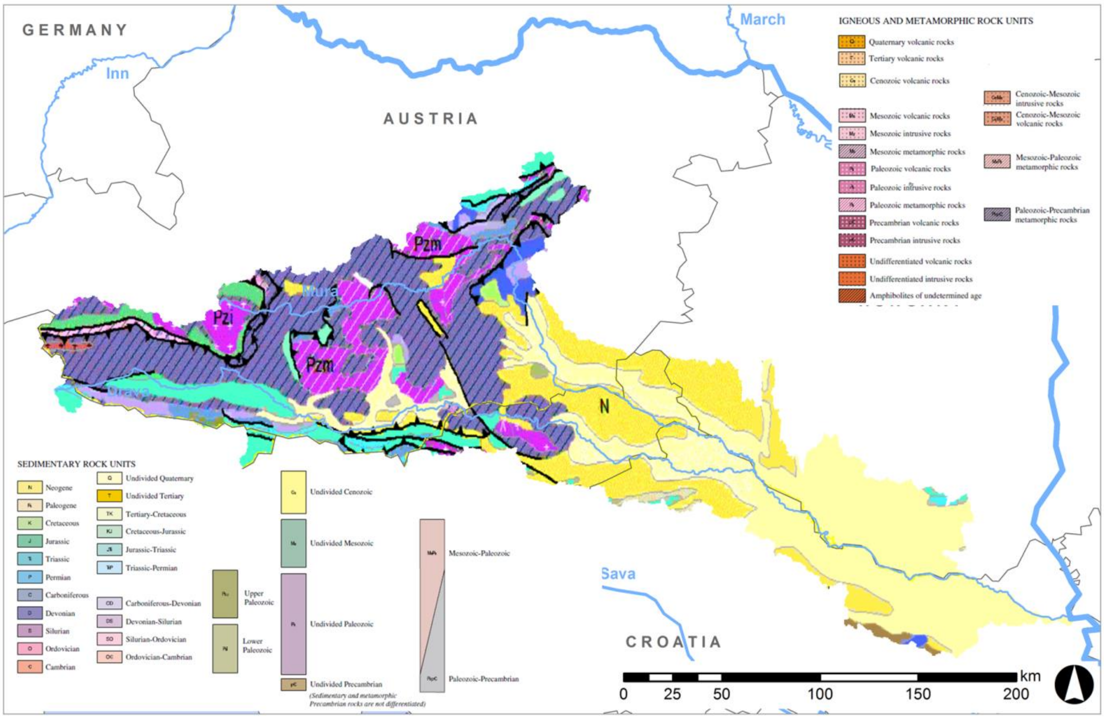


Figure 4.3 Geology of the Drau catchment (based on data from digHAÖ, 2007; USGS www.sciencebase.gov/ catalog/item/535e9ee2e4b08e65d60fa23e). Large parts of the upper catchment are made of metamorphic and igneous rock (purple, magenta). The middle and downstream part of the catchment is dominated by tertiary and quatenary sediments (yellow).

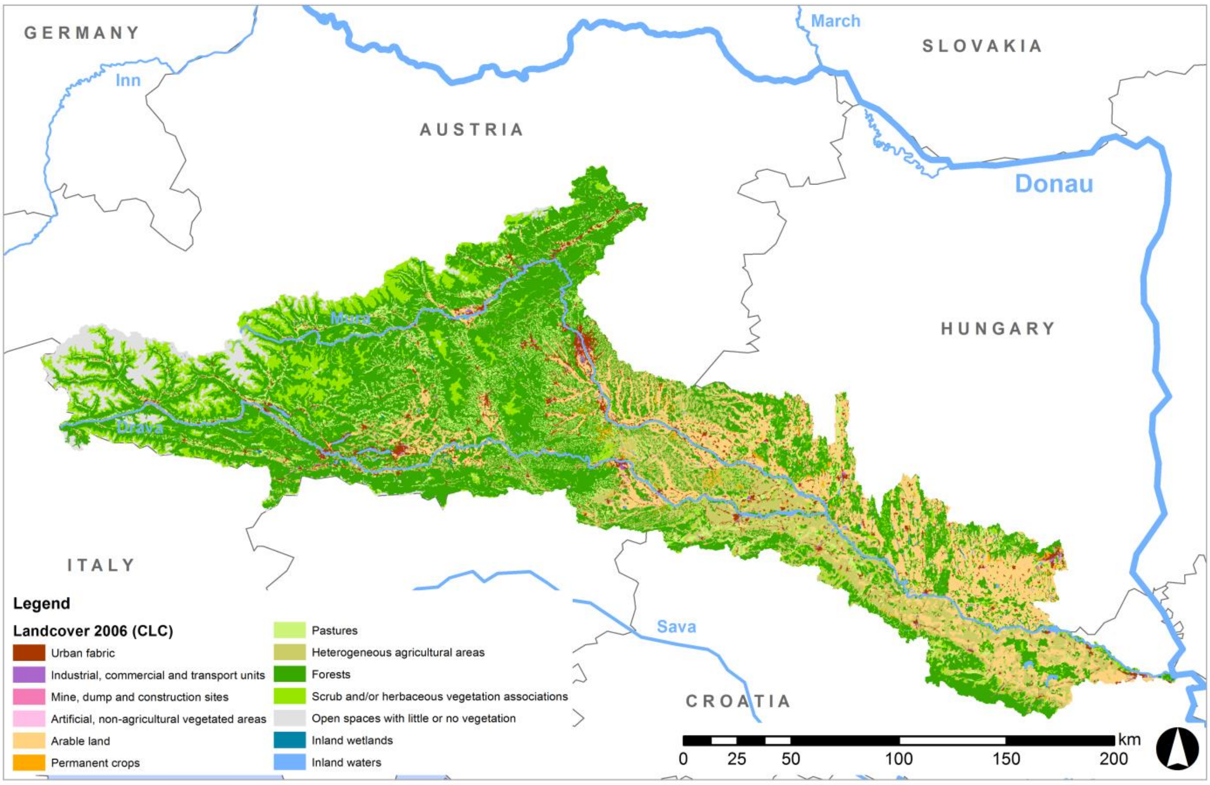


Figure 4.4 Landcover of the Drau catchment (based on data from digHAÖ, 2007; www.eea.europa.eu and Corine Land Cover 2006).

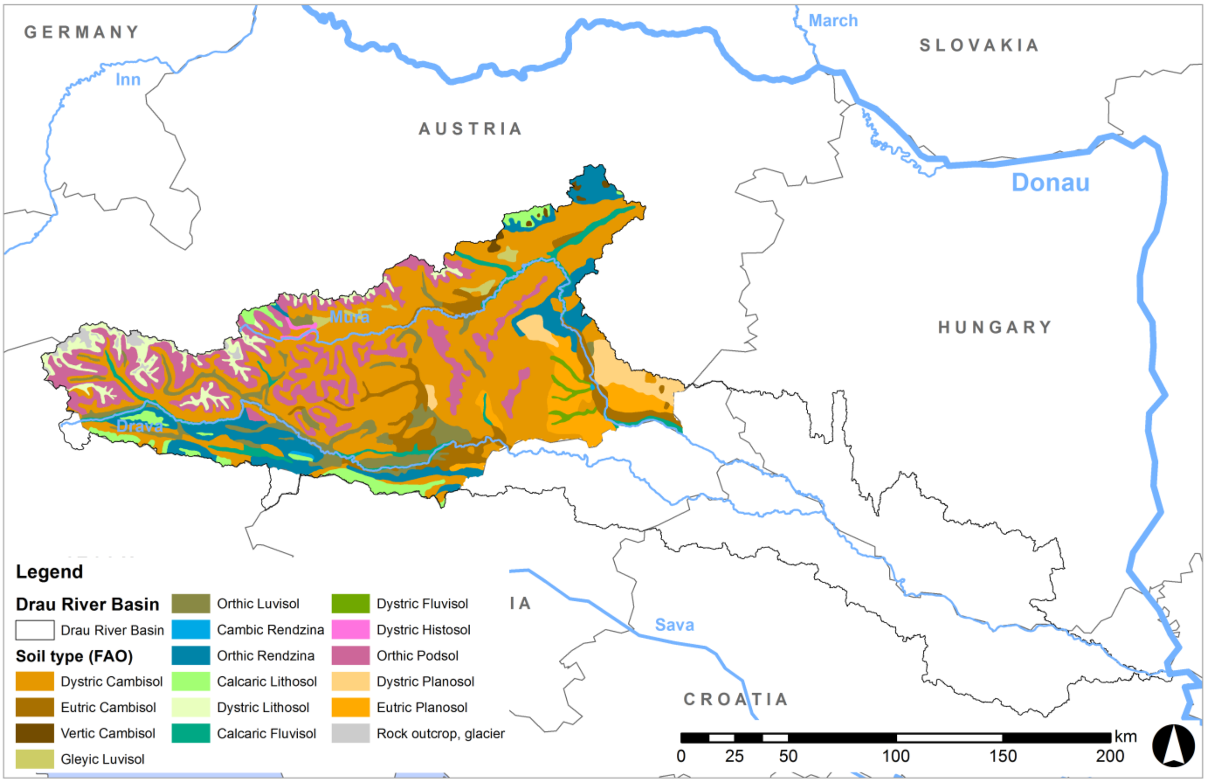


Figure 4.5 Spatial distribution of different soil types at the Upper Drau and Upper Mur catchment (based on data from digHAÖ, 2007).

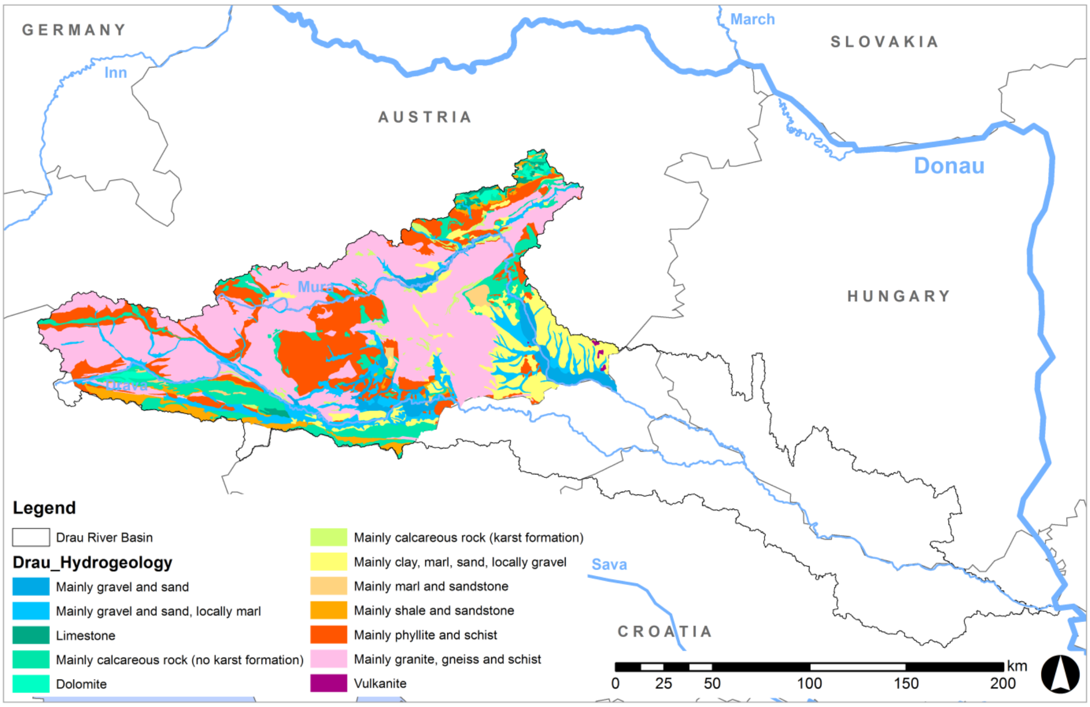


Figure 4.6 Hydrogeology of the Austiran part of the Drau catchment (based on data from digHAÖ, 2007).

4.2 Landscape Unit

Seven landscape units were delineated, but only the Upper Drau catchment – landscape unit one – is characterised here.

In general, landscape unit one exhibits a dendritic drainage pattern. Only in the southern part of the catchment, where the geology changes form the crystalline to calcareous rock, a more trellis pattern is present (Figure 4.7). Within most of landscape unit one, the drainage density is about 700-1000 m.km^{-2} (Figure 4.8). The middle stretch of the Drau and large parts of the Gail River, a left-bank tributary to the Drau, follow predetermined geological structures (Figure 4.9). The hydrogeological classes are presented in (Figure 4.10).

The mean elevation of landscape unit one is about 1633 m and the relief is mountainous. The highest mountains (>2800 m a.s.l.) are located in the north-western region of this unit (Figure 4.11). The elevation of the Drau valley bottom is between 1200 m a.s.l. at the source and at about 500 m a.s.l. at the downstream part of the landscape unit. The hill slopes are presented in Figure 4.12, which visualizes the narrow valley in the upstream part and the wider valley at Lienz, where the Drau River confluences with the Isel River. Downstream of Lienz, the valley becomes a little narrower and the Drau River starts to oscillate from one side of the valley to the other.

Most of the catchment has hill slopes steeper than 25%. However, it has to be noted that the underlying elevation data, which was used for the calculation of the hill slopes, was only available at low resolution (raster width about 90 m).

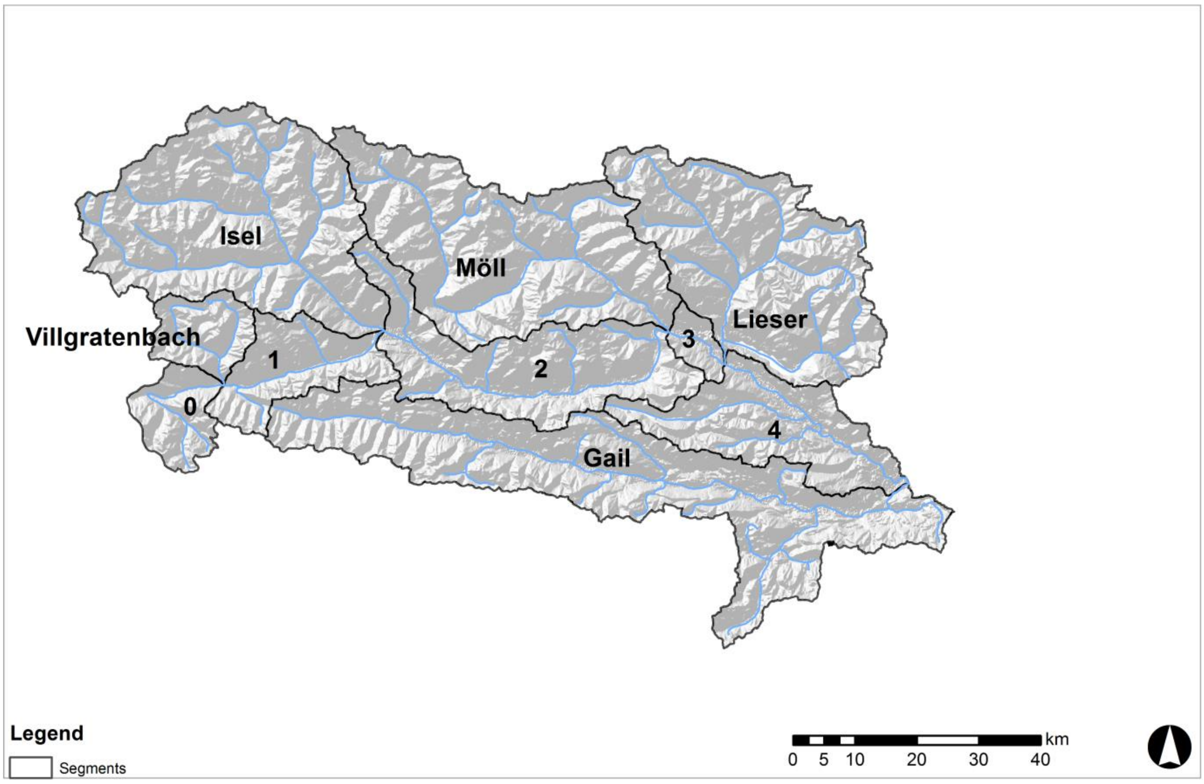


Figure 4.7 Overlay of segments (landscape unit 1) with river network.

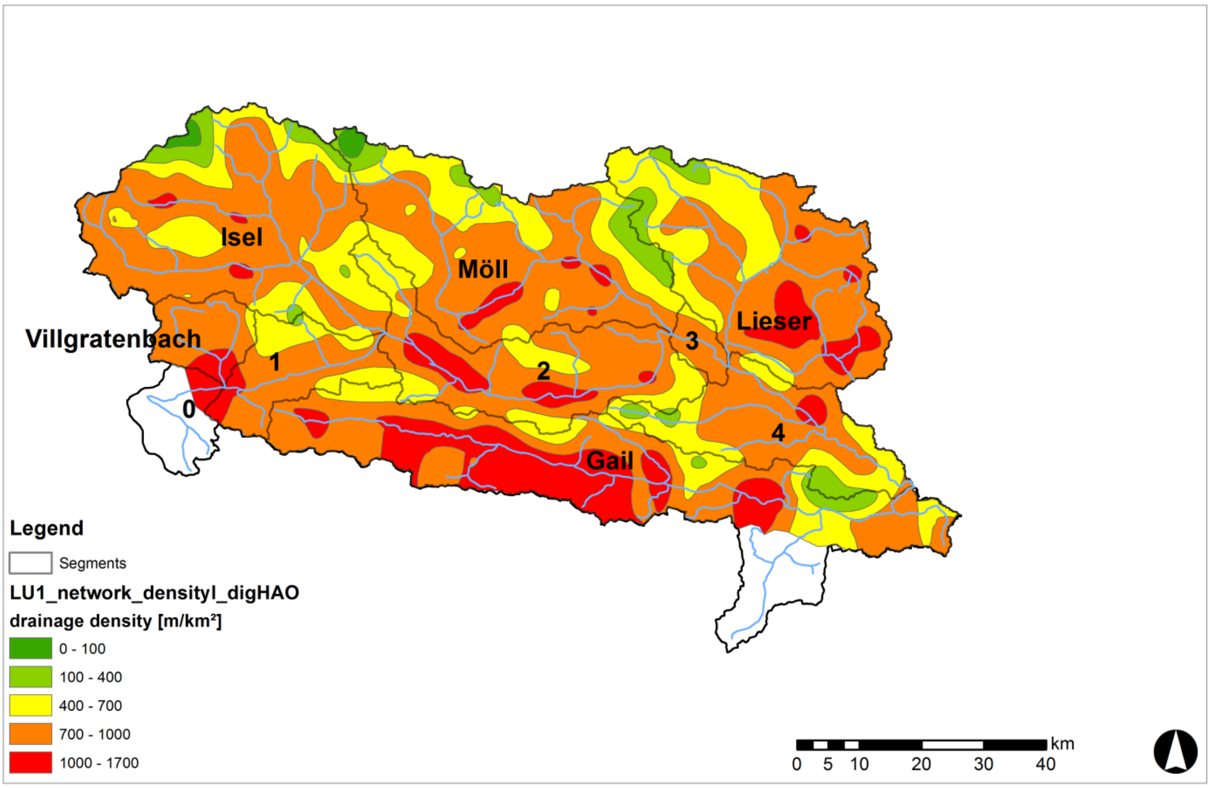


Figure 4.8 Overlay of segments (landscape unit 1) with drainage density.

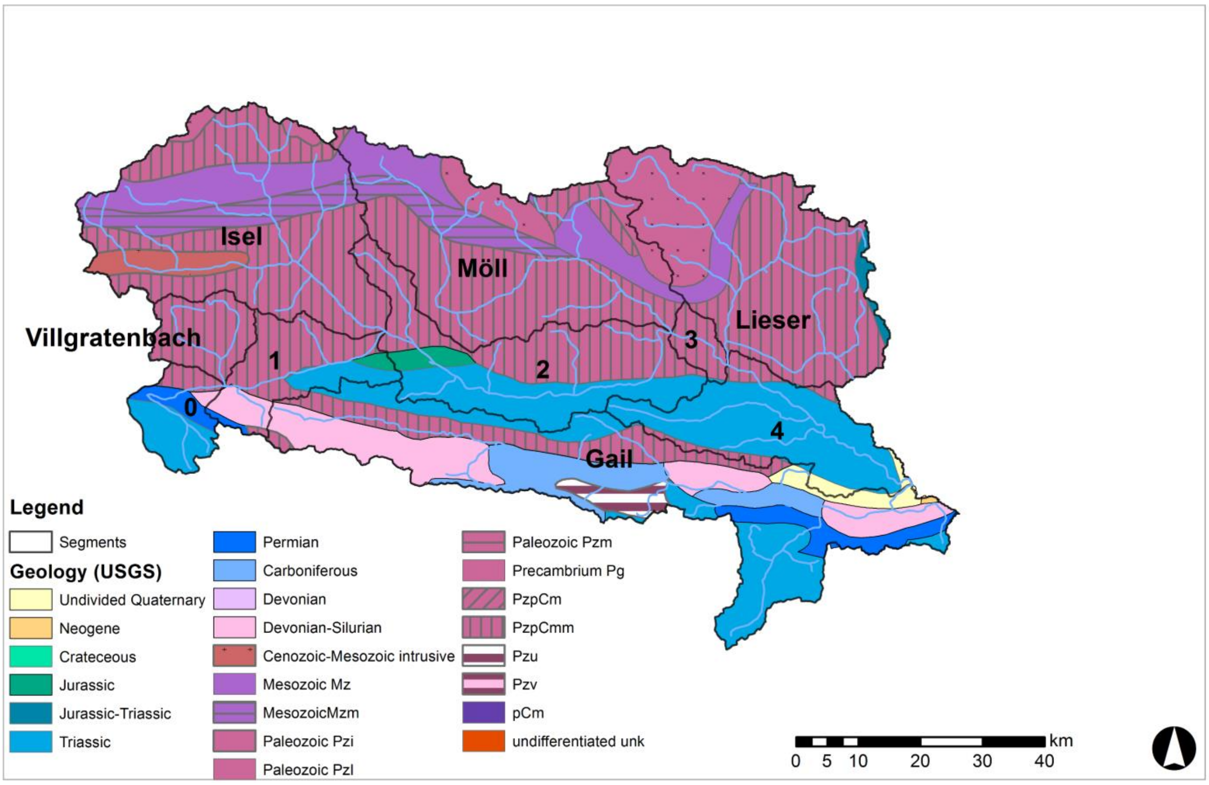


Figure 4.9 Overlay of segments (landscape unit 1) with geology.

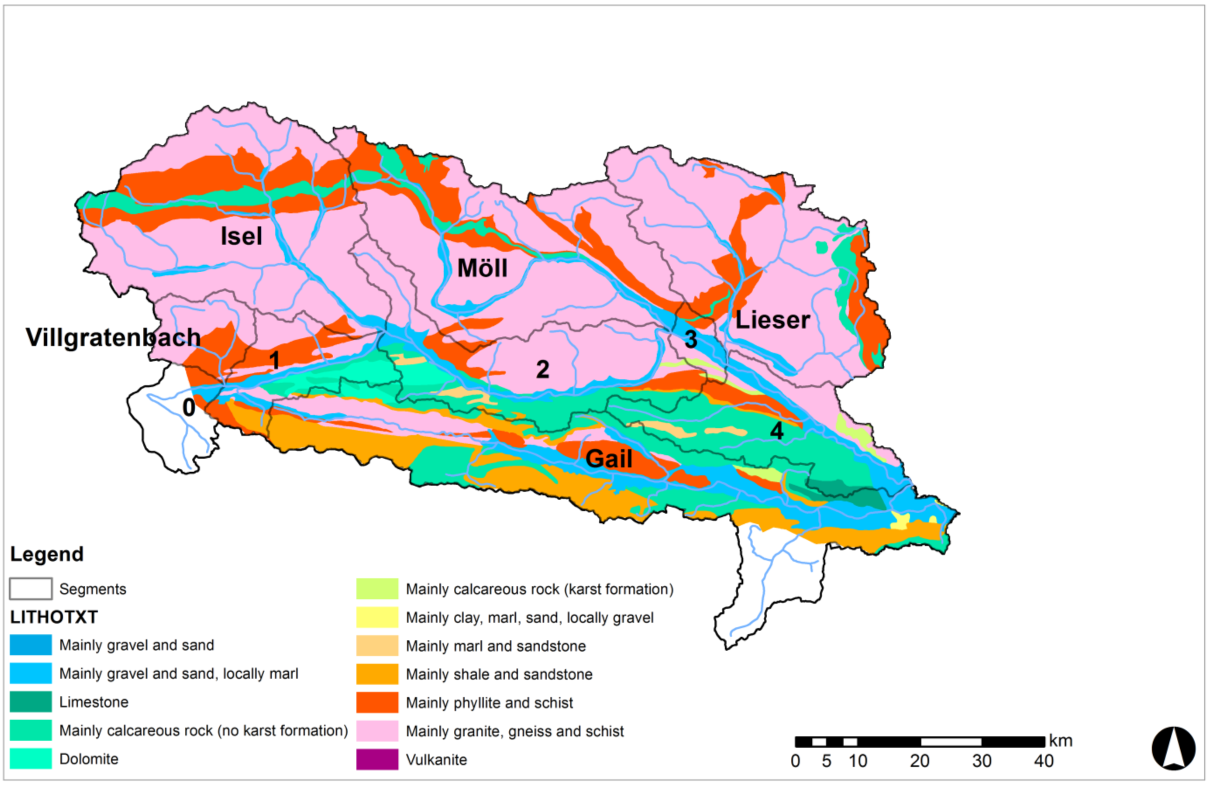


Figure 4.10 Overlay of segments (landscape unit 1) with hydrogeology.

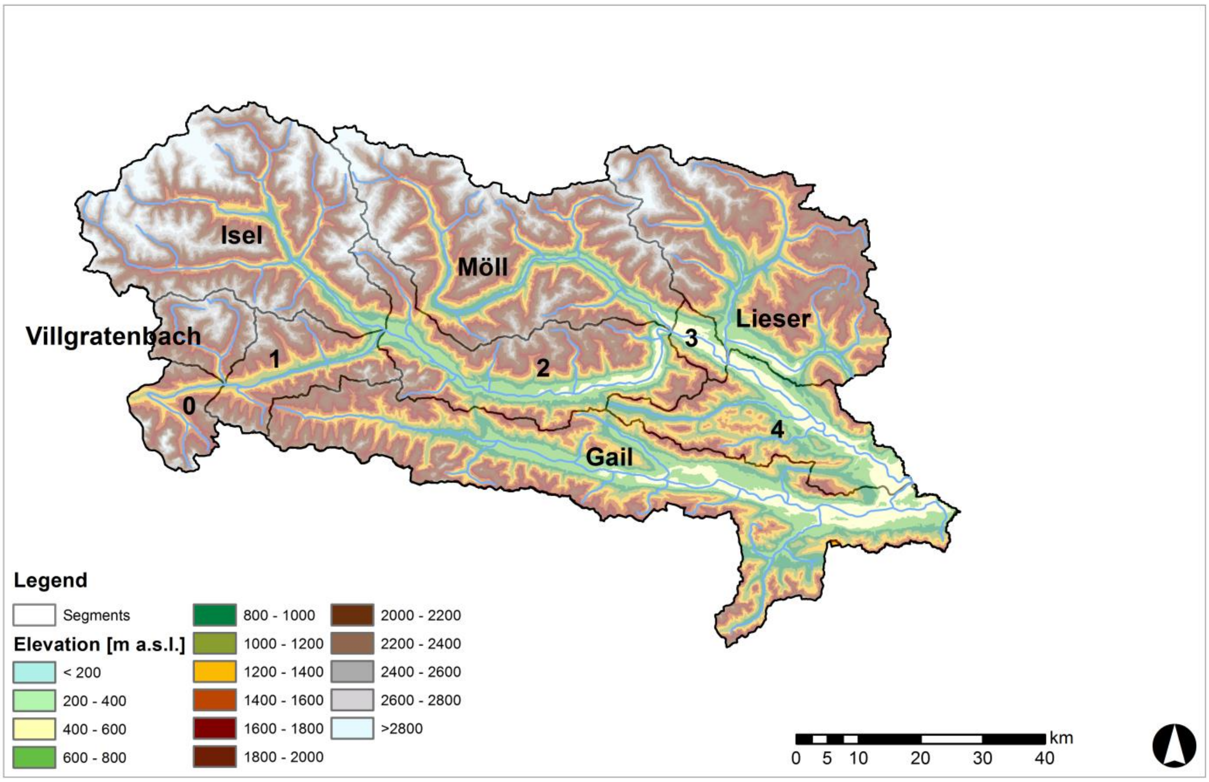


Figure 4.11 Overlay of segments (landscape unit 1) with elevation.

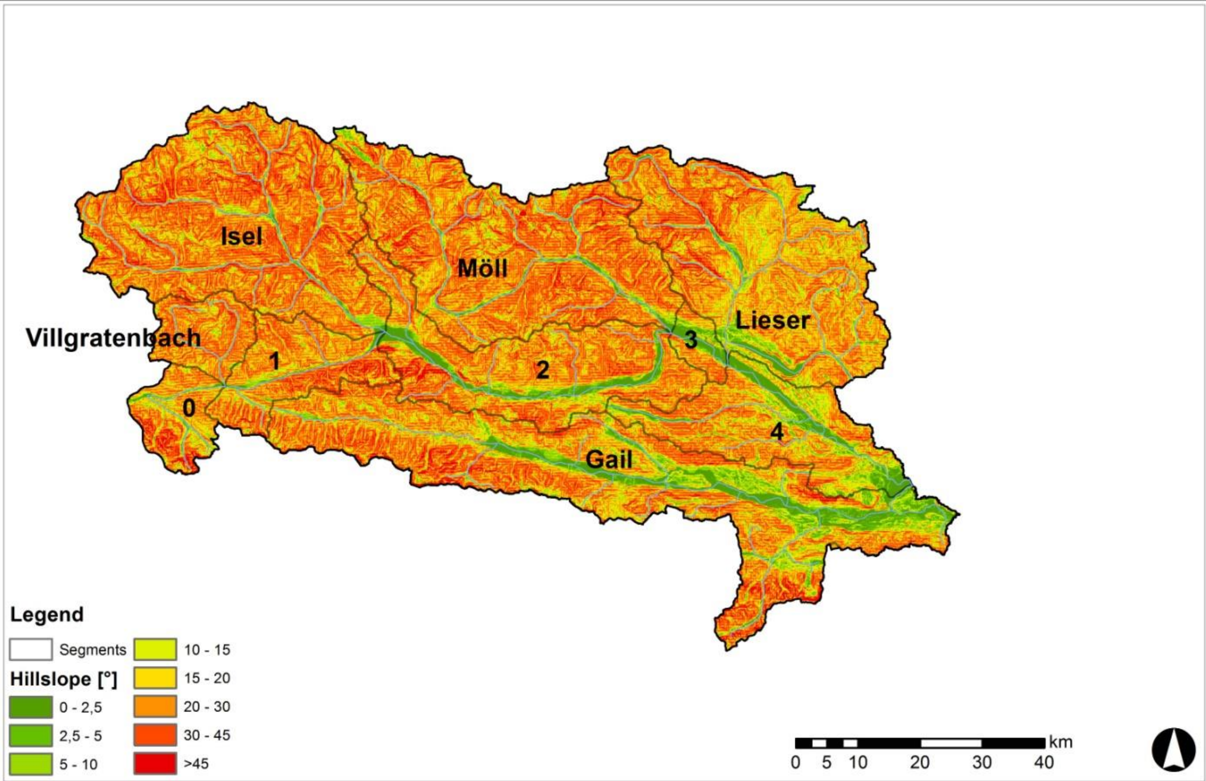


Figure 4.12 Overlay of segments (landscape unit 1) with hillslope.

The mean annual precipitation for landscape unit one is about 1320 mm. The spatial distribution of mean annual precipitation, based on sub-catchments (Figure 4.13), is highly variable and values range from 700 mm up to 2500 mm. The catchment of the Gail River, compared to the rest of the Drau catchment, exhibits a higher mean annual precipitation (about 1570 mm). Heavy precipitation for 15 min at a 2-years return period increases in an easterly and downstream direction (Figure 4.14), with intensities of 12,5 to 15 mm per 15 minutes in the upstream parts of the catchment, and up to 25 mm per 15 minutes in the downstream parts.

The mean annual evapotranspiration for landscape unit one (Figure 4.15) ranges from 100-200 mm at the highest altitudes and up to 600-625 mm in the downstream parts of the Drau valley.

Similar to the mean annual precipitation, high spatial variability can be seen in the mean annual discharge values for sub-catchments (Figure 4.16). The mean for the entire investigated catchment area is about 910 mm, but the mean for the Gail catchment is again significantly higher: about 1070 mm, compared to the 870 mm of the residual area. As additional information to the formation of discharge, the land cover and runoff-coefficients are shown in Figures 4.17 and 4.18, respectively.

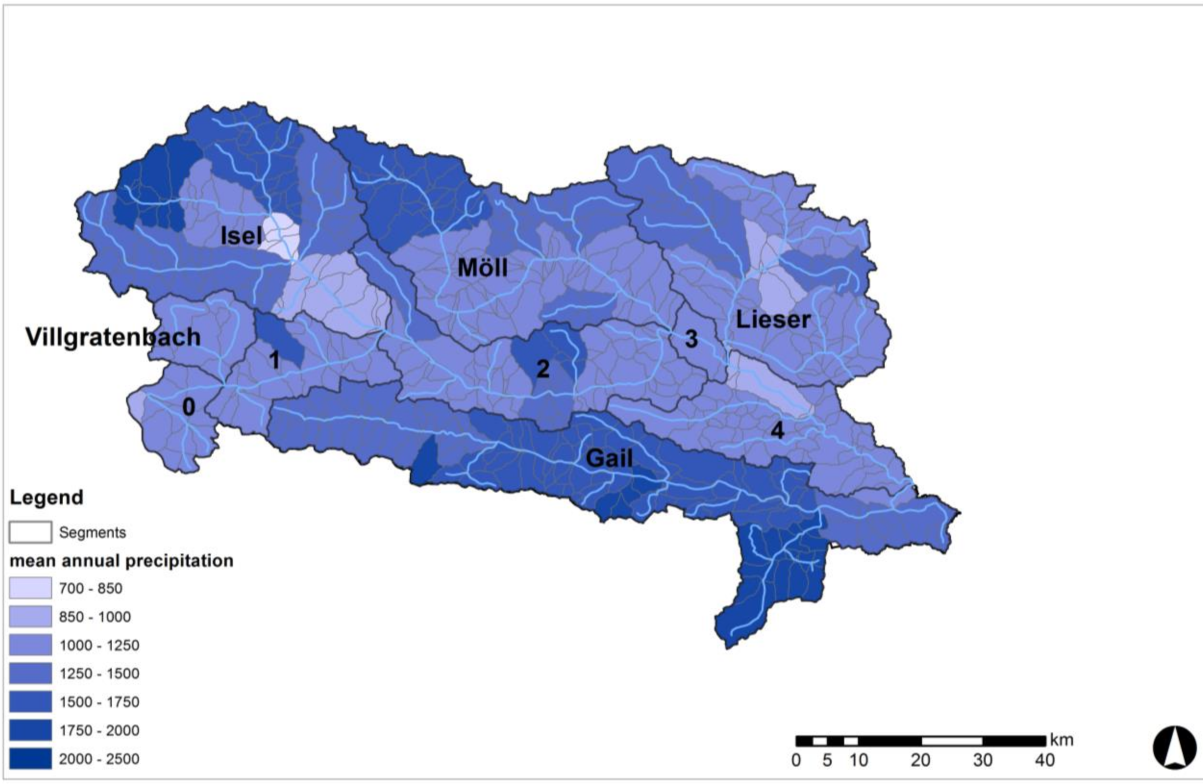


Figure 4.13 Overlay of segments (landscape unit 1) with mean annual precipitation.

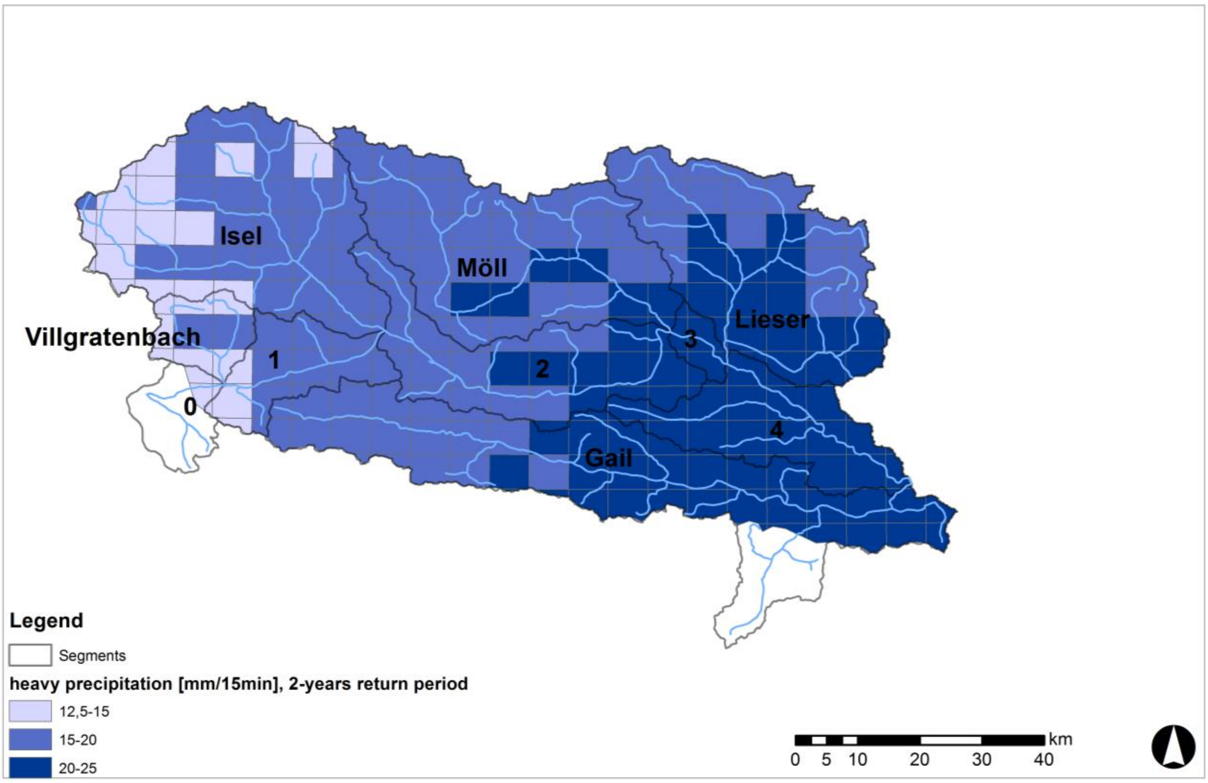


Figure 4.14 Overlay of segments (landscape unit 1) with heavy precipitation.

