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	D3.5 Large Rivers
Title	Large river regulation and rehabilitation in Europe – six selected case studies
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Due date to deliverable: extra deliverable; not scheduled

Actual submission date: 10 November 2015

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)	

To be cited as: Geest, G.J. van, G.W. Geerling & A.D. Buijse [eds.] (2015) Large river regulation and rehabilitation in Europe – six selected case studies. REFORM deliverable 3.5 (FP7 Grant Agreement 282656).

Cover photo: Groyne fields, low discharge and navigation on the Waal branch near Ewijk (Rhine Rhine, the Netherlands; photo: Tom Buijse)

Summary

Problem and objectives

Large rivers have been selected as one of the satellite topics both within WP3 and WP4, because of their particular features which could not be analysed in the case study catchments framework. Large rivers are rivers with a catchment larger than 10,000 km^2 and > 100 m^3/s. This encompasses rivers such as the Danube, Rhine, Rhône, Ebro, Vistula but also major tributaries such as the Sava, Narew, and Main rivers. Most fulfil major socio-economic functions, which will remain strongly modified and thus direct the options for rehabilitation. Because of their multifunctional use, large rivers can often only be partially rehabilitated or mitigated to achieve Good Ecological Potential according to the Water Framework Directive.

Methods

This report addresses both hydrological modifications and restoration (rehabilitation, mitigation) following a DPSIR approach. The historical trajectory of driving forces, river regulation (100 – 200 years) and rehabilitation (20 years) is used to underpin and illustrate the state-of–the-art regarding the effectiveness and potential of large river rehabilitation. For this, experiences and case studies from various large rivers in Europe are presented. For each case study the following information is given:

- General characteristics of the river (stretch);
- Description of historical state or reference condition(s) used in the rehabilitation project;
- Functions of the river (stretch): for which socio-economic functions is the river used, and what are the resulting pressures for its ecological functioning?
- The effects of identified pressures on hydromorphology and ecology;
- Mitigation and rehabilitation measures; what measures have been taken or planned to improve the hydromorphological and ecological status of these rivers?
- Ecological effects of measures.

Results

In this report, six case studies have been described that are spread across Europe. These case studies are representatieve of various European conditions with regard to climate, hydromorphological characteristics and catchment size. The case studies are situated in three biogeographical regions and six countries, viz. Atlantic region: River Trent (UK) and Delta Rhine (Netherlands), Continental region: Middle Vistula (Poland), Lower Danube and Po River (Italy) and Mediterranean region: Ebro (Spain). All these rivers can be characterized as large rivers (viz. catchment area larger than 10,000 km^2), although they differed strongly in climatic zone, river length, catchment size, discharge, slope and river style. Large rivers can be considered as unique ecosystems and results are difficult to generalize. Still these case studies together give a good impression on the present regulation and rehabilitation of large rivers in Europe.

The case studies share but also differ substantially in drivers and associated pressures. Both flood protection and navigation are important drivers for the occurrence of many pressures. The rivers Trent, Po, Ebro and Delta Rhine have a large number of drivers and associated pressures, while the Danube Delta and middle Vistula are less impacted. For the majority no information was available regarding the extent of drivers and pressures.

There was a general pattern in the chronological sequence of the impact of drivers and associated pressures. The primal drivers for early regulation of all rivers were flood protection (embankments) and agriculture (deforestation). For most, these forms of river

regulation started already centuries ago. Navigation became an important driver during the 19th century requiring further channelisations. As a result, the occurrence of highly dynamic habitats strongly declined caused by stabilisation of the river bed (by groynes, bank protection) as well as by deepening of the main channel. Of our case studies, only the river Vistula in Poland is currently not regulated for navigation purposes, and – hence – large parts of the main channel of the river have not been channelised. More recently, especially after the Second World War, many dams were constructed in the rivers, which resulted in a decreased longitudinal connectivity, thereby impeding conditions for migratory fish and other species. Additionally, the hydrological regime of rivers was strongly altered and sediment supply to downstream sections was strongly reduced. Especially the rivers Trent, Po, Ebro and Lower Danube have been severly impacted by the construction of dams.

For the majority of the case studies, only limited information was available regarding the impacts of pressures on hydromorphology and ecology. Large rivers are impacted by multiple stressors which complicate to identify the primal causes for degradation. It seems that the sequence of drivers (and associated pressures, see above) have initiated major transition points for ecological processes and biota along large rivers. We discuss the effects briefly in respect to the time line of occurrence of these drivers and pressures.

There are some striking differences in the restoration measures taken. Along the lowland stretches of large rivers, such as the Lower Danube and the Delta Rhine, measures focus on restoring lateral connectivity gradients between main channel and floodplains. Because of constraints imposed by navigation, only a limited number of measures are taken that improve conditions for lateral migration to rejuvenate riparian zones and bar and island formation, because these will affect navigational depth in the main channel. Along the river Trent and Po (and to some extent, the Delta Rhine), measures are taken that increase variation in width and depth of the main channel, which variation is an important variable for the occurrence of several hydromorphological processes. Restoring conditions for island and shoal formation will only be carried out along the river Vistula where navigation is not an important driver.

In summary, along relatively intact river stretches, such as the Vistula and Danube delta only a limited amount of measures can already improve ecological conditions. In highly regulated rivers such as the river Trent and Delta Rhine having extensive and diverse pressures a large number of measures are required and have been taken or planned. By contrast, the Mediterranean Rivers Ebro and Po are also highly regulated, but along these rivers only a small number of measures are planned at present.

Acknowledgements

REFORM receives funding from the European Union’s Seventh Programme for research, technological development and demonstration under Grant Agreement No. 282656.

Table of Contents

Contents

1. Introduction

Almost all large rivers in Europe are heavily regulated, channelized and dammed, which often started centuries ago. Consequently channels incised, floodplains aggradated and hydroperiods have been modified to support hydropower generation, navigation and freshwater supply and to protect the hinterland from flooding (Figure 1.1; Tockner et al. 2009). As a consequence, former extensive aquatic/terrestrial transition zones lack most of their basic ecological functions. Along large rivers in Europe and North America, various floodplain restoration or rehabilitation projects have been planned or realised in recent years (Buijse et al. 2005a; Tockner et al. 2009). However, restoration ecology is still highly in development and the literature relevant for river restoration is rather fragmented (Buijse et al., 2002). In addition, documentation of case studies is rather scarce, and – hence – there is little insight into success and failure factors for river rehabilitation.

The river floodplain rehabilitation worldwide is based on the concept of restoring of the lateral dimension and natural processess induced by the “flood pulse” of the lotic systems, affected by human activities (Ward and Stanford, 1989; Junk et al., 1989; Molles et al., 1998; Toth et al., 1998; Tockner et al., 1998; Schiemer et al., 1999; Tockner et al., 2000). The measures for ecological restoration projects in Europe on the river floodplains before the issue of Water Framework Directive (WFD) have been addressed to one or two river floodplain functions/services, viz. water storage for flood mitigation, nature/biodiversity conservation or both (Marin et al., 1997; Vadineanu et al., 1998; Schiemer, 1999; Smits et al., 2000; Hughes, 2000; Klijn and Duel, 2000; Cals and Drimmelen, 2000; Schneider 2002, Morris et al., 2005), nutrient cycling (Heiler et al., 1995) and less to the multiple ecological objectives as river system integrity and ecological status.

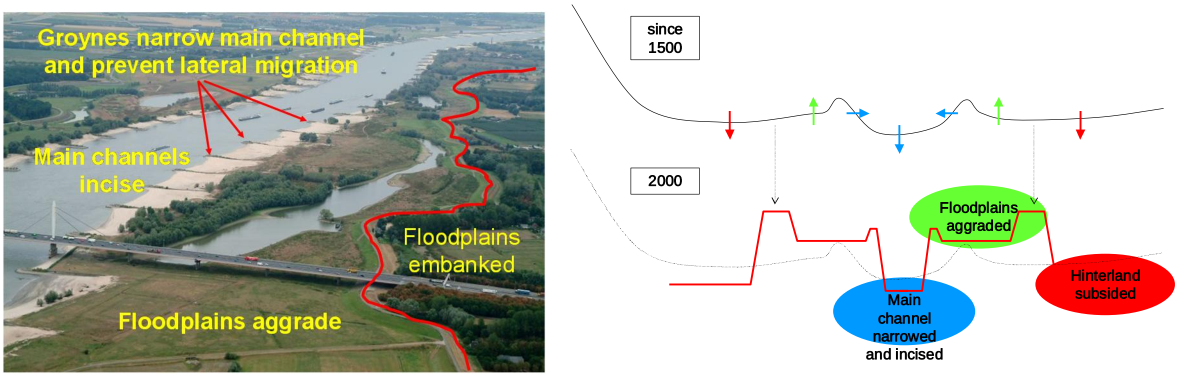

Figure 1.1 Aerial view of the Waal branch of the River Rhine (the Netherlands) showing several hydromorphological modifications and their impacts (left; photo: Bert Boekhoven) and a schematic presentation of the morphological changes (right; source: Van der Molen & Buijse 2005)

The implementation of the WFD initiated that more emphasis is given to measures aiming to improve ecological status and functions of the rivers systems. Concepts as ,,fluvial territory”, ,,room for rivers” ” or ,, free space for rivers”, ,,espace de liberté fluvial”, ,,erodible corridor”, or simply ,,wetland (or floodplain) restoration”, have been developed across Europe. Thus the concept ,,Room for Rivers” was promoted in the Netherlands as an alternative to a new round of dike raising to prevent floods (Silva et al., 2001; Buijse et al., 2002; Vis et al., 2003), whereas the term ,,Fluvial Territory” is related to the Spanish River Restoration Strategy (Ollero et al., 2007; Ollero et al., 2009) which is an adaptation of the French ,,espace de liberte fluvial” and ,,erodible corridor” (Piegay et al., 1996; Malavoi et al., 1998; Piégay et al., 2005) and the Italian term ,,*fascia di pertinenza fluvial”* (Govi and Turitto, 1994). All these terms define river floodplain management strategies based on enlargement of the fluvial space that includes river bed, riparian corridor and the floodplain and their dynamics.

The large-river floodplain rehabilitation projects are long term undertakings. For successful rehabilitation of river-floodplain systems of the Rhine-Meuse Delta, it was found that three clusters of factors appear to be decisive (Lenders, 2003): the first cluster comprises the use of reference and target images for the identification of measures (Buijse et al. 2005b; Nilsson et al. 2007), the second cluster includes the need for accurate environmental surveys, and the third emphasizes the importance of the involvement of social aspects (Past-Wohl 2007). In this report, the reference and target images of several large rivers are discussed, as well as hydromorphological modifications and restoration measures (rehabilitation, mitigation), following a DPSIR-approach.