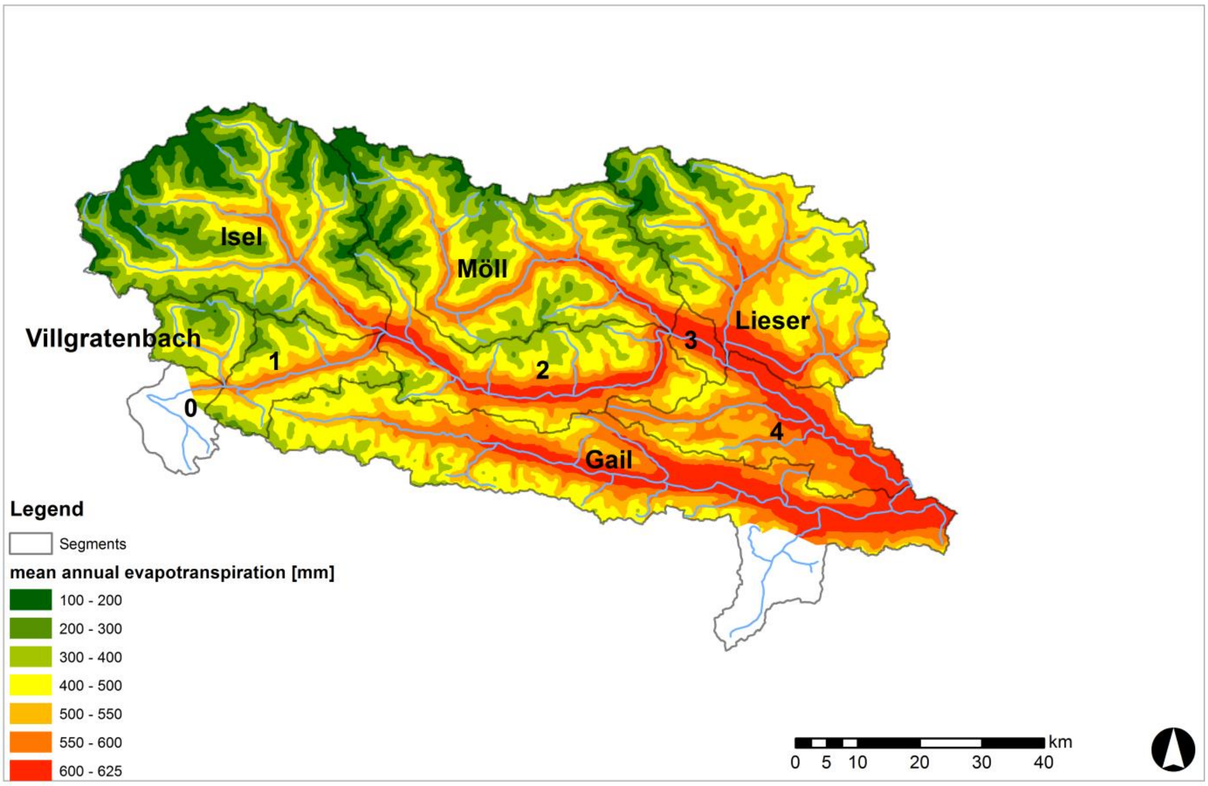


Figure 4.15 Overlay of segments (landscape unit 1) with mean annual evapotranspiration.

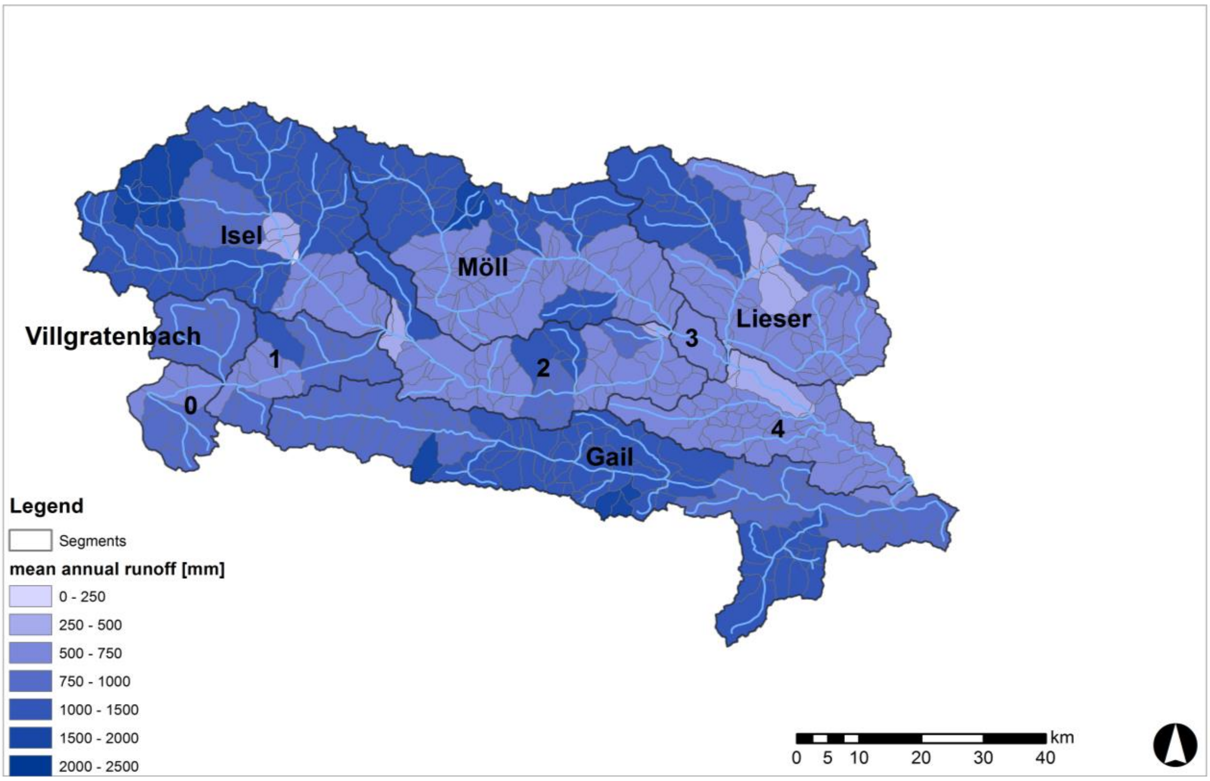


Figure 4.16 Overlay of segments (landscape unit 1) with mean annual runoff.

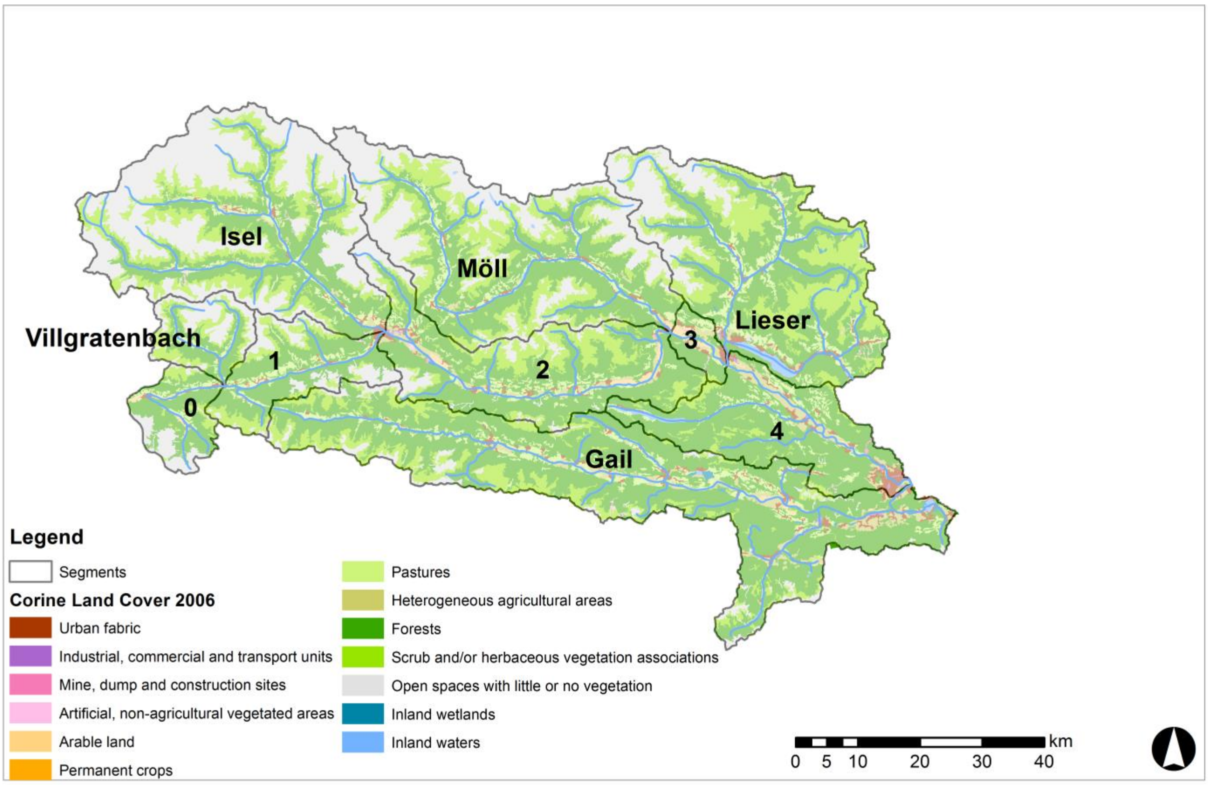


Figure 4.17 Overlay of segments (landscape unit 1) with land cover.

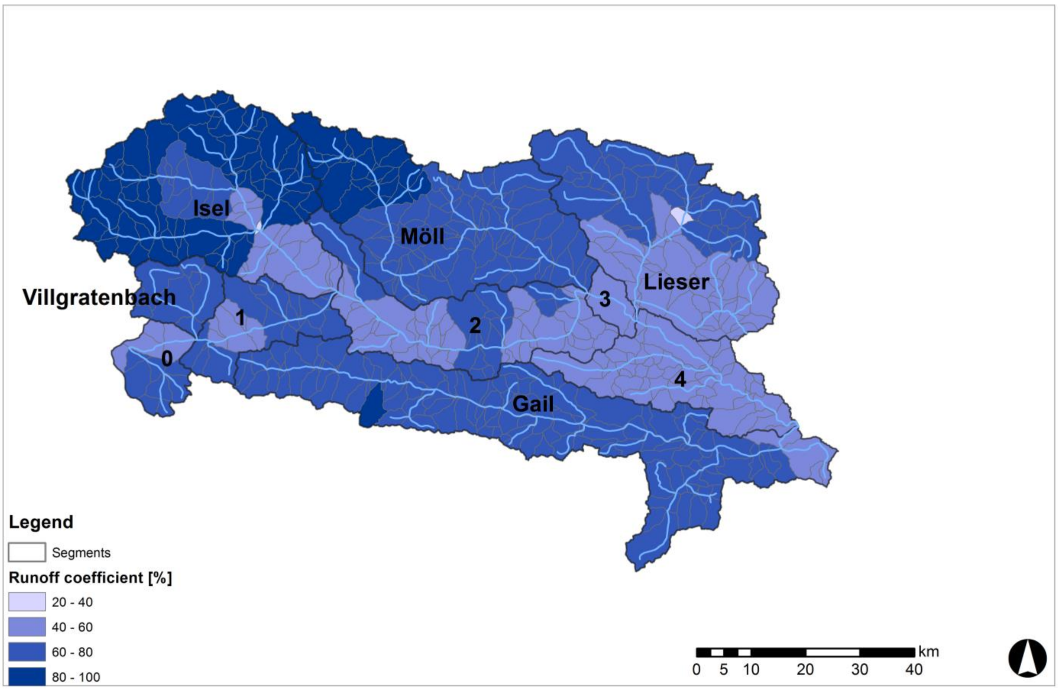


Figure 4.18 Overlay of segments (landscape unit 1) with runoff coefficient.

Further information concerning the hydrogeological properties of landscape unit one is presented in Figures 4.19, 4.20 and 4.21 and soil types are presented in Figure 4.22. For a large proportion of the catchment area, soil erodibility is moderate (Figure 4.23). However, the soil erosion rates (Figure 4.24) are mainly negligible (0-0,5 $t.ha^{-1}.yr^{-1}$).

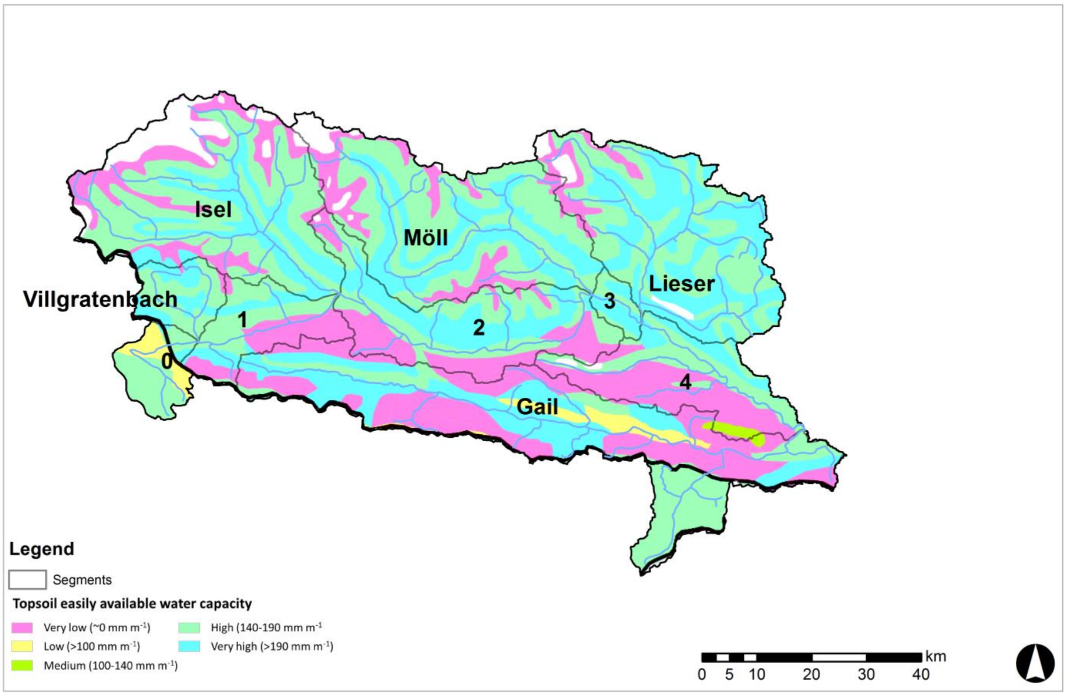


Figure 4.19 Overlay of segments (landscape unit 1) with easily available water capacity of the topsoil.

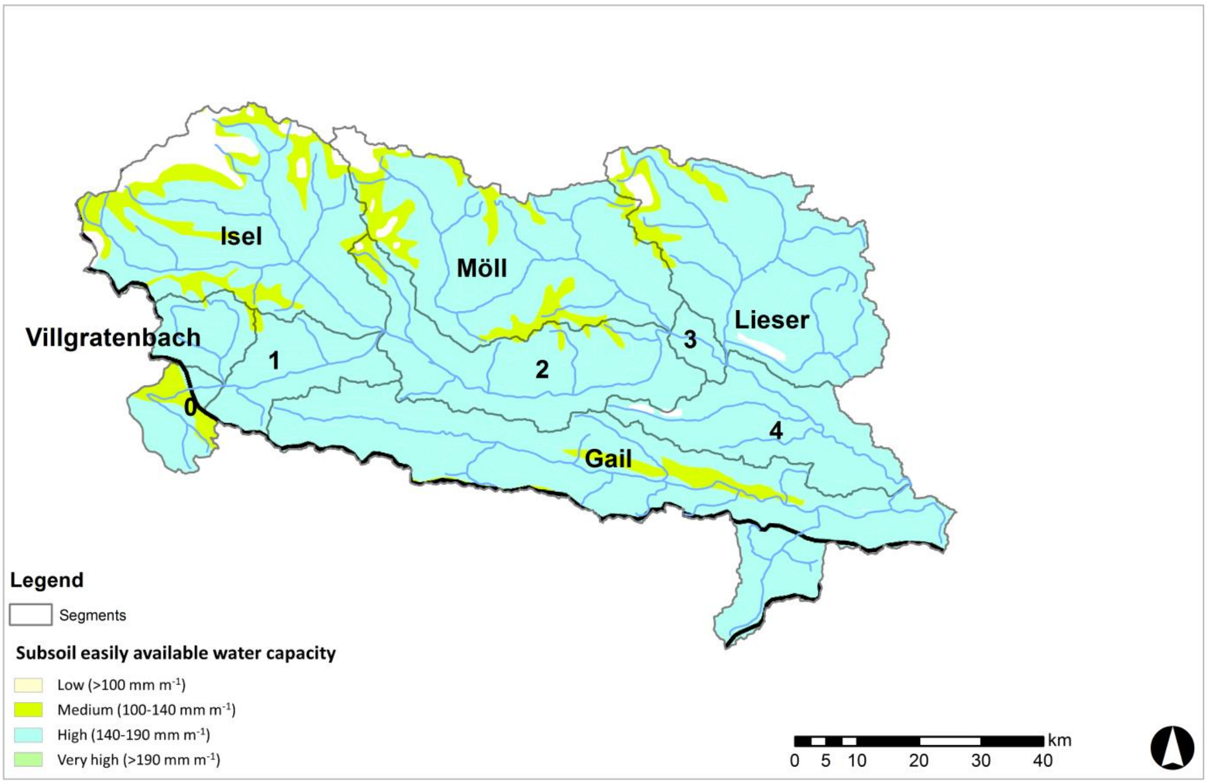


Figure 4.20 Overlay of segments (landscape unit 1) with easily available water capacity of the subsoil.

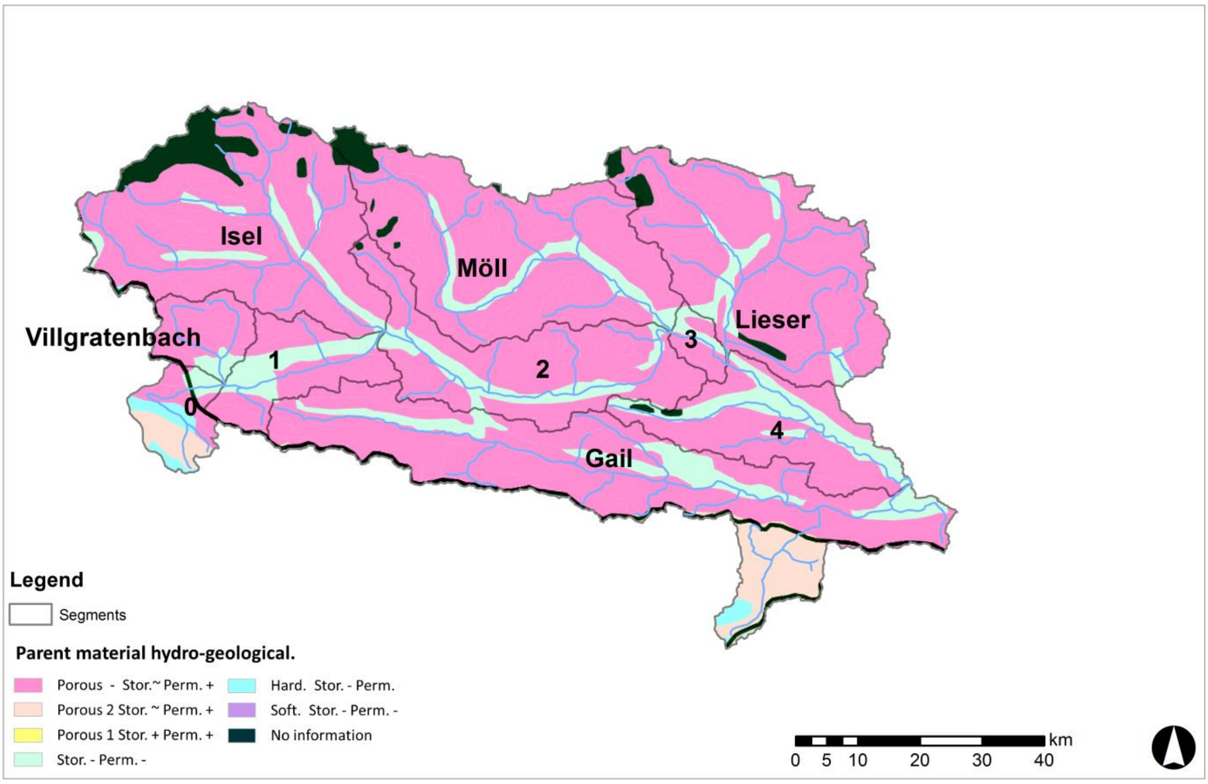


Figure 4.21 Overlay of segments (landscape unit 1) with porosity of the parent material.

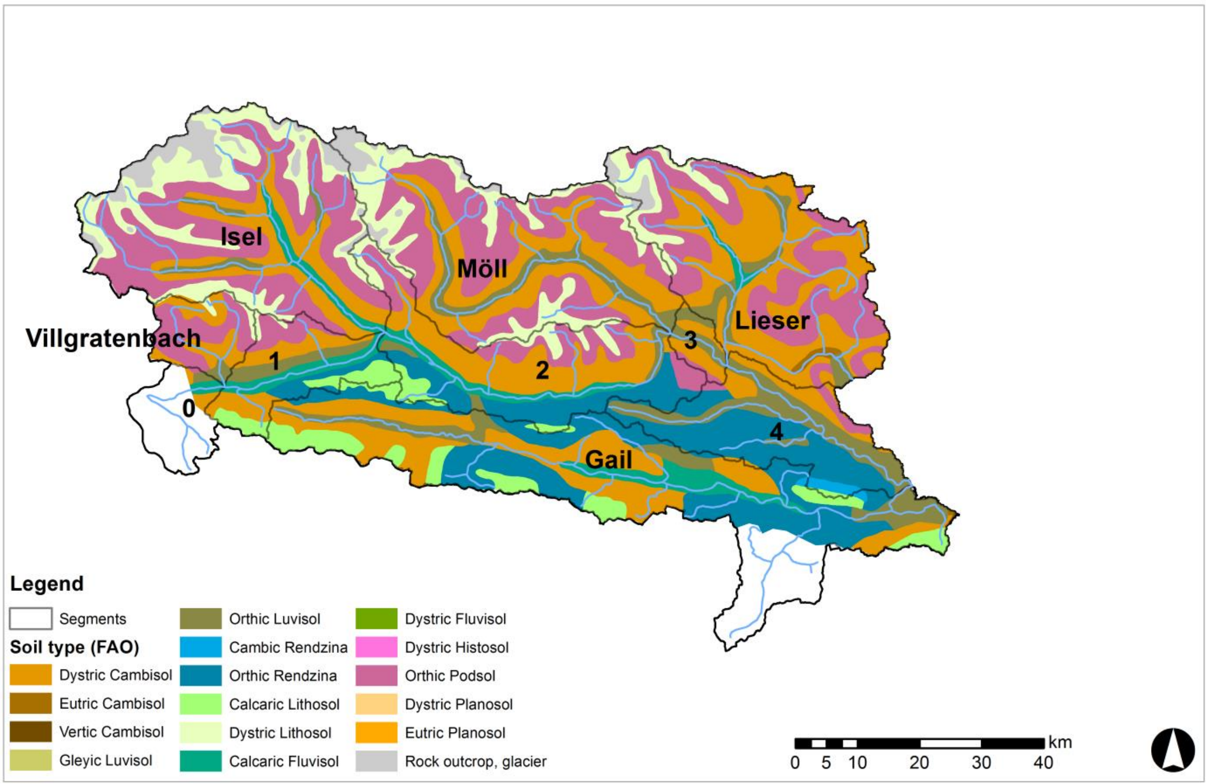


Figure 4.22 Overlay of segments (landscape unit 1) with soil types.

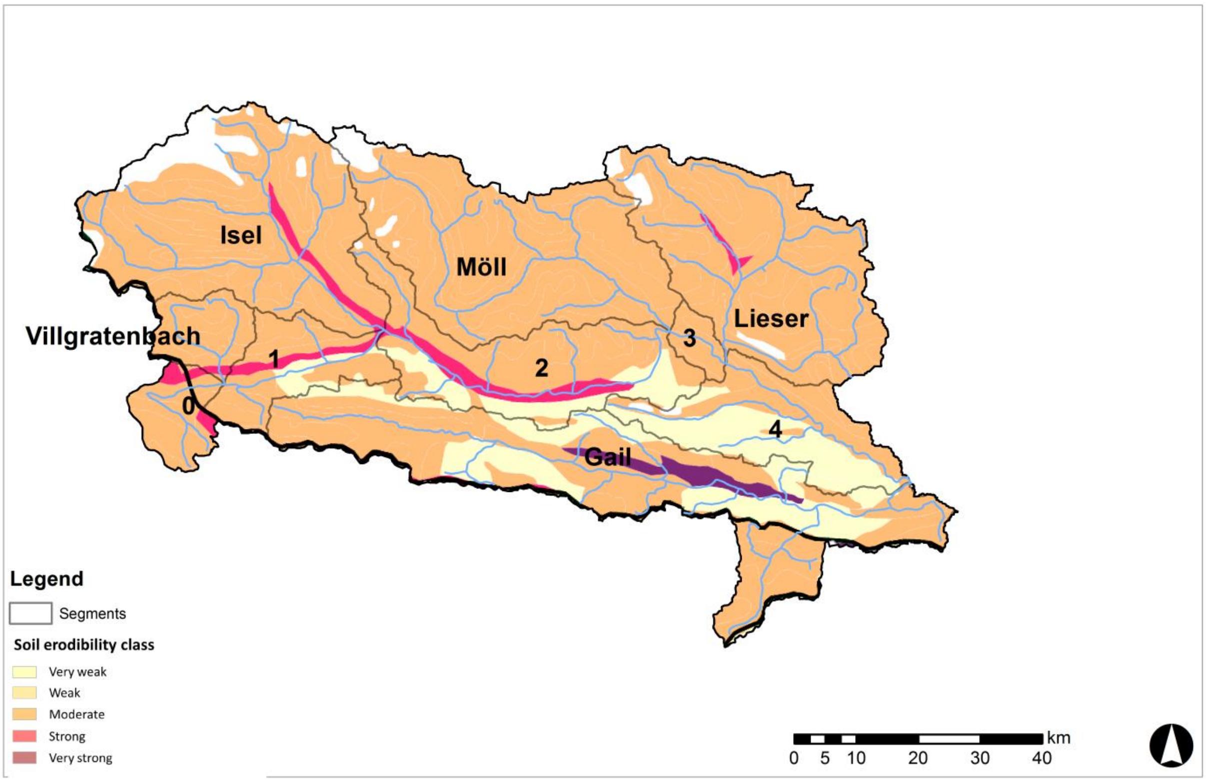


Figure 4.23 Overlay of segments (landscape unit 1) with soil erodibility.

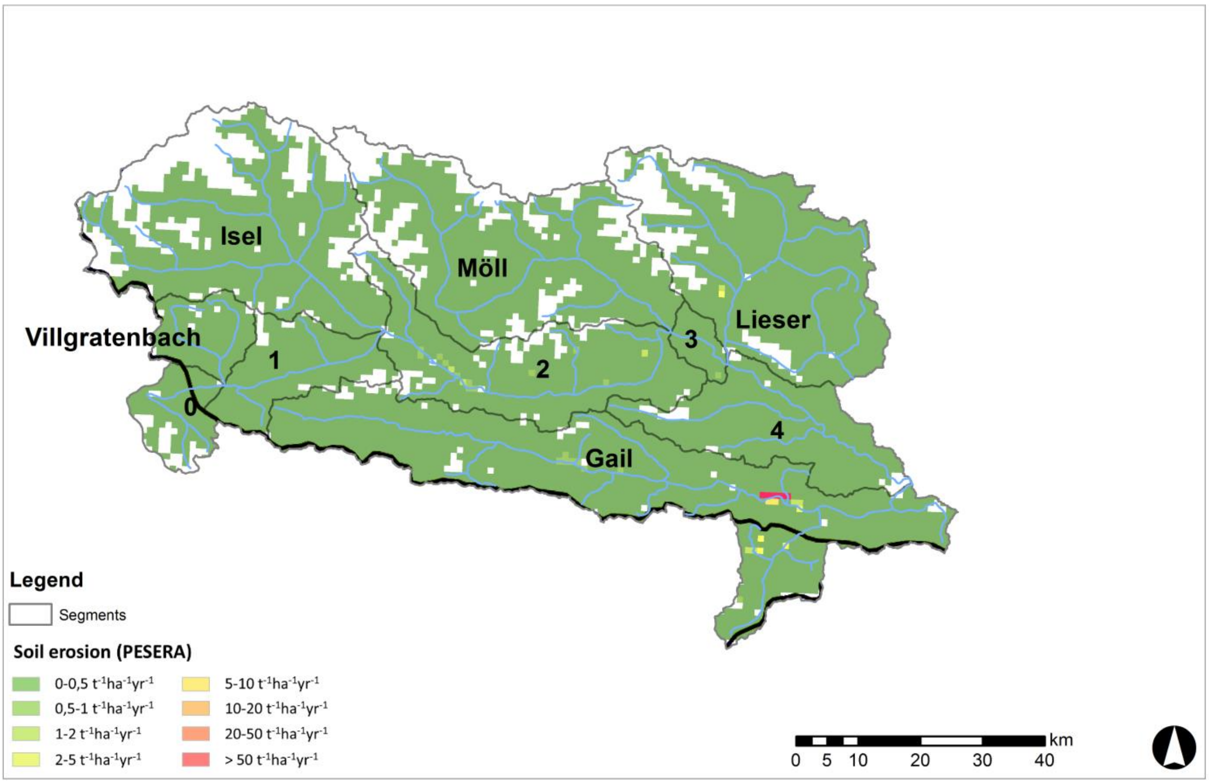


Figure 4.24 Overlay of segments (landscape unit 1) with soil erosion rates.

The potential riparian vegetation types for the upper Drau catchment are presented in Figure 4.25. At the Drau River, two riparian vegetation types are (potentially) present, the grey alder riparian forest (between the source and Amlach) and the grey alder – white willow riparian forest (rest of landscape unit one), respectively.

In Figure 4.26, the gradient of the Drau River and of its larger tributaries are illustrated. In the upstream parts of the rivers, high gradients (>20‰) are present. However, the main part of the Upper Drau River exhibits gradients below 5‰.

To gain an impression of the catchment concerning transverse structures and other physical pressures like reservoirs, residual water stretches and hydro-peaking, overviews are given in Figures 4.27 and 4.28.

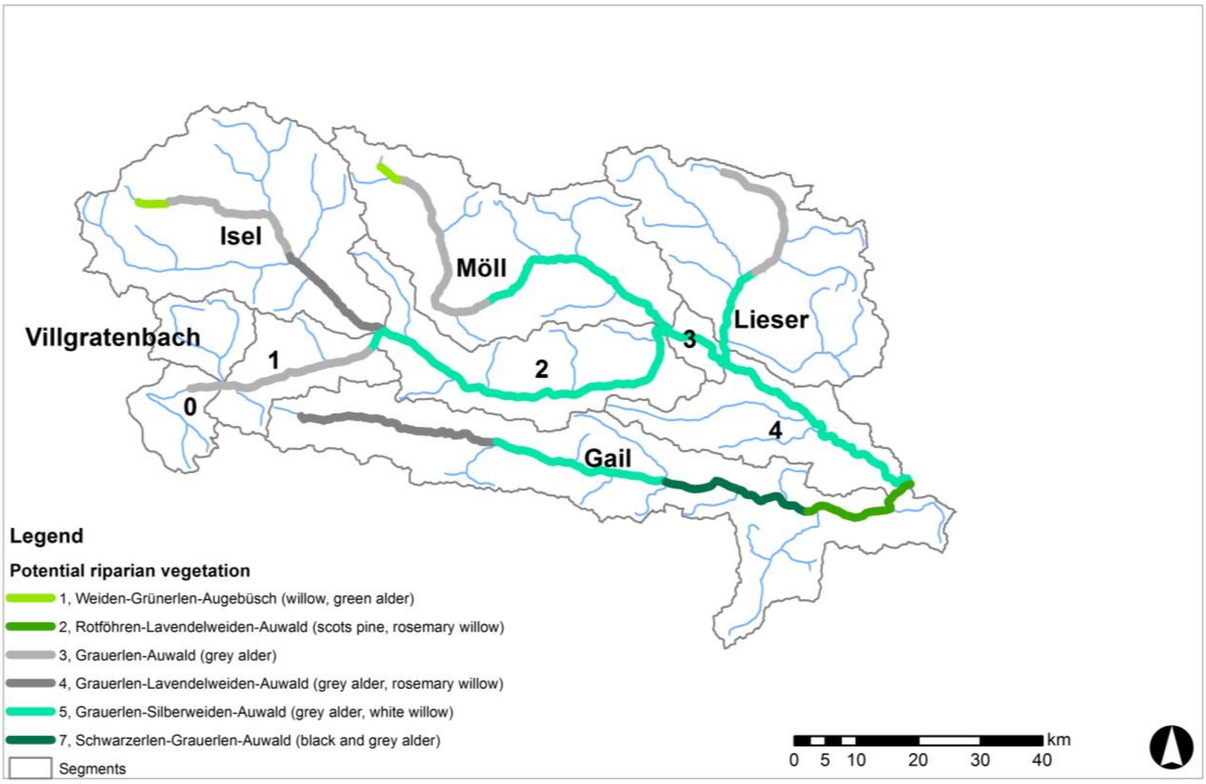


Figure 4.25 Overlay of segments (landscape unit 1) with potential riparian vegetation.

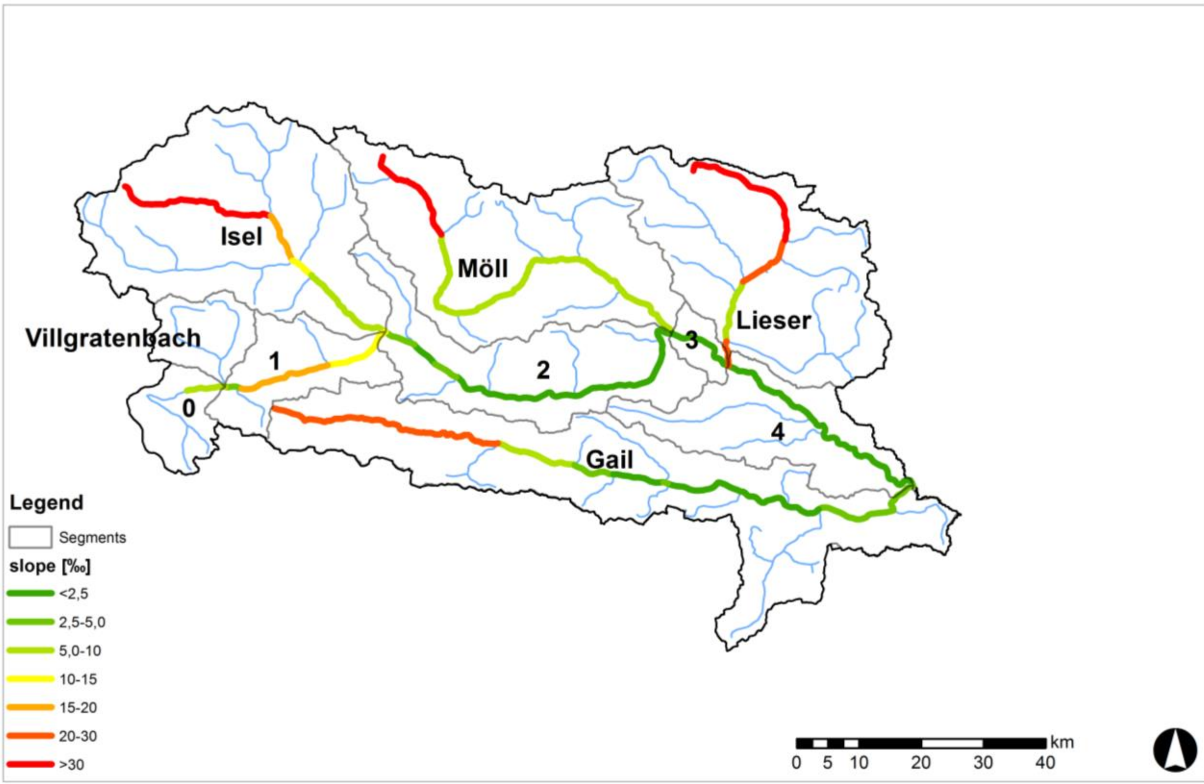


Figure 4.26 Overlay of segments (landscape unit 1) with river gradient.

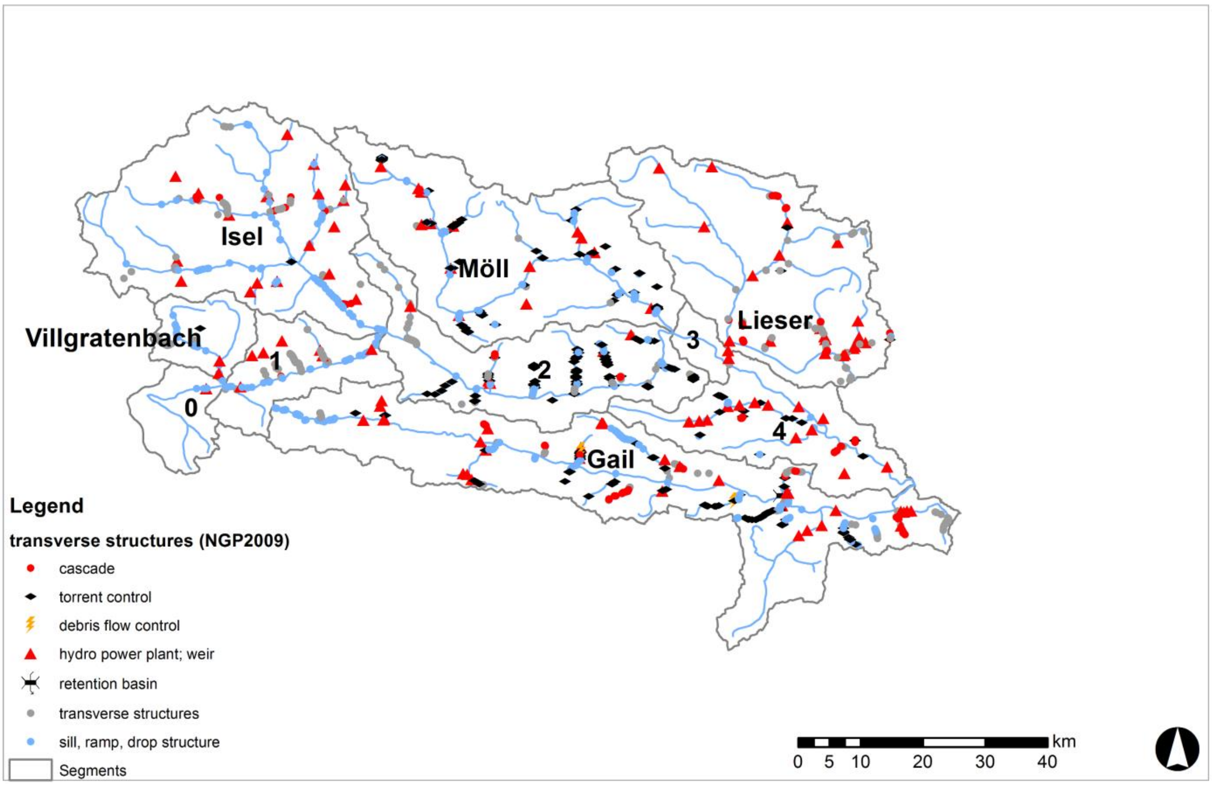


Figure 4.27 Overlay of segments (landscape unit 1) with transverse structures.

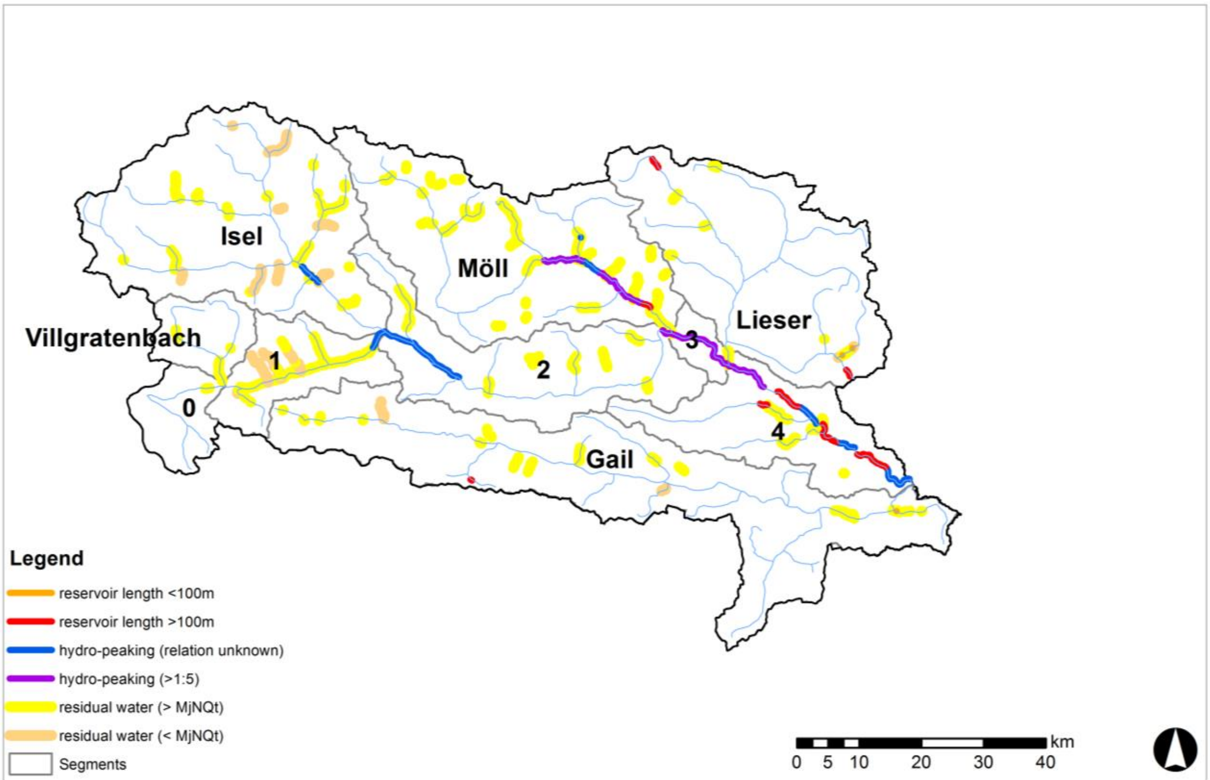


Figure 4.28 Overlay of segments (landscape unit 1) with physical pressures.

4.3 Segment

In landscape unit one nine segments were delineated. Five of them represent the main tributaries of the Upper Drau River: Villgratenbach, Isel, Möll, Lieser and Gail. In Tables 4.1 to 4.3 all segments are characterized.

Table 4.1 Characteristics of the 9 segments of the Upper Drau River – elevation, river gradient, geology and land cover (I).

Segment	Area [km²]	Elevation [m a.s.l.]			River gradient [‰]	Geology (>10%)	Land cover 2006 (>10%)
		mean	min	max			
0	176,33	1791,6	1073	3074	5-10	54,86% Triassic 22,85% Permian 18,32% Palaeozoic-Precambrian metamorphic rocks	56,12% Coniferous forest 15,46% Bare rocks
Villgraten-bach	176,82	2099,3	1076	2919	-	100% Palaeozoic-Precambrian metamorphic rocks	31,86% Coniferous forest 26,15% Mixed forest 25,44% Sparsely vegetated areas
1	306,60	1719,7	666	2863	Till Gailbach 2,5-5 Till Isel 10-20	60,90% Palaeozoic-Precambrian metamorphic rocks 17,90% Triassic 14,86% Devonian – Silurian	50,07% Coniferous forest 16,55% Natural grassland 12,82% Sparsely vegetated areas
Isel	1206,44	2138,9	668	3736	Till Tauern-bach >30 Till Michl-bach 10-20 Till Drau 5-10	58,50% Palaeozoic-Precambrian metamorphic rocks 17,97% Undivided Mesozoic 13,44% Mesozoic metamorphic rocks	26,12% Mixed forest 13,48% Bare rocks 22,34% Moors and heathland
2	690,43	1432,9	549	3146	Mainly <2,5	56,04% Palaeozoic-Precambrian metamorphic rocks 38,46% Triassic	39,03% Coniferous forest 17,05% Natural grassland 14,16% Mixed forest
Möll	1106,02	1905,8	551	3654	Till Zirknitz >30 Till Drau 5-10	56,92% Palaeozoic-Precambrian metamorphic rocks 18,35% Undivided Mesozoic 12,77% Palaeozoic intrusive rocks 11,93% Mesozoic intrusive rocks	31,39% Coniferous forest 20,79% Natural grassland 14,84% Sparsely vegetated areas 13,30% Bare rocks

Table 4.2 Characteristics of the 9 segments of the Upper Drau River – elevation, river gradient, geology and land cover (II).

Segment	Area [km²]	Elevation [m a.s.l.]			River gradient [‰]	Geology (>10%)	Land cover 2006 (>10%)
		mean	min	max			
3	70,66	894,6	531	2130	<2,5	100% Palaeozoic-Precambrian metamorphic rocks	40,71% Coniferous forest 14,61% Complex cultivation patterns 10,94% Pastures 10,25% Mixed forest
Lieser	1031,83	1652,7	537	3328	Till Malta >20 Till Seebach 5-10 Till Drau 20-30	63,89% Palaeozoic-Precambrian metamorphic rocks 27,24% Palaeozoic intrusive rocks	35,21% Coniferous forest 20,42% Natural grassland
4	504,32	1030,7	479	2200	<2,5	83,09% Triassic 12,47% Palaeozoic-Precambrian metamorphic rocks	40,06% Coniferous forest 29,10% Mixed forest
Gail	1405,37	1224,2	485	2681	Till Valentin-bach >30Till Kirch-bach 5-10 Till Drau mainly <2,5 -	26,19% Triassic 25,29% Devonian-Silurian 17,58% Palaeozoic-Precambrian metamorphic rocks 15,47% Carboniferous	31,60% Coniferous forest 29,81% Broad-leaved forest - -

Segments zero and four are mainly composed of calcareous rock, whereas segments one, two and three are dominated by metamorphic, siliceous rocks. In all segments of the Upper Drau River (segments 0-4), coniferous forest has the highest share of the land cover (from 39-56%). However, the composition of the remaining land cover classes. In segment zero bare rock (about 16%), is a major category, whereas natural grassland is important in segment one and two (both 17%). Complex cultivation patterns (15%) are characteristic of segment 3 and in segment four mixed forest cover is quite extensive (30%).

All segments are impacted by physical pressures such as transverse structures and hydropower plants. However, most of the structures are located on tributaries. On the Drau River, a residual water stretch is located in segment one, and segment two is highly impacted by hydro-peaking. In segment four the hydropower chain of the Drau starts. Only in segment 2 are there no transverse structures, such as hydropower plants or torrent controls, located directly at the Drau River, and, furthermore, only the most upstream and the most downstream sections of this segment are impacted by hydro-peaking.

As reported previously, soil erosion rates are low for all segments and the meteorological and hydrological parameters vary greatly across space and time.

Table 4.3 Characteristics of the 9 segments of the Upper Drau River – hydrological characteristics, soil erosion rates and physical pressures.

Drau segment / Tributary	Mean annual prec. [mm]	Mean annual potential evapotrans. [mm]	Mean annual discharge [mm]	Mean soil erosion [$tha^{-1}yr^{-1}$]	Physical pressures – hydropower		
					Hydro-peaking	Residual water	Reservoirs-length > 100m
0	1093	437	702	< 0,5	No	Scattered (>MjNQt)	No
Villgratenbach	1186	369	887	< 0,5	No	Scattered (>MjNQt)	No
1	1202	450	813	< 0,5	At the downstream ent of the segment	Almost entiere stretch (at some tributaries <MjNQt)	No
Isel	1332	348	1066	< 0,5	Downstream of Kineburg	Scattered (>MjNQt and <MjNQt)	No
2	1266	497	807	Mainly < 0,5 Isolated spots with up 5	Downstream of Lienz and downstream of Sachsenburg	Scattered, but only at tributaries (>MjNQt)	No
Möll	1291	403	962	< 0,5	Downstream of Flattach	Scattered	Upstream of Mühldorf
3	1045	580	508	Mainly < 0,5 Isolated spots with up 2	Entire stretch (ratio >1:5)	No	No
Lieser	1194	460	776	Mainly < 0,5 Isolated spots with up 10	No	Scattered (at some tributaries <MjNQt)	Two, in the upstream parts of the catchment
4	1174	568	622	< 0,5	Almost entierely influenced	Scatterd – mainly at tributaries	Hydropower plant chain starts at Paternion
Gail	1569	534	1069	Mainly < 0,5 Isolated spots with up 50	No	Scattered, mainly at tributaries	one, at a tributary

In Figure 4.29 the location of the gauging stations is given and temporal variation / changes in precipitation and discharge are shown in Figures 4.30 to 4.32. In most of the sub-catchments decreasing trends in precipitation and discharge were observed over the period 1951-2000. Additional information for several gauging stations is given in Tables 4.4 and 4.5.

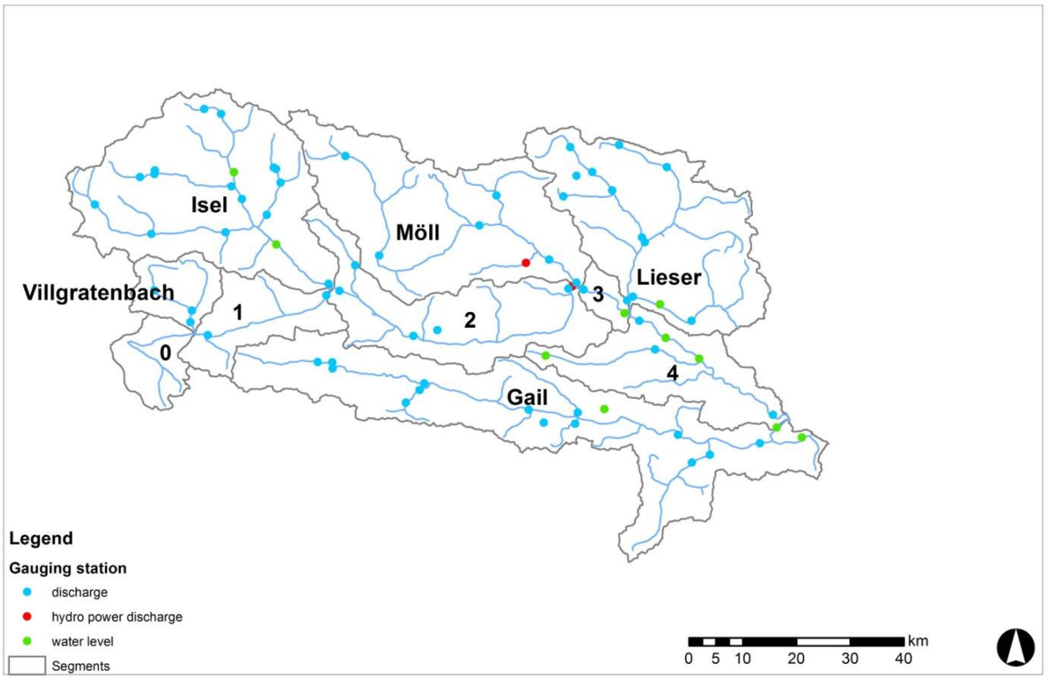


Figure 4.29 Overview of gauging stations located in the Upper Drau catchment.

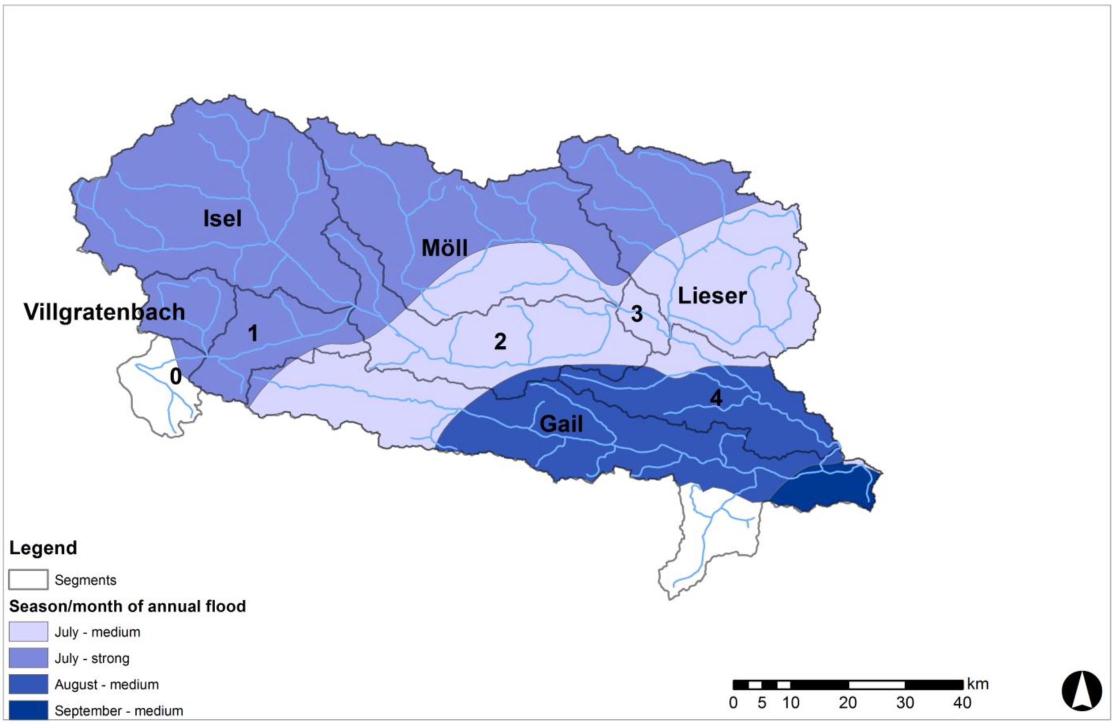


Figure 4.30 Overlay of segments (landscape unit 1) with the season/month of annual flood.

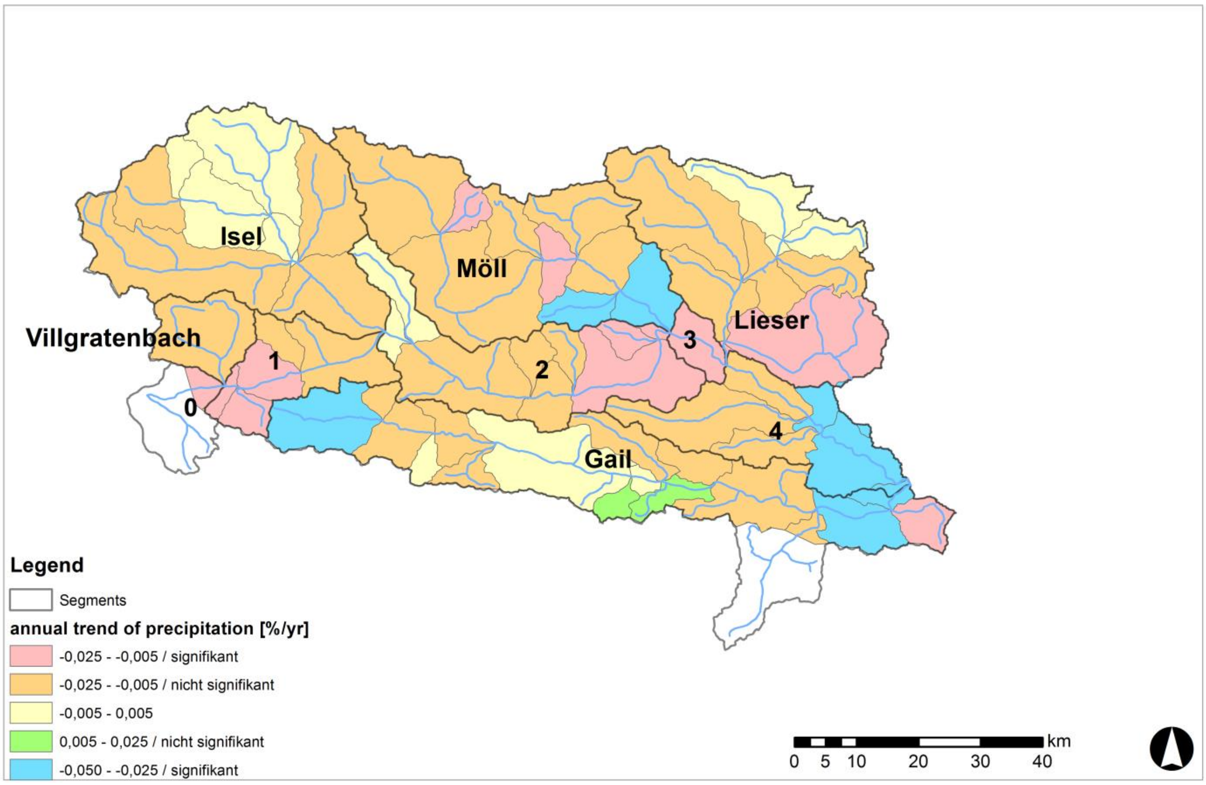


Figure 4.31 Overlay of segments (landscape unit 1) with annual trends in precipitation.

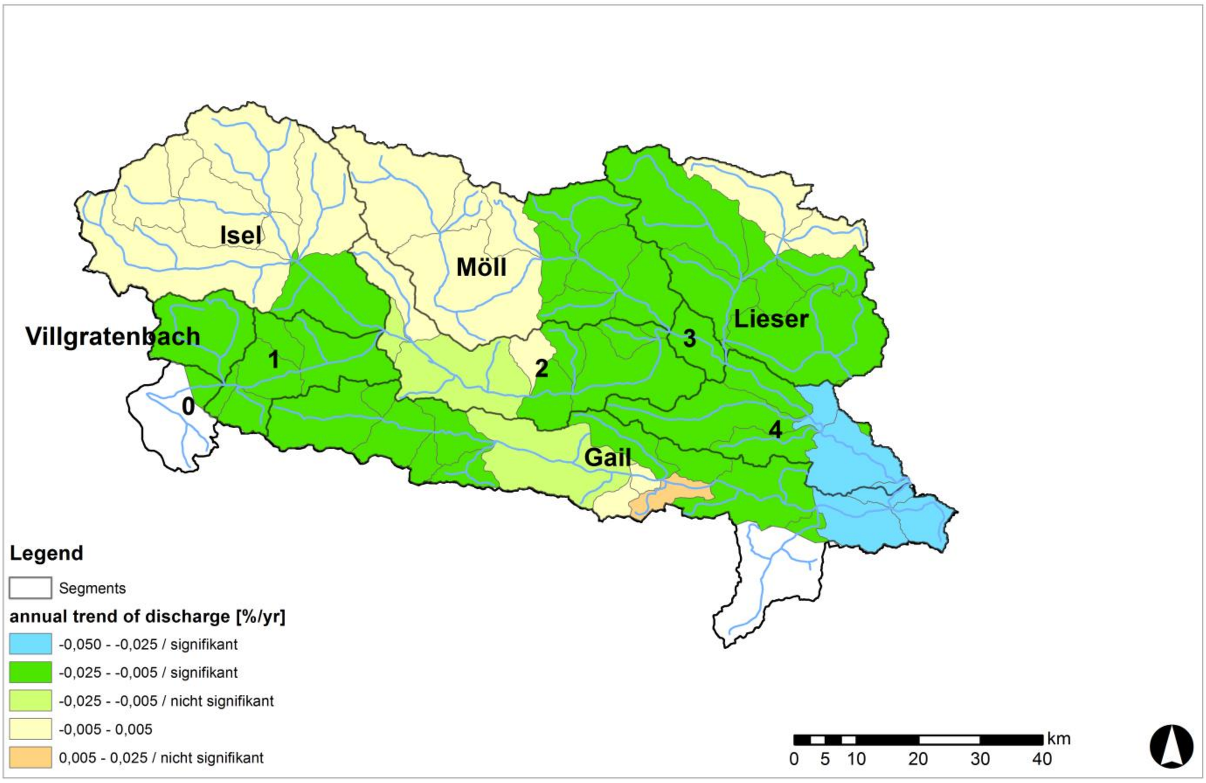


Figure 4.32 Overlay of segments (landscape unit 1) with annual trends of discharge.

The hydrological regime of the Drau River is mainly influenced by glacier- and snowmelt. During winter, precipitation is stored in the form of snow and ice. Thus, low flow periods occur during the winter, whereas the mean maximum discharges take place during the summer months when snow and ice starts to melt.

With increasing distance from the glaciers, the area under glaciers in the entire catchment area decreases. This is also represented in the hydrological regime of the Drau. The Isel River, with several glaciers in its drainage area, exhibits a nivo-glacial regime, but after its confluence with the Drau the glacial impact decreases and a nival regime is reached. In Figures 4.33 and 4.34 the mean monthly discharges for several gauging stations within the Drau catchment are presented.

Table 4.4 Hydrological parameters for several gauging stations along the Drau River and some tributaries (I). * from Hdrographical year book 2010 (1999-2010)

Drau segment / Tributary	Gauging station	Drainage area [km²]	Season / month of annual flood	Characteristic discharge* [m^3s^{-1}]					
				MjNQt	NQ	MQ	MJHQ	HQ1	HQ100
0	Ambach	162,1	July	1,48	0,73	3,38	15,8	-	-
Villgratenbach	Eggeberg	35,2	July	0,25	0,19	0,99	6,28	-	-
1	Lienz-Falkensteinsteg	668,0	July	4,51	0,69	13,4	77,8	-	-
Isel	Waier	285,3	July	1,48	0,93	10,6	93,0	-	-
	Lienz	1198,7		6,11	3,00	38,9	282	-	-
2	Lienz-Peggetz	1876,2	July	11,4	5,13	53,3	327	-	-
	Oberdrauburg	2112,0		14,5	8,47	62,6	371	300	950
	Sachsenburg (Brücke)	2561,4		20,0	13,2	72,6	378	320	1050
Möll	Flattach	705,3	July	4,45	0,32	18,1	116	90	450
3	Drauhofen	3674,4	July	26,7	3,36	107	592	540	1400
Lieser	Spittal	1035,5	July	5,91	1,99	21,7	177	125	500
4	Amlach	4789,6	July	34,8	19,8	128	670	620	1650
Gail	Maria Luggau (Moos)	146,1	July	1,18	0,44	4,28	41,8	21	270
	Federaun	1304,9	August-September	14,5	5,80	44,5	414	325	900

Table 4.5 Hydrological regime of the Upper Drau River and some tributaries.

Drau segment / Tributary	Gauging station	Hydrological regime (Mader et al., 1996)	Description
Isel	Waier	NIG 7, very strong	Nivo glacial regime, low flow period in Winter, maximum discharge in July>June>August>September Precipitation is stored in form of snow and ice (Glacial influence).
	Lienz	NIG 6, very strong	Nivo glacial regime, low flow period in Winter, maximum discharge in June>July>Aug>Mai
2	Oberdrauburg	NIV 6, strong	Nival regime, low flow period in Winter, maximum discharge in June>July>Mai>Aug Precipitation is stored in form of snow.
	Sachsenburg (Brücke)	NIV 6, strong	Nival regime, low flow period in Winter, maximum discharge in June>July>Mai>Aug
Möll	Flattach	NIV 6, distinct	Nival regime, low flow period in Winter, maximum discharge in June>July>Mai>Aug
3	Drauhofen	NIV 6, distinct	Nival regime, low flow period in Winter, maximum discharge in June>July>Mai>Aug
Lieser	Spittal	GEN 6, distinct	Moderate nival, low flow period in winter but less distinct than in nival or nivo glacial regime, maximum discharge in June>Mai>July>April/Aug
Gail	Maria Luggau (Moos)	HNI, clear	Autumn nival regime, complex flow regime with secondary maximum First maximum in May/June (due to snowmelt), second maximum in autumn (due to precipitation)
	Federaun	HNI, clear	Autumn nival regime, complex flow regime with secondary maximum First maximum in May/June (due to snowmelt), second maximum in autumn (due to precipitation)

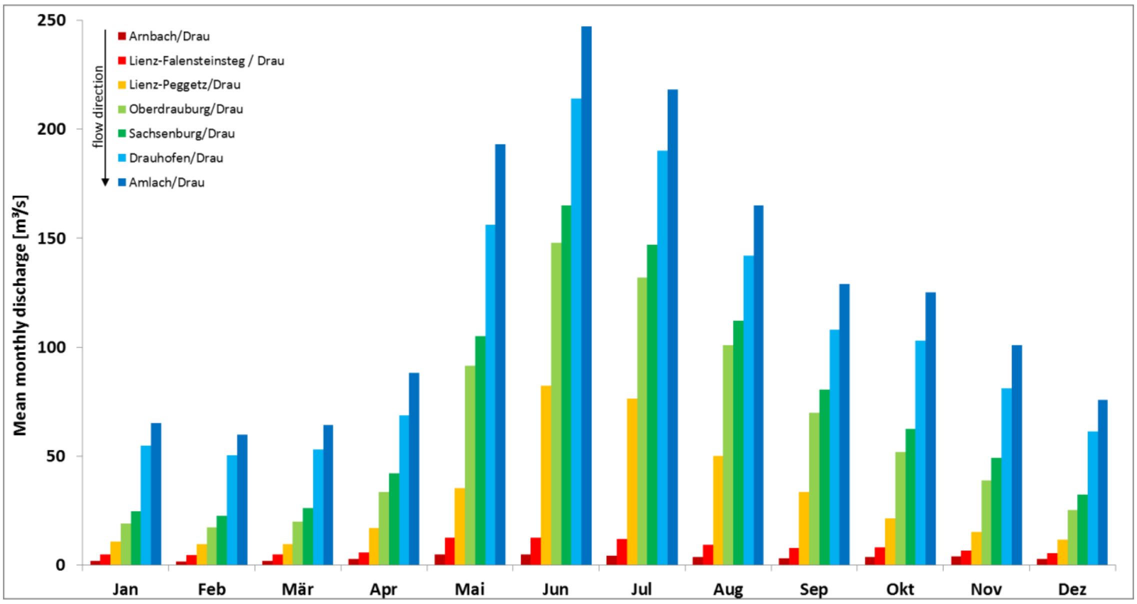


Figure 4.33 Mean monthly discharge of the longest available time series (period is different for each gauging station) of the Upper Drau River.

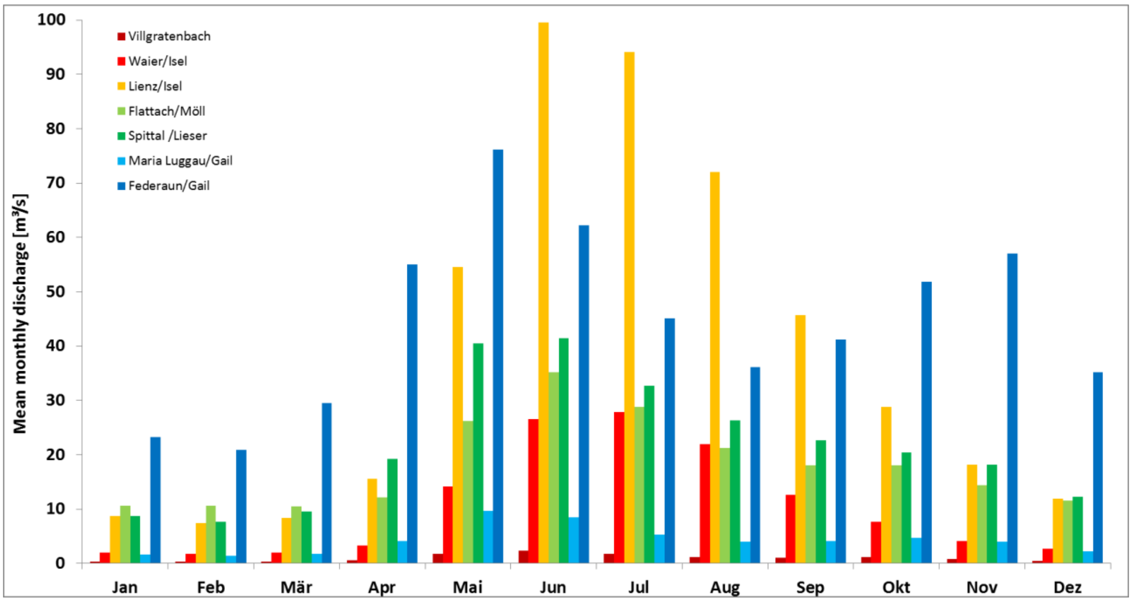
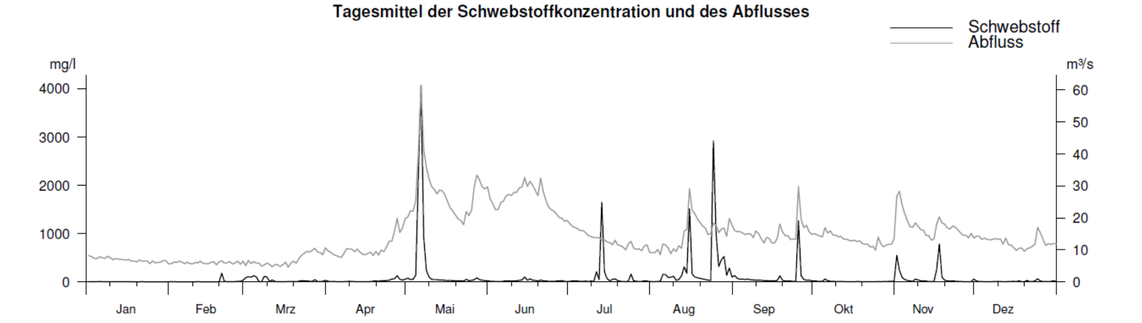


Figure 4.34 Mean monthly discharge of the longest available time series (period is different for each gauging station) of some tributaries to the Drau.

Along the Upper Drau River several suspended sediment and bed load monitoring stations have been installed. In Figures 4.35 to 4.38, summaries of the suspended load measurements are presented for four different stations. From all four measurement sites, a high variability in the suspended sediment concentrations and yields can be observed between years and within the year 2010.

Mst.-Nr.:	231092	Messstellenname:	Lienz-Falkensteinsteg	Seehöhe (PNP) [müA]:	679.87
		Gewässer:	Drau	Einzugsgebiet [km²]:	668
		Art:	kontinuierliche Schwebstoffmessstelle	Beobachtungsbeginn:	01.01.2006

Tagesmittel der Schwebstoffkonzentration und des Abflusses



Tagesfracht in 1000 t

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	.0041	.0020	.0454	.0108	.1294	.0333	.0193	.0048	.1860	.0242	1.224	.0206
2	.0048	.0015	.0651	.0058	.0964	.0278	.0385	.0049	.0926	.0185	.5894	.0109
3	.0033	.0013	.0591	.0091	.1000	.0205	.0276	.0101	.0747	.0159	.1948	.0082
4	.0038	.0013	.0734	.0045	.3050	.0152	.0238	.0095	.0751	.0160	.0885	.0067
5	.0056	.0016	.0496	.0033	10.36	.0203	.0184	.2194	.0610	.0967	.0507	.0057
6	.0027	.0010	.0037	.0030	**23.12**	.0321	.0213	.1593	.0708	.0306	.0269	.0061
7	.0030	.0008	.0017	.0046	3.375	.0418	.0225	.0842	.0554	.0186	.0180	.0076
8	.0028	.0011	.0548	.0075	.7429	.0475	.0118	.0625	.0479	.0161	.0914	.0084
9	.0023	.0009	.0547	.0108	.2839	.0371	.0228	.0861	.0468	.0120	.0605	.0127
10	.0021	.0012	.0042	.0082	.1352	.0400	.0136	.0276	.0437	.0103	.0301	.0103
11	.0023	.0016	.0180	.0054	.1184	.0553	.4129	.0487	.0372	.0106	.0223	.0055
12	.0022	.0014	.0054	.0035	.1076	.0809	.0601	.1266	.0275	.0078	.0215	.0043
13	.0021	.0010	.0022	.0037	.0998	.1091	2.216	.5006	.0313	.0069	.0096	.0112
14	.0017	.0009	.0012	.0024	.0965	.2866	.2019	.2849	.0237	.0056	.0072	.0109
15	.0016	**.0006**	.0035	.0033	.0731	.0907	.0715	4.171	.0217	.0055	.0162	.0126
16	.0015	.0013	.0026	.0030	.0593	.1762	.0284	.2970	.0212	.0051	.4851	.0060
17	.0012	.0010	.0039	.0060	.0583	.0924	.0538	.1904	.0358	.0099	1.368	.0230
18	.0013	**.0006**	.0053	.0112	.0500	.0761	.0791	.1504	.2063	.0074	.1561	.0056
19	.0011	.0019	.0059	.0133	.0399	.0385	.0331	.1208	.0415	.0049	.0547	.0043
20	.0012	.0604	.0030	.0099	.0409	.1088	.0164	.0945	.0226	.0043	.0305	.0312
21	.0037	.0050	.0116	.0184	.0350	.0521	.0089	.0744	.0227	.0044	.0215	.0063
22	.0013	.0036	.0179	.0209	.0217	.0362	.0040	.0484	.0189	.0039	.0303	.0082
23	.0009	.0035	.0184	.0269	.0977	.0292	.0220	.0425	.0140	.0028	.0221	.0234
24	**.0006**	.0030	.0139	.0422	.0444	.0261	.1847	5.632	.0135	.0021	.0165	.0945
25	.0010	.0032	.0121	.0645	.0614	.0262	.0183	1.461	4.101	.0105	.0117	.0245
26	.0007	.0095	.0086	.0910	.1199	.0296	.0120	.4040	.2175	.0049	.0079	.0106
27	.0011	.0061	.0370	.2164	.2422	.0384	.0081	.7350	.0727	.0086	.0065	.0082
28	.0010	.0183	.0077	.0684	.1290	.0437	.0092	.6024	.0508	.0070	.0066	.0065
29	.0012		.0074	.0575	.0879	.0194	.0236	.1633	.0459	.0124	.0071	.0125
30	.0015		.0081	.0981	.0674	.0152	.0167	.5488	.0311	.0119	.0752	.0198
31	.0011		.0326		.0546		.0076	.1463		.0251		.0108

Schwebstoffkonzentration in mg/l

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	27	19	17	14	22	4	21	2	24	25	30	17
Min.	1	<1	1	2	11	7	<1	4	8	2	5	3
Mit.	3	11	35	23	280	24	91	297	84	11	84	12
Max	71	1963	958	272	12072	227	27530	25957	4453	195	2231	264
Tag	21	20	2	27	6	14	13	24	25	31	17	24

Schwebstofftransport in kg/s

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	26	19	17	13	22	4	20	2	24	23	14	17
Min.	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Mit.	<1	<1	<1	<1	15	<1	1	6	2	<1	2	<1
Max	<1	14	9	6	859	8	438	622	188	4	45	3
Tag	2	20	8	27	6	14	13	24	25	5	17	24

Jahreswerte

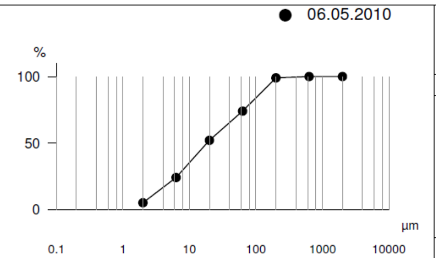
	Schwebstoffkonzentration in mg/l				Schwebstofftransport in kg/s			
	Berichtsjahr		Reihe 2006-2009		Berichtsjahr		Reihe 2006-2009	
	Wert	Datum	Wert	Datum	Wert	Datum	Wert	Datum
Min.	<1	21.07.	<1	19.01.06	<1	19.02.	<1	19.01.06
Mit.	80		86		2.39		2.09	
Max	27530	13.07.	59834	30.07.08	859	06.05.	1589	01.09.08

Überschreitungsdauer der Schwebstoffkonzentration
Berichtsjahr (J) / Reihe 2006-2009(R)

mg/l	Tage(J)	Tage(R)	mg/l	Tage(J)	Tage(R)	mg/l	Tage(J)	Tage(R)	mg/l	Tage(J)	Tage(R)
20000	2	3	6000	6	6	600	31	36	80	106	121
18000	2	3	4000	8	8	500	33	39	60	131	139
16000	2	3	2000	11	15	400	36	46	40	173	172
14000	2	3	1000	19	24	300	43	53	20	242	244
12000	3	4	900	22	25	200	53	67	10	297	323
10000	5	4	800	23	28	150	68	80	5	342	344
8000	6	5	700	29	33	100	86	105	0	365	365

Konzentration

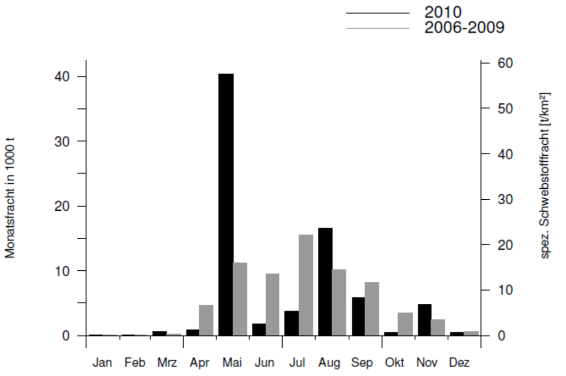
Korngrößenverteilung



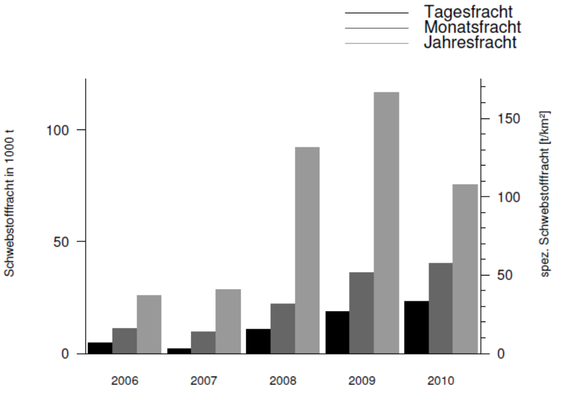
Datum: 06.05.2010
Zeit: 07:25 MEZ
Q = 71 m³/s
s_0 = 4824 mg/l

Klassen [µm]	D [%]
0.2	
0.63	
2	5
6.3	24
20	52
63	74
200	99
630	100
2000	100
µm	

Monatsfracht und spez. Schwebstofffracht
Berichtsjahr / Reihe 2006-2009



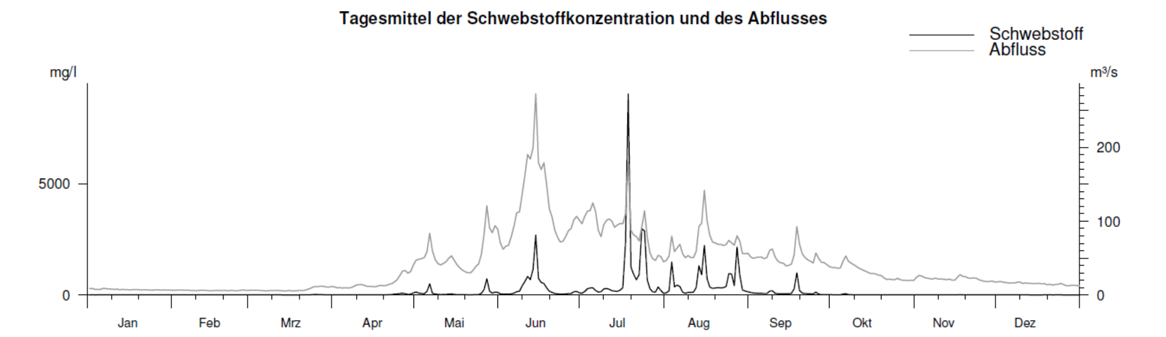
Jahresfracht und größte Tages- und Monatsfracht



Q nach Erhebungen der Tiroler Wasserkraftwerke-AG, durch Kraftwerksbetrieb beeinflusst, im Jul, Aug und Sep nach ergänzten Daten ermittelt, vom 28. Feb bis 19. Mrz durch Baggerungen beeinflusst, am 20. Feb Spitze durch Erdrutsch bei Leisach (Aufstau der Drau)

Figure 4.35 Observation results of suspended load at the gauging station Falkensteinsteg at the Drau River (source: Hydrographical yearbook 2010).