Definitions of DPSIR-approach

In this report, the Driver-Pressure-State-Impact-Response (DPSIR) scheme is used for the elaboration of these clusters. The DPSIR-scheme is a flexible framework that can be used to determine the effects of human activities to the state of the environment and the identification of (proper) measures for ecological rehabilitation of rivers and other ecosystems. According to the DPSIR conceptual framework, Drivers are the social, demographic and economic developments in societies and the corresponding changes in life styles, overall levels of consumption and production patterns. In practise, drivers are often defined as socio-economic sectors that fulfil human needs. Drivers function through human activities may intentionally or unintentionally exert Pressures on the environment. Pressures include the release of substances (emissions), physical and biological agents, the use of resources and the use of land. Examples of such pressures in rivers are channelization (caused by the Driver Navigation for ‘shipping’) or reduction of flooding area (due to embankments due to the Driver ‘Flood protection’). The pressures exerted by human influence may lead to unintentional or intentional changes in the State of the ecosystem. The state is the abiotic condition of soil, air and water, as well as the biotic condition (biodiversity) at ecosystem/habitat, species/community and genetic levels. Usually these changes are unwanted and are seen as negative (damage, degradation, etc.). The pressures exerted by society may directly impact the ecosystem of rivers, such as dredging or river normalisation, or may be transported and transformed through a variety of natural processes to indirectly cause changes in ecosystem conditions. Changes in the quality and functioning of the ecosystem have an Impact on the welfare or well-being of humans through the provision of ecosystem services. Impacts are the consequences for human and ecosystem health, resource availability and biodiverstiy from adverse environmental conditions. In practise, impacts reflect the negative environmental effects of pressures. Humans make decisions in Response to the impacts on ecosystem services or their perceived value. Responses are actions taken to prevent, compensate, ameliorate or adapt to changes in the (impaired) state of the environment by seeking to control drivers or pressures. As a consequence of this response, it is expected that the negative effects of the pressures on the state of the ecosystem will be reduced.

For successful rehabilitation of rivers using a DPSIR-approach, it is necessary to understand the multidimensional scale of processes in these landscapes. During the last decades, our perception of river-floodplain systems has been significantly improved by the application of new theoretical concepts. Ward (1989) conceptualized the dynamic and hierarchical nature of river ecosystems in a four-dimensional framework (Figure 1.2): (i) Upstream-downstream interactions constitute the longitudinal dimension; (ii) the lateral dimension includes interactions between the channel and riparian/floodplain systems; (iii) Significant interactions also occur between the channel and contiguous groundwater, the vertical dimension; and (iv) time provides the temporal scale. River ecosystems have developed in response to dynamic patterns and processes occurring along these four dimensions. A holistic approach that employs a spatio-temporal framework, and that perceives disturbances as forces disrupting major interactive pathways, result in a more complete understanding of the dynamic and hierarchical structure of natural and altered lotic ecosystems (Ward, 1989).

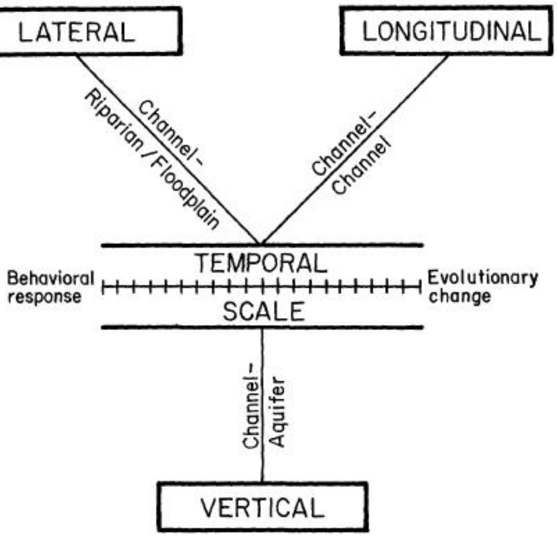

Figure 1.2 A conceptualization of the four-dimensional nature of lotic ecosystem (Source: Ward 1989)

The effect of the river on habitats is often expressed in the term ‘connectivity’. Habitats with high connectivity are strongly influenced by the river, and – hence – both ecosystem structure and function, as well as succession are strongly influenced the river. Other floodplain habitats, however, may only be mildly influenced by river processes, and – as a result – autogenic processes prevail (Van den Brink et al. 1996). Unregulated river-floodplain systems have strong gradients in connectivity, in the longitudinal, vertical and lateral dimension. Superimposed on these spatial gradients is the dimension ‘time’, which represents succession under varying influence of connectivity.

Case studies

In this report, case studies of several large European rivers are represented. In this report, six case studies have been described that are spread across Europe. These case studies are representatieve of various European conditions with regard to climate, hydromorphological characteristics and catchment size. The case studies are situated in three biogeographical regions and six countries, viz. Atlantic region: River Trent (UK) and Delta Rhine (Netherlands), Continental region: Middle Vistula (Poland), Lower Danube and Po River (Italy) and Mediterranean region: Ebro (Spain). The cases studies represent large rivers (catchment area > 10,000 km2) with an average discharge larger than 100 m3/s (or even larger respectively 25,000 km2 and 200 m3/s). This encompasses rivers such as the Danube, Rhine, Rhône, Ebro, Vistula but also major tributaries such as the Sava, Narew, Main rivers (Figure 1.3). Most fulfil major socio-economic functions, which will remain and thus direct the options for rehabilitation. These rivers have all been addressed in detail in the recent book “Rivers of Europe” (Tockner et al., 2009), but the extent and impact of hydromorphological modifications are less in this standard book. Also, the DPSIR-approach was specifically touched upon, which may give more insight into success and failure factors for ecological rehabilitation of large rivers.

In the chapters of the case studies, the following information is given (see appendix I for a more detail description):

- General characteristics of the river (stretch);

- Description of historical state or reference condition(s) used in the rehabilitation project;
- Functions of the river (stretch): for what socio-economic functions is the river used, and what are the resulting pressures for ecological functioning of these rivers?
- The effects of identified pressures on hydromorphology and ecology;
- Mitigation and rehabilitation measures; what measures are planned or have been taken to improve the hydromorphological and ecological status of these rivers?
- What are ecological effects of measures?

Figure 1.3 Major River Basins in Europe (source: https://en.wikipedia.org/wiki/List_of_rivers_of_Europe)

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2. The River Trent (United Kingdom)

Authors: Michelle Smith, Natalie Angelopoulos, Richard Noble, Andy Nunn and Ian Cowx (UHULL)

Acknowledgements:

The authors would like to thank Andrew Crawford at the Environment Agency for the information he provided about river rehabilitation projects on the River Trent.

2.1 Introduction and characterisation

The River Trent is one of the UK's largest rivers, with a length of 274 km it is the third longest river in England and Wales (Trent Rivers Trust, 2015). It flows from its source at Biddulph Moor (elevation 275 m) in north Staffordshire to the Humber Estuary at Trent Falls (elevation 0 m), south of Hull (Figure 2.1) (Environment Agency, 2010; Trent Rivers Trust, 2015). With a catchment that occupies 8% of the land area of England (Figure 2.1), it drains the Midlands region (Atkins, 1992) and flows through the counties of Staffordshire, Derbyshire, Leicestershire, Nottinghamshire, Lincolnshire and Yorkshire.

The river offers good opportunities to explore restoration activities as it faces a number of pressures, including heavy urbanisation in the headwaters (Birmingham) and throughout the catchment, intense agriculture practices and land-use change, industrial development, river realignment for flood protection, hydropower development and mining. As a consequence, opportunities for restoration are constrained and challenging.

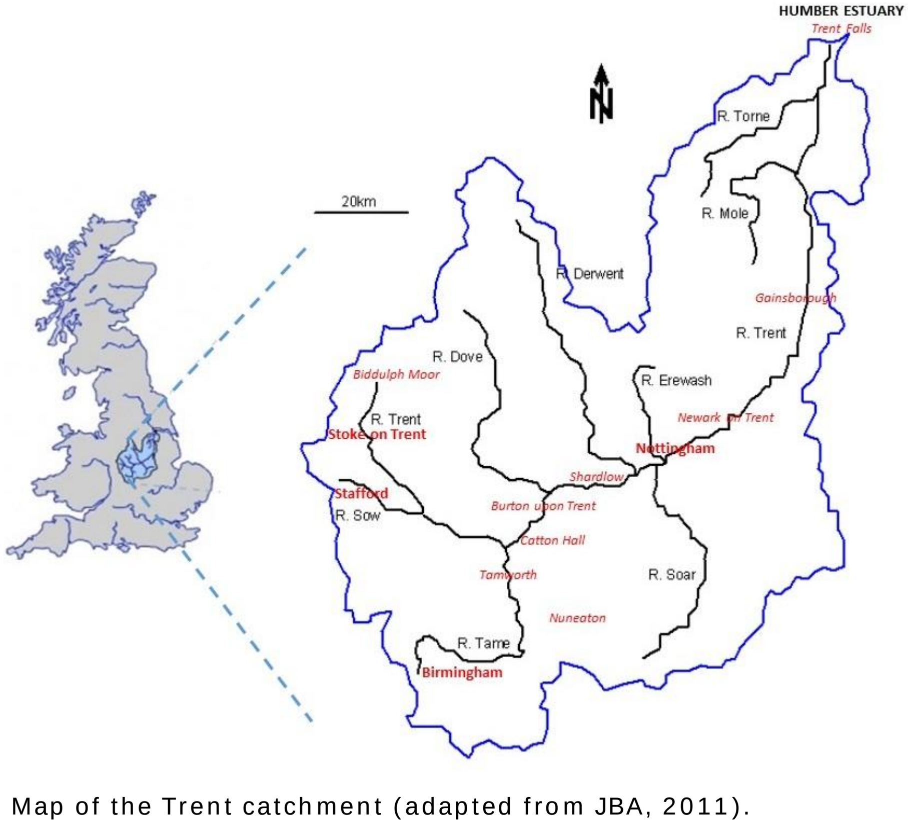

Figure 2.1. Map of the Trent catchment (adapted from JBA, 2011).

Regional context

The River Trent is set within the Humber river basin district (Figure 2.2). The Humber river basin district covers an area of 26,109 km^2, from the North York Moors to Birmingham, the Pennines to the North Sea and Stoke-on-Trent to Rutland, and supports a population of 10.8 million people (Environment Agency, 2009a). The Humber river basin district is one of the most geologically diverse regions in England, ranging from internationally important peat lands in the upland areas of the Peak District, South Pennines and North York Moors, to fertile river valleys across Derbyshire and the Yorkshire Dales, to free-draining chalk rivers in the Yorkshire and Lincolnshire Wolds (Environment Agency, 2009a).

The River Trent drains a catchment of almost 10,500 km^2 containing a population of over 6 million people (Trent Rivers Trust, 2015); 2272 km^2 of the catchment area is under tidal influence (JBA, 2011). The fluvial River Trent drains a catchment of 8228 km^2 and is made up of a number of large sub-catchments, including the Rivers Sow, Tame, Dove, Derwent, Soar, Idle, Mease and Erewash (JBA, 2011) (Figure 2.2). Given its size and importance to society, the River Trent was included as a large river case study in “Rivers of Europe” (Soulsby et al., 2008). The river’s catchment statistics are summarised in Table 2.1.