Mst.-Nr.:	212167	Messstellenname:	Lienz	Seehöhe (PNP) [müA]:	667.20
		Gewässer:	Isel	Einzugsgebiet [km²]:	1186.6
		Art:	kontinuierliche Schwebstoffmessstelle	Beobachtungsbeginn:	01.01.2006



Tagesfracht in 1000 t

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	.0039	.0031	.0032	.0073	.5571	.3402	.6925	.4174	.5213	.0479	.0131	.0118
2	.0058	.0036	.0039	.0051	.3662	.1830	1.590	.8913	.4053	.0449	.0166	.0105
3	.0035	.0036	.0035	.0050	.2921	.2437	2.922	11.72	.3915	.0418	.0143	.0095
4	.0039	.0036	.0041	.0043	.2435	.2218	3.240	1.955	.3327	.0412	.0146	.0079
5	.0044	.0035	.0038	.0051	1.001	.3460	3.534	2.753	.3527	.2013	.0120	.0077
6	.0076	.0036	.0032	.0047	3.849	.7838	1.944	2.449	.2821	.2766	.0118	.0074
7	.0069	.0032	.0031	.0052	.4275	1.496	1.041	.6106	.3157	.0822	.0122	.0082
8	.0062	.0034	.0033	.0075	.1869	1.735	1.106	.3561	.9145	.0554	.0160	.0129
9	.0058	.0031	.0035	.0136	.1108	5.048	2.372	.5579	1.069	.0431	.0162	.0124
10	.0053	.0036	.0035	.0140	.0843	9.046	2.707	.5216	.3623	.0376	.0200	.0119
11	.0063	.0041	.0034	.0109	.0924	14.55	2.435	.6365	.2337	.0327	.0192	.0109
12	.0044	.0040	.0029	.0077	.1274	11.47	1.757	1.864	.2226	.0263	.0202	.0077
13	.0056	.0033	.0023	.0076	.1568	24.84	1.421	11.52	.2260	.0259	.0193	.0059
14	.0047	.0036	.0023	.0096	.2291	70.34	1.423	8.040	.1837	.0214	.0148	.0057
15	.0044	.0043	.0026	.0073	.1199	11.99	1.917	30.08	.1875	.0187	.0145	.0061
16	.0037	.0033	.0023	.0058	.0765	8.453	2.902	6.421	.2791	.0160	.0201	.0070
17	.0042	.0032	**.0021**	.0069	.0625	8.097	56.59	2.484	1.738	.0146	.0405	.0065
18	.0037	.0029	.0022	.0098	.0532	4.286	**197.8**	1.902	8.898	.0145	.0183	.0082
19	.0036	.0035	.0026	.0101	.0417	1.731	9.659	2.017	1.203	.0136	.0181	.0072
20	.0033	.0034	.0040	.0118	.0374	1.087	6.810	2.044	.4414	.0111	.0145	.0096
21	.0037	.0028	.0037	.0201	.0362	.5549	4.849	2.006	.2949	.0121	.0123	.0059
22	.0041	.0032	.0053	.0320	.0425	.3478	6.644	2.057	.2544	.0110	.0131	.0066
23	.0030	.0029	.0079	.0604	.0686	.2285	32.50	2.430	.2194	.0105	.0124	.0072
24	.0033	.0030	.0203	.0822	.0755	.2339	33.08	7.826	.1858	.0151	.0128	.0088
25	.0032	.0035	.0277	.1625	.4245	.3320	4.737	6.472	.6986	.0127	.0098	.0053
26	.0036	.0041	.0225	.2285	1.870	.4897	1.375	2.692	.1814	.0104	.0098	.0040
27	.0037	.0038	.0251	.1820	8.025	.5695	.6239	23.37	.0876	.0093	.0093	.0038
28	.0031	.0033	.0134	.0739	1.439	1.387	.5433	5.883	.0808	.0109	.0092	.0061
29	.0033		.0105	.1105	.6437	1.549	2.038	1.143	.0715	.0121	.0086	.0051
30	.0032		.0081	.3558	1.080	.9551	.9610	.8742	.0541	.0098	.0115	.0047
31	.0033		.0142		.9460		.3034	.7167		.0088		.0041

Schwebstoffkonzentration in mg/l

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	4	5	18	3	21	4	1	1	30	22	25	15
Min.	2	5	2	5	14	23	53	57	14	5	5	2
Mit.	6	6	9	22	100	341	851	559	115	12	8	6
Max	16	16	41	242	2627	8093	45542	15932	2853	124	32	20
Tag	6	25	25	30	27	13	17	27	18	5	17	9

Schwebstofftransport in kg/s

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	4	25	18	3	21	4	31	1	30	31	29	15
Min.	<1	<1	<1	<1	<1	1	3	2	<1	<1	<1	<1
Mit.	<1	<1	<1	<1	8	71	146	54	8	<1	<1	<1
Max	<1	<1	<1	12	363	2777	13325	2507	344	8	1	<1
Tag	6	25	31	30	27	13	18	27	18	5	17	9

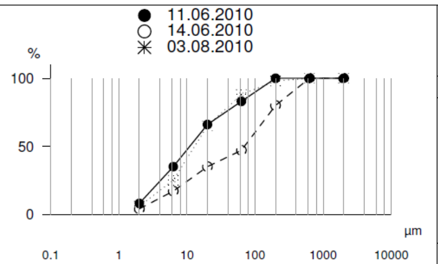
Jahreswerte

	Schwebstoffkonzentration in mg/l				Schwebstofftransport in kg/s			
	Berichtsjahr		Reihe 2007-2009		Berichtsjahr		Reihe 2007-2009	
	Wert	Datum	Wert	Datum	Wert	Datum	Wert	Datum
Min.	2	04.01.	<1	16.11.07	<1	18.03.	<1	16.11.07
Mit.	171		89		24.3		9.23	
Max	45542	17.07.	16062	19.05.08	13325	18.07.	2413	04.09.09

Überschreitungsdauer der Schwebstoffkonzentration
Berichtsjahr (J) / Reihe 2007-2009(R)

Konzentration mg/l	Tage(J)	Tage(R)	mg/l	Tage(J)	Tage(R)	mg/l	Tage(J)	Tage(R)	mg/l	Tage(J)	Tage(R)
20000	2		6000	10	2	600	45	30	80	127	139
18000	2		4000	12	4	500	57	35	60	139	151
16000	2		2000	19	9	400	66	46	40	147	171
14000	5		1000	35	18	300	72	58	20	169	198
12000	5		900	36	21	200	92	81	10	236	243
10000	5	1	800	36	23	150	100	96	5	362	297
8000	8	2	700	39	25	100	115	126	0	365	336

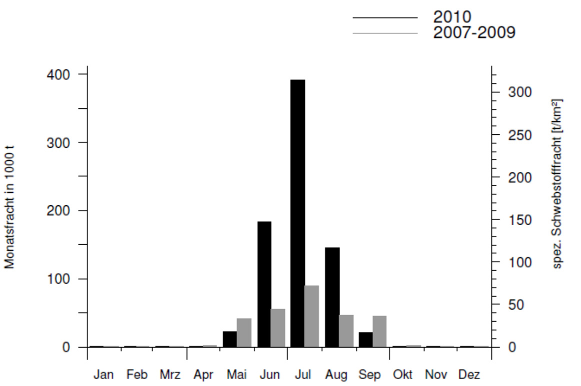
Korngrößenverteilung



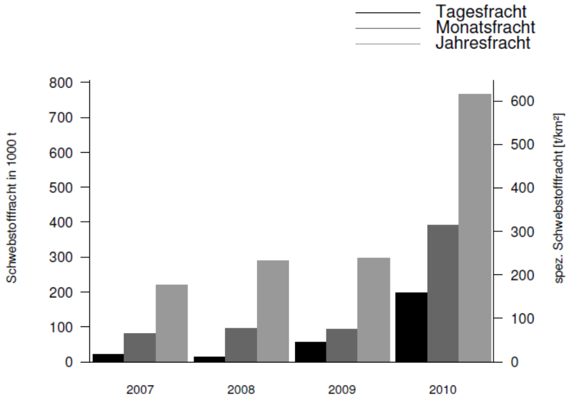
Datum: 03.08.2010
Zeit: 07:30 MEZ
Q = 116 m³/s
s_0 = 4269 mg/l

Klassen [µm]	D [%]
0.2	
0.63	
2	6
6.3	25
20	65
63	88
200	98
630	100
2000	100
µm	

Monatsfracht und spez. Schwebstofffracht
Berichtsjahr / Reihe 2007-2009



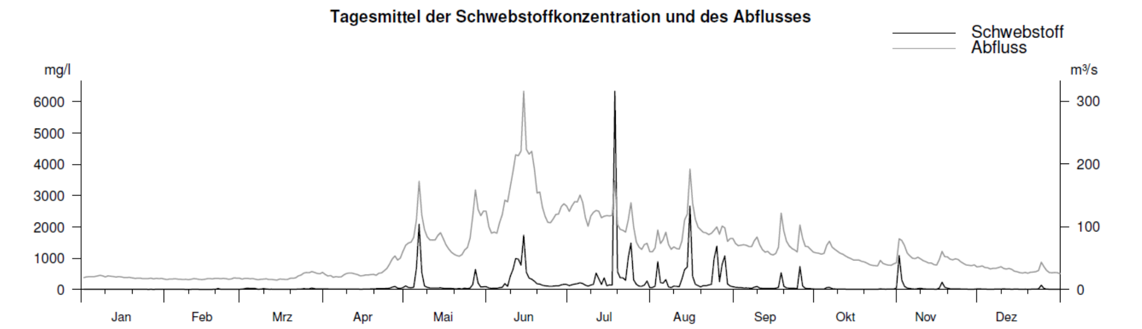
Jahresfracht und größte Tages- und Monatsfracht



durch Kraftwerksbetrieb beeinflusst, am 17. und 18. Jul Spitze durch heftige Unwetter im Virgental, im Jän, Mrz und Dez nach ergänzten Daten ermittelt

Figure 4.36 Observation results of suspended load at the gauging station Lienz at the Isel River, a major tributary to the River Drau (source: Hydrographical yearbook 2010).

Mst.-Nr.:	213660	Messstellenname:	Dellach-OWF	Seehöhe (PNP) [müA]:	599.73
		Gewässer:	Drau	Einzugsgebiet [km²]:	2197.3
		Art:	kontinuierliche Schwebstoffmessstelle	Beobachtungsbeginn:	01.01.2007



Tagesfracht in 1000 t

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	.0104	.0064	.0209	.0412	.6996	.4368	1.330	.3330	.4463	.0808	7.812	.0707
2	.0120	.0062	.0403	.0323	.4138	.2804	1.754	.6063	.3834	.0666	1.992	.0425
3	.0118	.0061	.0692	.0265	.3687	.3305	2.091	7.873	.3709	.0579	.6048	.0348
4	.0112	.0063	.0454	.0211	.5376	.2902	2.275	1.440	.3087	.0596	.2298	.0290
5	.0106	.0057	.0579	.0226	8.421	.5503	2.780	1.560	.3127	.4409	.1419	.0232
6	.0137	.0060	.0442	.0230	32.66	.7416	2.287	2.774	.2660	.4638	.0808	.0290
7	.0137	.0051	.0100	.0198	5.797	2.357	1.386	.5045	.2181	.1496	.0645	.0319
8	.0121	.0049	.0185	.0260	.9500	1.219	.9225	.3462	.5010	.0991	.1211	.0457
9	.0096	.0046	.0404	.0330	.5143	6.069	1.429	.6262	.7110	.0728	.1500	.0493
10	.0103	.0049	.0251	.0349	.3419	10.65	1.755	.5647	.2813	.0590	.0859	.0555
11	.0130	.0077	.0115	.0346	.3072	18.71	5.918	.5037	.1979	.0555	.0649	.0421
12	.0096	.0064	.0148	.0322	.3203	18.53	3.657	2.198	.1824	.0484	.0547	.0343
13	.0075	.0047	.0077	.0272	.3571	15.17	1.645	6.629	.1841	.0434	.0493	.0244
14	.0079	**.0043**	.0066	.0170	.4254	51.32	3.889	7.760	.1642	.0386	.0356	.0287
15	.0106	.0047	.0091	.0199	.2694	10.96	1.222	48.56	.1518	.0326	.0326	.0303
16	.0069	.0052	.0093	.0211	.1948	6.827	1.496	5.002	.2046	.0295	.2469	.0185
17	.0066	.0048	.0096	.0244	.1760	6.300	1.514	1.634	.4619	.0332	1.213	.0180
18	.0076	.0052	.0118	.0389	.1614	4.436	**110.0**	1.059	6.156	.0275	.3380	.0253
19	.0064	.0081	.0122	.0371	.1190	2.437	5.122	.6905	.8396	.0319	.1901	.0155
20	.0061	.0532	.0144	.0468	.1058	2.321	3.115	.9910	.3409	.0290	.0947	.0225
21	.0061	.0132	.0127	.0554	.1304	1.535	3.072	.9408	.2470	.0315	.0746	.0395
22	.0067	.0082	.0274	.0606	.0938	1.173	2.367	1.128	.2230	.0281	.0890	.0287
23	.0061	.0067	.0312	.0772	.2259	.9989	10.50	1.295	.2062	.0192	.0886	.0635
24	.0055	.0065	.0613	.0943	.1456	.9184	20.09	10.12	.1345	.0178	.0633	.5199
25	.0052	.0072	.0493	.1488	.3284	1.036	2.679	12.69	8.037	.1001	.0465	.1065
26	.0058	.0096	.0449	.3163	1.598	1.194	1.096	1.945	.8411	.0401	.0376	.0339
27	.0050	.0112	.1159	.4533	9.069	1.190	.6252	8.918	.2320	.0359	.0320	.0214
28	.0056	.0099	.0609	.1747	2.384	1.691	.5669	9.863	.1590	.0390	.0297	.0178
29	.0060		.0427	.1513	.7970	1.966	.9615	1.219	.1388	.0462	.0343	.0203
30	.0061		.0370	.3214	.9262	1.857	1.828	.7876	.0909	.0493	.0604	.0169
31	.0066		.0547		.9757		.3126	.6191		.2156		.0140

Schwebstoffkonzentration in mg/l

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	30	27	1	13	21	4	31	1	30	24	29	20
Min.	2	2	2	7	13	29	44	44	13	4	7	4
Mit.	5	5	18	25	182	308	484	413	89	16	77	16
Max	40	308	156	164	3788	4808	25737	9449	2511	407	1854	318
Tag	15	20	6	27	6	14	18	27	25	31	1	24

Schwebstofftransport in kg/s

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	30	14	1	5	21	4	31	1	30	24	15	17
Min.	<1	<1	<1	<1	<1	2	3	3	<1	<1	<1	<1
Mit.	<1	<1	<1	<1	26	67	75	53	9	<1	5	<1
Max	<1	7	3	9	776	1882	5532	1893	340	22	178	15
Tag	15	20	6	27	6	14	18	15	25	31	1	24

Jahreswerte

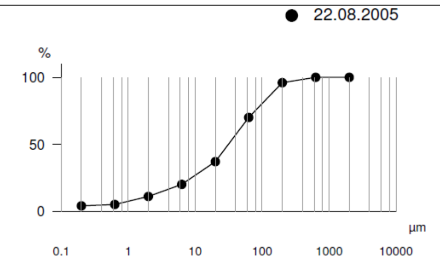
	Schwebstoffkonzentration in mg/l – Berichtsjahr: Wert	Datum	Schwebstofftransport in kg/s – Berichtsjahr: Wert	Datum
Min.	2	30.01.	<1	30.01.
Mit.	138		20.0	
Max	25737	18.07.	5532	18.07.

Überschreitungsdauer der Schwebstoffkonzentration
Berichtsjahr (J)

Konzentration

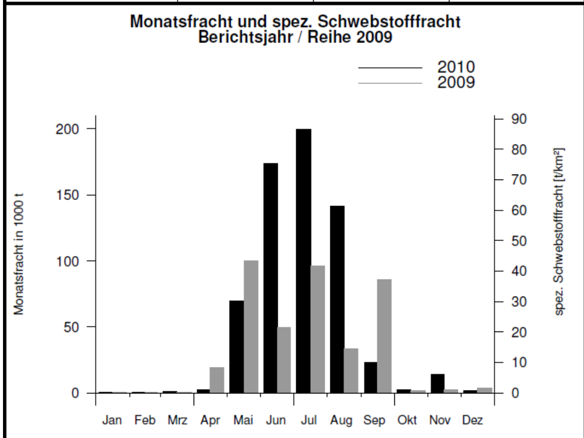
mg/l	Tage(J)	mg/l	Tage(J)	mg/l	Tage(J)	mg/l	Tage(J)
20000	1	6000	6	600	38	80	136
18000	1	4000	8	500	42	60	157
16000	1	2000	16	400	50	40	189
14000	1	1000	29	300	55	20	253
12000	1	900	32	200	77	10	328
10000	1	800	34	150	102	5	359
8000	4	700	34	100	127	0	365

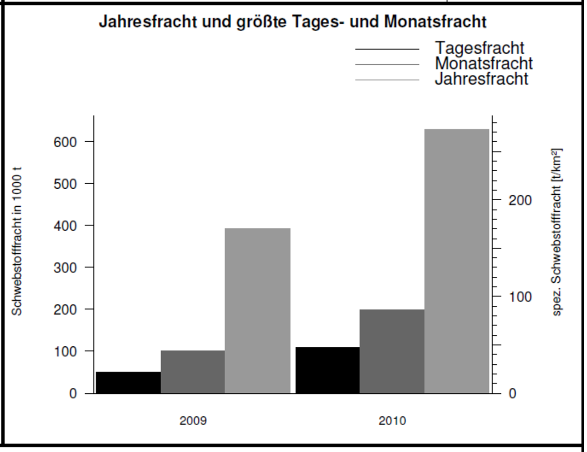
Korngrößenverteilung



Datum: 22.08.2005
Zeit: 00:00 MEZ
Q = 108 m³/s
s_0 = Lücke mg/l

Klassen [µm]	D [%]
0.2	4
0.63	5
2	11
6.3	20
20	37
63	70
200	96
630	100
2000	100
µm	



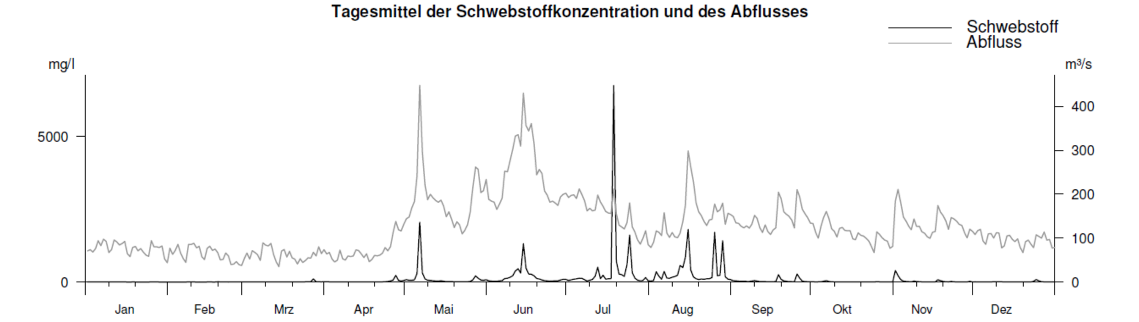


Q aus Oberdrauburg, im Mrz, Apr, Jun, Jul, Aug, Sep und Nov nach erg. Daten ermittelt

Figure 4.37 Observation results of suspended load at the gauging station Dellach at the Drau River (source: Hydrographical yearbook 2010).

Mst.-Nr.:	213215	Messstellenname:	Amlach	Seehöhe (PNP) [müA]:	522.79
		Gewässer:	Drau	Einzugsgebiet [km²]:	4713.5
		Art:	kontinuierliche Schwebstoffmessstelle	Beobachtungsbeginn:	01.01.2009

Tagesmittel der Schwebstoffkonzentration und des Abflusses



Tagesfracht in 1000 t

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1	.0562	.0264	.0380	.0728	1.068	.7670	.9845	.2604	.6606	.1417	7.380	.1097
2	.0605	.0158	.0575	.0636	.8049	.5317	1.403	.4441	.5056	.0976	4.024	.0995
3	.0540	.0203	.0396	.0330	.9857	.4957	1.764	3.936	.3800	.0980	1.399	.0940
4	.0604	.0261	.0683	.0246	1.268	.3834	1.872	2.052	.3043	.1852	.4354	.0640
5	.0817	.0182	.0588	.0291	7.434	.7049	2.490	.9332	.2767	.4860	.2988	.0571
6	.0403	.0146	.0520	.0453	83.76	.8909	2.314	5.485	.2841	.7231	.2023	.0835
7	.0759	**.0124**	.0399	.0228	8.373	2.797	1.326	1.332	.2600	.2906	.1379	.0922
8	.0658	.0524	.0840	.0281	2.122	2.771	.5742	1.173	.4308	.1384	.4623	.1092
9	.0272	.0300	.0803	.0448	1.062	4.096	1.033	1.683	.7764	.1036	.2501	.1336
10	.0312	.0325	.0627	.0437	1.069	5.863	1.321	1.724	.4397	.0765	.1778	.1220
11	.0511	.0231	.0713	.0458	.8212	11.16	2.704	2.094	.2178	.1121	.1019	.0776
12	.0371	.0290	.0390	.0565	.6083	13.79	7.942	5.705	.1817	.0979	.0891	.0599
13	.0310	.0146	.0244	.0441	.5253	8.422	1.879	5.878	.2264	.0811	.0712	.0568
14	.0363	.0132	.0163	.0359	.7650	52.52	3.806	13.23	.1589	.0809	.0576	.0569
15	.0370	.0295	.0528	.0284	.4415	14.97	1.454	55.17	.1224	.0738	.0944	.0506
16	.0192	.0387	.0523	.0328	.2730	8.434	1.592	9.608	.1758	.0464	.0825	.0396
17	.0159	.0250	.0326	.0205	.2978	8.502	1.673	3.556	.2320	.0493	1.266	.0582
18	.0295	.0246	.0403	.0262	.2807	6.075	**151.3**	1.839	5.152	.0603	.6678	.0316
19	.0266	.0823	.0287	.0355	.1512	2.661	9.499	1.206	1.582	.0510	.3387	.0238
20	.0205	.0408	.0224	.0331	.1952	2.391	3.141	1.432	.6114	.0503	.1678	.0473
21	.0234	.0353	.0193	.0438	.1616	1.600	2.858	1.168	.3765	.0477	.1068	.0510
22	.0212	.0324	.0434	.0590	.1064	.9530	2.088	1.325	.2887	.0407	.3302	.0478
23	.0187	.0192	.0324	.1101	.1781	.7219	7.452	1.496	.2232	.0311	.1476	.2085
24	.0160	.0189	.0495	.1491	.1738	.5082	28.44	2.003	.1580	.0243	.1191	.7996
25	.0521	.0208	.0707	.2956	.3705	.6115	3.508	27.57	6.693	.1946	.0979	.4001
26	.0529	.0267	.0747	.7017	1.562	.7207	1.322	2.981	2.333	.0947	.0779	.1296
27	.0327	.0243	.6617	2.437	5.122	.7046	.5547	3.365	.4772	.0484	.0651	.0946
28	.0257	.0205	.0981	.6015	3.025	1.283	.3586	22.47	.2944	.0453	.0618	.0463
29	.0262		.0866	.3822	1.271	1.705	.5085	2.058	.2173	.0532	.3287	.0453
30	.0142		.0613	.6584	1.202	1.661	1.649	1.460	.2049	.0420	.0767	.0308
31	**.0124**		.1024		1.684		.3332	1.111		.0590		.0289

Schwebstoffkonzentration in mg/l

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	17	23	21	7	22	3	9	1	15	24	30	19
Min.	2	2	2	2	9	17	26	31	10	3	5	3
Mit.	5	5	13	24	136	181	437	358	49	11	41	12
Max	27	118	287	927	3833	3860	26569	5284	797	187	900	264
Tag	26	19	27	27	6	14	18	25	25	4	1	23

Schwebstofftransport in kg/s

Mon	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Tag	31	14	21	5	22	3	31	1	15	24	29	19
Min.	<1	<1	<1	<1	<1	2	2	2	<1	<1	<1	<1
Mit.	<1	<1	<1	2	47	61	93	69	9	1	7	1
Max	4	10	19	117	1918	1879	7952	2061	237	28	192	19
Tag	26	19	27	27	6	14	18	15	25	4	1	23

Jahreswerte

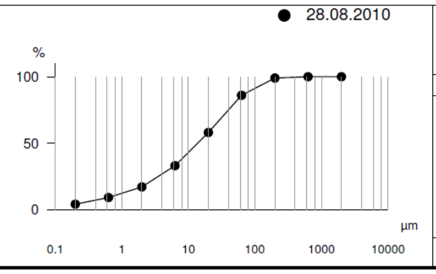
	Schwebstoffkonzentration in mg/l (Berichtsjahr)		Schwebstofftransport in kg/s (Berichtsjahr)	
	Wert	Datum	Wert	Datum
Min.	2	23.02.	<1	14.02.
Mit.	107		24.8	
Max	26569	18.07.	7952	18.07.

Überschreitungsdauer der Schwebstoffkonzentration
Berichtsjahr (J)

Konzentration

mg/l	Tage(J)	mg/l	Tage(J)	mg/l	Tage(J)	mg/l	Tage(J)
20000	1	6000	1	600	27	80	123
18000	1	4000	4	500	32	60	140
16000	1	2000	11	400	38	40	161
14000	1	1000	16	300	49	20	215
12000	1	900	18	200	59	10	301
10000	1	800	21	150	78	5	352
8000	1	700	24	100	105	0	365

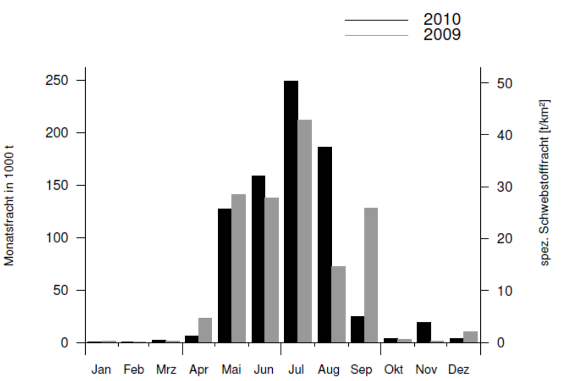
Korngrößenverteilung



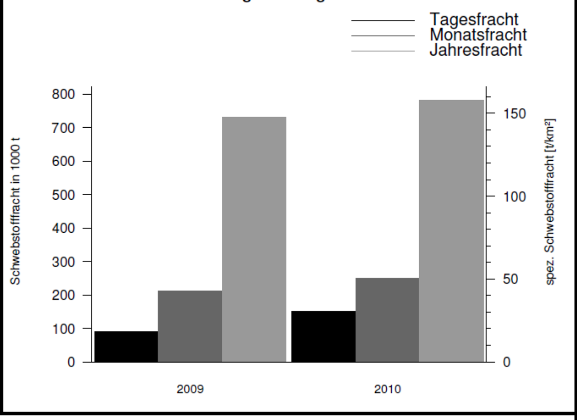
Datum: 28.08.2010
Zeit: 09:00 MEZ
Q = 185 m³/s
s_0 = 3335 mg/l

Klassen [µm]	D [%]
0.2	4
0.63	9
2	17
6.3	33
20	58
63	86
200	99
630	100
2000	100
µm	

Monatsfracht und spez. Schwebstofffracht
Berichtsjahr / Reihe 2009



Jahresfracht und größte Tages- und Monatsfracht



zeitweise durch Kraftwerksbetrieb beeinflusst, von Jän bis Mai, Jul, Aug, Sep, Nov und Dez n. erg. Daten erm.

Figure 4.38 Observation results of suspended load at the gauging station Amlach at the Drau River (source: Hydrographical yearbook 2010).

Three bed load monitoring stations are located within the investigated catchment area (Figure 4.39). Two of the stations are located in Lienz, one on the Drau and one on the Isel River. The third station is located several kilometres downstream of Lienz, in Dellach. Some characteristics of the monitoring stations are given in Table 4.6. Each monitoring station is equipped with geophones, and bed load measurements are carried out with mobile basket samplers. In addition, three bed load traps are installed at the monitoring station at Dellach. In Figure 4.40 and Table 4.7, summary bed load measurements (e.g. specific bed load rate, grain size distribution and characteristic grain sizes) are presented.

Lienz - Drau | Lienz - Isel | Dellach - Drau

Figure 4.39 Bed load monitoring stations in the Upper Drau basin at Lienz (River Drau and River Isel) and at Dellach (Drau River).

Table 4.6 Information on bed load monitoring stations (Habersack et al., 2013)

Monitoring station	Catchment area [km²]	Gradient [‰]	MQ [m^3s^{-1}]	Description of the monitoring system
Lienz – River Isel	1198,7	3,5	38,9	Geophones, mobile basket sampler "Large Helley Smith" Gauging station (discharge)
Lienz – River Drau	668,0	2,5	13,4	Geophones, mobile basket sampler "TIWAG-Sammler" Gauging station (discharge)
Dellach – River Drau	2112,0	1,9	62,6	Geophones, mobile basket sampler "Large Helley Smith", 3 bed load traps Gauging station (water level)

Table 4.7 Characteristic grain sizes for three continuous bed load measurements at the monitoring sites Lienz (River Drau and Isel) and Dellach (River Drau). Further details can be found in Habersack et al., 2013.

Measure-ment site	date	Discharge [m^3s^{-1}]	Characteristic grain size [mm]							
			d_{10}	d_{50}	d_{90}	d_{16}	d_{84}	d_m	U	Cc
Lienz (Drau)	08.06.2011	42,7	1,17	2,29	7,62	1,29	5,86	4,55	2,44	0,77
Lienz (Isel)	23.06.2008	222	11,52	39,89	90,06	15,48	77,91	46,32	4,16	1,20
Dellach (Drau)	04.08.2009	181,2	1,74	19,61	70,21	3,13	58,79	28,05	15,26	1,63

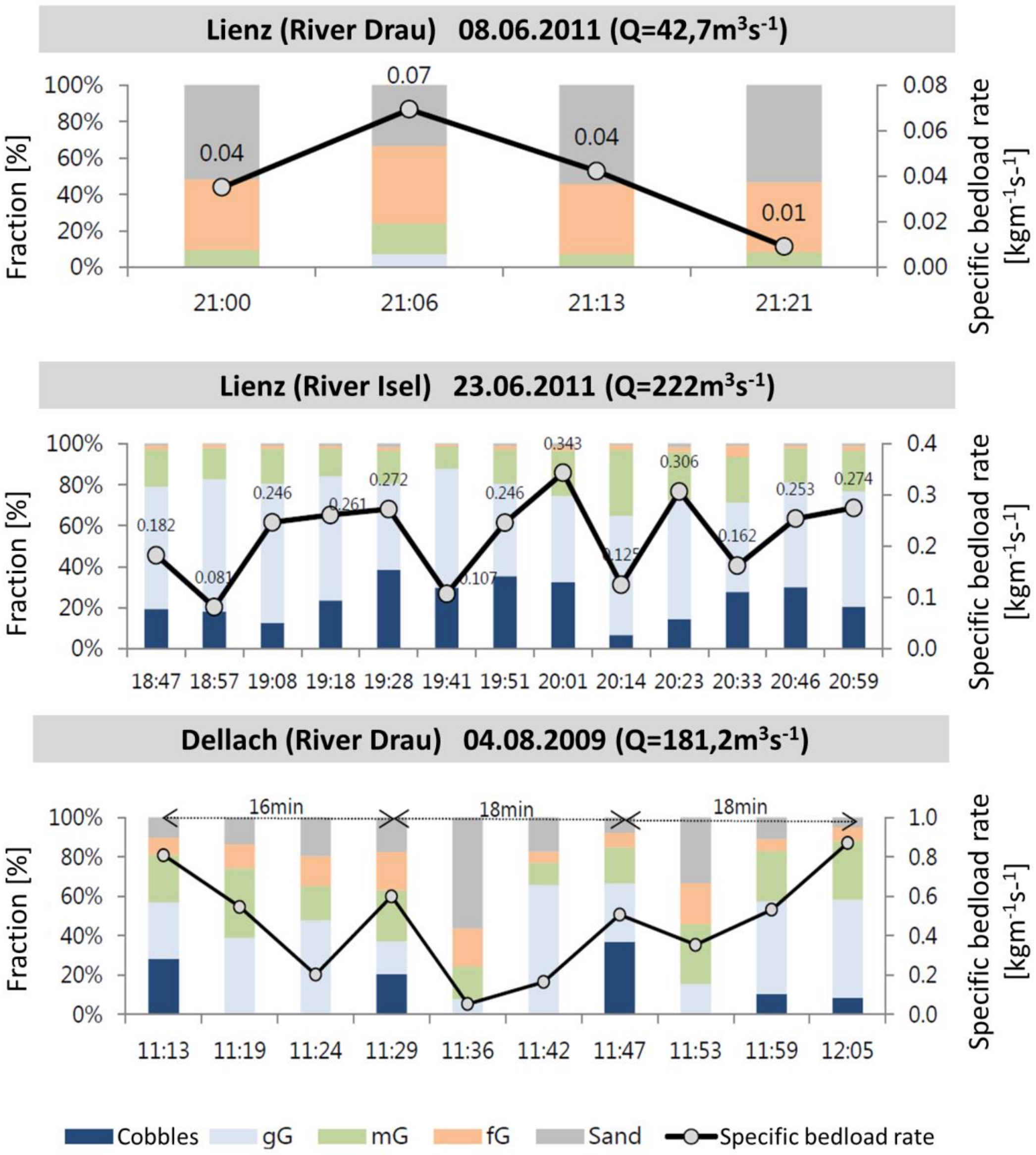


Figure 4.40 Examples of three continuous bed load measurements with the basket sampler – grain sizes (colored columns) and specific bed load rate (line) (Habersack et al., 2013).

The bed load yield calculated for several years and monitoring sites is given in Table 4.8. Similar to the suspended sediment data, the temporal and spatial variability of the bed load is high.

Table 4.8 Bed load yield calculated for several years and monitoring sites based on geophone data (Habersack et al., 2013)

Year	Discharge yield [hm³.yr⁻¹]			Bed load yield [t.yr⁻¹] – D>22,4 mm		
	Lienz (Isel)	Lienz (Drau)	Dellach – Oberdrauburg (Drau)	Lienz (Isel)	Lienz (Drau)	Dellach (Drau)
2007	1114	324	1602	1300	800	4100
2008	1409	416	2020	4600	4000	21700
2009	1432	510	2212	12500	12300	40000
2010	1293	440	1878	11100	3500	18800
2011	1243	419	1833	7400	5900	13700
2012	1607	431	2235	10200*	23100	15100

Muhar et al. (2004) evaluated the actual riparian vegetation for many rivers in Austria. At the Upper Drau River, two different riparian vegetation complexes are present – one dominated by grey alder and the second one by grey alder and white willow (Figure 4.41). The extent of the riparian vegetation is small in the upstream section of the Drau River and between Nörsach and Dellach, and in all other regions the extent is medium.

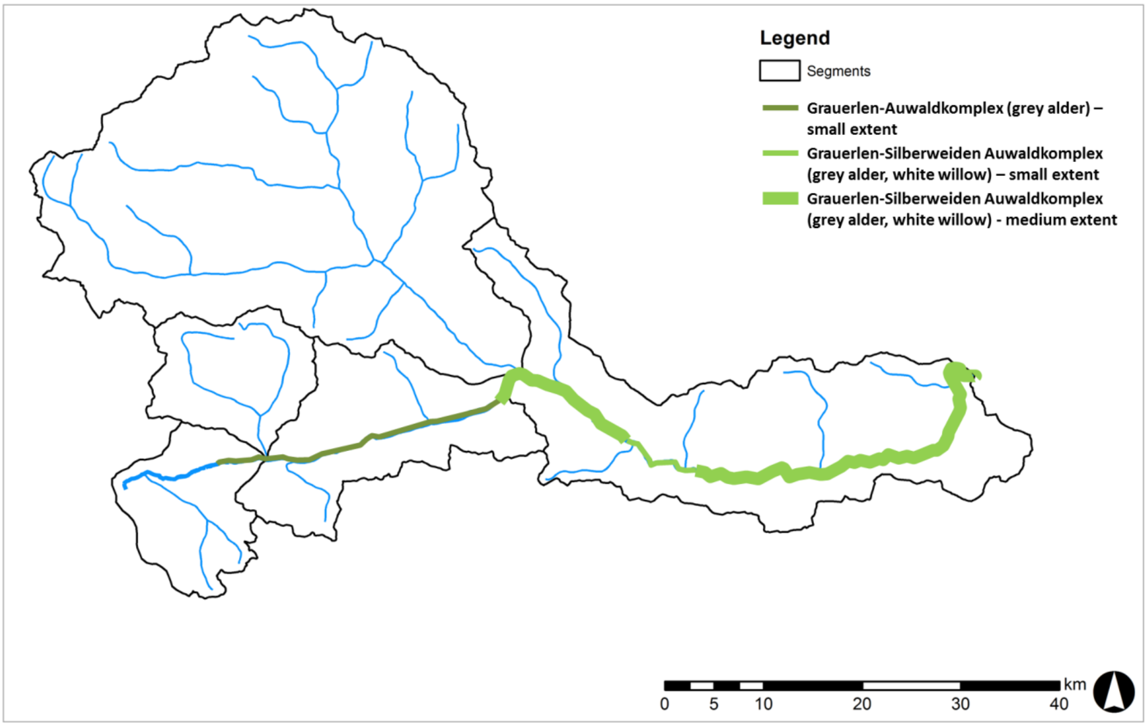


Figure 4.41 Actual riparian vegetation complex and its extent along the Upper Drau River (Muhar et al., 2004).

4.4 Reach

Only reach 2.10 (regulated reach "Berg") and reach 2.18 (restored reach "Kleblach"), which are both used as case studies in WP4, are evaluated here. The location of the investigated reaches and their surroundings are shown in Figure 4.42. Digital elevation models of these two reaches are presented in Figure 4.43.

The mean bankfull width for the regulated reach (2.10) is about 54 m and for the restored reach (2.18/Kleblach) it is about 72 m, respectively (Table 4.9). However, the wetted width at the restored reach is highly variable and varies from about 45 m to over 100 m at an one-year flood (Figure 4.44). Similar to the variation in width, the mean and maximum water depths of the restored reach show a high variability (Figure 4.45). This can be seen in the spatial distribution of modelled flow velocities and water depths (Figure 4.46). The variations in these parameters are important indicators of good ecological quality of the river. In the regulated case, the variation in width is negligible and indicated by the digital elevation model, the bed structure is quite homogeneous.

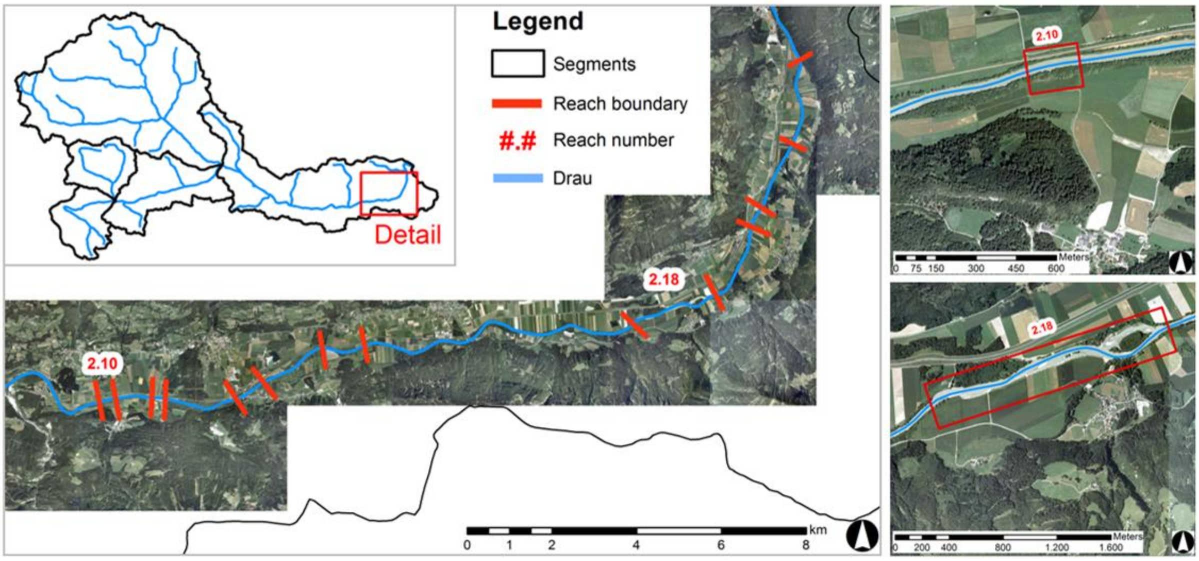


Figure 4.42 Location and surrounding of the characterised reaches, 2.10 (regulated) and 2.18 (restored) (Photos: Amt der Kärntner Landesregierung, http://gis.ktn.gv.at/atlas/)

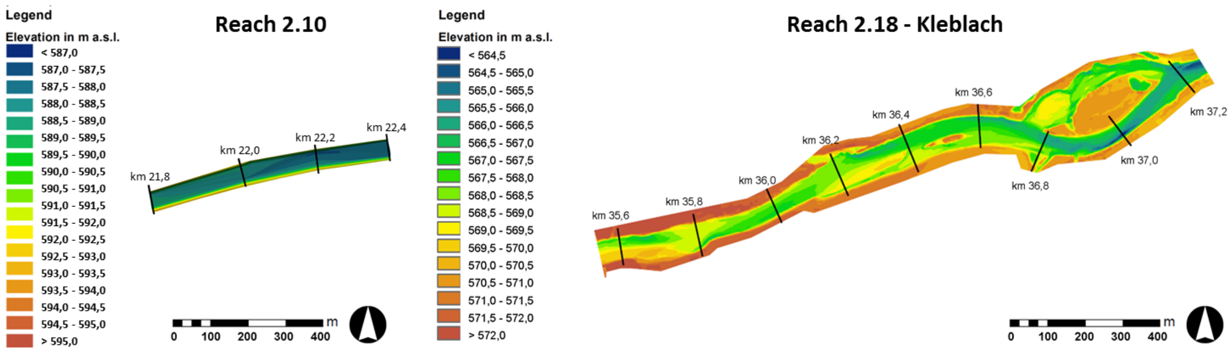


Figure 4.43 Elevation models for reach 2.10 (km 22,0 to km 22,2) and reach 2.18.

Table 4.9 Channel dimensions – width and depth

2.10*	2.18 – Kleblach (without side channel)**		
Mean bankfull width	Mean width (HQ1)	Mean water depth (HQ1)	Mean maximum water depth (HQ1)
54 m	72,06 m	2,61 m	3,78 m
* based on profiles, ** based on hydrodynamic model			

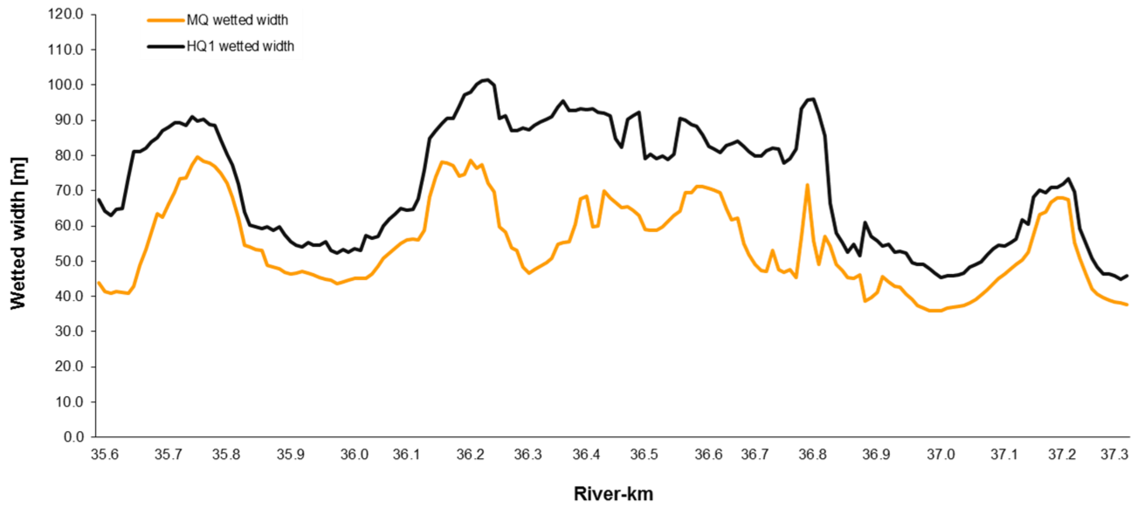


Figure 4.44 Wetted width (only for the main channel) for two modelled discharges, mean discharge and a one-year flood, respectively.

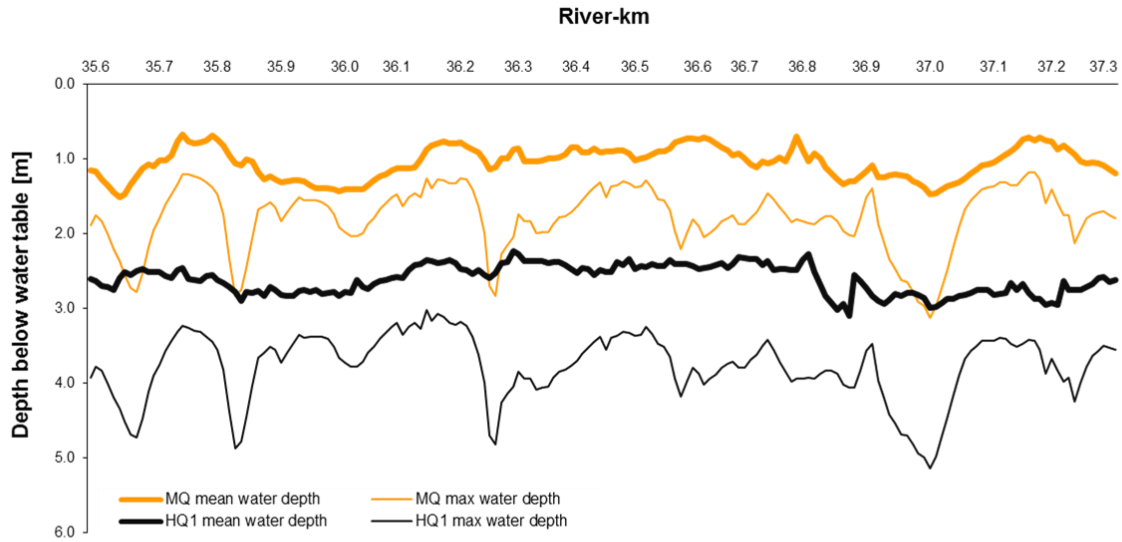


Figure 4.45 Mean and maximum water depth at the restored reach (only for the main channel).

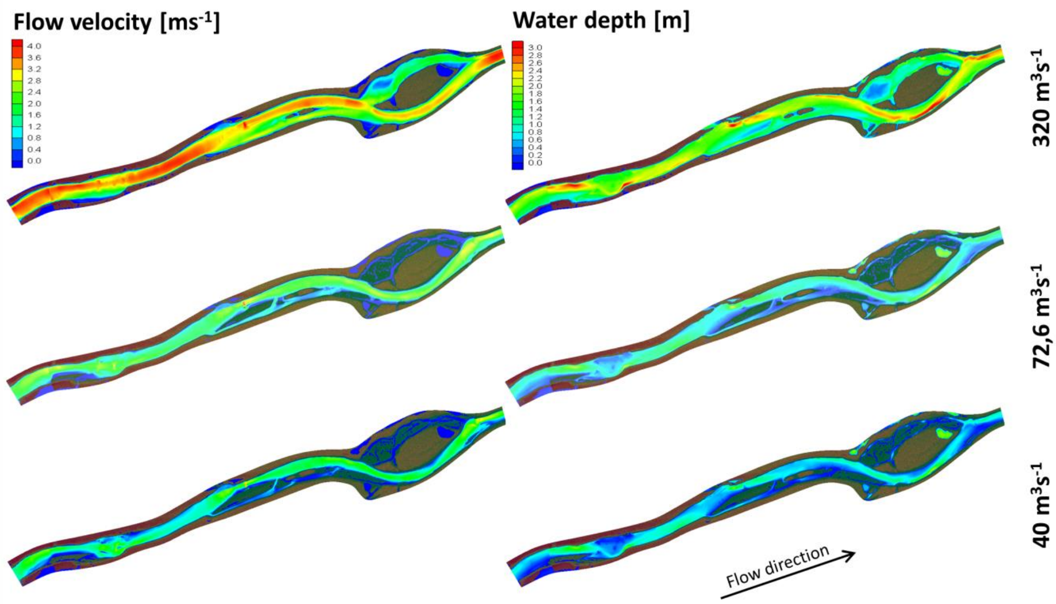


Figure 4.46 Flow velocities and water depths for three different discharges at the restored reach.

In the river widening section of Kleblach (reach 2.18), bed sediment calibre was analysed at several spots in the main channel. The grain size distributions and characteristic grain sizes are presented in Figures 4.47 and 4.48. The mean grain size varies between 20 mm and 29 mm. Data concerning the side channel is presented in Figure 4.49. The grain sizes are smaller compared to the main channel, but exhibit a wider range. The finest grain sizes were found on the vegetated mid-channel bars. Information on bed sediment calibre at the restored reach was not available.

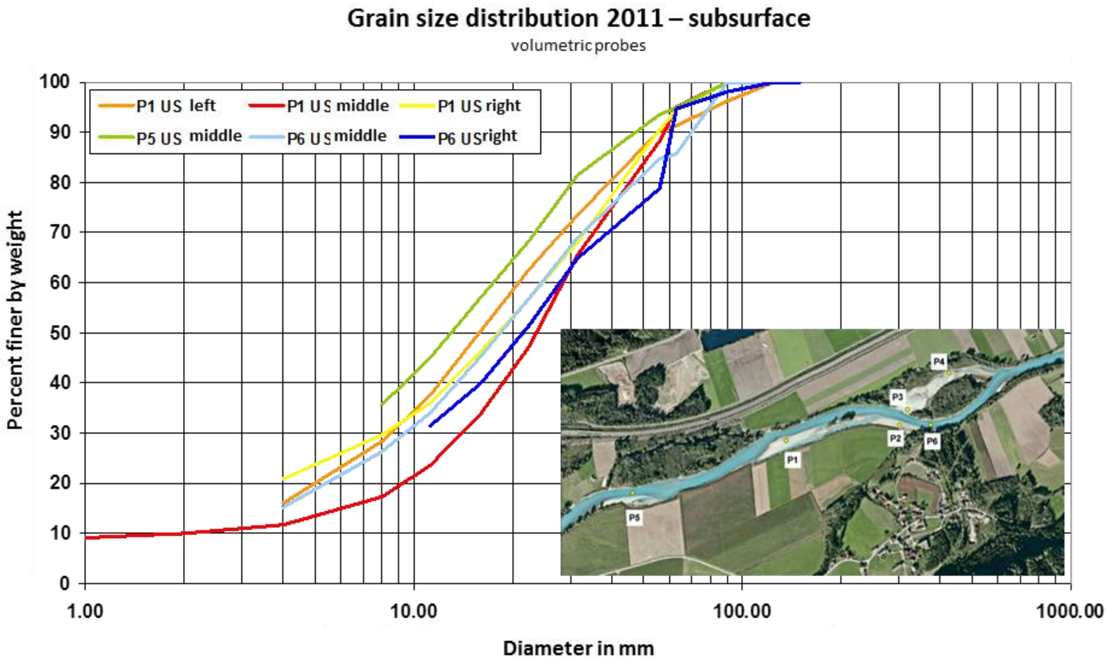


Figure 4.47 Grain size distribution of subsurface volumetric samples, taken 2011.

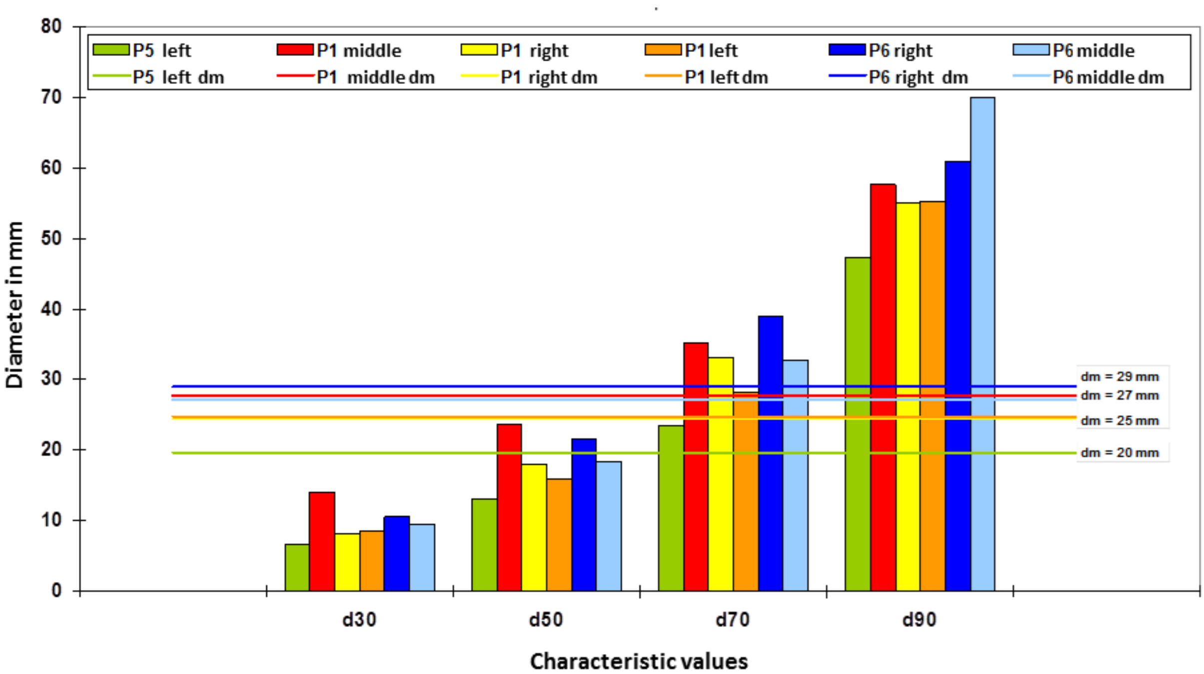


Figure 4.48 Characteristic values of subsurface samples.

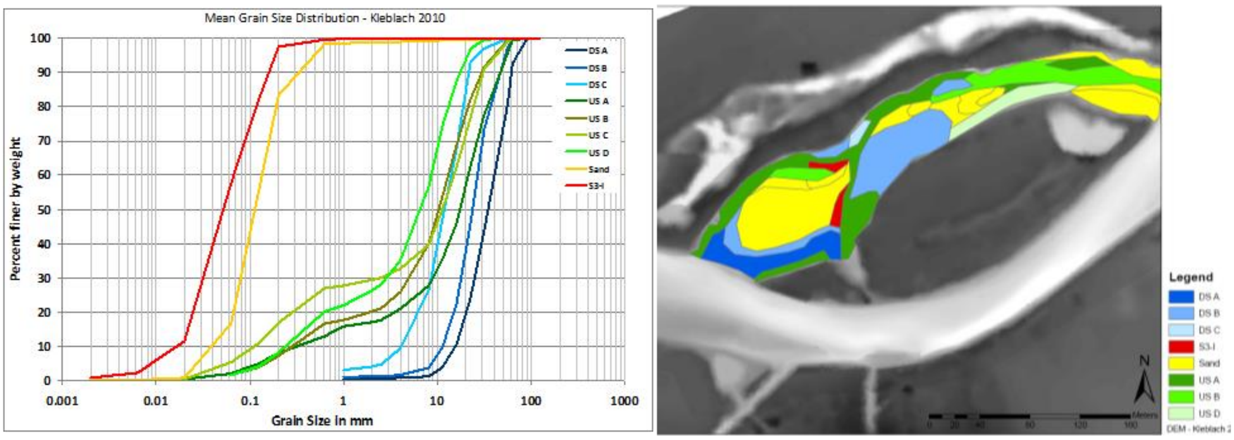


Figure 4.49 Grain size distributions in the side channel, 2010.

In the restored reach bank protection (rip rap) is present on both banks, whereas in the restored reach protection is partially removed. In Figure 4.50 the assessment results of the national river basin management plan 2009 (BMLFUW 2010) in terms of bank dynamics are shown. The regulated reach and the upstream part of the restored one were assigned to the class “widely reinforced banks”. The downstream part of Kleblach was assessed to be locally reinforced.

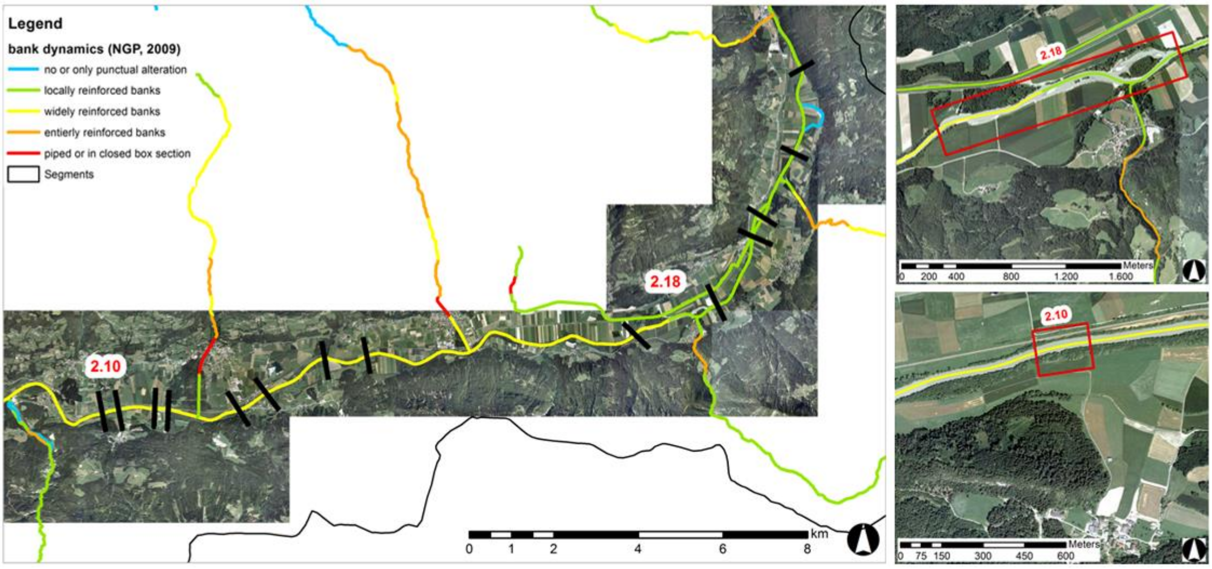


Figure 4.50 Assessment of bank dynamics within the scope of the national river basin management plan (BMLFUW, 2010).

The assessment within the national river basin management plan 2009 (BMLFUW, 2010) shows local alterations of the bed dynamics and a locally reinforced bed for the entire regulated reach and the upstream part of the restored reach (Figure 4.51). This classification of the restored reach might be due to the definition of that class. Reaches with no bed reinforcement but located downstream of torrent controls or other transverse structures, which might have an impact on the substrate, can be assigned to this class. Therefore the locations of transverse structures and the bed dynamics are illustrated in Figure 4.52. Tributaries are highly altered by several transverse structures, mainly torrent controls.

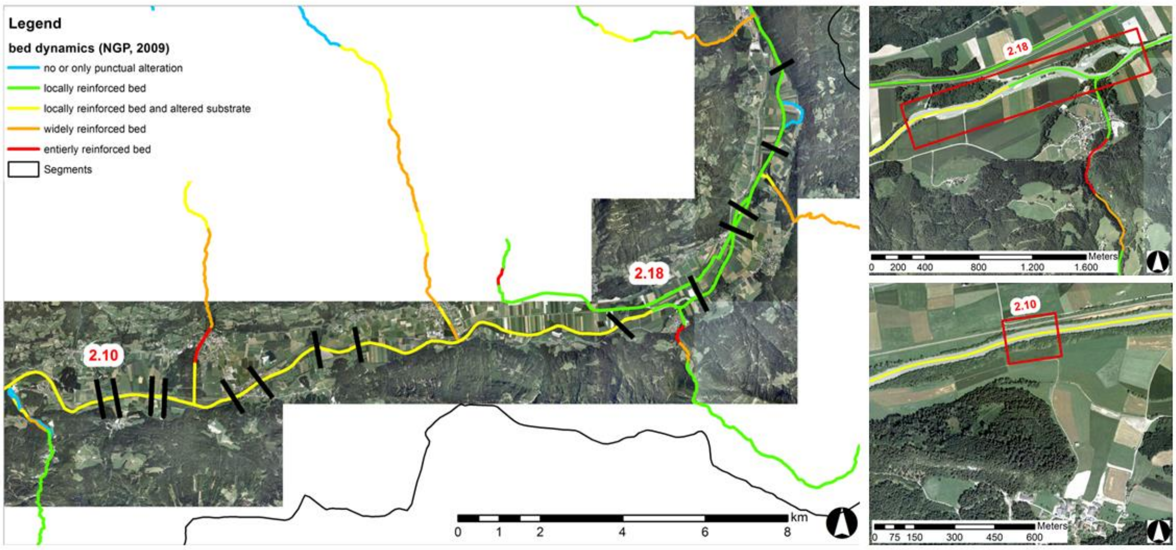


Figure 4.51 Assessment of bed dynamics within the scope of the national river basin management plan (NGP, 2009).

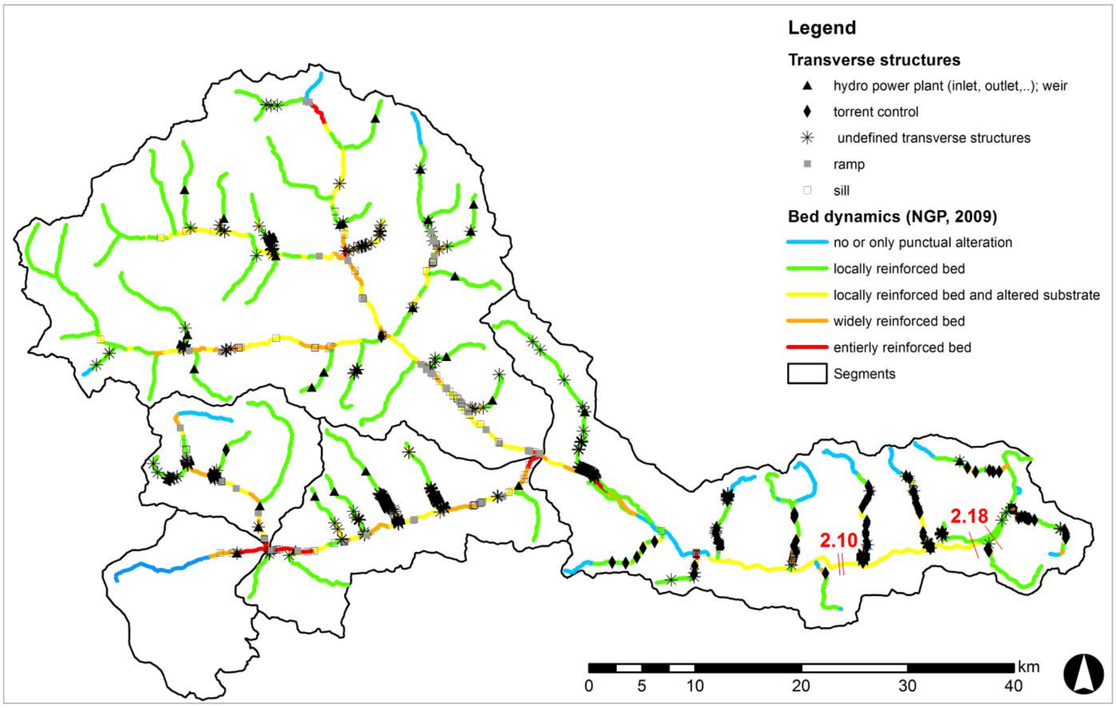


Figure 4.52 Overview of transverse structures and results of assessed bed dynamics (BMLFUW, 2010).

In the regulated reach (2.10), riparian vegetation is continuously present on both banks. The lateral extent is small, about 8 m on the northern bank and 30 m on the southern bank. The vegetation structure is homogeneous and the canopy cover is dense. For the restored section, a vegetation map is available for the downstream part (Figure 4.53). Within the side channel, different vegetation phases are present (e.g. pioneer phase, herbs and shrubs) and their structure (stand density, species composition,…) is diverse. On the floodplain areas, early successional woodland is the dominant vegetation phase. The canopy cover is dense and the structure is homogeneous.

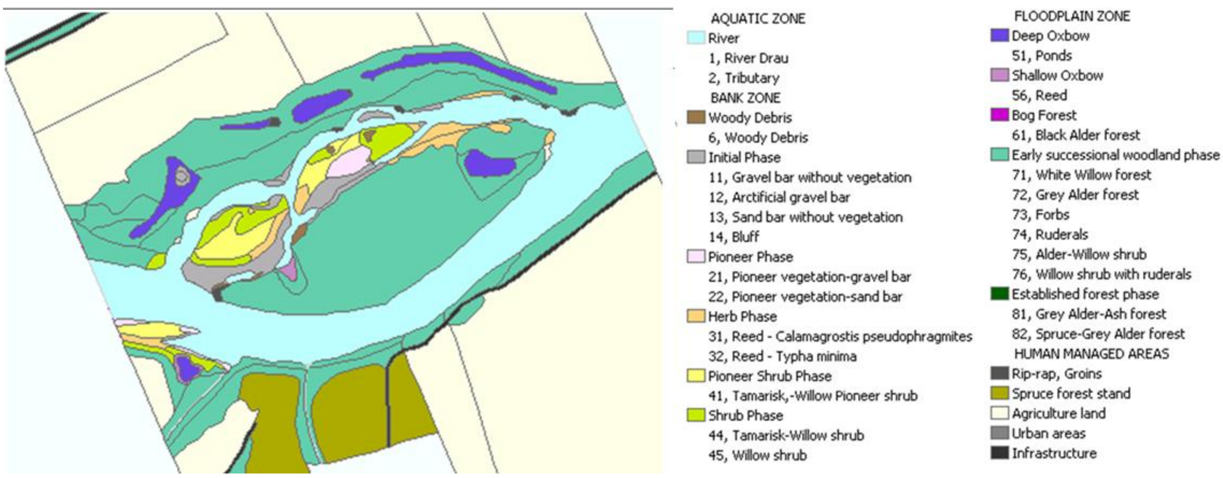


Figure 4.53 Riparian and aquatic vegetation at Kleblach (Angermann et al., 2011).

5. Characterising temporal change of spatial units

Temporal changes of spatial units are only evaluated for the Upper Drau catchment.

5.1 Catchment and landscape unit

Changes in land cover, precipitation, discharge and groundwater levels were assessed at the catchment and landscape unit scale. In the period 1950 to 1995 different trends in land cover changes were observed (Figure 5.1). The share of extensive grassland and arable land decreased in favour of forest, artificial surfaces and intensive grassland (Krausmann et al., 2003). This development might have had different impacts on the runoff and sediment production. Forests are areas with delayed runoff-production. As these areas increased over the last 50 years the concentration time of water might have increased and flood-risk decreased. However, as artificial areas, which account for a rapid runoff-production, also increased the effect of forests might be balanced or even reversed.

In terms of sediment production, the decrease of arable land in favour of woodland or grassland might have decreased soil erosion and thus fine sediments entering the river. However, there is a big difference in soil erodibility under different crops (e.g. maize and grains), but also farming practices have an impact on soil erosion rates.

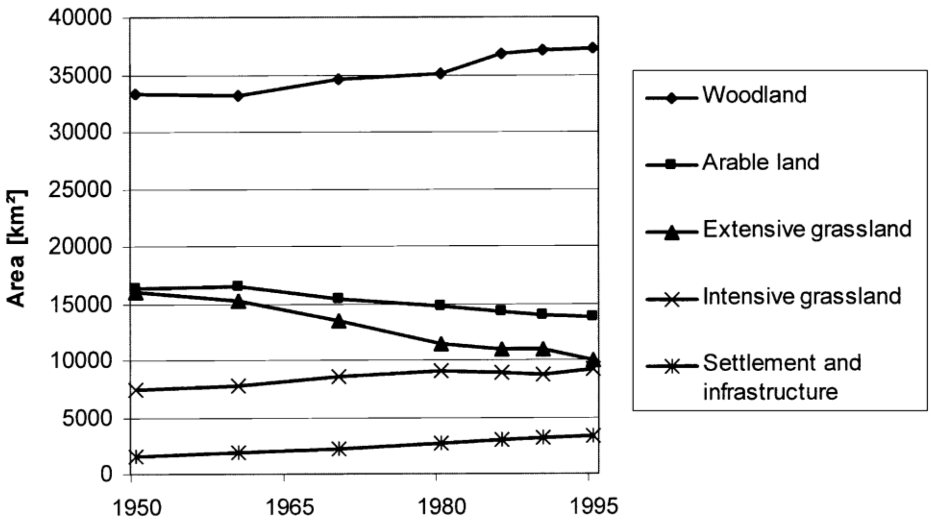


Figure 5.1 Aggregated land-cover changes in Austria 1950-1995 (Krausmann et al., 2003).

A more detailed analysis of land cover changes from 1990 to 2000 is based on Corine land cover data. Not all trends reported in Krausmann et al. (2003) were detected in the Corine land cover changes. The results indicate that land cover has changed in less than 1 % of the catchment area (segments: 0, 1, 2 Villgratenbach and Isel), and more than 90% of these changes can be allocated to decreases in the area of glaciers and perpetual snow in favour of bare areas (Table 5.1). The locations of land cover changes are illustrated in Figure 5.2. Similar to the results of Krausmann et al. (2003), a decreased proportion of pasture (extensive grassland) and increases in artificial surfaces were observed. The increasing trend in woodland could not be confirmed by the Corine data set.

Table 5.1 Land cover changes 1990-2000, at the Upper Drau catchment – upstream of Sachsenburg.

Land cover changes 1990-2000	area [km²]
Mineral extraction sites to mixed forests	0.07
Pastures to discontinuous urban fabric	0.21
Pastures to mineral extraction sites	0.07
Pastures to non-irrigated arable land	0.84
Pastures to complex cultivation patterns	0.18
Complex cultivation patterns to discontinuous urban fabric	0.15
Broad-leaved forest to Mineral extraction sites	0.11
Coniferous forest to natural grasslands	0.36
Glaciers and perpetual snow to bare areas	**21.76**

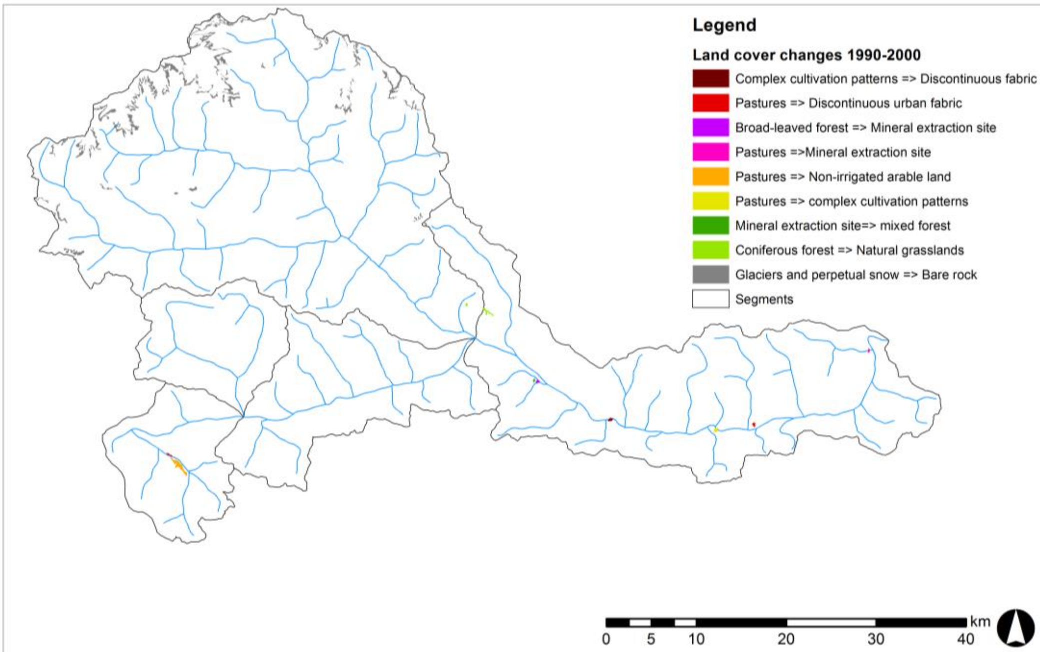


Figure 5.2 Locations of land cover changes 1990-2000.

Changes in precipitation and discharge were observed over the period 1951 to 2000 (Table 5.2). In 72,5% of the catchment area a decreasing trend of precipitation was observed, but only in 15% of the area was the change significant. In terms of discharge development, a decreasing trend was observed in almost half of the drainage area. In 39,7% of the catchment area the decreases were significant. The spatial distribution of these trends are shown in Figures 5.3 and 5.4. Both investigated reaches are located in areas with decreasing precipitation and discharge.

Table 5.2 Changes in precipitation and discharge over the period 1951 to 2000.

Changes in % per year	Share on entire catchment area [%] – Upper Drau till Sachsenburg	
	Precipitation	Discharge
-0,005 to 0,005	21,4	45,0
-0,025 to -0,005 not significant	57,5	9,2
-0,025 to -0,005 significant	15,0	39,7
Outside of Austria	6,1	6,1
Decrease (total)	**72,5**	**48,9**
No change	**21,4**	**45,0**

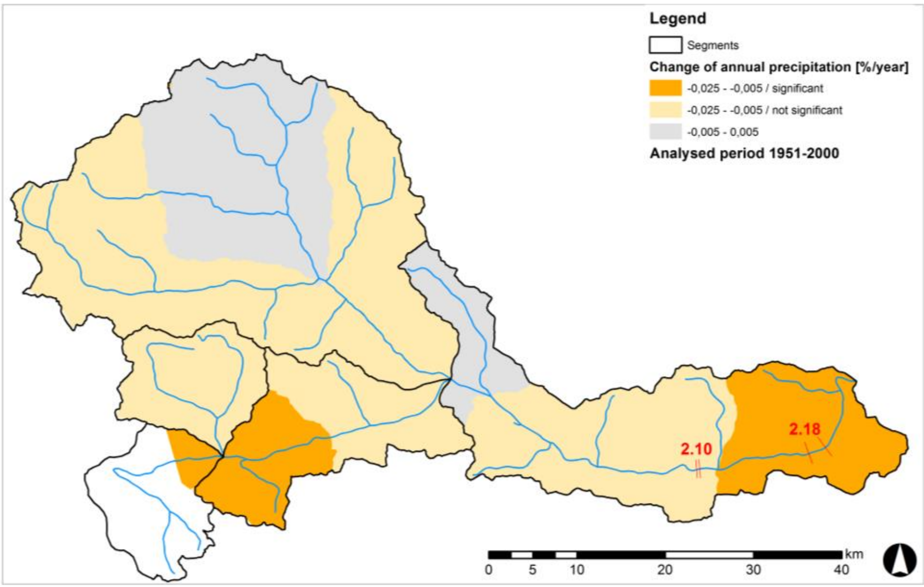


Figure 5.3 Change of annual precipitation based on the period 1951 to 2000 (HAO, 2007).

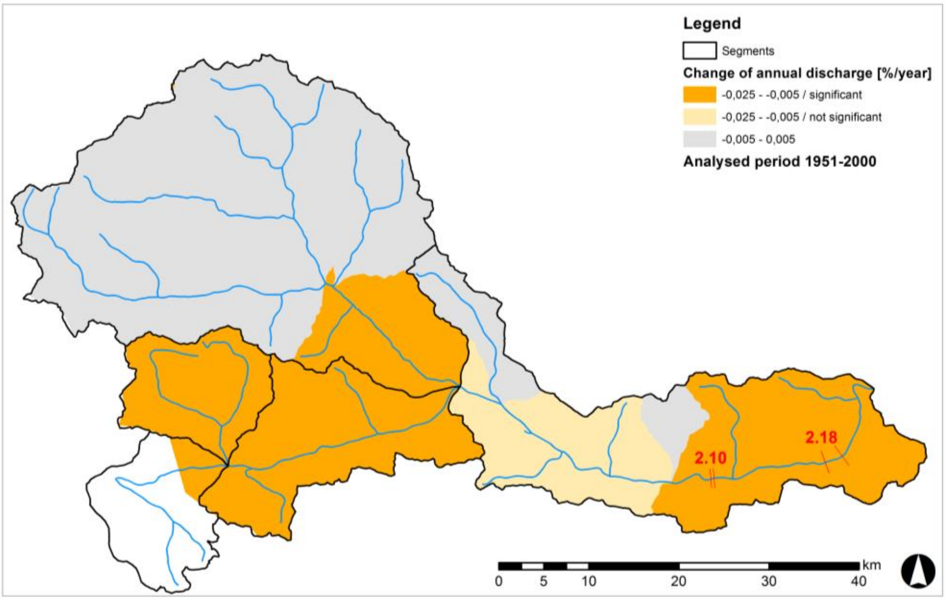


Figure 5.4 Change of annual runoff based on the period 1951 to 2000 (HAO, 2007).

The research period of groundwater level development was not as long as those for precipitation and discharge analyses. Decreasing water levels were identified in the area Lienz (Figure 5.5). However, most of the groundwater bodies at the Upper Drau catchment were not investigated.

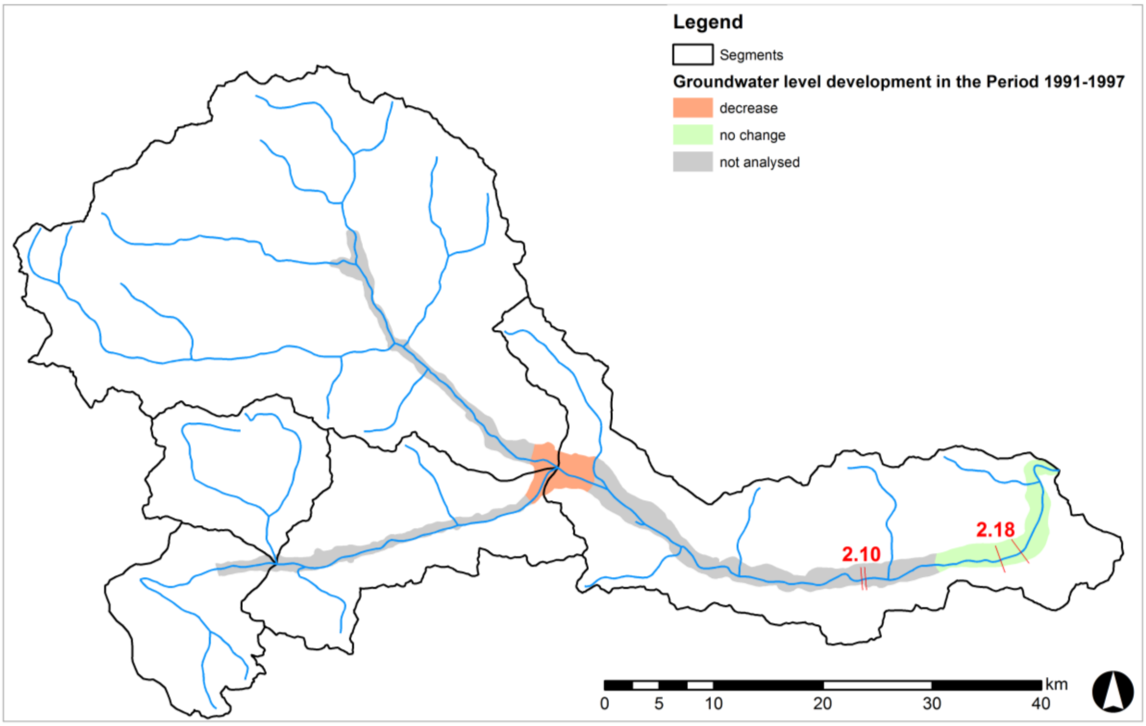


Figure 5.5 Changes in groundwater levels from 1991 to 1997 (HAO,2007).