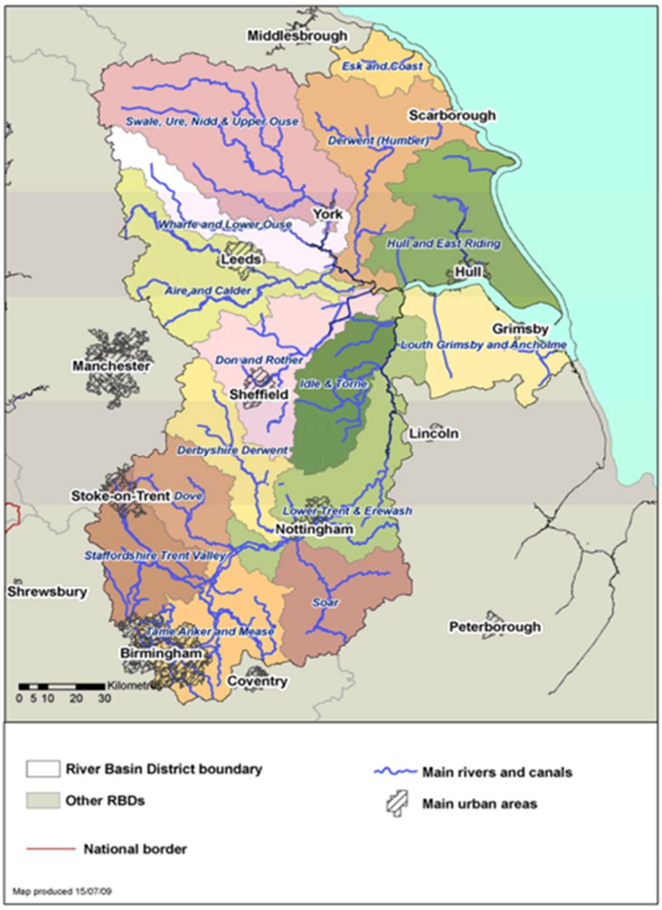

Figure 2.2. Humber river basin, England. Different colours show the sub-catchments that make up the Humber river Basin (Source: Environment Agency, 2009a).

Table 2.1. Characteristics of the River Trent catchment, UK (Soulsby et al., 2008).

Feature		Value
Mean catchment elevation (m)		111
Catchment area (km^2)		10466
Mean annual discharge (km3)		0.9
Mean annual precipitation (cm)		74.6
Mean air temperature (°C)		8.9
Number of ecological regions		1
Land use (% of catchment)		
	Urban	17.3
	Arable	47.7
	Pasture	27.5
	Forest	4.0
	Natural grassland	2.3
	Sparse vegetation	0.1
	Wetland	0.5
	Freshwater bodies	0.6
Protected area (% of catchment)		9.3
Number of large dams (>15 m)		-
Native fish species		30
Non-native fish species		8
Large cities (>100 000 people)		6
Human population density (people/km^2)		590
Annual gross domestic product ($ per person)		25692

The physical characteristics of the Trent catchment vary from low-lying ground such as the flood plains in the River Tame and River Trent catchments to the steep landscape of the Peak District (Figure 2.3a) (Atkins, 1992). The geology varies through the catchment (Figure 2.3b); in the upland areas, soils are thin and less productive than the mudstones and loamy soils in the flatter, lowland areas (Edwards et al., 1997; Jarvie et al., 1997; Environment Agency, 2010). The Trent catchment is complex, draining rural areas in the headwaters of the Rivers Dove and Derwent, mostly underlain by a Carboniferous geology of limestone in the south and millstone in the upper Derwent, and flowing through several urban areas including Nottingham, Newark and Gainsborough (Jarvie et al., 1997; Soulsby et al., 2008). The Rivers Tame and Soar tributaries have highly urbanised catchments that are gently undulating (≈ 100-200 m asl) and composed of glacial tills covered by loamy clay soils (Soulsby et al., 2008). Downstream of Nottingham, the catchment is underlain by Sherwood sandstone, a major UK aquifer (Soulsby et al., 2008). The annual effective rainfall varies between 100 mm in the lower reaches and 1000 mm in the headwaters of the Derwent, with the majority of the catchment receiving less than 300 mm; the average annual rainfall across the catchment is 720 mm (Trent Rivers Trust, 2015) (Figure 2.3c). The Trent catchment contains substantial urban and industrial areas and consequently the river receives high volumes of effluent discharge.

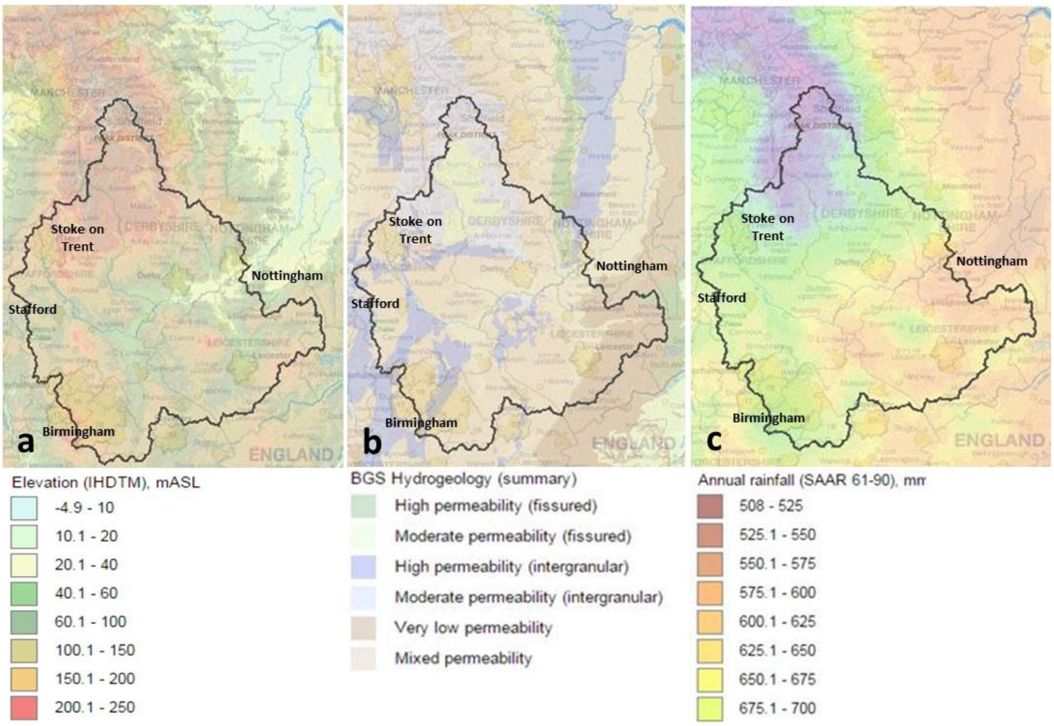

Figure 2.3. (a) Elevation, (b) hydrogeology and (c) annual rainfall in the River Trent catchment (the upper catchment is identified by the black boundary and the lower catchment is to the north-east, source: www.ceh.ac.uk/data/nrfa/data/spatialdata.html?28009)

The present channel conditions are homogenous, morphologically uniform and relatively inactive (JBA, 2009, 2010) (Figure 2.4a and 4b). The channel is over-deepened in response to lack of lateral migration, floodplain gravel reworking and inputs of course material for bank protection (JBA, 2009, 2012).

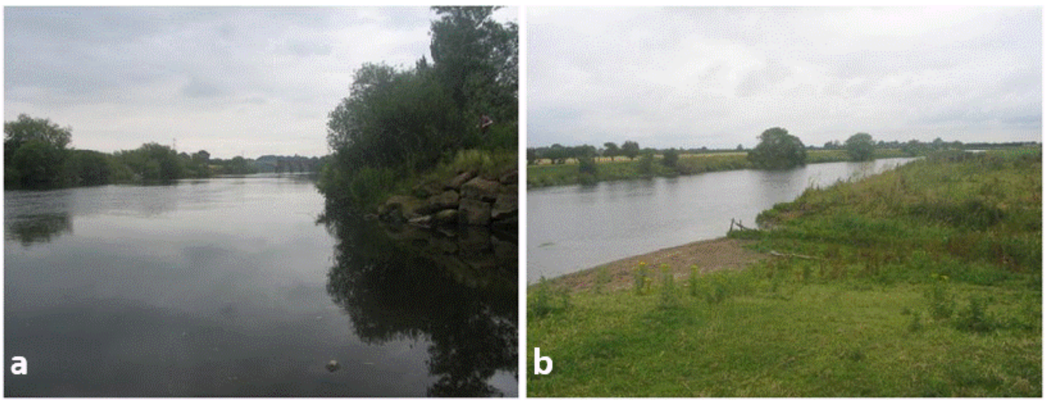

Figure 2.4. The River Trent at (a) Holme Pierrepont and (b) Winthorpe (Photos: Andy Nunn).

2.2 Historical hydrogeomorphological situation or reference situation

The River Trent has evolved complex responses to changes in climatic and catchment drivers since the Holocene and subsequent to the last Ice Age (12ka BP). The channel has demonstrated periods of braiding, stable anastomosing behaviour linked to forested floodplain conditions and single-thread meandering (JBA, 2009, 2011, 2012). Channel bifurcation and splitting has been recorded in the past, but has reduced since the 13th Century (mainly during the 20th Century) (JBA, 2012). The River Trent between the confluence with the River Dove and the weir at Gunthorpe in Nottinghamshire possibly ran simultaneously in two channels prior to 1592, bifurcating at several points along its course until the end of the 16th Century (Petts & Large, 1996). Maps of the late 18th Century show the Trent was a meandering river with an approximate sinuosity of 1.60 through the downstream sector (Large & Petts, 1996; Petts & Large, 1996; Large & Prach, 1998). Presently, the River Trent shows no propensity to braid; the channel currently appears to be a generally stable alluvial single-thread channel with limited gravel shoaling and localised areas of erosion (Large & Petts, 1996; Large & Prach, 1998; JBA, 2011), although there has been island development and gravel shoaling in the past (JBA, 2009, 2012).

The earliest form of regulation of the River Trent was for powering mills dating from the 12th Century (Petts & Large, 1996). The earliest records of engineering works date from 1699, in “Act for making and keeping the River Trent in the counties of Leicester, Derby and Stafford navigable”. It became effective in 1714 when a 2.74-m-wide hailing path was constructed along the north bank of a 31-km stretch of the River Trent between Burton-upon-Trent and Shardlow (Petts & Large, 1996). However, the majority of the modifications up to the 18th Century were intended to protect farmlands and highways. Bank revetments were used to prevent erosion and channel movement, and by the end of the 18th Century, wing dykes were introduced to deflect flow away from vulnerable banks (Petts & Large, 1996). Training weirs were used to narrow the channel and facilitate the removal of shoals by self-scouring, and longitudinal weirs were used to cut-off side channels and bays, to reduce channel width by joining islands to one bank. Silt was deposited behind weirs and was consolidated into new banks colonised by vegetation. This resulted in narrowing of the river channel, initiating scouring, thus deepening the river channel (Petts & Large, 1996). Over time, anthropogenic influence has resulted in partial decoupling of the channel and floodplain, including embanking and bank protection, infilling of side channels and warping to deliberately increase overbank deposition (Petts & Large, 1996).