5.2 Segment

Most data was available for the Carinthian part of segment two. This is also the section were most of the river restoration measures were realised. Therefore, mainly this part of the Upper Drau River was analysed. Changes of water levels (Figure 5.6) and changes in the thalweg (Figure 5.7), are illustrated for the last twenty years.

From 1991 to 1998 (Figure 5.6, blue line), river degradation occurred at several locations, especially in the section between Gröfelhof-Stein and Radlach, and Kleblach-Lind till Sachsenburg. Aggradation, indicated by a raise of water levels, was present only at a few locations. After the implementation of restoration measures at Gröfelhof-Stein, Dellach, Feistritzbach-Berg, Greifenburg-Amlach and Radlach, incision stopped and bed levels started to aggrade. Nevertheless, in other areas river bed degradation was still present (e.g. between km 615 and km 618, and downstream of Oberdrauburg, Radlach and Sachsenburg). Between 2008 to 2013 only one restoration measure (Obergottesfeld) was implemented. This measure caused a major change in the bed levels (Figure 5.6, green line). Within the restored reach and some kilometers upstream the bed levels increased. In contrast, at the downstream end of the meassure, the river bed incised.

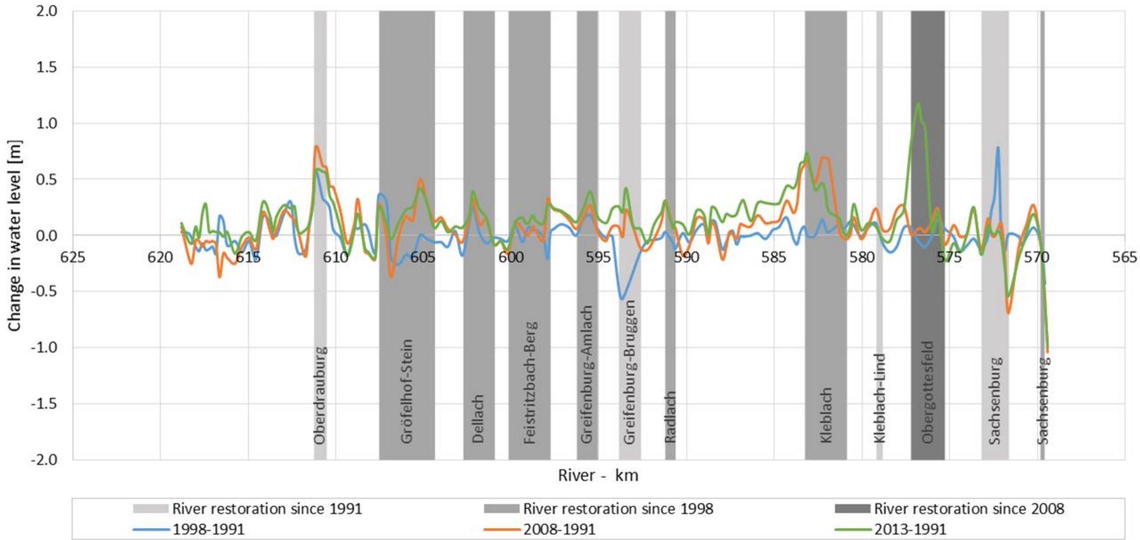


Figure 5.6 Water level changes at low flow along the upper Drau River (only Carinthian part). The water level of 1991 was used as reference. River restorations are indicated by the grey, vertical bars.

By evaluating changes of the thalweg elevation, trajectories similar to those of the water level changes can be detected. The thalweg decreased from 1991 to 1998 (Figure 5.7, blue line). Due to the implementation of restoration measures in the period 1998 to 2008, the bed levels increased in several locations (Figure 5.7, orange line). Between 2008 to 2013 (Figure 5.7, green line), the change in the thalweg elevations were small. This again indicates, that the rate of change has been slowed down.

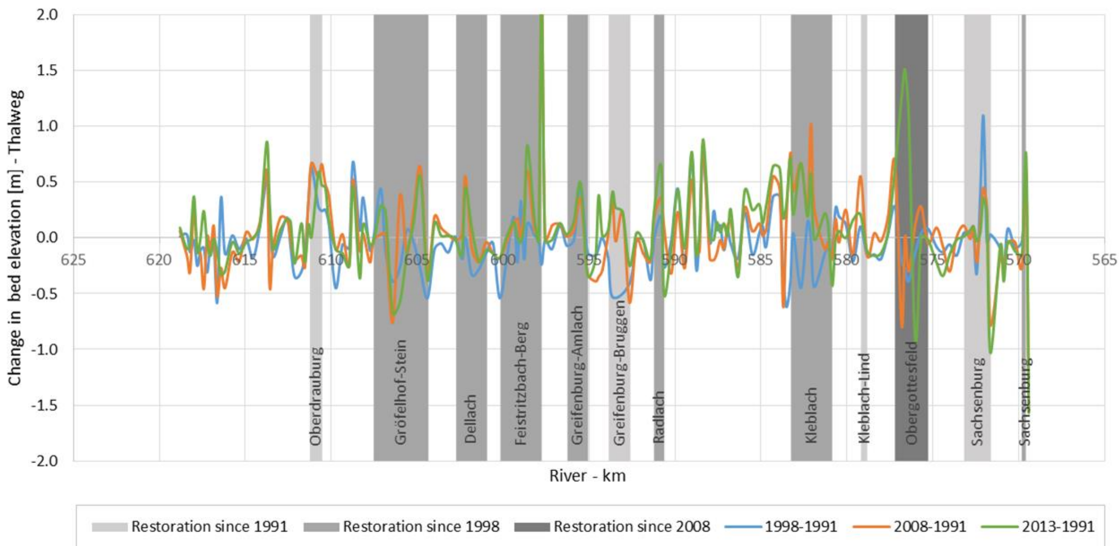


Figure 5.7 Change of the thalweg in the period 1991 to 2013 for the Carinthian part of the Upper Drau River. The thalweg elevation of 1991 was used as reference height.

Hydrological alterations (water diversion and hydro-peaking) at the Upper Drau catchment are presented in Figure 5.8. The runoff of a small part of the catchment (0,6%) is diverted to another catchment. Many other water diversions, where the water is returned to the same river, are also present within the drainage area. This kind of water diversion is indicated as residual flow sections. Most of them are located at tributaries. However, within segment one the Drau is directly influenced by such an alteration. In addition to the residual water stretches, areas which are impacted by hydro-peaking are also illustrated. The Drau River is directly affected by hydro-peaking only in the locality of Lienz.

The locations of transverse structures which might cause alterations to the sediment continuity are depicted in Figure 5.9. It can be assumed that weirs (mainly for hydropower use) have a major impact on the sediment regime, as large amounts of coarse sediments (bed load) are trapped upstream of these structures. In terms of torrent controls, the type and function of each structure determines the throughput ratio of sediments. However, as it is the purpose of such a structure to retain sediment up to a certain degree, the sediment regime is impacted. Within the catchment area many other undefined structures are present. Most of them can be expected to impact on the sediment regime. All structures have at least an impact on the temporal progress of the sediment transport. In Figure 5.10, areas which can not or can not fully contribute to the downstream sediment regime are indicated. In total, 69% of the catchment area of the Upper Drau is detached by structures, 34% by weirs, 23% by torrent controls and about 12% by undefined structures.

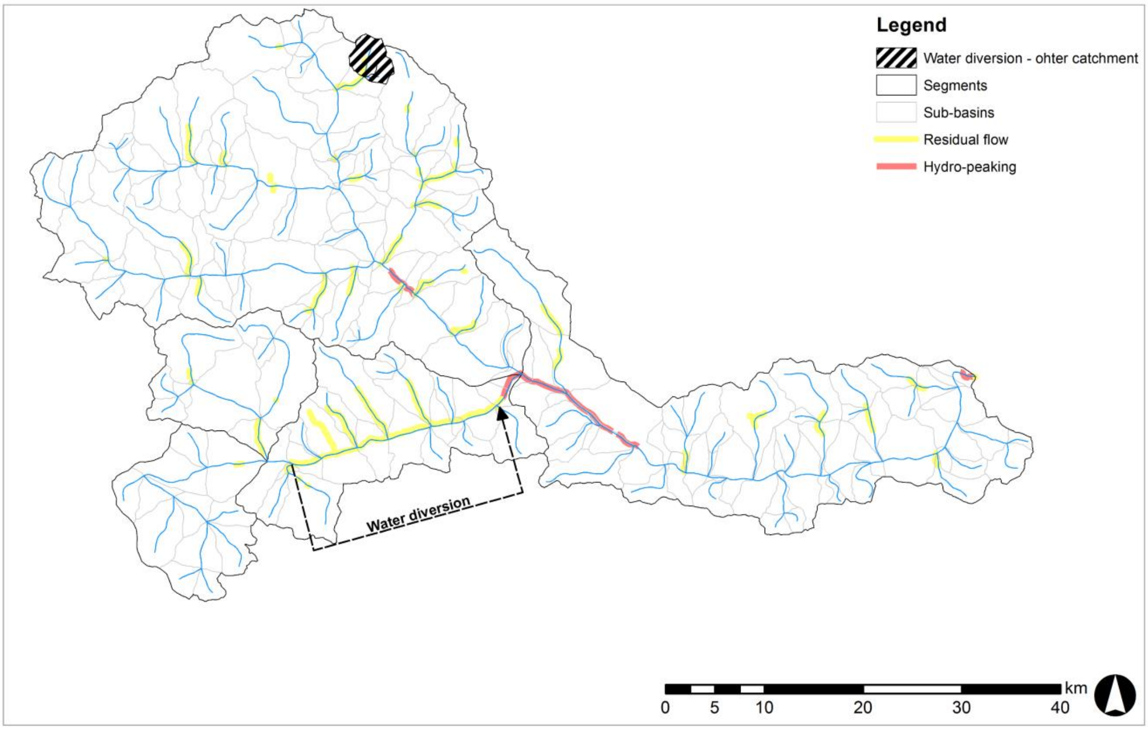


Figure 5.8 Alterations of the hydrology by anthropogene impacts e.g. water diversion into other catchments (area: ~15,23km²), hydro peaking and residual flow.

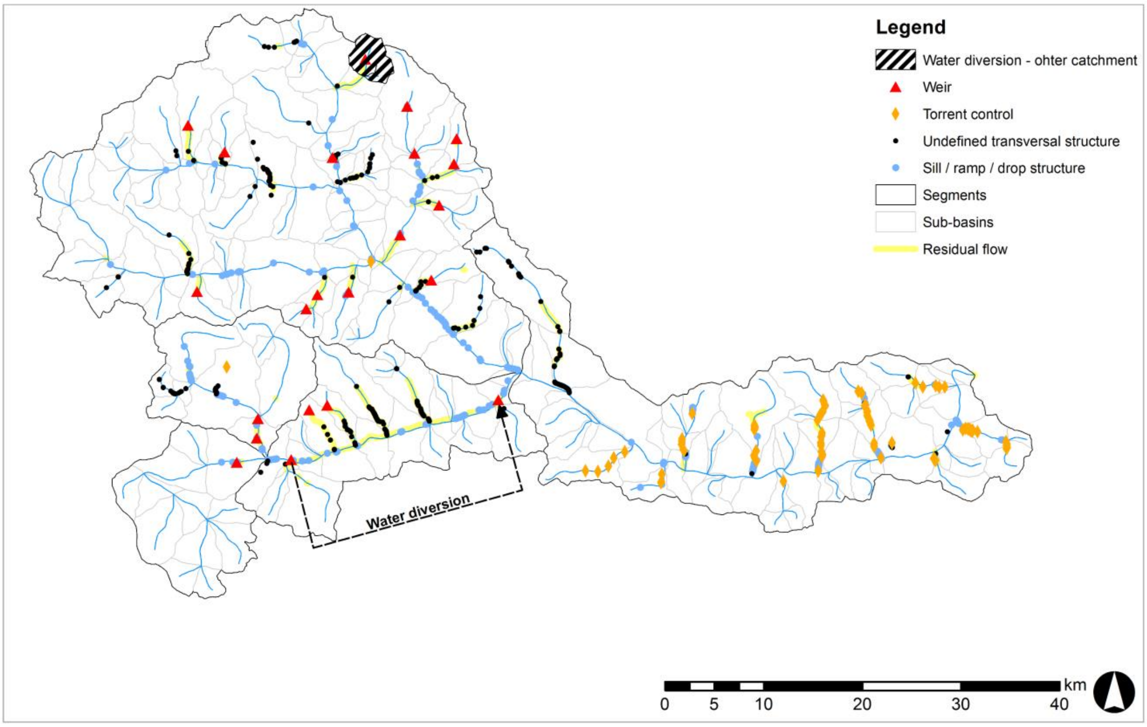


Figure 5.9 Interruption of the natural sediment regime by different structures.

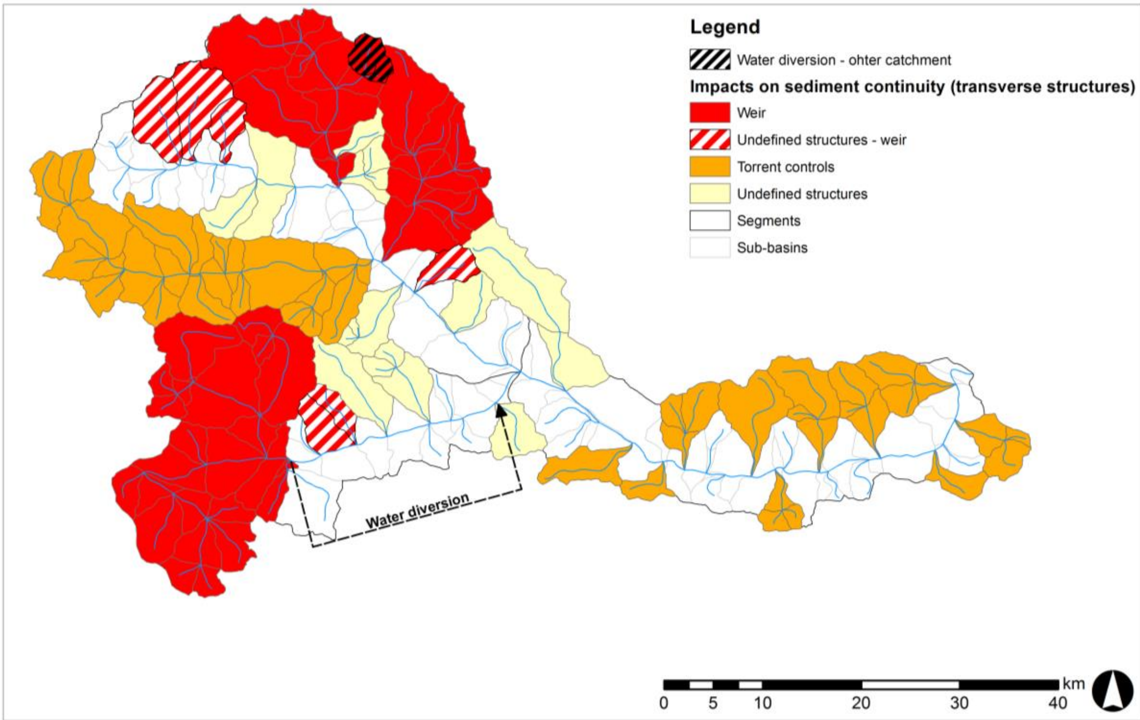


Figure 5.10 Areas which can not or not fully contribute to the downstream sediment regime.

Changes in riparian vegetation and channel setting were also evaluated (Table 5.3). In general it can be said that since the river regulation of the Drau, vegetation succession starting with pioneers is no longer possible over long stretches. The main reason for this is the absence of recruitment areas. Succession of already present riparian vegetation (e.g. from early successional woodland to mature forest) can occur only on the floodplains. However, in the restored reaches a more natural development of riparian vegetation is possible. Depending on the morphodynamics and the geomorphological features, areas appropriate for recruitment can be available.

Table 5.3 Changes in riparian vegetation extent and channel setting.

River section	Riparian vegetation		Changes in channel setting
	Franzisko-Josephinische Landesaufnahme (1870-1873) / Franziszeischer Kataster (1822-1828)	Google Earth (present situation)	
Untervierschach - Sillian	No extensive riparian areas	Trees/shrubs along the river, with minimal lateral extension, seems to be only one row of trees.	The channel setting has not been changed much over long stretches. Only in a small area downstream of the border to Italy, the river was straightened.
Sillian - Abfaltersbach	No extensive riparian areas	Trees/shrubs along the river, with minimal lateral extension, seems to be only one row of trees.	In the area of Tassenbach, the river was regulated before 1870. The original course and the regulated one are indicated in Figure 5.11. This is also the location where a weir for water diversion (hydropower use) was constructed.
Abfaltersbach – Leisach (water diversion / residual flow section)	In some sections, riparian areas cover up to 75% of the valley bottom. However, the valley is very narrow (confined section).	The riparian areas from 1870 are still present along most of the river.	No changes in channel setting
Leisach - Lienz	At Amlach, riparian forest is present at both banks (lateral extent is about 150 m on the right and about 35 m on the left). Further downstream no riparian forest is indicated on the map.	The riparian areas from 1870 are still present from Leisach till Amlach, but between Amlach and Lienz the lateral extent is very small.	The channel setting has been changed before the surveys of 1870 were carried out. The former sinuous to meandering section of the river was regulated and straightened (Figure 5.11)
Lienz -Wacht	About 300 m downstream of the confluence with the Isel, a continuous riparian forest, with extensive lateral extent (about 0,5 km) starts on the right bank. On the left side, the continuous riparian forest starts further downstream and it exhibits a smaller lateral extent (150 to 200 m at maximum).	The longitudinal extent of the riparian forest is comparable with the extent of 1870, but the lateral extent has been strongly decreased (20-30 m or less). Instead of the riparian forest, the area is used for agriculture.	Before 1870, river regulation measures were carried out at this section. The former braiding section of the river was narrowed to a straight, single thread river (Figure 5.11).

Table 5.3 (continued)

River section	Riparian vegetation		Changes in channel setting
	Franzisko-Josephinische Landesaufnahme (1870-1873) / Franziszeischer Kataster (1822-1828)	Google Earth (present situation)	
Wacht till the Carinthian border	Continuous riparian forest is present at this reach. The riparian forest covers up to 50% of the valley bottom, but with variable extents on the left and right side.	A small riparian belt (about 10-20 m) follows the river course. The lateral extent of 1870 is not accomplished.	Small changes in channel setting were conducted before 1870.
Carinthian border - Stein	No riparian areas are present over large stretches. The surroundings of the river is mainly used as pastures. Only at some locations riparian forest is present, but only on one side of the river.	A small riparian belt is present along the river. The riparian extent from 1822 is mainly reached or even exceeded.	In 1822 the river was transitional, then it became regulated and, except at the river widening, it exhibits one thread.
Stein - Dellach	No riparian areas are present over large stretches. The surroundings of the river are mainly used as pastures.	A small riparian belt or at least single trees are present along the river.	Today the river planform is single thread but in 1822 the river was anabranching/braiding.
Dellach - Berg	Only few areas with riparian forest. The surroundings of the river are mainly used as pastures.	A small riparian belt or at least single trees are present along the river. In some areas the riparian extent is larger than in 1822 (e.g. at Berg)	The position of the river is more or less identical to the location in 1822. However, the former braiding/anabranching river planform was changed to a single thread river type.
Berg - Steinfeld	Only few areas with riparian forest. The surroundings of the river are mainly used as pastures.	A small riparian belt or at least single trees are present along the river (Figure 5.12).	The position seems to be identical to the past, but the planform transitional – braiding/anabranching has been altered to a single thread type.
Steinfeld - Lind	In the upstream part of this section (till Gajach) almost no riparian forest is present. Between Gajach and Kleblach on the northern bank, and at Kleblach at both sides a continuous riparian forest is present.	The extent of the riparian forest in 1822 is not reached (Figure 5.12).	The anabranching/braiding river of 1822 was regulated to a single thread one. In 2001 a river restoration measure was implemented and a side channel was installed.
Lind-upstream of Sachseburg	A riparian forest is present at one side of the river.	The extent of the riparian forest was decimated; however, a small continuous belt is still present.	In 1822 side channels were present, but after river regulation works a single thread river was engineered. In 2011, large parts of this reach were restored (including the installation of two side channels).
Sachsenburg till Möll	Almost no riparian forest is present.	The extent of the riparian forest is similar to the one in 1822.	Position of the river is unchanged; however, the river has been narrowed.

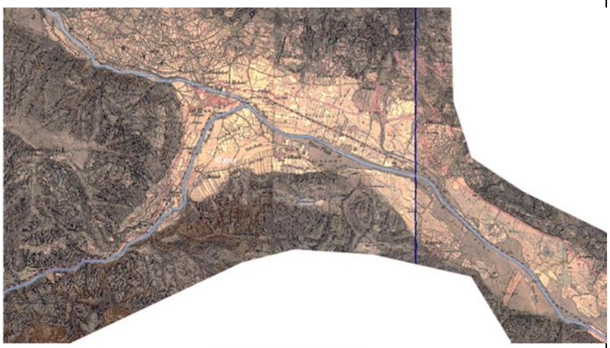
Sillian - Abfaltersbach	Lienz
	
	
	

Figure 5.11 Changes in channel position and planform from 1774 - Atlas Tyroliensis (top), 1870-1873 - Franzisko-Josephinischen Landesaufnahme (middle) to 2000/2004 (aerial photos, Google Earth).

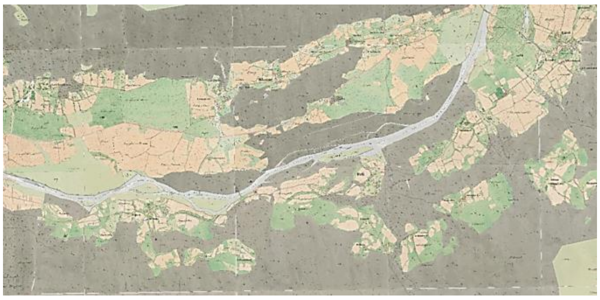
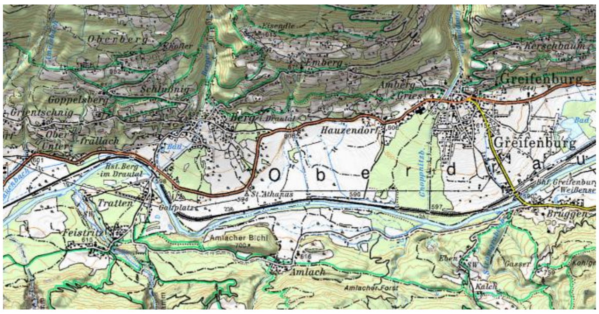
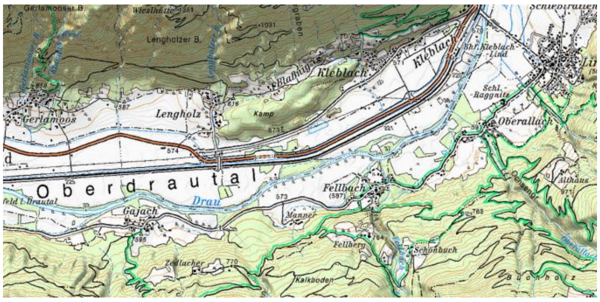
Berg-Greifenburg	Kleblach
	
	
	

Figure 5.12 Changes in channel position and planform from 1822-1828 – Franziszeischer Kataster (top), before river restoration 2001 (ÖK50, middle), to 2006 (aerial photos, Google Earth).

5.3 Reach

In this section only reaches 2.10 (regulated reach - Berg) and 2.18 (restored reach – Kleblach) are considered. Since the regulation works in the last century, the planform and channel geometry of reach 2.10 have not been changed. As shown in Figure 5.6 (section 5.2), an increase in water levels at low flow occurred over the period 1991 to 2013. The changes in the river planform of reach 2.18 are presented in Figure 5.13. In the regulated condition (before 2001) the river type was single thread. The restoration works included the installation of two side channels and river bed widening at several locations.

The development of the mean bed levels at Kleblach is presented in Figure 5.14 and the changes in thalweg are presented in Figure 5.15. Since the restoration measures were set, the mean bed levels of the river have increased and the degrading trend has stopped. Except in the downstream, the mean bed levels are significantly higher than during the regulated condition in 2001 (Figure 5.16). Since 2004, from about km 36,8-37,2 a decreasing trend in the bed levels is present.

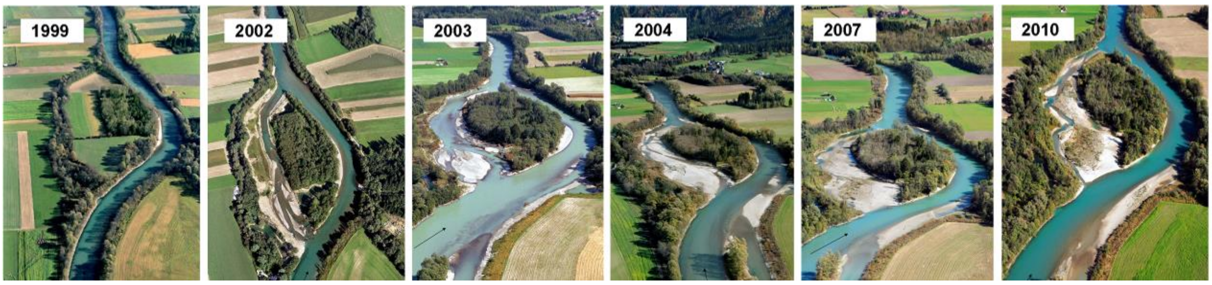


Figure 5.13 Development of the river restoration at Kleblech from 1999 till 2010 (pictures: Amt der Kärntner Landesregierung).

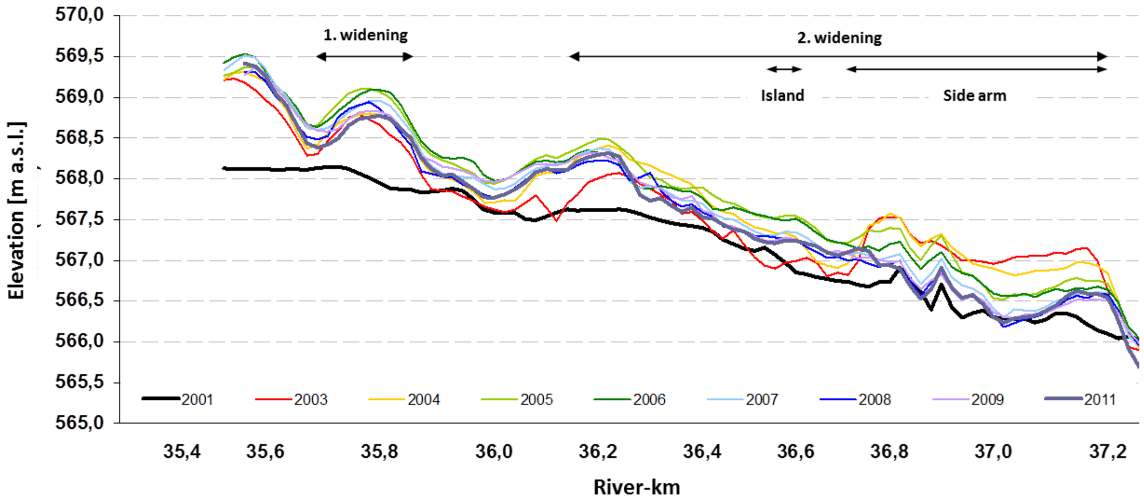


Figure 5.14 Development of the mean bed level of the main channel from 2001 (regulated) to 2011.

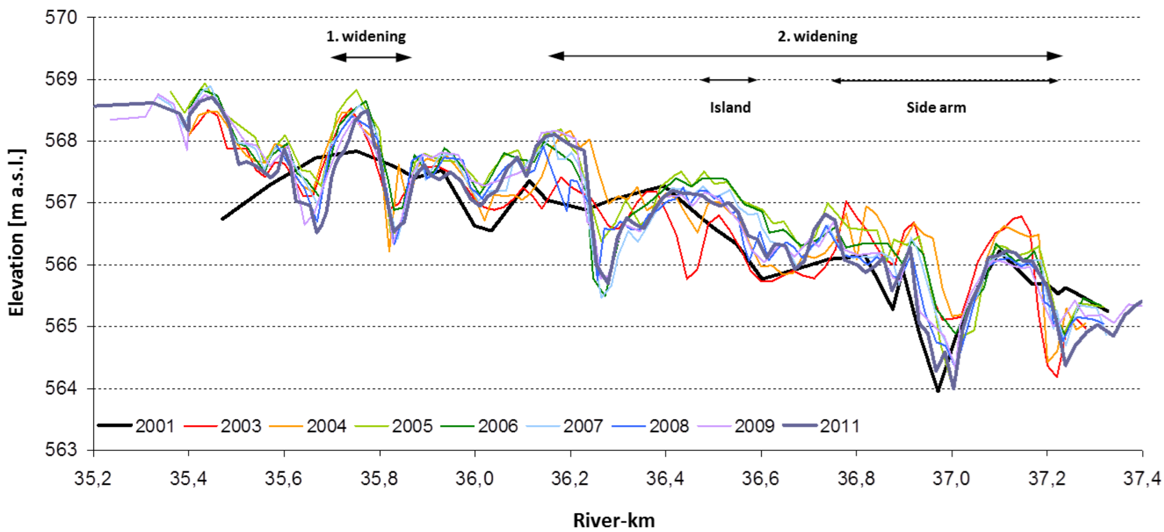


Figure 5.15 Changes of the thalweg of the main channel from 2001 to 2011 (Habersack et al., 2011).

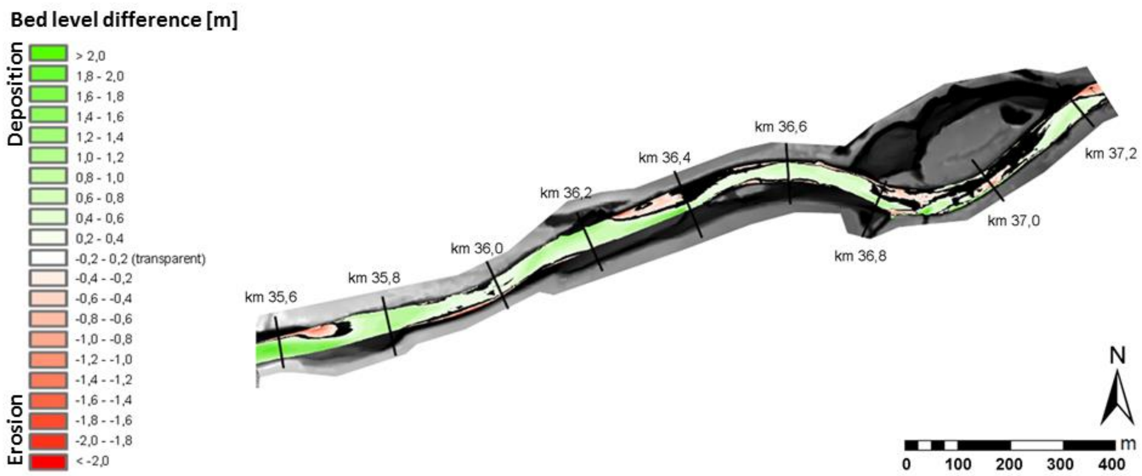


Figure 5.16 Bed level differences from 2001 to 2011, calculated for the river bed extent of 2001 – before restoration (Habersack et al., 2011).

The development of the wetted width (only the main channel) clearly indicates a high spatial variability compared to the regulated reach. The temporal variability is also visible in Figure 5.17 and it indicates that morphological changes (e.g. river bank erosion, aggradation,…) can occur. The variation in width and also the variation in depth (Figure 5.18) are important indicators for the ecological quality of the river reaches. Similar to the wetted width, the variation of mean and maximum depth has increased since the implementation of the measures.

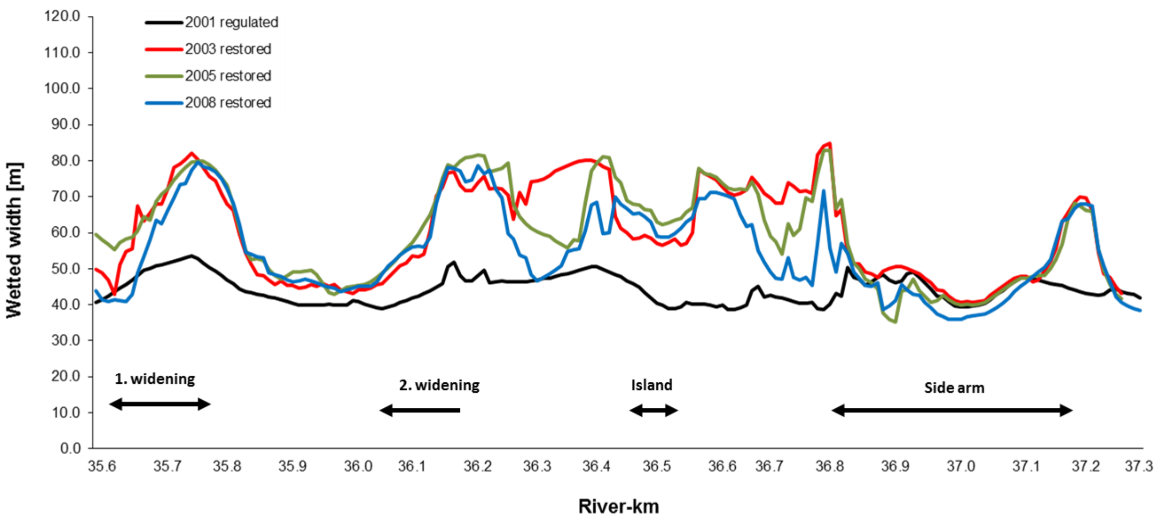


Figure 5.17 Variation of the wetted width of the main channel in Kleblach at mean flow (Q=73,8 m3s-1) from 2001 to 2008 (Habersack et al., 2011).

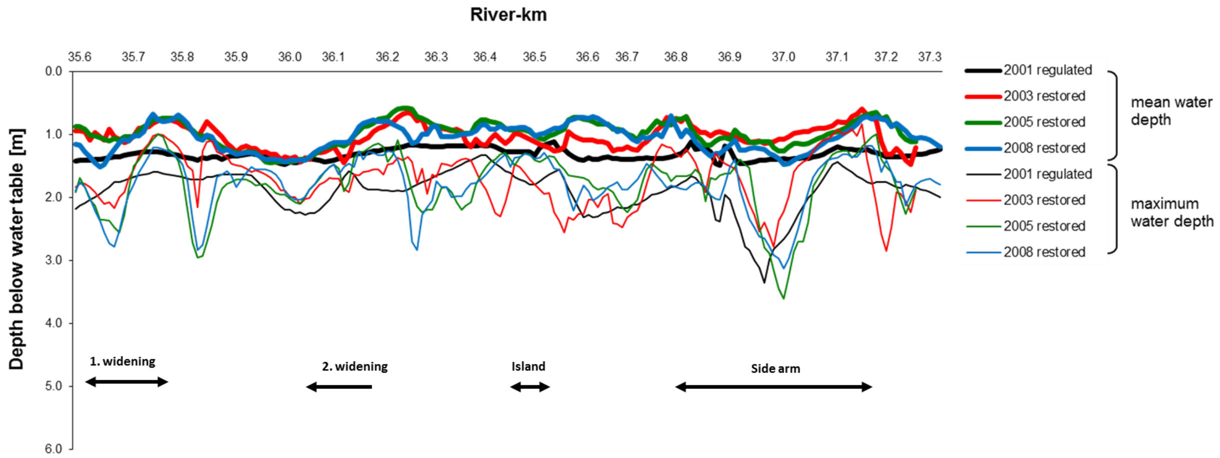


Figure 5.18 Variation of the mean and maximum depth in the main channel of Kleblach at mean flow (Q=73,8 m3s-1) from 2001 to 2008 (Habersack et al., 2011).

The changes of the bed levels and the channel width, due to the restoration measures and the self-dynamic widening have caused alterations of the flow parameters. In Figure 5.19, the spatial distribution of water depths and the wetted area are shown for the regulated (2001) and the restored (2008) condition. Analyses of the flow parameters (flow velocity (Figure 5.20), bed shear stress (Figure 5.21) and water depth (Figure 5.22)) for different discharges again reveal the higher variation of the parameters in the restored reach compared to its regulated state. This further indicates the higher quality and heterogeneity of aquatic habitats.

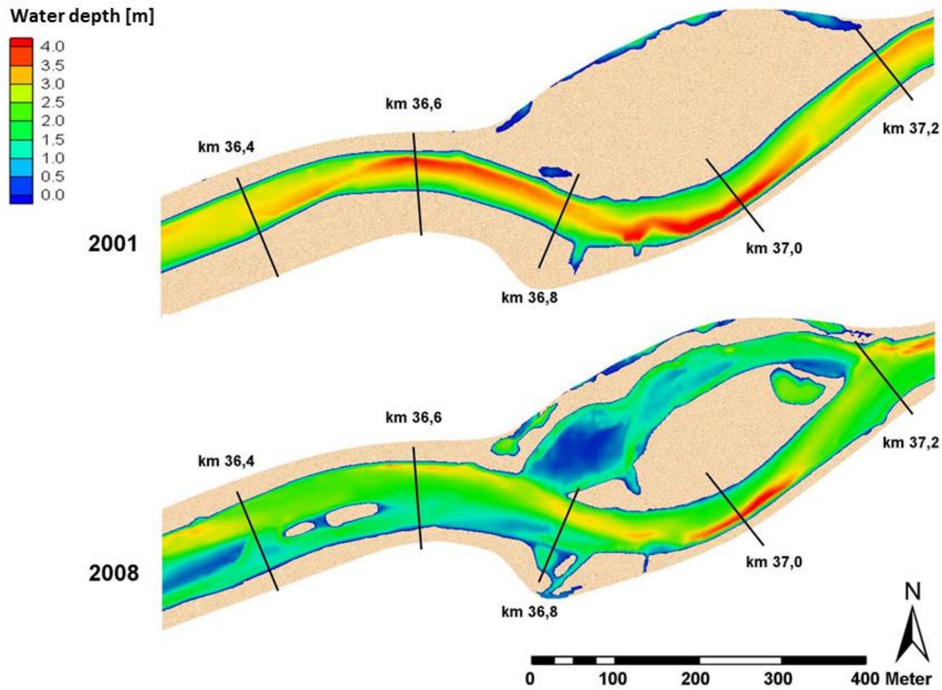


Figure 5.19 Spatial distribution of water depths and the variation of the wetted area at the regulated condition (2001, top) and the restored reach (2008, bottom) (Habersack et al., 2011). The modelled discharge is 260 m3s-1.

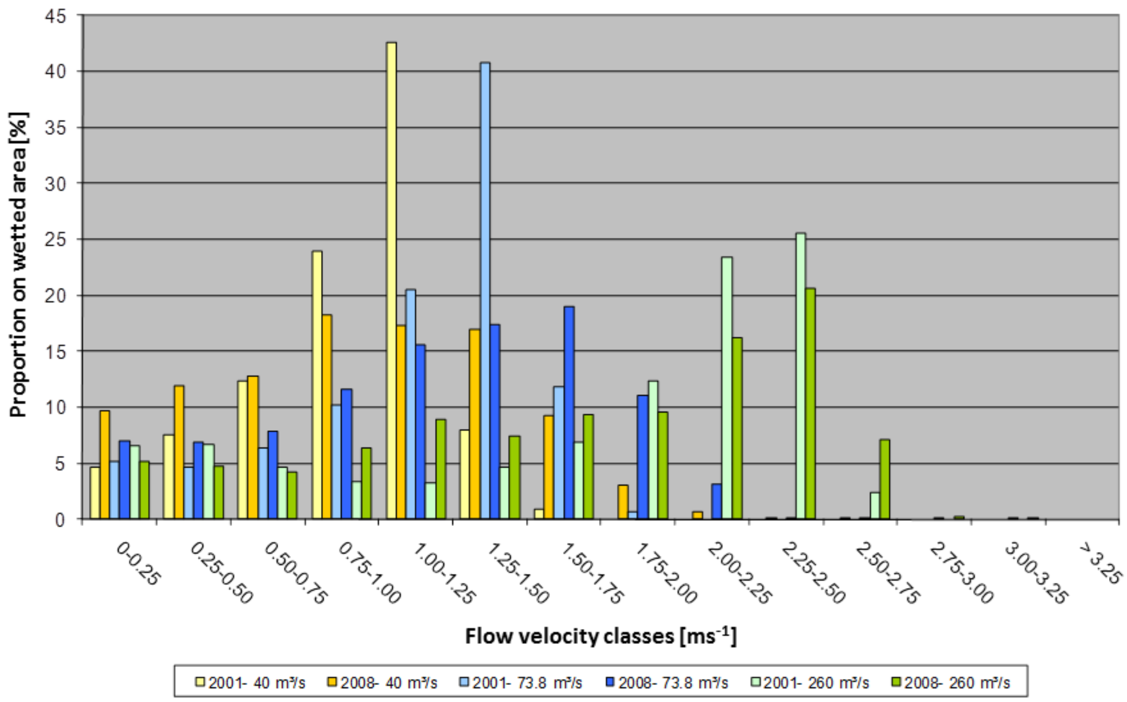


Figure 5.20 Distribution of flow velocities at different discharges (40 m3s-1, 73,8 m3s-1 and 260 m3s-1) in the regulated (2001) and the restored (2008) condition of Kleblach.

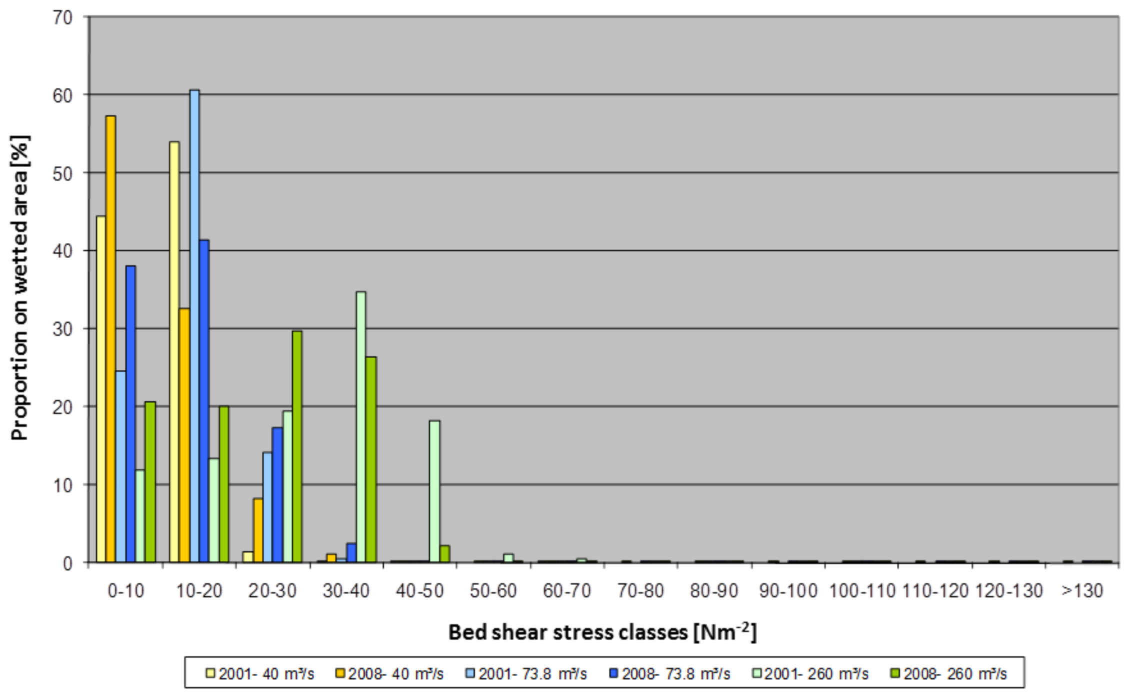


Figure 5.21 Distribution of bed shear stress at different discharges (40 m3s-1, 73,8 m3s-1 and 260 m3s-1) in the regulated (2001) and the restored (2008) condition of Kleblach.

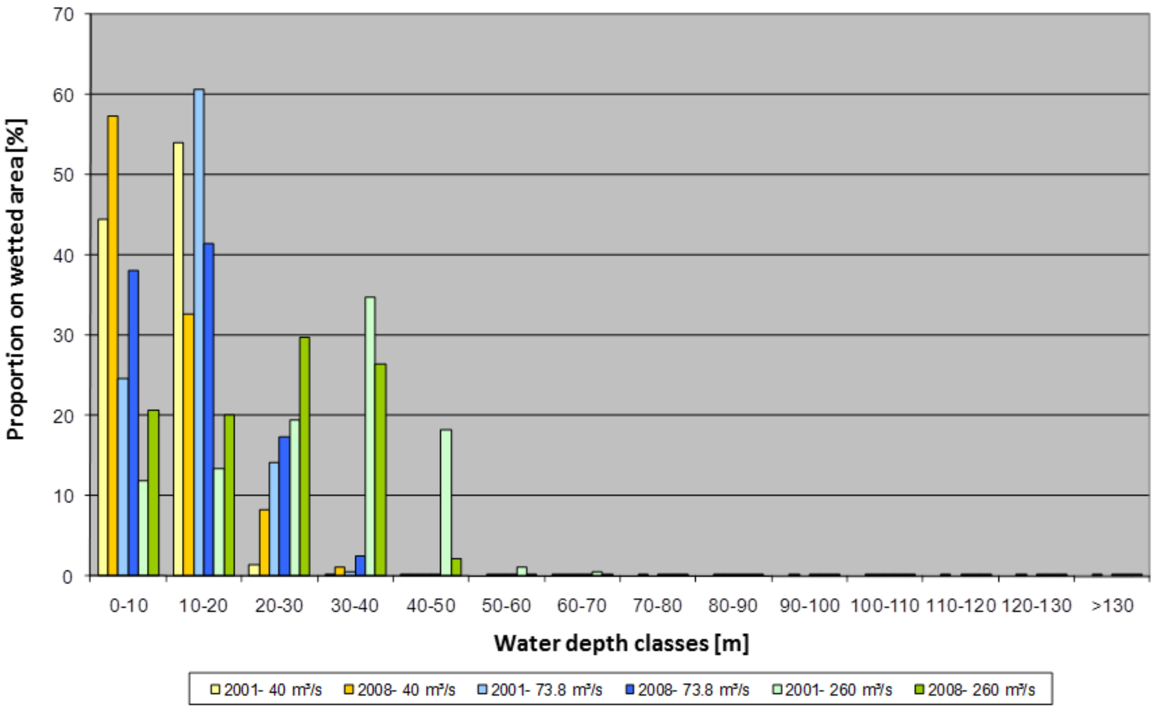


Figure 5.22 Distribution of water depths at different discharges (40 m3s-1, 73,8 m3s-1 and 260 m3s-1) in the regulated (2001) and the restored (2008) condition of Kleblach.

In Figure 5.23 and 5.24, changes of bed sediment calibre are shown for three different positions. Samples taken at the middle of the main channel show that the characteristic grain sizes tend to be higher in 1993 (regulated condition) than in 2011 (restored condition). Further, significant differences between the surface and the sub-surface grain sizes are visible at the restored condition. In the side channel, there is no trend (increasing or decreasing bed calibre) visible in the temporal development of the characteristic grain sizes.

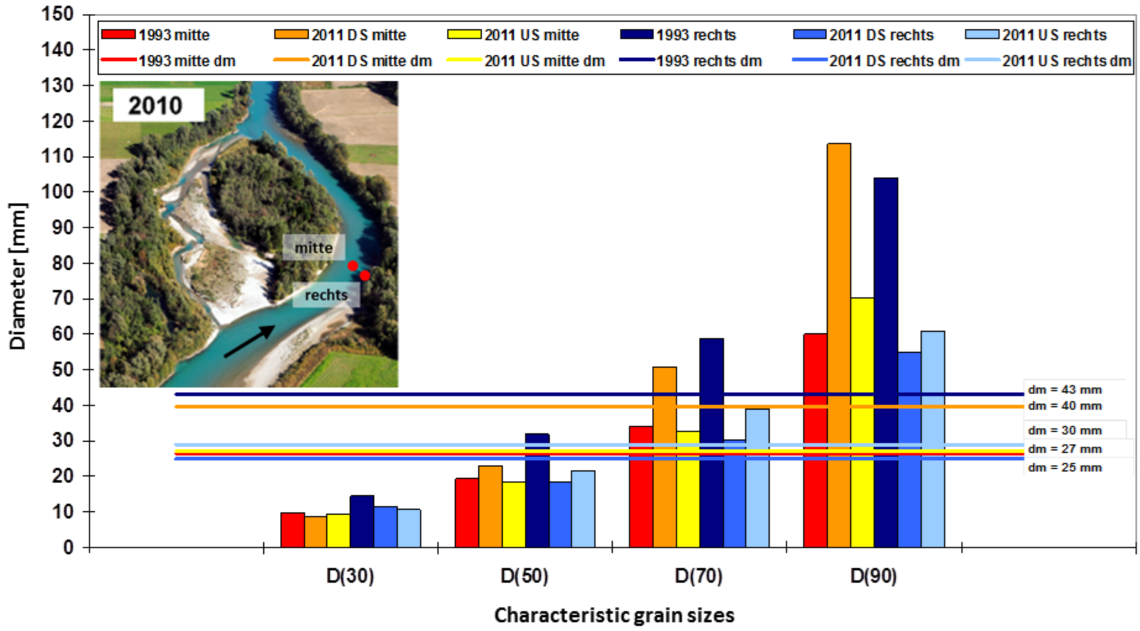


Figure 5.23 Variation of characteristic grain sizes (sub-surface … US, surface … DS) for two locations from 1993 to 2011 (Habersack et al., 2011).

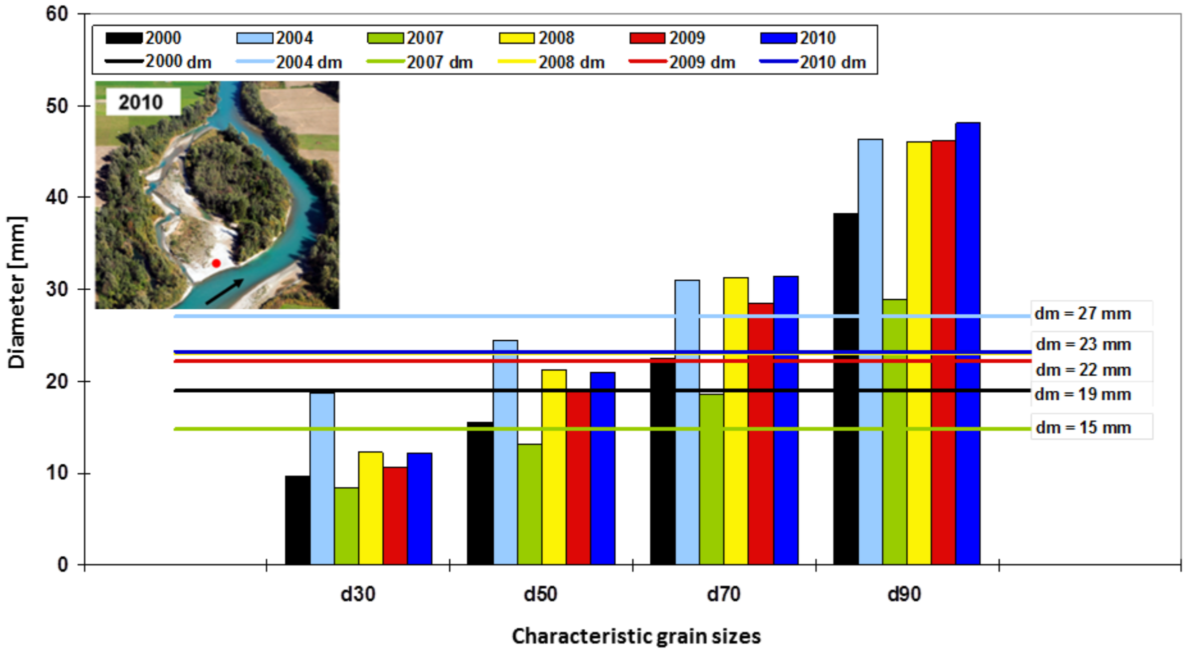


Figure 5.24 Variation of characteristic grain sizes in the side channel of Kleblach from 2000 to 2010 (Habersack et al., 2011).

6. Indicators of present and past condition

All indicators are evaluated only for the Upper Drau catchment, upstream from its confluence with the Möll River.

6.1 Catchment

About two thirds of the catchment area exhibits a siliceous geology and about 11% a calcareous one (Table 30). The remaining area is located in either quaternary/other sediments (17%), or no data was available (6%).

The water yield of 0,59% of the drainage area is transferred into another catchment, where it is used for energy production (hydropower plant). There are many other water diversions in the drainage basin, however, in these cases the water is always redirected back into the river from which it was abstracted.

90% of the Upper Drau catchment is covered with forests and semi-natural areas, including 2% of glaciers and perpetual snow. Between 1990 to 2000, a 0,85% change in catchment land cover was accounted for by a change from glaciers to bare areas This trend is expected to continue (APCC, 2014) and might cause changes in the hydrological regime and the fine and coarse sediment production.

Over the last 50 years (1950 to 1995), artificial surfaces and forested areas have increased (Krausmann et al., 2003). For example, the settlement area of the city Lienz has expanded greatly over the last 60 years (Figure 6.1).

Table 6.1 Indicators of present condition at the catchment scale.

Key process	Indicator	
Catchment area and runoff ratio	Drainage area (till the confluence with the Möll river)	2556 km²
	Water yield	927 mm
	Annual runoff ratio (average annual runoff/average annual rainfall)	0,72
	Water transfer into another catchment	
	Drainage area	15,2 km²
	Water yield	1300 mm
	Annual runoff ratio	0,84
Geology	Siliceous	66,5%
	Calcareous	10,9%
	Mixed / other	16,6%
	No data	6,0%
Land cover	Artificial surfaces	1,57%
	Agricultural areas	8,41%
	Forests and semi-natural areas	90,01%
	Wetlands	0,00%

Figure 6.1 Increase in urban and industrial, commercial and transport units, Lienz (https://portal.tirol.gv.at/LBAWeb/luftbilduebersicht.show).

6.2 Landscape unit

The landscape unit is dominated by parent material with a high permeability (about 79% of the entire catchment till Sachsenburg). Two percent of the area is covered with glaciers and perpetual snow. As indicated above, forest and semi-natural areas are the main land cover classes. These are responsible for a delayed runoff production. Areas of intermediate and rapid runoff production occupy a similar share of the entire area. In recent years, artificial areas and forests have increased. The impact on the runoff production is hard to determine.

The mean soil erosion rate based on PESERA (Kirkby et al., 2004) lies between about 560 and 101.580 t.ha^{-1}.year^{-1}. This is just a very rough estimate. Changes in the soil erosion rates can be expected as a consequence of changes in land cover and farming practices. For example, between 1990 to 2013 there has been an increase in the area under maize production (~1%, 7.528 ha, BMLFUW, 2014), which is more susceptible to soil erosion.

Table 6.2 Overview of indicators of present condition at the landscape unit scale.

Key process	Indicator	
Runoff production	High permeability (parent material)	78,7%
	Low permeability (parent material)	13,1%
	Glaciers and perpetual snow	2%
	Large surface water bodies	0%
	Area of rapid runoff production	31,6%
	Area of intermediate runoff production	27,5%
	Area of delayed runoff production	39,1%
Sediment production	Soil erosion rate [tha^{-1}yr^{-1}] (min and max for the entire catchment)	559 – 101.575
	Area with potential source of coarse sediment (bare rock and sparsely vegetated areas)	28,2%

6.3 Segment

The present condition of the segments are evaluated based on the water flow, the sediment regime and river morphological adjustments. Information concerning the hydrology of the Upper Drau River is given in Table 6.3.

The hydrology of segment one is influenced by a hydropower plant. Almost the entire downstream part of this segment is characterised as a residual flow stretch (reach 1.2 and 1.3). The residual flow in this area is larger than the MjNQt. In the other segments, residual flow reaches are located only at tributaries (see Figure 5.8). The downstream part of segment one and the upstream part of segment two (reach 1.4, 2.1 and 2.2) are affected by hydro-peaking.

Table 6.3 Indicators of present condition at the segment scale – water flow.

Key process	Indicator	Isel at Lienz	Drau at Lienz	Drau at Sachsenburg
Water flow	Flow regime type	Nivo glacial	-	Nival
	Average annual flow [m^3s^{-1}]	38,9	53,3	72,6
	Average monthly flow [m^3s^{-1}]			
	Jan	8,69	15,8	24,6
	Feb	7,37	13,9	22,5
	Mar	8,38	16,0	26,2
	Apr	15,6	26,3	42,0
	May	54,5	81,1	105
	Jun	99,6	125	165
	Jul	94,1	117	147
	Aug	72,0	85,6	112
	Sep	54,7	57,8	80,5
	Oct	28,8	46,3	62,4
	Nov	18,1	31,0	49,1
	Dec	11,9	21,2	32,4
	BFI (Base flow index)	0,32	0,34	0,41
	HQ1	-	-	320
	HQ2	-	-	380
	HQ5	-	-	490
	HQ10	-	-	590

Beside the impacts on hydrology, the sediment regime is also altered. As shown before (Figure 5.10), 69% of the catchment is more or less detached from the downstream parts of the Drau River. Major parts of the potential sediment production areas are located within this area. This causes decreased sediment inputs into the downstream sections of the river and thus, less sediment is available for transportation. Due to this impact (detached potential sediment delivery areas) and the river regulation measures over the last century (e.g. bank reinforcement, enhancement of the transport capacity of water and sediment) erosional tendencies and bed incision have occurred in segment two.

Three bed load and three suspended load monitoring stations are located in landscape unit one. The monitoring stations are located in segments one and two and on the Isel River. In Table 6.4, the suspended sediment load and the bed load is given for the three stations for the year 2010. Further indicators to characterise the present condition of the Upper Drau River are presented in Table 6.5. Further, it should be noted that over long distances the Drau River has been channelized (c.f. Table 5.3) and banks have been reinforced by rip rap.

Table 6.4 Indicators of present condition at the segment scale – sediment flow

Key process	Indicator	Falkensteinsteg (Drau)	Lienz (Isel)	Dellach (Drau)
Sediment flow	Suspended sediment load [tyr^{-1}]	75.41	766.417	629.368
	Bed load [tyr^{-1}]; D>22,4 mm	3.5	11.1	18.8

Table 6.5 Indicators of present condition at the segment scale – river morphology adjustments

Key process	Indicator	Segment 0	Segment 1	Segment 2
River morphology adjustments	Average valley gradient [‰]	05-Oct	Till Gailbach 2,5-5 Till Isel 10-20	<2,5
	Valley confinement	Semi-confined	Mainly confined	Mainly semi-confined
	River confinement (alluvial plain width/bankfull river width)	Jun-42	Mar-99	Aug-45

6.4 Reach

Channel self-maintenance (Table 6.6), channel adjustment (Table 6.7 and 6.8), vegetation succession and wood delivery (Table 6.9) are assessed at this scale to determine the condition of reach 2.10 and reach 2.18.

Reach 2.10 exhibits a higher specific stream power than reach 2.18 due to the smaller channel width and the higher channel gradient. The possibility for lateral adjustment through bank erosion is completely inhibited in the regulated reach (2.10), whereas in some parts of the restored reach (2.18) lateral erosion is possible.

Since 1822, the sinuosity, braiding and anastomosing indices have not changed for reach 2.10. However, small alterations of the braiding index were recorded for reach 2.18 and the anastomosing index decreased over this period from 2,16 to 1,32.

In both reaches the channel width is smaller compared to 1822. Nevertheless, the reduction in channel width is higher (reduction by about 33%) in the regulated than in the restored reach (reduction by about 21%).

In the regulated reach (2.10), no geomorphic features/units indicating narrowing/widening, aggradation/incision, or changes in bed sediment calibre could be determined. However, for the restored section features indicating aggradation are present, especially in the side channel. Additionally, features indicating narrowing could also be identified at the side channel.

Table 6.6 Indicators of present condition at the segment scale - channel self-maintenance.

Key process	Indicator	Reach 2.10 (regulated)	Reach 2.18 (restored)
Channel self-maintenance / reshaping	Specific stream power at HQ_1 and bankfull channel width [Wm^{-2}]	99	65
	Bed sediment size D50 [mm]	Assumed to be similar to the grain sizes of Kleblach in 2001 (regulated condition) 19,25	18,33
	Channel gradient [‰]	1,7	1,5
	Mean bankfull channel width	~54 m	~72 m (at HQ_1)
	Bankfull channel depth	~3,8 m	~2,6 m (at HQ_1)
	Width to depth ratio	14,2	27,7
	River type	13 (sinuous-straight, gravel-bed river)	11 (wandering, gravel-bed river)

Table 6.7 Overview of indicators of present condition at the segment scale – channel adjustments (I)

Key process	Indicator	Reach 2.10 (regulated)	Reach 2.18 (restored)
Channel adjustments (lateral migration planform change)	Eroding banks	none	In the side channel (SC) almost entire left bank; In the main channel (MC) at certain locations on the left bank
	Laterally aggrading banks	Not present	On the right side in the downstream part of the side channel
	Lateral channel migration rate [my^{-1}]	No lateral channel migration possible	Mean lateral erosion 0,5 (left bank SC) 0,3 (right bank SC) 0,3 (left bank MC) Max lateral erosion 1,9 (left bank SC) 1,4 (right bank SC) 3,0 (left bank MC)
	Changes in sinuosity index *	1,01 (1822) 1,01 (2014)	1,03 (1822) 1,03 (2014)
	Changes in braiding index *	1, no bars (1822) 1, no bars (2014)	1, no bars (1822) 1,42 (2014)
	Changes in anastomosing index *	1, no islands (1822) 1, no islands (2014)	2,16 (1822) 1,32 (2014)
* The reference condition for the evaluation of the indicated channel changes is the "Franziszeischer Kataster" from 1822-1828.			

Table 6.8 Indicators of present condition at the segment scale – channel adjustments (II)

Key process	Indicator	Reach 2.10 (regulated)	Reach 2.18 (restored)
Channel adjustments (narrowing/widening)	Changes in active channel width*	Decreased by about 33%	Decreased by about 21%
	Changes in active channel depth*	-	-
	Changes in active channel width to depth ratio*	-	-
	Presence of geomorphic features/units indicative of narrowing	None	Within the side channel, the upstream mid channel bar is becoming stabilized by vegetation.
	Presence of geomorphic features/units indicative of widening	None	-
Channel adjustments (bed incision/aggradation)	Presence of geomorphic features/units indicative for incision	-	-
	Presence of geomorphic features/units indicative for aggradation	-	In the side channel, the mid channel bars gain in elevation and vegetation is partially buried.
	Changes in bed sediment structure indicating incision	-	-
	Changes in bed sediment structure indicating aggradation	-	In the main channel, the grain sizes decreased from 1993 to 2011.
Channel adjustments (vegetation encroachment)	Aquatic/riparian encroachment	None	Present in the side channel, esp. in the upstream area (stabilization by vegetation)
Channel adjustments (constraints on channel adjustment)	Width of erodible corridor	No erodible corridor present	Narrow corridor present
	Proportion of potentially erodible channel margin	0	About 13% at both sides of the main channel
	Proportion of river bed that is artificially reinforced	0	0
	Number of high, intermediate, low blocking structures	None	None
* The reference condition for the evaluation of the indicated channel changes is the "Franziszeischer Kataster" from 1822-1828.			

Table 6.9 Indicators of present condition at the segment scale – vegetation succession and wood delivery

Key process	Indicator	Reach 2.10 (regulated)	Reach 2.18 (restored)
Vegetation succession (Riparian vegetation)	Proportion of riparian corridor under mainly … *	Mature and old trees 100%	Mature and old trees 97,6% Early growth to juvenile 9,8% Pioneers 2,6%
	Presence of wood- or riparian tree-dependent geomorphic units / features	Absent	Frequent in the side channel, occasional in the main channel
	In-channel wood accumulations	None	Present in the side channel.
Wood delivery	Channel blocking jams	None	None
	Wood in the riparian corridor	Negligible	Extensive in the side channel, negligible in the main channel
* Distribution of different age classes is based on the area covered by riparian vegetation and not the entire reach.			

In Figure 6.2, the flooded area in reaches 2.10 and 2.18 for different discharges are presented. The extent of the flooded areas shown by HORA (Natural Hazard Overview and Risk Assessment Austria) is only accessible when all flood protection measures fail. In terms of the two reaches, the railway dam (north of the river) causes a decrease in the flood extent.

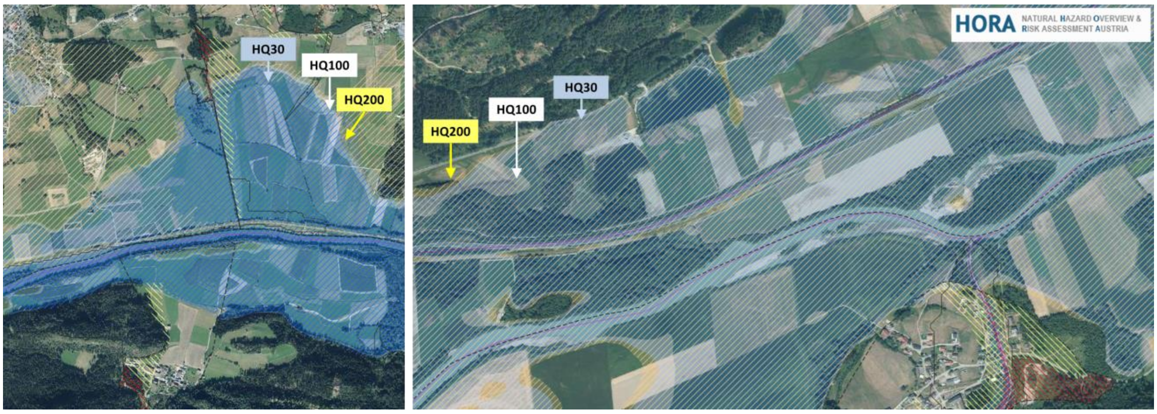


Figure 6.2 Extent of flooded area modelled with different discharges for reach 2.10 (left) and reach 2.18 (right)(data source: www.hora.gv.at).

7. Decision tree for catchment-based evaluation of the sediment regime and continuity

The application of the decision tree is exemplified here on a restored reach of the Drau River for the time period between 2008 and 2013.

7.1 Data collection

First, data has to be collected at the catchment level, which comprises data concerning sediment production and sediment barriers in the catchment upstream from the investigated reach. In the case of a catchment score of 4 (bad) or better, the data collection continues with the river network, where data concerning the sediment budget is relevant. Finally, if a river network score of 4 (bad) or better is obtained, data expressing the artificiality and the sediment budget of the investigated reach itself have to be investigated. In the case of reduced data availability, parameters which are necessary for the application of the decision tree have to be estimated.

7.1.1 Catchment data

(i) Data concerning sediment production

The following information was available for estimating the sediment production in the catchment upstream from the investigated reach:

- Areas of sub-catchments
- Topographic map of catchment
- Non- or sparsely vegetated areas in sub-catchments
- Geological map of catchment
- Average rainfall calculated for sub-catchments
- Volumes of loose, transportable sediment stored at the bottom of torrents

(ii) Data concerning sediment barriers

A map locating every barrier disabling fish passage and corresponding meta data was used for identification of sediment barriers in the catchment. Barriers were classified according to the permeability of the type of crossing structure for sediment transport (Figure 7.1). Sediment throughput coefficients were assigned to every barrier class. Together with the calculated sediment production in sub-catchments, the reducing effect of sediment barriers on sediment supply to the river network could be estimated.

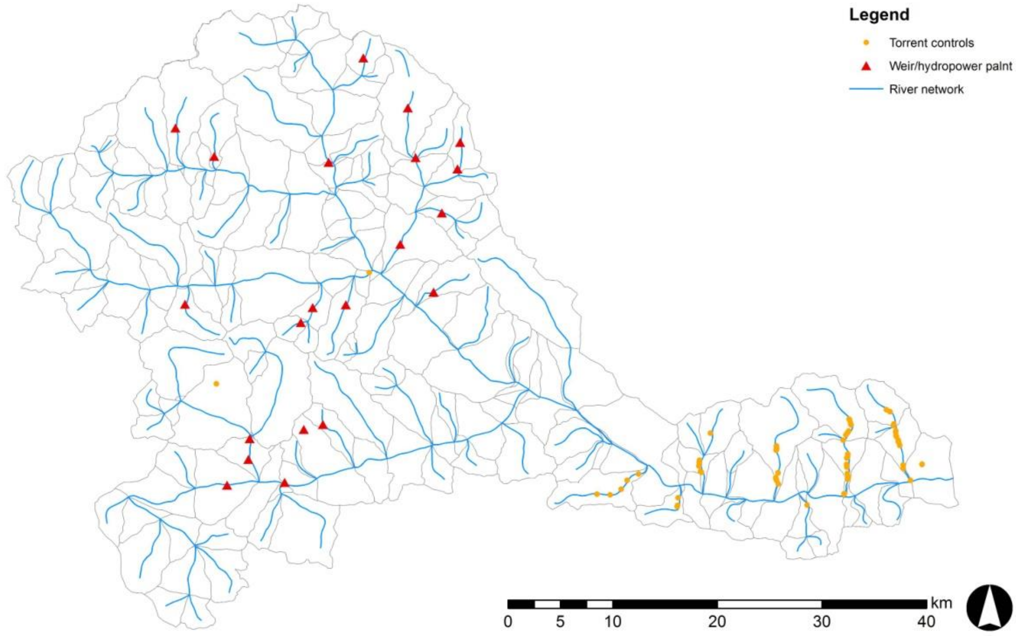


Figure 7.1 Sediment barriers in the catchment of the investigated reach at the Drau River. Throughput coefficients were defined according to the type of crossing structures.

7.1.2 River network data

(i) Data concerning the sediment budget

The Carinthian government have performed water level measurements during low flow in winter, in most years since 1886. Additionally, since 1991, 4 data sets of repeated cross section surveys are available. Both data sets allow investigation of bed level changes and corresponding sediment budgets. Large substrate samples along the entire Upper Drau River gave insight into downstream fining due to selective transport and abrasion (Figure 7.2).

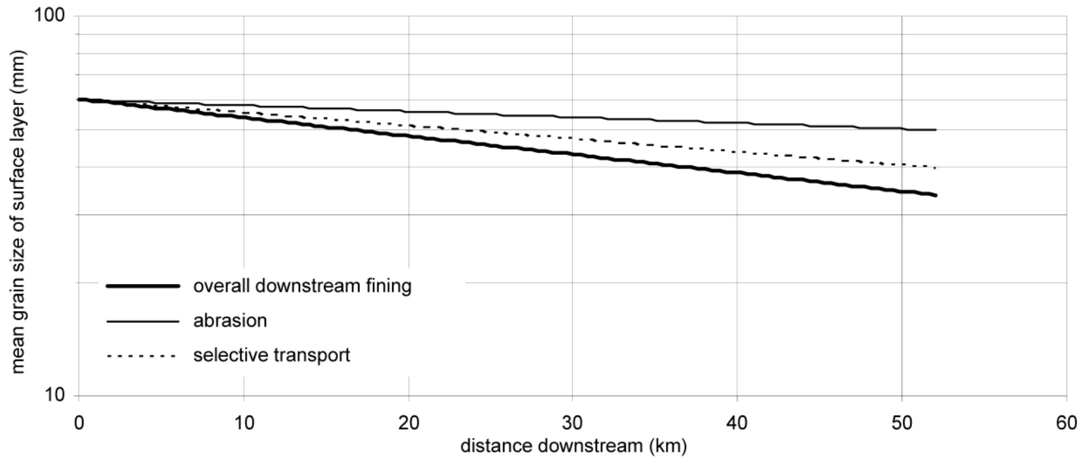


Figure 7.2 Effects of abrasion on grain size in the Upper Drau River (Habersack, 1997)

Substantial efforts have been made to measure sediment transport using basket samplers and bedload traps since the 1990s and there have been continuous measurements with geophones since 2006. These data allowed a bedload rating curve (Figure 7.3) to be established and bedload yields to be calculated.

Grain size analyses of riverbank sediments allowed assessment of the proportion of sediment which entered the river as bedload as a result of bank erosion.

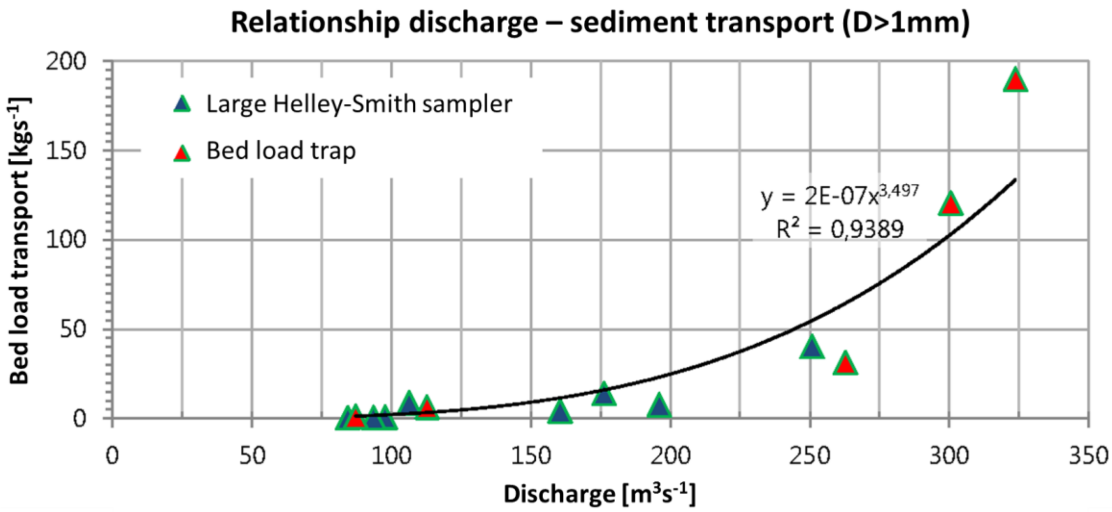


Figure 7.3 Bedload rating curve obtained at the bedload monitoring site in Dellach (Habersack et al., 2013)

(ii) Data concerning artificial sediment supply/sediment extraction

Intensive gravel mining up to the 1990s and sediment excavation during excavation works significantly has affected the sediment budget of the Upper Drau River. Habersack (1997) attested gravel mining to have caused 69% of the observed channel incision between 1931 and 1991. Hence, data was collected concerning dredging activities in the course of restoration works as well as data concerning the amounts of reintroduced sediment within the investigated period between 2008 and 2013.

7.1.3 Reach data

For evaluation of the investigated reach at the reach scale, cross section surveys were available for investigation of the sediment budget. The results of a 2D-hydrodynamic-numerical model and field visits were used to assess the influence of channel constraints (bank protection, groynes, etc.) on reach morphology and hence the artificiality of the reach.

7.2 *Application - Sediment continuity assessment*

7.2.1 Catchment Evaluation

Figure 7.4 displays the connectivity of the reach to the upstream sub-catchments. Based on the estimated sediment production in the sub-catchments, a catchment score of 2 (good) was obtained.

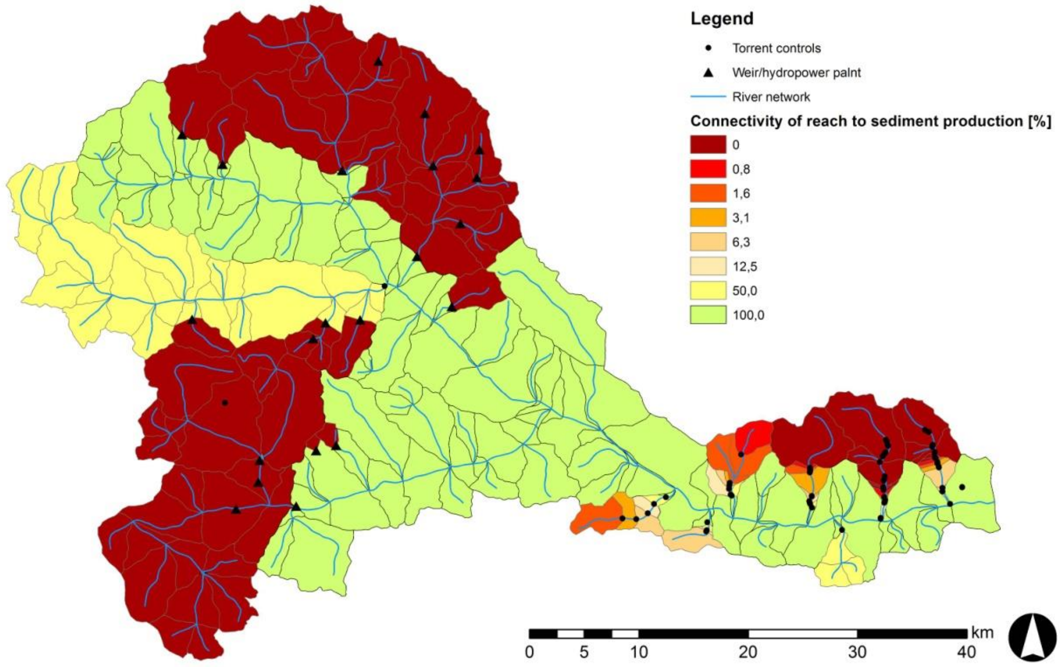


Figure 7.4 Connectivity of the investigated reach to the sub-catchment upstream based on throughput coefficients of sediment barriers.

7.2.2 River network evaluation

Based on the bedload rating curve obtained at the monitoring site in Dellach and the repeated cross section surveys along the entire Upper Drau, the longitudinal variation of bedload transport was calculated (Figure 7.5). Assuming that no significant changes occurred upstream from that section, the bedload discharge calculated at the upstream end could be compared to the bedload discharge that was supplied to the reach (restored reach 'Kleblach' in Figure 7.5) to evaluate the sediment transfer. The supplied bedload is about half the amount that enters the river network, and the river network score is a combination of the catchment factor and the river network factor. Accordingly, the overall state of sediment supply is in an acceptable condition (river network score F_{rn} = 3). After a torrent control at the Feistritzbach was replaced by a more permeable structure in the year 2009, the sediment that was mobilised after reconstruction significantly increased the bedload transport at river-km 600 (Figure 7.5). More similar measures in tributaries would improve the river network score. The effect of a recently implemented restoration measure can be seen at river-km 577. Aggradation in the widened bed reduces the amount of sediment that is transported downstream. However, it has to be considered that this effect is temporary until a morphology, that corresponds to the conditions of sediment supply and reach artificiality, is established.