2.3 Drivers: socio economic activities

Land use varies throughout the River Trent catchment. The headwater areas are dominated by agriculture and there are numerous urban areas (Soulsby et al., 2008). There is a history of a wide range of industrial activities in the catchment, including vehicle manufacturing and heavy engineering in Birmingham, pottery in Stoke-on-Trent, brewing in Burton-on-Trent, and textiles, coal mining and steel production (Jarvie et al., 2000; Soulsby et al., 2008). A number of fossil-fuel-based power stations are also present in the catchment (Soulsby et al., 2008), which previously had significant impacts on water temperature and fish growth in the Trent (Sadler, 1980; Cowx, 1991; Jacklin, 1996) and still entrain and impinge fishes (J. Rawlinson, *pers. comm.*; Carter & Reader, 2000). The lowland areas of the catchment are important for agriculture, especially mixed and dairy farming (Jarvie et al., 2000; Soulsby et al., 2008). The main socio economic uses (drivers) of the River Trent catchment are: urbanisation, agriculture, industry, navigation and mining.

The construction of numerous weirs on the main river and many tributaries during the Industrial Revolution enabled economic development (Figure 2.5), disrupting longitudinal connectivity and fragmenting the catchment. In addition, the catchment has been heavily polluted in the past and many reaches around the cities, such as Birmingham, were devoid of fish (Lester, 1975; Cooper & Wheatley, 1981; Cowx & Broughton, 1986; Mann, 1989; Cowx, 1991; Jacklin, 1996; Whitton & Lucas, 1997). Salmon disappeared from the catchment in the late 19th or early 20th Centuries, but the species has been showing signs of recovery since the late 1980s, following promulgation of the 1973 Water Act (Cowx & O'Grady, 1995). There have also been efforts to improve longitudinal connectivity since the 1980s, by installing fish passes on all major weirs in the lower reaches, most recently in conjunction with hydropower development schemes (AMEC, 2012).

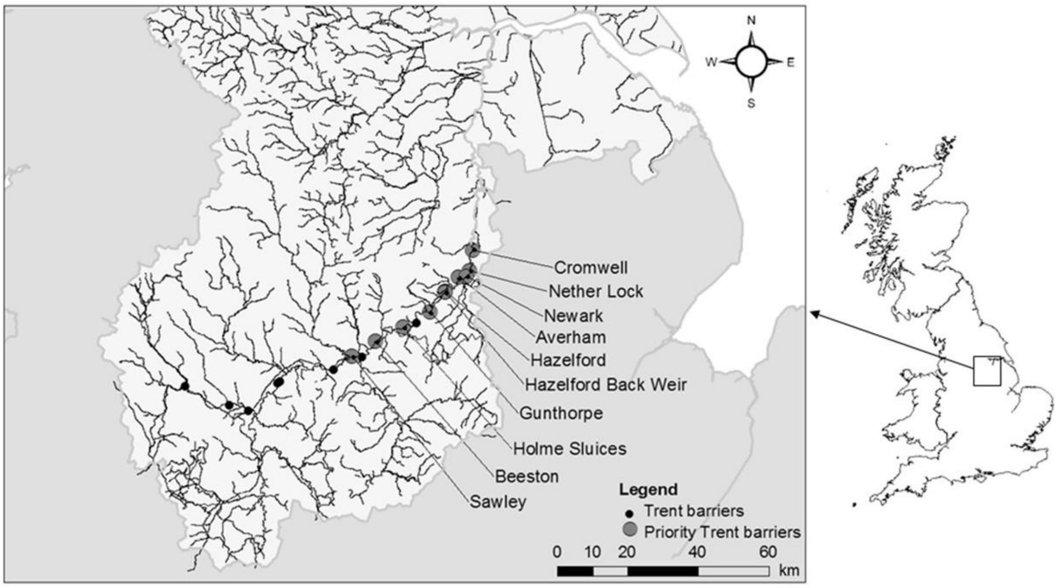

Figure 2.5. Barriers in the River Trent assessed for longitudinal passage improvements for Atlantic salmon, European eel and river lamprey (Source: Nunn et al., 2012a).

The main River Trent is also subject to flow modification by a number of reservoirs, especially in the Derwent catchment, and flows are heavily supplemented by water transferred from the adjacent Severn catchment to supply major conurbations around Birmingham. Effluent discharge (flow enhancement) through water-treatment works may be as much as 30% of the flow in the lower reaches during natural low-flow conditions. Water is also used for brewing, mineral washing, dust suppression and cooling water (Environment Agency, 2009a). There are also a number of quarries in the lower part of the Trent and power stations in the valleys (Environment Agency, 2009a).

Tame, Anker and Mease: The rivers in this sub-catchment mainly pass through urban areas, including Birmingham, Solihull, Nuneaton, Tamworth and Burton-upon-Trent. There is some heavy industry in the area, but this has declined in recent years. To the north and east of this sub-catchment, most of the land outside of Birmingham is used for agriculture, particularly arable farming (Environment Agency, 2009a). The largest inputs to the river in this part of the catchment are from sewage treatment works servicing the major conurbations (Harkness, 1982; Environment Agency, 2009a).

Staffordshire Upper Trent Valley: This sub-catchment supports abstraction for public water supply, spray irrigation and industry (Environment Agency, 2009b; Noble et al., 2009). Poor water quality and habitat have historically been an issue in the River Trent downstream of Stoke-on-Trent (Lester, 1975), but water quality has improved in the past 20 years, particularly from sewage treatment works and storm discharges (Jacklin, 1996; Robson & Neal, 1997; Jarvie et al., 2000; Neal & Robson, 2000; Environment

Agency, 2009b). There is a history of coal mining in the catchment and this has led to issues with contamination and rising mine waters (Environment Agency, 2009a).

Dove: This sub-catchment supports abstraction for public water supply, spray irrigation, industrial use and hydropower. In the upper reaches, Carboniferous limestone is quarried for use in the aggregates and cement industries. Physical modifications for urban flood protection and water storage and supply are key pressures in the sub-catchment.

Derbyshire Derwent: The Derbyshire Derwent sub-catchment is an important public-water supply for the East Midlands and South Yorkshire. The reservoirs on the River Derwent and in the nearby River Dove sub-catchment are required to release compensation flows to the Rivers Derwent and Amber. Discharges from sewage treatment works and industrial processes are released into the lower Derwent. Physical modifications that impede fish movement (Cowx & O'Grady, 1995), flood protection and the supply and storage of water are key pressures on the river in this sub-catchment.

Soar: Physical modifications due to urbanisation (Leicester) and for water storage and supply, and barriers to fish movement are key pressures on the river in this sub-catchment.

Lower Trent and Erewash: The Trent becomes navigable downstream of Shardlow and has been deepened by locks and weirs. Through Nottingham, the river is urbanised with hard banks (Environment Agency, 2009b). The river widens downstream of Nottingham towards Newark. As the river flows north towards the Humber Estuary, land on both sides of the river is low-lying and flat, with networks of land-drainage ditches and dykes, and used for agriculture. There is a series of quarries throughout the catchment; gravel deposits have been developed adjacent to the river and some former gravel pits have been redeveloped for recreation (e.g. the National Water Sports Centre) or as wetland areas for wildlife (e.g. Attenborough Nature Reserve) (Environment Agency, 2009b). Mine waters from recently closed collieries are carefully managed in this district (Environment Agency, 2009b).

Idle and Torne: Both rivers rise and flow through heavily urbanised areas with heavy industry. Many collieries in the catchment have recently closed, so mine water has to be carefully managed. The dominant land use is agriculture, and abstraction and flood defences are pressures on the river system (Environment Agency, 2009b). The confluences of the Idle and Torne with the Trent are controlled by sluices, with water released by gravity at low tide and pumps at high tide.

2.4 Current pressures and effects on processes & ecology

There are a number of pressures acting upon the River Trent (REFORM WIKI pressure categories), the intensity of which varies within the catchment, especially in relation to urban development. The problems are particularly prevalent for populations of migratory fishes, which have been heavily impacted by a legacy of extensive modification of the catchment by flow regulation, construction of artificial barriers and channel modification, as well as poor water quality (Cowx & O'Grady, 1995; Jacklin, 1996; Nunn et al., 2007a, 2009, 2011, 2012a, b; Nunn & Cowx, 2012). Pressures result in hydromorphological degradation, which has implications for the ecological status of the River Trent, which is currently defined as "poor potential", with a target of achieving "good ecological potential" by 2027 (JBA, 2012). The first round of River Basin Management Plans (RBMPs) identified that only 3% of rivers in the Trent catchment are currently achieving "good" or better ecological status/potential (Figure 2.6), with 17% graded as "good" or better biological status, 39% as "poor" and 6% as "bad" (Environment Agency, 2009a). Pressures and degradation of river processes have implications for the ecological status of the River Trent for a number of reasons, as described below.

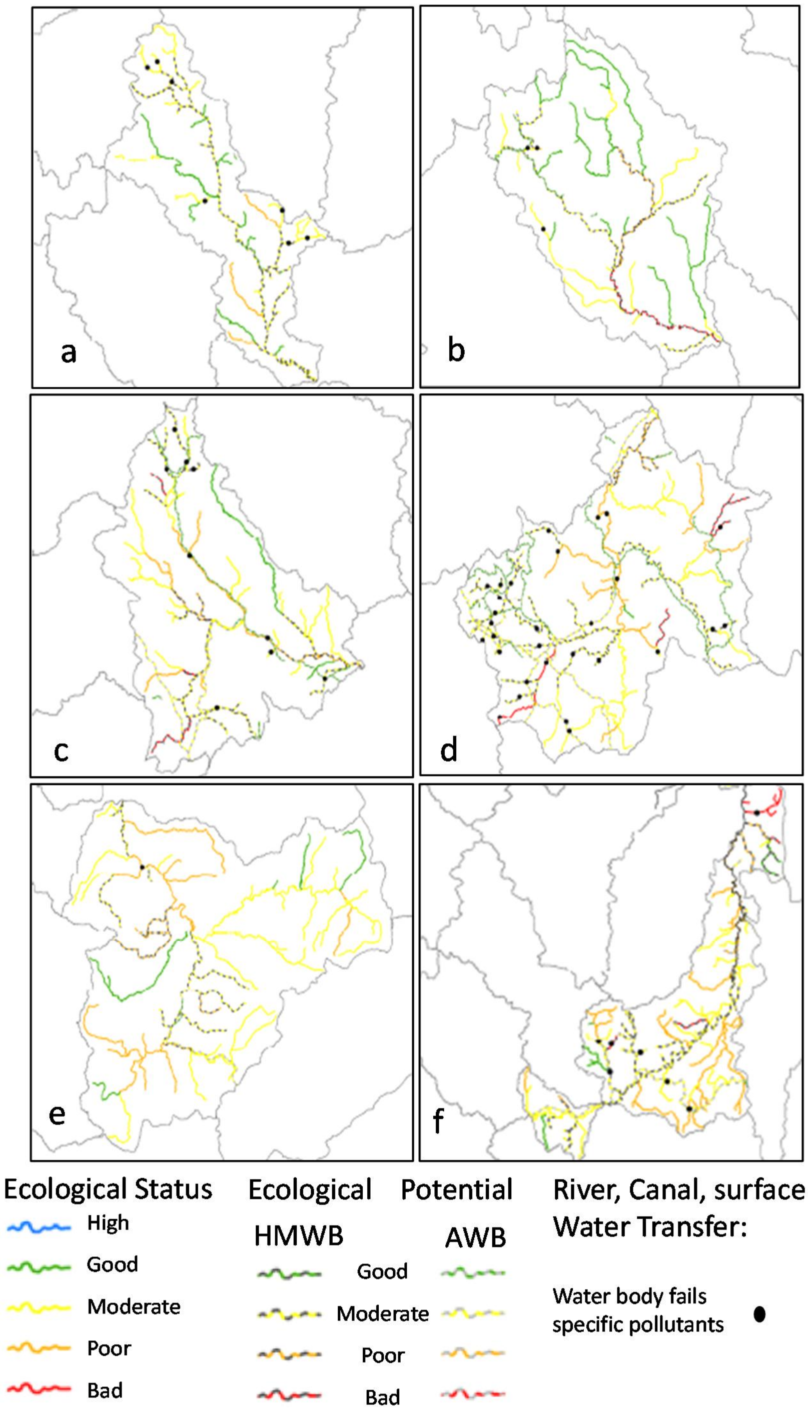

Figure 2.6. The current ecological status/potential for the rivers in the Trent catchments (a) Derbyshire, (b) Dove, (c) Staffordshire Trent Valley, (d) Tame, Anker and Mease, (e) Soar, (f) Lower Trent & Erewash (adapted from Environment Agency, 2009a).

Water abstraction and flow regulation: Naturally low flows occur in the Trent and are caused by extended periods of low rainfall, which are common in central England; these periods can be extended or aggravated by flow regulation and unsustainable levels of abstraction for public water supply, industry, agriculture or domestic use (Environment Agency, 2009b; Noble et al., 2009). Additionally, ground-water pumping can locally reduce spring flows and water levels, impacting upon groundwater-fed wetlands (Environment Agency, 2009b). Water abstraction and flow regulation change the natural flow regime of the River Trent, causing further changes in hydromorphological processes, such as sediment transfer and vegetation encroachment.

It also leads to changes in hydromorphological variables, such as average flow, volume of water, bank erosion, channel width, depth and velocity, substrata size and riparian cover (Environment Agency, 2009b). Subsequently, these changes affect habitat availability, with changes in flow particularly influencing the spawning migrations, habitat shifts and dispersal of fish and habitat maintenance in hydro-dynamically determined environments that are of profound ecological importance. Water abstraction and flow regulation alters the duration and frequency of flooding in the lower Trent, this can reduce the availability of flow refugia, lowering the diversity and abundance of biota capable of recovering from flooding.

River fragmentation: The industrial heritage of much of the Humber and Trent basins means that there is a large number of potential barriers to fish migration (Cowx & O'Grady, 1995; Nunn et al., 2007a, 2009, 2011, 2012a, b; Nunn & Cowx, 2012). The Trent was an important salmon river prior to the Industrial Revolution, with the majority of production in the Rivers Dove, Derwent and Trent main stem (Cowx & O'Grady, 1995). Numerous weirs (Figures 2.5 & 2.7a) and tidal sluices (Figure 2.7b) are present in the Trent catchment, >2194 weirs are listed in the Environment Agencies National Obstruction's Database, most of which cause obstruction to the natural continuum of the river (Sykes, 2004). These obstructions consequently affect hydromorphological processes, such as water flow and sediment movement, further influencing hydromorphological variables, such as flow magnitude, channel width, water depth, riparian recruitment, siltation and substratum size. The weirs on the Trent should be passable by most fishes at moderate or high flows, but potentially impede upstream movements during low flows (Sykes, 2004). In addition, the tidal barriers prevent natural mixing between fresh and saline waters, which can have consequences for ecological communities (Environment Agency, 2009b) and prevent free movement of migratory species, such as eel (Nunn et al., 2009, 2011, 2012b; Nunn & Cowx, 2012). Many of the weirs on the Trent were built in the industrial past and are protected under heritage legislation, so cannot be easily modified. Some weirs have been modified for small-scale hydropower development and can cause conflict with improving ecological status, but equally they can provide an opportunity to build fish-passage facilities to improve connectivity. An example on the Trent is the low-head hydropower scheme at Beeston Weir, which became operational in 2000, where environmental enhancement was incorporated into the design (AMEC, 2012). This included reducing the size of the scheme and the volume of excavated material to be removed, introducing a fish screen/bubble curtain, improving passage for both salmonid and non-salmonid fishes, and including a tail-race design to recreate a suitable hydraulic regime for gravel-shoal habitat re-creation.

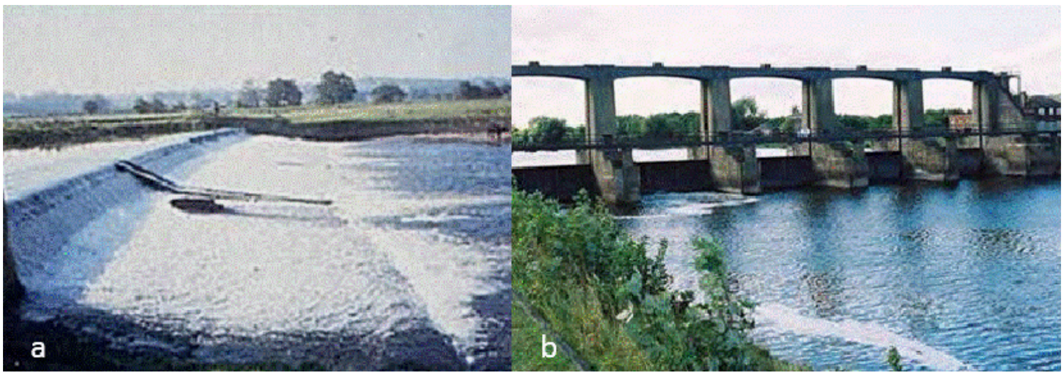

Figure 2.7. a) Cromwell Weir and b) Holme Sluices on the River Trent.

Morphological alterations: Navigation, drainage, flood prevention and creation of new channels for watermills or irrigation have all driven morphological alterations, such as channelisation, embankments, instream habitat removal and gravel extraction through dredging, in the River Trent (Environment Agency, 2009b). Downstream of Shardlow, the Trent becomes navigable and is deepened by locks and weirs. Through the city of Nottingham the river is influenced by the surrounding urban land use, which results in homogenisation of the channel and riverine habitats, as well as dramatic losses of habitat structures, habitat complexity and freshwater biota, such as fish and invertebrates. The morphological alterations also change the hydromorphological processes, such as channel planform, gradient, flow resistance, sedimentation and entrainment, bank stabilisation and vegetation encroachment, of the river. This further affects hydromorphological variables, such as flood duration and magnitude, channel width, water depth, the percentage of fines, substratum size, bank stability and height, riparian corridor width and lateral connectivity, which ultimately affects ecological status.

Downstream of Nottingham, the river widens as it flows northwards and is flanked by low-lying, flat land with networks of land-drainage ditches and dykes to enable arable agriculture (Environment Agency, 2009a). Wetlands and flood plains are associated with the lateral (riverine-riparian-flood plain) dimension of river systems (Ward & Stanford, 1989), but many in the Trent catchment have been disconnected through channelisation, embankments and modifications to support urbanisation, navigation and flood protection. In some instances, concrete banks and wake wash prevent the colonisation of slow-flowing, littoral areas by vegetation and therefore reduce the availability of suitable habitat to larval and juvenile fishes and the recruitment of phytophilic fish. Some former gravel pits have since been redeveloped, providing recreational facilities and wetland areas for wildlife (Environment Agency, 2009a).

Sediment input: Increased sediment loading is extensive across the Trent catchment as a result of soil erosion by land-based activities, such as forestry, construction and agricultural intensification, along the river (Environment Agency, 2009b; JBA, 2011). Hydromorphological effects are increased siltation of impoundments behind weirs and navigable waterways, obstruction of drains and waterways, increased flood risk and increased turbidity (Environment Agency, 2009b).

Water quality: Water-quality pressures in the Trent catchment occur due to a number of issues, including industrial and domestic effluent discharge, especially around the large conurbations, such as Birmingham, Nottingham, Leicester, Derby and Stoke-on-Trent, where poor water quality and habitat has impacted upon fisheries (Lester, 1975; Jacklin, 1996; Environment Agency, 2009a). Although water quality has much improved in the last 20 years (Martin, 1994; Jacklin, 1996; Robson & Neal, 1997; Jarvie et al., 2000; Neal & Robson, 2000; Langford et al., 2010, 2012), the presence of nitrate in surface and groundwaters, organic pollution, sediment input, pesticides and phosphorus in rivers and standing waters is still an issue and impacts upon fisheries (Nunn et al., 2014a, b). Numerous collieries have closed in recent years, and mine waters therefore need to be carefully managed and will require the implementation of new mine-water pumping stations by the Coal Authority to prevent pollution of the major aquifer in the area (Environment Agency, 2009a). Additional water-quality pressures are acidification, recreation, chemicals and other pollutants (Environment Agency, 2009b).

The imposition of pollution control measures by the Trent River Authority and its successors, Severn-Trent Water Authority, the National Rivers Authority and the Environment Agency, has resulted in improvements in the water quality of the River Trent (Cowx & Broughton, 1986; Mann, 1989). The diversion of industrial effluents to sewer, improved sewage treatment, introduction of biodegradable detergents and the cessation of coal gasification have all contributed to the progressive improvement in water quality (Jacklin, 1996). This, in turn, has resulted in a resurgence of the fish populations of the river (Mann, 1989). In the 1980s, the Trent was renowned as one of the premier river fisheries in the country, with catches usually dominated by roach (*Rutilus rutilus* (L.)) (Lyons, 1998). Since then, continued improvement in water quality has caused a shift in fish community structure, with a decline in the dominance of roach coinciding with an increase in the numbers of chub (*Leuciscus cephalus* (L.)) and bream

(*Abramis brama* (L.)) (Cowx, 1991). Currently, the fish community of the lower Trent is characterised by roach, bream, chub, perch (*Perca fluviatilis* L.), bleak (*Alburnus alburnus* (L.)), dace (*Leuciscus leuciscus* (L.)) and gudgeon (*Gobio gobio* (L.)), although species such as barbel (*Barbus barbus* (L.)) and carp (*Cyprinus carpio* L.) are increasing in importance (Cooper & Wheatley, 1981; Cowx & Broughton, 1986; Mann, 1989; Cowx, 1991).