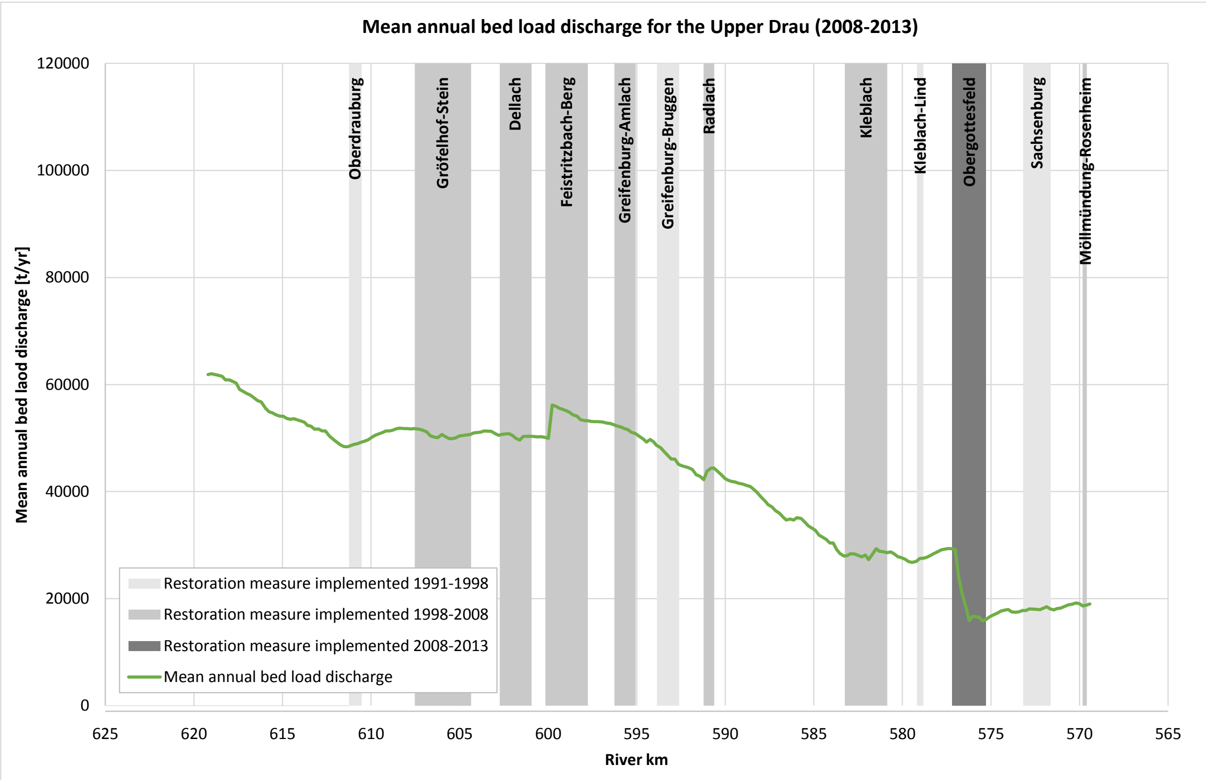


Figure 7.5 Longitudinal variation of bedload transport at the Upper Drau River in the time period 2008-2013.

7.2.3 Reach evaluation

Finally, the reach is investigated for its artificiality and its sediment budget. Both determine the reach factor, which in combination with the catchment and the river network factor, determines the final reach score.

As can be noted in Figure 7.5, between 2008 and 2013 the restored reach at Kleblach reached a balanced sediment budget after restoration implementation in 2002/2003. The artificiality was already strongly reduced by the restoration measures. Figure 7.6 shows the constraints along the water edges at approximately mean discharge, which represent the artificiality of the reach. In the case of very good conditions of sediment supply (River network Score S_c = 1), the evaluated reach would obtain a reach score of 2 (good) or a stable 3 (acceptable) condition. However, given the preconditions of sediment supply defined by alterations in the catchment and in the river network, the overall conditions in the reach for sustainable morphodynamics are barely rated as acceptable (3), and are close to a bad (4) condition.

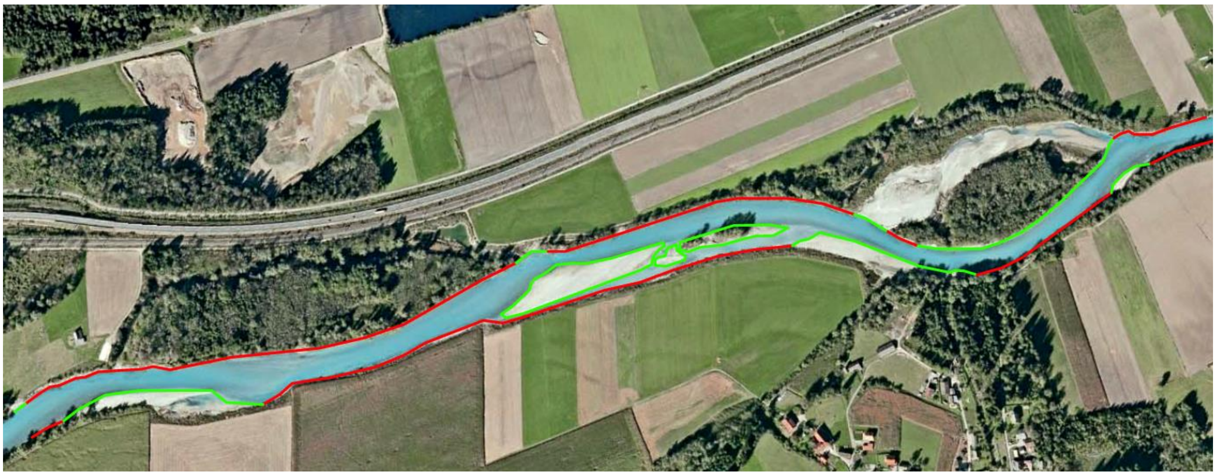


Figure 7.6 Bank protection constraining the flow at mean discharge in the evaluated reach (restored state in 2008).

7.3 Summary of the application of the decision tree

According to the results, the proposed decision tree is an essential complementary tool to evaluate regulated or restored river reaches as a precondition for an integrated morphological quality assessment. It is clear from the analysis that in a hierarchical scaling dependency of the smaller scales from the larger ones the integration of catchment, landscape unit and segment scale processes is crucial for planning and implementation of sustainable river engineering measures, river restorations and flood risk management at the reach scale. The decision tree reveals that dominant processes exist that must not be averaged out in a reach evaluation by other hydro-morphological parameters (e.g. bed configuration, cross section variability, presence of vegetation, …) that are depending on the large scale sediment regime and continuity.

The results of a morphological evaluation cannot be better than the score derived by the decision tree.

8. Interpreting condition and trajectories of change

In this section, the focus is on two reaches , 2.10 and 2.18 respectively, which are both located in segment two. The segments are influenced by the same controls (e.g. land cover, geological setting, climate,...) and human alterations present in the upstream catchment (landscape unit one). The main difference between the two reaches is that reach 2.10, which is located 13,2 km upstream of reach 2.18, is still in a regulated condition, whereas at reach 2.18 restoration measures have been carried out between 2001 and 2002. The interpretation of the past and current condition, as well as the controls on change and the assessment of the sensitivity are based on the results represented in previous sections. Additionally, future trajectories are presented for both reaches.

8.1 Current condition

Reach 2.10 is a highly regulated, single thread, straight, gravel-bed river reach (extended river type 13), with a specific stream power of 99 Wm^{-2}. Due to the regulation, only a few channel and floodplain geomorphic features/units typical for this river type (e.g. pools, riffles, large alternate point bars closely confining the low flow channel) are present. Wood or riparian tree-dependent geomorphic features are missing. Therefore the hydromorphological function is intermediate to poor.

Concerning reach 2.18 (the restored section), the hydromorphological function is good to intermediate. Channel and floodplain geomorphic features like islands, mid channel bars, riffles and pools are present throughout the reach. The specific stream power of the wandering gravel-bed river reach (extended channel type 11) is about 65 Wm^{-2}.

An overview of the current condition is given in Table 8.1.

Table 8.1 Overview the current condition of reach 2.10 (regulated) and 2.18 (restored).

Indicator	Reach 2.10 (regulated)	Reach 2.18 (restored)
Extended river type	13	11
Specific stream power (Wm^{-2})	99	65
Channel and floodplain geomorphic features	Slight indication of low flow channel, riffles and pools	Islands, mid channel and marginal bars, riffles and pools are present throughout the reach
Eroding banks	Not possible – rip rap at both sides	In 73% of the left and 24% of the right bank possible.
In-channel wood accumulation	Negligible	Present at the side channel
Hydromorphological function	**Intermediate to poor**	**Good to intermediate**

The hydromorphological alterations/artificiality of the river are mainly assessed by the alteration of lateral and longitudinal continuity. In both river reaches no blocking structures are present (no alteration). In reach 2.10, both banks are reinforced with rip rap so that the potential of the river to adjust laterally is inhibited (high alteration). In the case of reach 2.18, about three quarters of the banks are reinforced (intermediate alteration). These results in the following artificialities: reach 2.10 – artificial, and reach 2.18 – some significant artificial elements.

Neither geomorphic features/units of widening (not possible due to reinforced banks) nor narrowing are present at reach 2.10. By analysing the change of water levels for low flow conditions over the period 1991 to 2013, an increase in water levels could be shown for this reach. This indicates an aggrading trend of the bed levels. However, the changes were not linear, less aggradation occurred in the later period, 2008 to 2013.

The hydromorphological adjustments of reach 2.18 show a slightly aggrading trend of the bed levels, mainly due to the restoration measures (river widening) set in this reach. Geomorphic features showing aggradation, e.g. buried riparian vegetation, are present on the mid channel bar in the side channel. Additionally, narrowing tendencies in the side channel are indicated by the stabilizing work of vegetation.

In Reach 2.10 the riparian corridor is very small and no balance between the different vegetation phases is given. Within the vegetation classes no or only minor patchiness exists and no lateral gradient in riparian vegetation could be identified. In reach 2.18 the distribution of the different vegetation phases is only good in the downstream section (in the area of the side channel). In general, the patchiness of the vegetation in reach 2.18 is higher than in reach 2.10, and in several areas a lateral gradient can be noticed.

The current condition of reach 2.10 can be summarized as follows: The hydromorphological function is intermediate to poor, the reach is characterised as artificial and an aggrading trend of bed levels has been detected for the period 1991 to 2013. The riparian corridor function of this reach is bad and the artificiality is high.

Reach 2.18 is characterised by a good to intermediate hydromorphological function, significant alterations and a slighty aggrading trend in bed levels. In the side channel of this reach, narrowing tendencies were apparent. The function of the riparian corridor is evaluated as good to intermediate and some artificiality is given.

8.2 Controls on change

In the following, the controls of change of higher spatial scales (e.g. catchment, landscape unit or segment) on the reach scale are evaluated.

8.2.1 Catchment

The catchment area of all segments to Sachsenburg (Isel, Villgratenbach, segment 0-2) is about 2556 km². The runoff from a small part of the catchment, about 15,23 km² (0,6%), is diverted into another drainage basin. Within the catchment several water diversions exist, but the evaluated reaches are not influenced by them (residual flow sections are mainly in tributaries of the Drau River, except the water diversion at

Tassenbach, segment 1, which is located directly on the Drau River and causes 23 km of residual flow).

Within the period 1951 to 2000, a decrease in annual precipitation and discharge was detected in several sub-catchments. Reach 2.10 and 2.18 have been affected by a decreasing discharge of 0,005 -0,025 % per year. In Table 8.2, the mean flow at the gauging station Sachsenburg is given for different periods of time.

The groundwater bodies in this area were not investigated (reach 2.10) or no changes in the groundwater levels occurred (2.18). Only in the area of Lienz were decreasing groundwater levels detected for the period 1991-1997.

Table 8.2 Mean flow (MQ) discharge at Sachsenburg for different time periods (Lebensministerium, 2012).

	Discharge [$m^3.s^{-1}$]		
	1951-2010	**2005-2010**	**2010 only**
MQ	72.6	65.2	68.3

The geology of the drainage area consists to 66,5% of siliceous rock, 10,9% calcareous rock and 16,6% other material (e.g. different kinds of sediments). For 6% of the catchment no data is available. Since in the last century torrent controls, hydropower plants and other transversal structures were constructed, parts of the catchment no longer or only partially contribute to the downstream sediment regime. In total, 69% of the catchment is more or less detached. Due to the different properties of the geology in terms of fine and coarse sediment production, an overview of the detached areas and their geology is given in Table 8.3.

Table 8.3 Detached areas and their geology.

Detached by	Proportion of the entire catchment area [%]			
	silicious	**calcerous**	**sediments, unknown**	**no data**
Undefined structures	9.5	0.9	1.7	0
Weirs	19.5	1.3	7.3	6.1
Torrent controls	1.8	2.7	18.3	0
Total (for each geological entity)	**30,7**	**5,0**	**27,2**	**6,1**

The catchment of the upper Drau River is mainly covered by forests and semi-natural areas (~90%), including 2% of glaciers and perpetual snow (CLC 2006). About 8,4% of the drainage basin is used for agriculture and 1,6% is classified as artificial surfaces.

Over the last 50 years (1950-1995) several changes in land cover and land use trends have been detected in Austria (Kraussmann et al., 2003). Beside the increase in woodland and intensive grassland, the highest relative increases were recorded for artificial areas, whereas arable land and extensive grassland decreased.

Very important for the hydrological regime of the Drau River, is the land cover class "glaciers and perpetual snow". In the period 1990 to 2000, this land cover class was reduced by about 21,79 km² and a further decrease of the remaining areas is expected (APCC, 2014).

Similar to the geology, the land cover of the areas detached by transverse structures was evaluated (Table 8.4). The 69% of the area that is detached includes 94,1% under forests and semi natural areas, 5,0% under agriculture and to 0,9% affected by artificial surfaces.

Table 8.4 Detached areas and their land cover.

Detached by	Proportion of the entire catchment area [%]			
	Artificial surfaces	Agricultural areas	Forest and semi natural areas	Wetlands
Undefined structures	0.2	0.7	11.2	0
Weirs	0.3	2	31.7	0
Torrent controls	0.1	0.7	22	0
Total	**0.6**	**3.4**	**64.9**	**0**

8.2.2 Landscape unit

In general, the main part of the investigated area has parent material with a high permeability (about 78,7%).

The current distribution of rapid, intermediate and delayed runoff production areas was shown in Table 6.2. Proportional to the increase in artificial surfaces (see Figure 5.1), areas with rapid runoff production have increased since 1950. However, as woodland which causes a delayed runoff also increased, this trend of rapid runoff might has been weakened or even reversed.

In the Upper Drau catchment the soil erosion rate is quite low (based on PESERA; Kirkby et al., 2004). Higher rates occur in only a few locations.

8.2.3 Segment

The three uppermost segments of the Drau River (segment 0-2) were investigated.

The partially-confined segment zero is characterised by a valley gradient of 5-10‰ and a single thread, straight channel type. The river confinement is between 6 and 42. For this segment, only negligible or minor changes in the channel setting were observed over the last 140 years (reference: Franzisko-Josephinische Landesaufnahme 1870-1873). Several low to medium impact spanning/crossing and partially blocking structures are present.

The channel planform type in segment one is single thread, straight but the confinement varies along the river. The first few kilometres are in a semi-confined valley and the gradient is a little lower than in segment zero. After a major transverse blocking structure (water diversion for hydropower) the valley becomes narrower (confined valley) and the valley gradient increases (10-20‰). The flow regime in the confined section is altered by the upstream water diversion (residual flow stretch).

At the end of the segment, before the Drau River merges with the Isel River, the valley widens again (unconfined) and the diverted water is discharged back into the river. This downstream part of segment one is altered by hydro-peaking.

Beside the major blocking structure in Tassenbach (hydropower / water diversion), several minor to medium impact spanning structures are located in this segment. In the area of Tassenbach major changes in channel setting were observed (reference: Atlas Tyroliensis 1774). The sinuous to meandering river was regulated to a straight river.

Segment two starts at Lienz, where the Isel and the Drau River merge. In the unconfined, upstream part of this segment, the channel planform has been changed from braiding/anabranching to a single thread and straight river. In the following partially-confined section (as far as the confluence with the Möll river), the channel setting has undergone several adjustments. The wandering to braiding/anabranching Drau River has been regulated to a single thread river.

Segment two is characterised by low valley gradients and no blocking structures. However, some minor to medium spanning structures are present. Several river restoration measures have been realized in this segment, to improve, among other aims, the ecological and morphological condition of the river.

In all three segments, bank reinforcement is present at almost every reach.

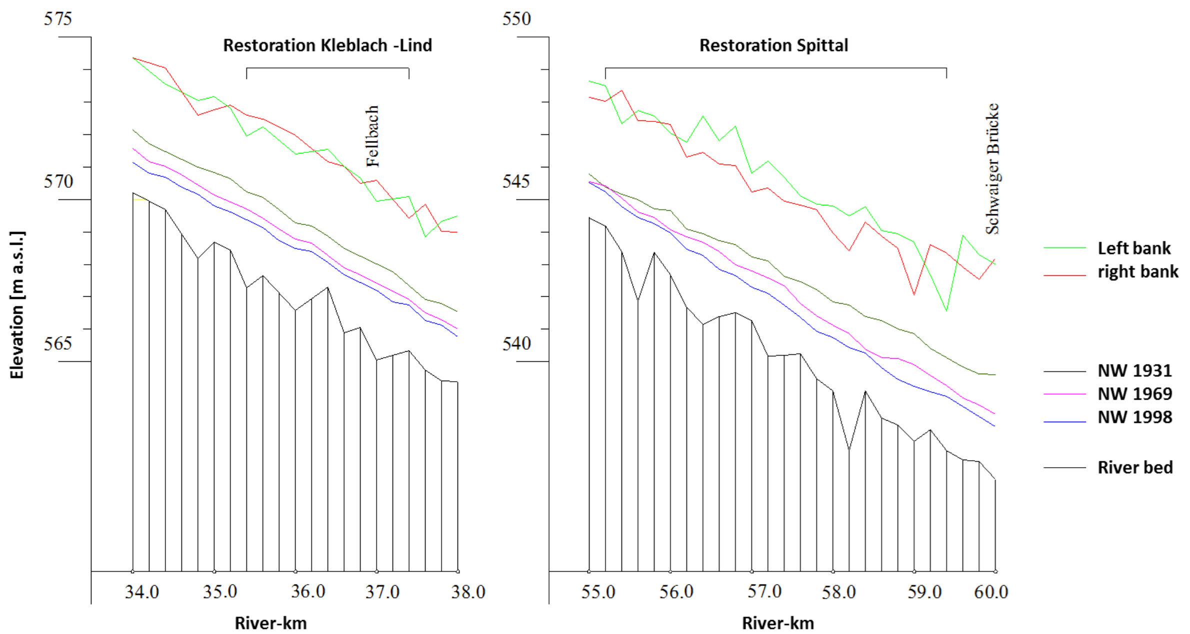


Figure 8.1 Bed incision at Kleblach-Lind (left) and Spittal (right) based on measured low flow water tables in the period from 1931 to 1998 (Habersack et al., 2011). Restoration measures were realized later.

Further it is stressed that in all three segments the sediment regime is highly influenced by transverse (blocking) structures located in the tributaries. Since their construction, a lot of sediment has been retained behind these structures and thus is lacking in their downstream sections and, of course, in the Drau River. In combination with the river regulations and enhancements of the transport capacities of the river, incision tendencies were observed over wide areas of the Drau (Figure 8.1; see also the low flow analysis and changes in thalweg presented in Figures 5.6 and 5.7, respectively).

8.2.4 Space-Time Inventory

A synthesized summary of temporal changes is given in Table 8.5.

Table 8.5 Synthesized summary of temporal changes

	Catchment scale	Landscape unit scale	Segment scale
Indicators of artificiality	Artificial surfaces increased Agricultural areas: From 1950 to 1995 increase in intensive grasslands, decrease in extensive grasslands and arable land; From 1990 to 2000, in less than one percent of the catchment, land cover changes were detected.	The area of rapid runoff production increases (urbanisation), but also the delayed runoff production areas increased (afforestation).	Beside the water diversion structure in segment one, only low to intermediate spanning/crossing and partially blocking structures are present. The downstream section of segment one and the upstream section of segment two are altered by hydro-peaking. - -
Changes in runoff and sediment production	From a small proportion of the catchment area, runoff is diverted to another catchment (about 0,6%). The analysis of the period 1951-2000 showed a decreasing trend of the annual discharge.	The areas covered with glaciers and perpetual snow decreased. From 1990 to 2000, 21,79 km² (0,85%) of this land cover class vanished. In 2006 only 2% of the Upper Drau catchment was covered with glaciers and perpetual snow. The analysis showed that 69% of the catchment is more or less detached from the downstream reaches by transverse structures, therefore the sediment regime is highly altered.	Due to regulation works, transport capacities were increased and in combination with sediment retention structures – mainly in the tributaries – degrading tendencies of the river were evaluated.

Along the Drau River, mainly a small, homogeneous riparian corridor is present. However, at a few locations, especially in the restored sections, a more natural vegetation structure was observed.

8.3 Reach sensitivity

Both reaches are sensitive to hydrological changes and very sensitive to changes in bed load yield. This is visible in the bed level development downstream of Kleblach (Figure 8.2). Just after the realization of the restoration measure (river bed widening), bed load was retained (aggrading bed levels) due to the reduced transport capacity. Thus less material passed this section and in consequence bed degradation occurred in the downstream parts.

Due to the detached areas, large parts of the catchment can no longer or only partially contribute to the downstream sediment regime. As the travel time of coarse sediments might take some time to move from the transverse structures to the investigated reaches, the full impact of the detachment might not have occurred yet.

As the transport capacity in the regulated reach is much higher than in the restored section, the sensitivity to changes in bed load yield is higher and impacts can cause abrupt changes.

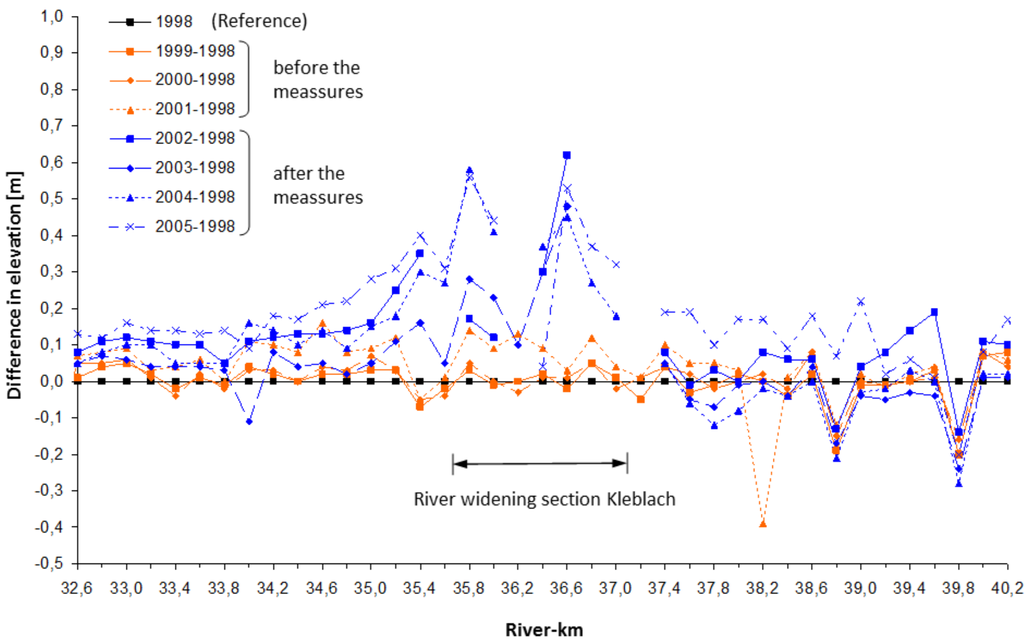


Figure 8.2 Low flow analysis in the area of the river restoration Kleblach.

Changes in hydrology, which can occur on different temporal and spatial scales (e.g. by hydro-peaking, changes in land cover, climate change), have several impacts on the sediment regime and thus the river morphology. Two of them are discussed below.

One is that the erosional force of water and the transport capacity are related to discharge magnitude. The higher the magnitude at a certain cross section the more sediments may be transported. The second one is the interaction of vegetation and morphodynamics. If the magnitude of floods with a certain reoccurrence period is decreased, vegetation encroachment, which causes a stabilization of bed sediments, may increase. This can cause a change in river typology e.g. from braiding to anabranching.

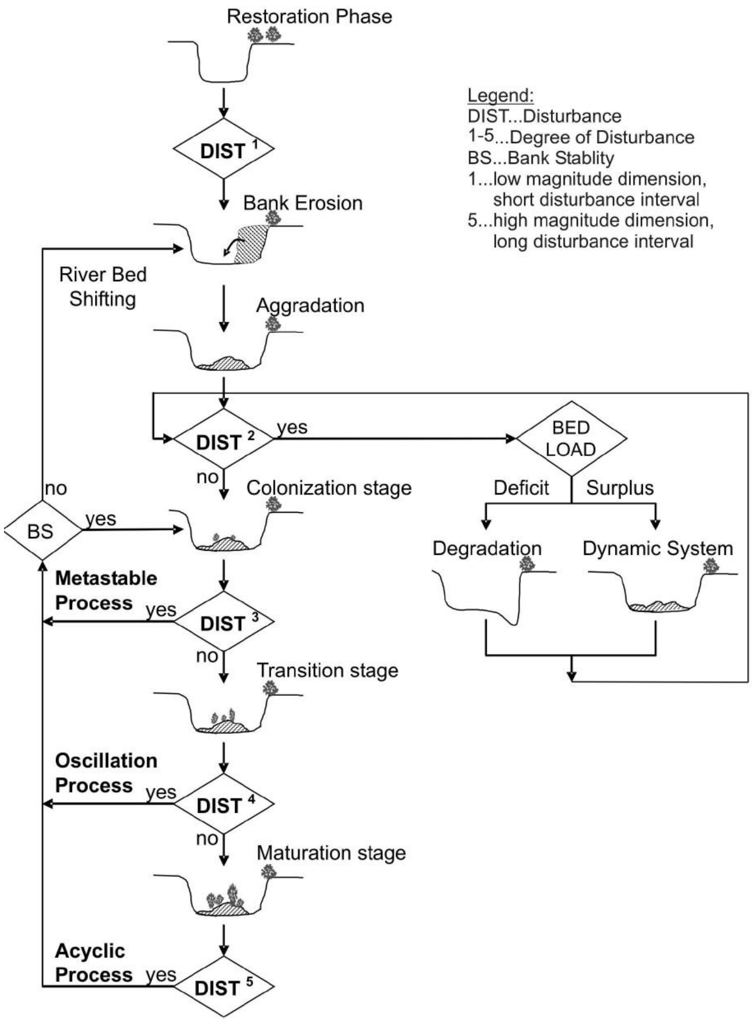


Figure 8.3 The dynamic disturbance regime approach (Formann, 2009). The cycle starts with self dynamic widening due to bank erosion (DIST 1) followed by a decrease in transport capacity. Material starts to deposit in the channel. Depending on the time until the occurrence of the next disturbance (DIST 1-5), vegetation might colonize the newly available areas or changes in the bed morphology might take place. Only if the disturbance interval (reccurrence period of a flood event) is larger than the recovery time (the time a plant needs to grow until it can withstand the disturbance of a certain magnitude) vegetation succession can occur. This in turn influences the hydraulics and the stability of the river bed, bars and banks and thus the reaction on further disturbances. Bank erosion is a key process within this concept. If the banks are stable, succession occurs; if not, the cycle starts from the beginning with side erosion followed by aggradations in the channel. The deficit or surplus of bed load is also important for the progress of restored river sections as it affects the development towards a degrading, aggrading or equilibrium system.

This was observed in the side channel of Kleblach (restored reach). Due to less high floods in the years after the implementation of the restoration measures, vegetation recruitment and succession has occurred in the side channel. The bars have become stabilized and as a consequence the channel has narrowed. Consecutive floods, which flooded the entire channel, have not been able to (re-)move the sediments as the vegetation has reinforced the soil and has decreased the shear stress exerted on the sediments. A schematic concept - "the dynamic disturbance regime approach" (Figure 8.3), which describes this process, was presented by Formann (2009).

8.4 Scenario based future changes

The following future trajectories for the two reaches are presented and discussed below:

- No change in management,
- Climate change,
- Further decrease of coarse sediment, and
- Re-establishment/enhancement of sediment continuity

More changes which might also occur at the investigated area are listed below, but are not further discussed here:

- Increase in fine sediment delivery due to changes in land use (e.g. more maize production at steeper areas -> higher soil erosion rates, increased construction of forest road –> increase in potential sediment sources,...)
- Decreases in sediment transport capacity of the river due to river restoration measures (espescially in the regulated reach)
- Increase in sediment inputs by removing bank reinforcements and allowance of self-dynamic river widening, and
- Increase in sediment transport capacity due to changes in land use (e.g. more artificial areas -> faster concentration time of water and thus higher discharges possible).

8.4.1 No change in management

Both reaches are located downstream of several river restoration areas which might have short-term impacts on the bed levels, e.g. alternating erosional or aggrading trendencies. However, in the long-term the main problem for both reaches is the impact of the detached catchment area on the sediment regime. Incision rates of about 1,5 cm per year have been measured in the Upper Drau River (Habersack et al., 2012). Due to the reduced sediment input, this rate might increase.

In combination with incision, which is expected to be higher in regulated reaches, problems with bank reinforcements, higher flood risks – dislocation of the river courses, scour of bridge piers,… - and ecological problems such as decreasing groundwater levels, disconnection of the channel and the riparian zone, loss of biodiversity and different habitats and species, and so on - will probably occur.

8.4.2 Climate change

Climate change might include decrease of glacier and perpetual snow areas, changes in the precipitation pattern (intensity and amount, but also a temporal shift), increase in water temperature and climate induced changes in land cover (e.g. increase of the climatic timberline).

Due to the changes in precipitation pattern and form (less solid precipitation like snow), the hydrological regime will be altered to a more balanced regime with increased discharge in the winter, decreased runoff in the summer, respectively. Decreases in annual discharge are also expected for the Upper Drau River. This might cause less morphodynamic disturbance (decrease in stream power and sediment transport capacity) and changes in the extent and composition of riparian areas.

Due to the regression of glaciers in favour of bare areas, which may be more prone to soil erosion, the potential sources of sediments may increase. The APCC (2014) indicates that significant increases in landslides, mudflows, rockfalls and other gravitational mass movements can be expected.

As there are uncertainties about the magnitudes of change of each impact factor and as there are so many of them (e.g. regression of glaciers –> more potential sediment sources, increase in precipitation intensity –> higher soil erosion rates, decrease of annual runoff –> decreased sediment transport capacity and morphodynamic disturbance, more balanced regime –> shift in riparian vegetation extent, increase in water and air temperature -> longer vegetative periods,…), which interact with each other, the overall development of the reaches are hard to predict.

8.4.3 Further decrease of coarse sediment

There are several plans to increase the electricity production by the construction of new hydropower plants in Austria. Some of them are planned to be constructed in the Drau Catchment. Beside changes in the hydrology, impacts on the sediment regime and thus the morphodynamics can be expected by the construction of transversal structures for water diversion or by residual flow stretches.

One of these hydropower plants is planned to be constructed on the Upper Isel River, in the area of Hinterbichl. There, a transversal structure to divert water is planned to be built. It can be assumed that the transverse structure does not fully allow the throughput of sediments and thus the upstream catchment will become detached and unable to contribute to the downstream sediment regime.

As the Upper Isel River (till Mattrei) is one of the last large tributaries to the Drau which is not impacted by major sediment retention structures, this disruption of the sediment continuity will have a major impact on the downstream region (e.g. decrease of coarse sediments).

Additionally, several smaller rivers merge with the Isel River in the planned residual flow stretch. A decreased flow (less sediment transport capacity) in this reach might cause aggradation within the discharge areas of the tributaries and thus higher flood risks. Therefore maintenance measures like gravel excavation will be needed. However, this again reduces the transported sediment volume to the downstream reaches.

Besides the problems with aggradation, less morphodynamics and lower flow levels might allow vegetation encroachment. For some species, like the German tamarisk (Myricaria germanica), the changes in fluvial dynamics might decrease its frequency and endanger its survival in this area.

The impact on both reaches (2.10 and 2.18) is a change in sediment input. Thus river bed degradation is possible. Due to the distance between the construction site and the location of the two reaches, the impact may be delayed (cf. travel time of bed load). Further effects of decreased coarse sediment were already discussed in the previous sections (e.g. 8.4.1).

8.4.4 Re-establishment/enhancement of sediment continuity

The main continuity interruption of coarse sediment is caused by weirs (mainly in connection with hydropower production) and torrent controls. In the case of hydropower plants there are several possibilities to re-establish or enhance the sediment throughput e.g. by sediment by-pass tunnels, conveyance of sediments through turbines, or by movable weirs which can be lowered down to the bed level during floods. At run-of-river hydropower plants, the management of the weir shutter in connection with the given discharges might also yield enhanced sediment continuity.

The primary function of torrent controls is to decrease the transported amount of material during large events to protect settlements from debris flows and flood risk. This function has to be preserved. However, there are different types of torrent controls which might protect the downstream settlements during flood events and at the same time, at least to some degree, maintain the self-dynamic clearance of the retention area during lower flow events. So, modification of torrent controls might increase the sediment continuity.

At the Feistritzbach River, a tributary to the Drau, an old torrent control was demolished and a new one, which allows self-dynamic clearance during lower flow situations, was constructed (Figure 8.4). By this measure, an increase in the sediment throughput has had been achieved.

Figure 8.4 New torrent control at the Feistitzbach (picture: WLV).

By applying these modifications at some of the transverse structures, the sediment yield in the two investigated reaches might be increased. These actions might help to stabilize the bed levels and increase the natural dynamics in the river reaches.

8.5 Conclusions

In the Drau case study, the multi-scale framework has been successfully applied and it has been demonstrated to be a valuable procedure to describe the interrelations between the different scales and processes.

Based on this report it is evident that the Drau River basin is undergoing a continuous change due to intensification of hydropower use, torrent control, climate change (e.g. retreat of glaciers). Furthermore, the application of the newly developed decision tree (see section) has demonstrated that the existing situation is on the edge of still having a minimum amount of sediment input coming from the catchment via the river sectors to the evaluated river reaches. Only a slight/small further decrease of the sediment input (further disruption of the sediment continuum) will lead to non-functioning of the ten kilometres of river restoration by river bed widenings that has so far been implemented.

This leads to the following general conclusion of the case study Drau in WP2:

According to the results, the proposed decision tree is an essential complementary tool to evaluate regulated or restored river reaches as a precondition for an integrated morphological quality assessment. It is clear from the analysis that in a hierarchical scaling dependency of the smaller scales on the larger ones the integration of catchment, landscape unit and segment scale processes is crucial for planning and implementation of sustainable river engineering measures, river restorations and flood risk management at the reach scale. The decision tree reveals that there exist dominant processes that must not be averaged out in a reach evaluation by other hydro-morphological parameters (e.g. bed configuration, cross section variability, presence of vegetation, …),which themselves depend on the large scale sediment regime and continuity.

The result of a morphological evaluation cannot be better than the score derived by the decision tree.

9. References

Angermann, K., Egger, G., Politti, E., Habersack, H., Blamauer, B., Tritthart, M., Klösch, M., Steineder, R. (2011): Ripclima – Risk assessment and management of Riparian ecosystems in condition of Climate Change in Austria. Final report A963615, ACRP, Klagenfurt and Wien.

APCC (2014): Österreichischer Sachstandsbericht Klimawandel 2014 (AAR14). Austrian Pnael on Climate Change (APPC), Verlag der Österreichischen Akademie der Wissenschaften, Wien, Österreich, 1096 Seiten. ISBN 978-3-7001-7699-2

BMLFUW (ed.) 2010: Nationaler Gewässerbewirtschaftungsplan 2009 – NGP 2009. BMLFUW-UW,4,1,2/0011-I/4/2010, Wien,

BMLFUW (ed.) 2012, Hydrographisches Jahrbuch von Österreich 2010. Wien: BMLFUW Abteilung VII/3.

BMLFUW, 2010, Nationaler Gewässerbewirtschaftungsplan 2009 - NGP 2009. Wien.

BMLFUW, 2014: Grüner Bericht 2014. www.gruenerbericht.at [Accessed 09.2014]

EEA 2002, Europe´s biodiversity - biogeographical regions and seas, European Environment Agency,

Formann, E. (2009): Evaluation of Riverine Processes and their Interrelationships in River Restoration based on Reduced Complexity Modelling and the Dynamic Disturbance Regime Approach. PhD at the Institute for Water Management, Hydrology and Hydraulic Engineering, University of Natural Resources and Life Sciences, Vienna, p. 107.

Habersack, H. (1997): Raum-zeitliche Variabilitäten im Geschiebehaushalt und dessen Beeinflussung am Beispiel der Drau. Wiener Mitteilungen, 144.

Habersack, H., Aigner, J., Kreisler, A., Rindler, R., Seitz, H., Tritthart, M. (2013): Geschiebemessungen an Drau und Isel 2007-2012. Im Auftrag des Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Wien.

Habersack, H., Klösch, M., Blamauer, B., Seitz, H., Kreisler, A., Holzapfel, P. (2011): Lebensader Obere Drau, Flussmorphologisches Monitoring – Endbericht. Amt der Kärntner Landesregierung, Spittal/Drau.

Habersack, H., Liedermann, M., Tritthart, M., Hauer, C., Klösch, M., Klasz, G., Hengl, M., 2012: Maßnahmen für einen modernen Flussbau betreffend Sohlstabilisierung und Flussrückbau – Granulometrische Sohlverbesserung, Buhnenoptimierung, Uferrückbau und Gewässervernetzung. Österr. Wasser- und Abfallw (2012) 64:571-581, Springer-Verlag, Wien.

HAÖ 2007, Hydrologischer Atlas Österreichs. 3. Lieferung, Vienna: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau.

Jarvis A., H.I., Reuter, A., Nelson, E., Guevara, 2008: Hole-filled seamless SRTM data V4. International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org.

Kirkby, M. J., Jones, R. J. A., Irvine, B., Gobin, A., Gobers, G., Cerdan, O., Von Rompaey, A. J. J., Le Bissonnais, Y., Daroussin, J., King, D., Montanarella, L., Grimm, M., Vieillefont, V., Puigdefabregas, J., Boer, M., Kosmas, C., Yassoglou, N., Tsara, M., Mantel, S,, Van Lynden, G, J, & Huting, J, 2004, Pan-European Soil Erosion Risk Assessment: The PESERA Map. Version 1 October 2003, Explanation of Special Publication Ispra 2004 No, 73 (S,P,I,04,73), European Soil Bureau Research Report No, 16, EUR 21176, 18pp, and 1 map in ISO B1 format, Luxembourg: Office for Official Publications of the European Communities.

Krausmann, F., Haberl, H., Schulz, N.B., Erb, K.-H., Darge, E., Gaube, V. (2003): Land-use change and socio-economic metabolism in Austria – Part I: driving forces of land-use change: 1995-1995. Land Use Policy, 20, 1-20.

Lebensministerium, 2013, eHYD [Online] Wien: Lebensministerium, Available: http://ehyd.gv.at/ [Accessed 2013].

Mader, H.T.S., & Wimmer, R. 1996, Abflussregime österreichischer Fließgewässer - Beitrag zu einer bundesweiten Fließgewässertypologie. Wien, Umweltbundesamt.

Muhar, S., Poppe, M., Egger, G., Schmutz, S. & Melcher, A. 2004, Flusslandschaften Österreichs - Ausweisung von Flusslandschaftstypen anhand des Naturraums, der Fischfauna und der Auenvegetation. Wien, bm:bwk,

Nachtnebel, H.P., Graf, M., Habersack, H., 1992: Gewässerbetreuungskonzept Obere Drau, Arbeitspaket Flussmorphologie. Studie, im Auftrag des BMLF und der Kärntner Landesregierung.

Nachtnebel, H.P., Habersack, H., 1996: Generelles Projekt zur Eindämmung der Eintiefungstendenzen an der Drau zwischen der Liesermündung und der Rosenheimer Brücke, Wien.

Rivas-Martínez, S., Penas, Á. & Díaz, T.E. 2004a Bioclimatic Map of Europe – Bioclimates. León, Spain: Cartographic Service, University of León.