2.5 Rehabilitation and mitigation measures

In the Trent catchment, 9.3 % of the area is designated as protected (Soulsby et al., 2008) and 316 areas are designated as Sites of Special Scientific Interest (SSSI) (Environment Agency, 2010). The Humber Basin RBMPs, compiled in 2009, provide the planned rehabilitation and mitigation measures in response to hydromorphological pressures within a regional context (i.e. across the Humber basin scale). Information for rehabilitation measures in the RBMPs is generic and not site specific, however, it provides a satisfactory overview of the types of measures that are being implemented and planned. These include:

Implemented

- Reduce surface-water abstraction
- Riparian-zone improvement
- Higher Level Stewardship scheme for farmers

Planned

- Restoration of peat moorlands
- A rolling programme of bankside and in-river habitat improvements
- Identifying priority obstructions and improving fish passage, either through provision of fish passes or removal of obstructions
- Partnership working to deliver habitat improvements through land-management practices
- Joint working towards restoration of a more natural inundation regime for more natural flow patterns and ecological functionality
- All new hydropower schemes should allow free passage of fish (including eel) without damage and should be ‘friendly’ to all species. Opportunities will be identified where schemes could be beneficial in providing solutions to current barriers
- Ensure new and existing power stations do not damage fish stocks due to thermal discharges, entrainment or impingement

Rehabilitation and mitigation measures planned and implemented in the Trent catchment:

Implemented

- On Trent Initiative: A major partnership project working to enhance the heritage value of the River Trent and its flood plain. The initiative has been in place since the mid-1990s and its key role is to deliver its agreed vision of ‘A Trent floodplain rich in wildlife habitats, landscape and historic features, for the benefit of all, both now and in the future’ by:
    - Creating a rich diversity of linked wetland habitats along the Trent from Stoke to the Humber Estuary.

- Respecting and enhancing local distinctiveness, character and diversity of the landscape.
- Encouraging the adoption of sustainable practices in agriculture, forestry, mineral extraction and building development.
- Conserving and enhancing the cultural identity and historic environment of the river valley.
- Encouraging sustainable recreation and tourism.
- Working with organisations and land managers to promote the value of wetlands and where appropriate the re-establishment of natural processes in floodplains.
- Encouraging others to adapt to, and mitigate the effects of, climate change.

- Staffordshire Trent Valley Headwater Streams Project: Promoting the spread of species by linking habitats and biodiversity hot spots along stream corridors
- Moors for the Future Partnership: Promoting responsible use, care of and restoration of the moors landscape
- Key spawning headwaters have been fenced off to provide buffer strips and prevent cattle poaching in the River Derwent, Derbyshire

Planned

- Restoration of peat moorlands in the Peak District
- East Midlands strategic river corridors project: Holistic management and enhancement of river corridors to benefit people, wildlife and help alleviate flood risk
- Identifying options for an eel pass at Cromwell Weir (the tidal limit of the Trent)
- Connecting borrow pits to the River Tame
- Trent Vale Landscape Partnership Project: Enhancement of river banks and less intensive use of adjacent land in the Lower Trent and Erewash stretch
- Investigate new flap-gate technology to increase fish-passage opportunities and seek removal of flap-gates and penstocks in the tidal Trent
- Flood-risk management measures: appropriate channel-maintenance measures
    - Minimise disturbance to bed (River Derwent, Bottle Brook to River Trent)
    - Remove woody debris only from upstream areas or areas of urban flood risk (River Derwent (from Bottle Brook to River Trent); River Trent (from Anker/Mease confluence to River Dove))
    - Align and attenuate flow to limit detrimental effects of these features (drainage) (River Derwent from Bottle Brook to River Trent)
    - Appropriate techniques and timing of vegetation control (River Dove; River Derwent from Bottle Brook to River Trent)
    - Appropriate water level management strategies, including timing and volume of water moved
    - Undertake bank rehabilitation/re-profiling work (Adlingfleet Drain upper catchment (tributary of Trent); River Trent from Anker/Mease confluence to River Dove)
    - Create flood bunds (earth banks) in place of floodwalls (River Derwent from Bottle Brook to River Trent; River Trent from River Soar to Carlton-on-Trent)

- Improve floodplain connectivity (River Trent from River Soar to Carlton-on-Trent)
- Increase in-channel morphological diversity
- Indirect/offsite mitigation works to be completed within the water body (offsetting measures) (River Trent from River Soar to Carlton-on-Trent; River Trent from Carlton-on-Trent to Laughton Drain)
- Operational and structural changes to locks, sluices, weirs, beach control, etc. (River Trent from River Soar to Carlton-on-Trent; River Derwent from Bottle Brook to River Trent)
- Preserve and where possible enhance ecological value of marginal aquatic habitat, banks and riparian zone (River Trent from River Soar to Carlton-on-Trent)
- Retain marginal aquatic and riparian habitats (channel alteration) (River Derwent from Bottle Brook to River Trent; River Trent from River Soar to Carlton-on-Trent)
- Management measure – selective vegetation control regime (River Derwent from Bottle Brook to River Trent; River Trent from Anker/Mease confluence to River Dove)
- Set-back embankments (a type of managed retreat) (River Derwent from Bottle Brook to River Trent; River Trent from River Soar to Carlton-on-Trent)
- Structures or other mechanisms in place and managed to enable fish to access waters upstream and downstream of the impounding works (Adlingfleet Drain upper catchment (tributary of Trent); River Derwent from Bottle Brook to River Trent)

There is little information available as to which of these measures detailed in the RBMPs have since been implemented or the outcomes of mitigation measures. Additional information on rehabilitation measures are provided in Table 2.2 (located in Figure 2.8). This information has been collected in addition to RBMPs and the majority has been supplied through personal communication with a member of Environment Agency staff.

Table 2.2. Rehabilitation and mitigation measures on the River Trent, 1990-present.

Project name	Date	Grid reference	Description of rehabilitation & mitigation measures
Trent Pathfinder	2005/6	SJ 880 453 to SJ 880 447	Remeander water course: Changed the course of the Trent and Fowlea Brook and put them in a designed concrete channel. Unfortunately, the downstream 10m was sloped upwards and the channel has largely been drowned out.
Stoke Fisheries enhancements	1996	SJ 879 443 TO SJ870 431	Remeander water course: Scheme to put 4 bends in the Trent between Victoria ground and Hanford roundabout.
Trentvale enhancements I	2003	SJ 865 429	Increase lateral channel migration: Pulling back banks on Trent and Trent/Lyme Brook confluence to encourage geomorphology development.
Trentside enhancements II	2004	SJ 864 422 to SJ 864 421	Re-vegetate riparian zones: Tree planting at d/s end of ST land.

Project name	Date	Grid reference	Description of rehabilitation & mitigation measures
Trees on the Trent	1995 - 1997		Re-vegetate riparian zones: Tree planting (over 100 sites) on a large number of sections of the Trent, between Stoke and Alrewas.
Strongford wetland	1990s	SJ 871 394	Restore wetland: Enhancements to the wetland which was itself caused by colliery subsidence.
Stone Meadows	2002	SJ 901 335 to SJ 910 325	Increase lateral channel migration & Restore wetland: Pull back river banks and wetland creation on the floodplain of the Trent.
Aston-By-Stone I	2001	SJ 920 315 to SJ 931 301	Increase lateral channel migration & Restore wetland: Pull back banks on a series of bends and creating wetland on ST land at Aston-by-stone
Hoo Mill Weir	1993	SJ 995 240	Install fish pass: Creation of a rock chute fish pass
Navigation Farm	2006	SK 008 207 to SK 017 204	Increase lateral channel migration & add sediment: Extensive bank pulling back and extensive gravel addition
Wolseley Bridge	2004	SK 024 205 to SK 026 204	Increase lateral channel migration: Bank pulling back
CHADS Planting and scrapes	1997	SK 097 175 to SK 104 174	Re-vegetate riparian zones: Bankside planting in floodplain
Wychnor	1994	SK 174 156	Install fish pass: Fish pass on weir
Catton Hall I (see Box 1)	2010	SK 192 149 to SK 195 147	Increase lateral channel migration & Restore wetland: Extensive bank pulling back and wetland creation
Catton Hall II (see Box 1)	2014	SK 195 147 to SK 202 150	Re-vegetate riparian zones: Tree planting along Trent and Mease at Catton
Catton Hall III (see Box 1)	2012	SK 205 158 to SK 206 168	Widen water course & addition of sediment.
Drakelow	2008	SK 228 207 to SK 229 209	Increase lateral channel migration, restore wetland & re-vegetate riparian zones:
Burton Washlands	1989 - 2003	Approx. SK 243 213 to SK 262 243	Restore wetland & re-vegetate riparian zones: A series of very extensive wetland and floodplain woodland creation schemes
Burton Fishpass 2013		SK 255 232	Install fish pass: Burton Weir
Burton Flood Defences	1999	SK 254 234 to SK 254 236	Flood defences incorporating habitat and river enhancements

Project name	Date	Grid reference	Description of rehabilitation & mitigation measures
River Eau	2010-present		Install fish pass: Fish friendly flap gates
Bottesford Beck	2010-present		Install fish pass: Fish friendly flap gates
Glazebrook	2000s	SK 455 299	Increase lateral channel migration:
Ully Gully	2000s	SK 463 308	Lateral connectivity, connect gravel pits
Thrumpton	2000s	SK 494 308	
Attenborough		SK 519 335	
Marina Pond	2000s	SK 627 396	
Farndon	2000s	SK 762 509	
Bingham	2000s	SK 801 562	
Winthorpe	2000s	SK 802 579	
Dunham	2000s	SK 819 738	
Willington	2000s		
Irmonger	2000s		

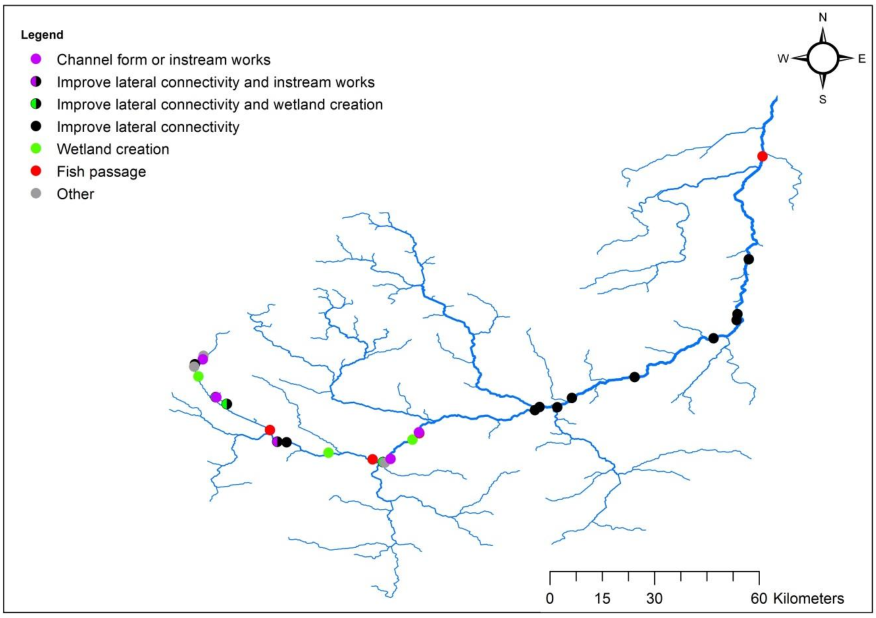

Figure 2.8. River rehabilitation projects on the River Trent between the confluence with the River Tame and the confluence with the River Dove.

- Increase lateral migration: During the last decade, attempts have been made to re-establish the link between the lower reaches of the River Trent and its floodplain by connecting a number of man-made waterbodies (Table 2.2, flooded gravel quarries) (Nunn et al., 2007b; Bolland et al., 2012). The main aim of the restoration project was to increase the availability and diversity (e.g. spawning and nursery habitat, refuge from floods) of habitat for fishes, particularly the early developmental stages, with a view to enhancing fish recruitment success within the lower reaches of the river. To date, approximately 12 such waterbodies have been connected to the lower reaches of the river, with more planned for the future (Nunn et al., 2007b).

CASE STUDIES

BOX 1 - Catton Hall

A large scale rehabilitation project was undertaken on the River Trent at Catton Hall, the principle aim of the study was driven by the WFD, to seek opportunities to improve hydromorphological and ecological status (Figure 2.9). Prior to rehabilitation work the stretch of river was highly channelized, straightened, dredged and was low energy; embankments reduced floodplain connectivity, stone pitching was used for bank training and there was limited coarse sediment present (Wozniczka et al. 2014). Rehabilitation works to improve habitat quality were undertaken on a 26.44 km length of river, between the confluence of the Rivers Anker/Mease, to the confluence with the River Dove, costing £51,030.92 (Wildlife Trusts, 2014). The project was undertaken in two phases.

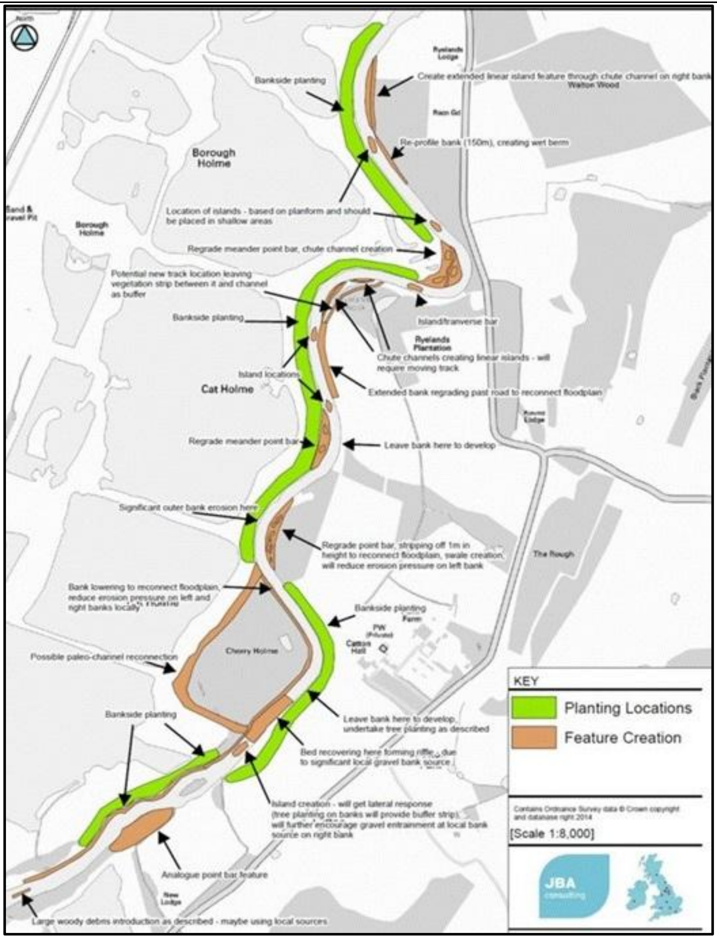

Figure 2.9. Catton Hall restoration proposal (Source: JBA, 2012).

Phase 1 - In 2012 a 5-km stretch through the Catton Hall and Barton Quarry estates was re-profiled to improve river habitat and functioning, to help reduce phosphate, phytobenthos benefit invertebrates (Wildlife Trusts, 2014). This was done by increasing channel width to allow shallows to form, excavating banks on the inside of meanders to form shallow gradients, reconnecting backwaters for refuges, removing stone bank protection, introducing large woody debris, placing willow trees with root wads to allow island formation and planting native woodland trees along both banks (Wozniczka et al. 2014). Reference conditions from the local area were used to inform project design, these included examples of natural recovery, natural processes and features such as island formation, riffle-pool-backwater sequence development and wooded sections (Wildlife Trusts, 2014).

Phase 2 – To create a large backwater linked to the main River Trent to act as a fish nursery and refuge, to create a new area of wet woodland and reed bed habitat (Wildlife Trusts, 2014). Cherry Holme is a former river island from where the channel bifurcated (JBA, 2012). This channel was abandoned between 1955 and 1964 but it is unclear whether this was due to artificial interference or through natural infilling of the left bank (JBA, 2012). During the second phase of the works two thirds of the paleo channel of the River Trent at Cherry Holme was excavated to create a new 400 m online backwater (Wildlife Trusts, 2014). Live willows were planted in the backwater to create islands and it was anticipated that these trees would grow quickly to form riverine/wet woodland (Wildlife Trusts, 2014). Approximately 6000 m^3 of excavated soil was transported and deposited at four sites at three nearby lakes to create shallows and suitable areas for the creation of new reed beds (Wildlife Trusts, 2014).

2.6 Ecological effects of measures

There is limited monitoring information available to identify ecological impacts of the measures implemented in the RBMPs and for the majority of projects presented in Figure 2.8 and Table 2.2. Lack of rehabilitation monitoring is an issue throughout Europe and most evaluation tends to be anecdotal observations.

Project evaluation of Catton Hall I & II case studies identified that rehabilitation measures endured extreme flow conditions. The islands and debris placed in straight sections were successfully established, in addition to the newly created back channels and bank re-profiling (Wozniczka et al., 2014). However, trees placed across the river on meanders were quickly washed away during very high flows, especially where the river was not widened during restoration works (Wozniczka et al., 2014). Overall, biological outcomes of the rehabilitation work were not monitored, only anecdotal observations suggest an increase in the number of fish present.

The connection of flooded gravel quarries and other man-made waterbodies to the River Trent channel enhanced riverine fish populations where lateral connectivity had been lost by increasing access to its floodplain and providing a diversity of habitats (spawning and nursery, refuge from floods) for fishes, particularly the early developmental stages. The function of many of the floodplain waterbodies as spawning areas for some species was confirmed by direct observation of spawning activity (carp and bream) or collection of eggs (pike), or inferred from the presence of newly hatched larvae (roach, perch and bleak) (Nunn et al., 2007b). It was also identified that artificial floodplain waterbodies of variable connectivity create habitats that are functionally similar to natural lowland river-floodplain ecosystems (Bolland et al., 2012). Connection of flooded gravel quarries and artificial waterbodies in the lower Trent was an efficient rehabilitation method to improve ecological status.

2.7 General remarks or conclusions

The ecological status of the River Trent is currently defined as “poor potential”, with a target of achieving “good ecological potential” by 2027. Numerous rehabilitation project are in place in the Trent catchment to improve hydromorphological processes and in turn, improve its ecological status, however, documentation of this information is poor. Mitigation measures detailed in the RBMPs are generic to the whole Humber river basin and are not site specific, therefore detailed information on specific measures for the Trent and the pressure they address is limited. In addition, information on the ecological effects of measures was extremely vague.

Scope for synergies in the Trent and Humber catchments are continuing to develop between sectors, such as flood risk and hydropower, and the incorporation of rehabilitation measures in to their planning and design.

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3. THE PO RIVER (Italy)

Authors: Barbara Belletti and Massimo Rinaldi (UNIFI)

3.1 Introduction to the Po River case study and Characterisation

With its 650 km the Po River is the longest and the only truly large river in Italy, where the catchment area is about 74000 km^2 (71000 km^2 in the Italian territory) and the mean discharge at the mouth is about 1540 m^3/s. It crosses great part of the northern Italy, from west to east, until it reaches the Adriatic sea through an extensive delta (i.e. 380 km^2) composed by 6 branches and that has been designated a World Heritage Site by UNESCO in 1999 (Figures 3.1 and 3.2).

The plain of the Po River forms the largest Italian plain and covers 24% of Italy. Italy currently has a population of 57 million with a density of 190 inhabitants per km^2. Over 16 million people live within the Po River basin that encompasses more than 3200 municipalities (Gumiero et al. 2009; Autorità di Bacino del Fiume Po 2006). Along the plain of the Po River are concentrated most of the economic and productive activities of Italy. Because of its geographical setting, its great length and large catchment together with the historical, social and economical events that interested the Po River since ancient times, it is considered the most important river in Italy.

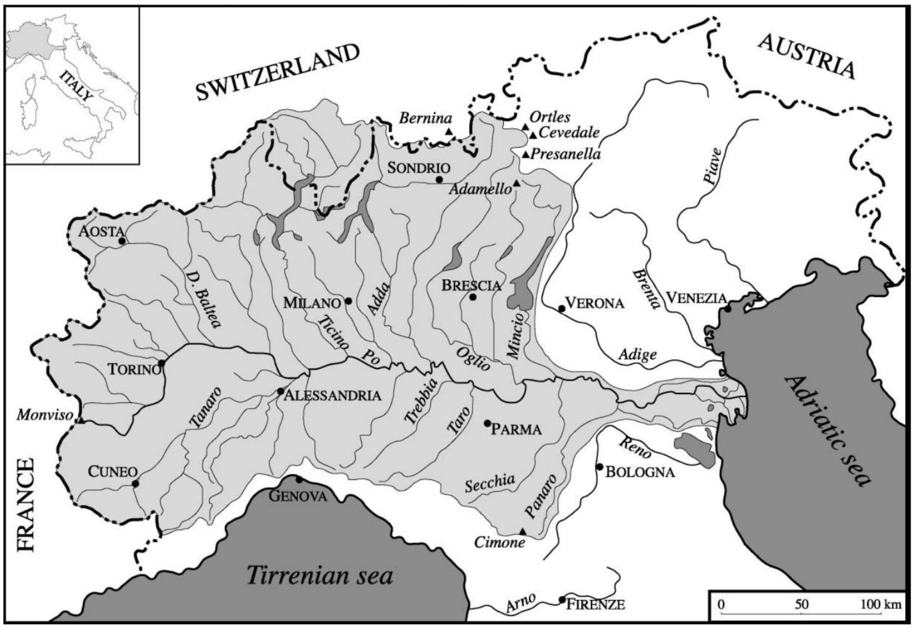

Figure 3.1 Geographical setting of the Po River catchment. Extracted from Marchetti 2002.

In the present chapter, a general description of the Po River and its catchment is provided. Based on the available information, a preliminary delineation of the landscape units has been carried out according to the hierarchical framework illustrated in the Deliverable 2.1. Most of the information collected and assembled comes from the following existing papers or published reports: Marchetti (2001), Autorità di bacino del Fiume Po (2006), Gumiero et al. (2009), Rinaldi et al. (2010) (some information was also derived from the website of the Po River Basin Authority, http://www.adbpo.it/on-multi/ADBPO/Home.html, and from http://it.wikipedia.org/wiki/Po).

Figure 3.2 Aerial view of the River Po in its middle course, near the '*Mezzana Bigli*' bridge. Photo: Autorità di Bacino del Po, extracted from Gumiero et al. 2009.

Figure 3.3 Italian biogeographic regions and localisation of the Po River catchment. Picture modified from http://vnr.unipg.it/habitat/glossario.jsp.

Regional context

The Po River catchment is mainly located in the continental biogeographical region, even if the overall catchment also includes the other two Italian geographical regions (i.e. Alpine and Mediterranean) (Figure 3.3).

Catchment

The Po River catchment is located in northern Italy, flowing through 7 different Italian regions: Piemonte, Valle d'Aosta, Lombardia, Emilia Romagna, Veneto, Liguria, Toscana and the Autonomous Province of Trento. The catchment area is about 74000 km^2.

The Po River originates in the Piemonte region from Mont Monviso (2200 m a.s.l.) and before reaching the Adriatic sea it is joined by 141 tributaries coming from both the Alps and the northern Apennines.

The most part of the catchment is below 600 m where the mean elevation is 736 m, and the maximum and the minimum are 4810 m (i.e. the White Mountain) and 0 (i.e. the sea level), respectively (Figure 3.4).

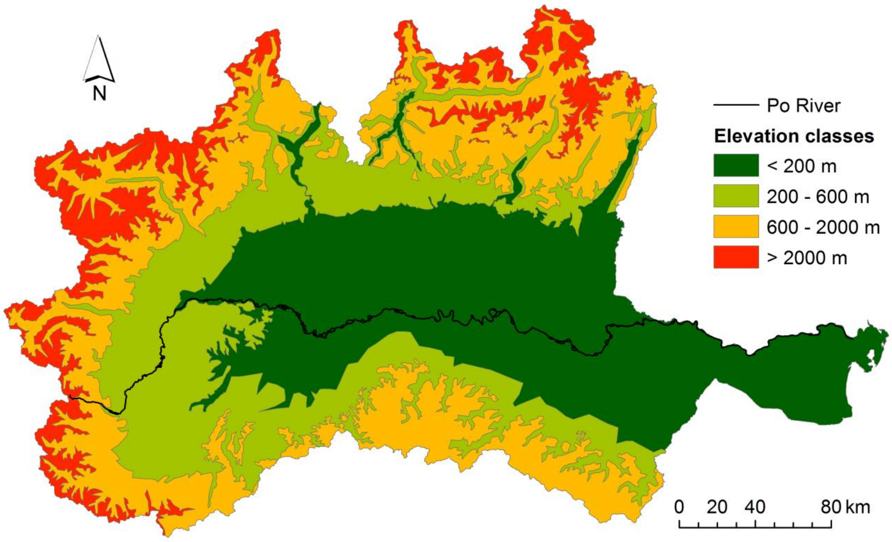

Figure 3.4 Range of elevation of the Po River catchment.

The Po River catchment can be divided into three areas of different lithology: (1) an Alpine sector of mostly crystalline metamorphic origin; (2) an Apennine sector of mostly sedimentary origin with a high clay component; and (3) a central alluvial area including the Padanian Plain and the Adriatic lowlands (Gumiero et al. 2009). The latter area has thick sediments (until 8000 m in some cases), and one of the highest known sedimentation rates. It is characterised by fluvial, glacial, delta, and lagoon sediments of Quaternary age, with textures ranging from coarse gravel at the foot of the mountains to silts and clays in the lowlands, with varying porosity and permeability (Gumiero et al. 2009) (Figure 3.5).

Figure 3.6 displays a sketch of the geomorphological units of the central Po Plain, which is approximately 80 to 100 km wide (from Marchetti 2002). It shows as the northern border of the Plain, near the Alpine foothills, has glacial amphitheatres which testify the strong influence of the Pleistocene glaciations along the main Alpine valleys (cf. Franciacorta and Garda amphitheatres in Figure 3.6) and thus also their influence on the development of the Po fluvial system. The glacial-interglacial transitions and their effects on sea level changes contributed to the Holocene evolution of the fluvial system, in particular to the formation of the present delta (Gumiero et al. 2009). The largest part of the Holocene plain was formed by the aggradation of the southern tributaries (the Apennine ones) (Marchetti 2002).

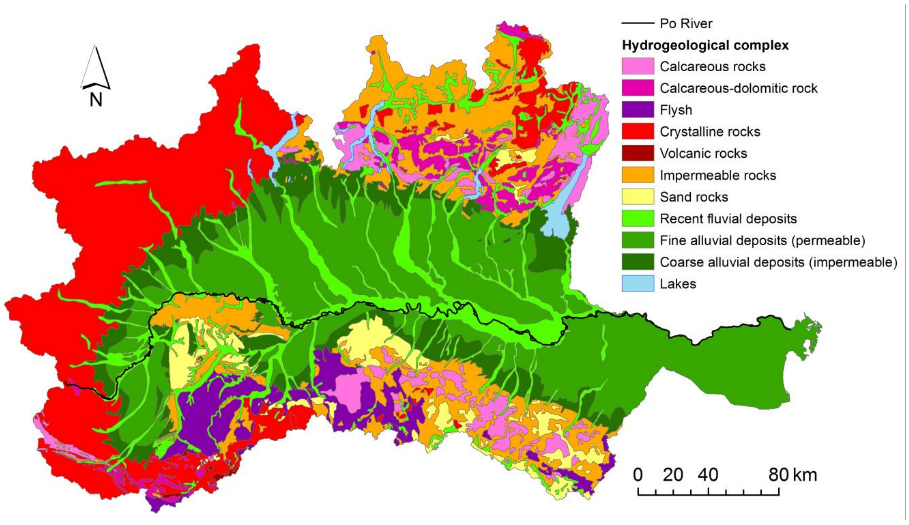

Figure 3.5 Hydrogeomorphologic complex of the Panaro catchment. Data source: ISPRA (http://www.sinanet.isprambiente.it/it/sia-ispra/download-mais).

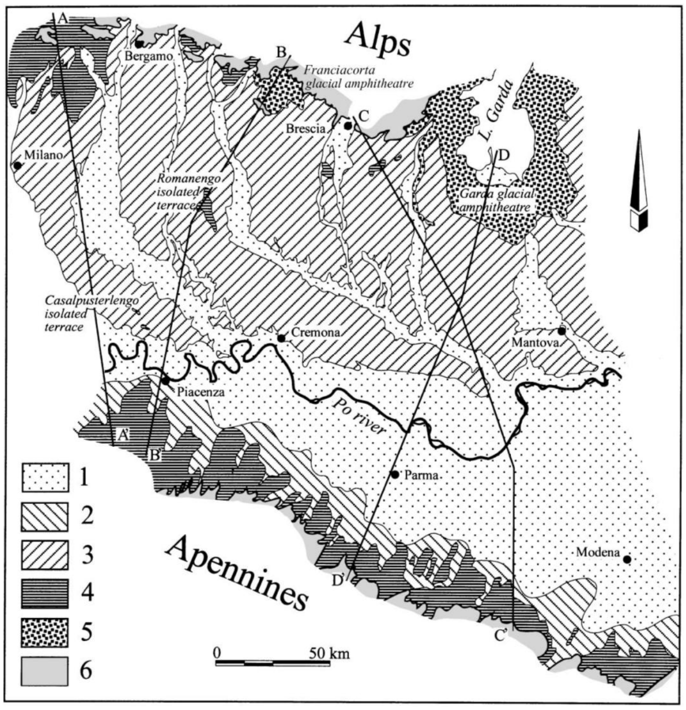

Figure 3.6 Geomorphological units of the central Po Plain: (1) Holocene fluvial deposits unit, (2) Late Pleistocene bajada unit, (3) Po Low Plain unit, (4) old terraces unit, (5) moraines, (6) bedrock. Extracted from Marchetti 2002.

The topographic setting of the Po River catchment seem to be the most significant drivers of climate and temperature regimes. The Alps protect the Po plain from northern cold winds, whereas the Apennines prevents the moist winds from the Tyrrhenian sea to reach the plain as well. The mean temperature ranges between 10 and 15°C where the lowest temperatures are reached in the mountain areas and the highest along the coast.

The regime of precipitations vary considerably across the catchment, where the highest precipitation is recorded in the lake district, in the lower part of the Alpine valleys and the lowest is recorded along the coast areas (Gumiero et al. 2009) (Figure 3.7).

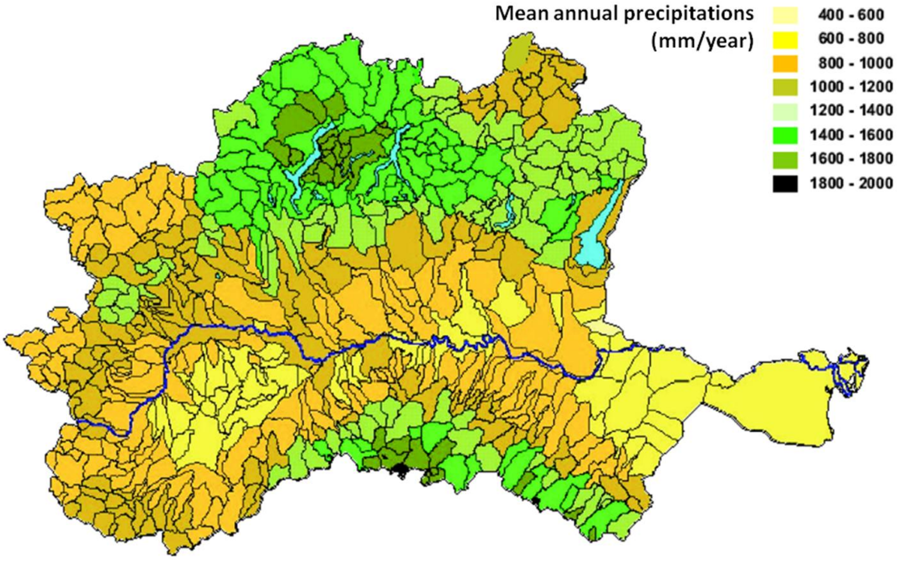

Figure 3.7 Mean annual precipitations in the Po River catchment.

The river regime in the Po River catchment reflects the different precipitation regimes of Alpine, Apennines and plain areas. Alpine tributaries have higher and more regular discharges (i.e. peak discharge in summer, after snow melt) than tributaries from the northern Apennines; the latter are characterized by unpredictable and destructive floods in spring and autumn that in turn cause flooding of the Po, and low discharge with frequent droughts in summer. In the Po Plain, exchanges between surface and ground water are rather complex; water loss for irrigation and down-welling altered the lowland river regimes. The superficial runoff ratio is about 68%, with greatest values in the Alpine, impermeable bedrock areas, while permeable alluvial deposits in the piedmonts allow water penetrating in the phreatic zone.

The catchment is mainly dominated by agricultural areas (i.e. arable lands), which dominate the Po plain. Forested and semi-natural areas prevail in the hills and mountain areas (Figure 3.8). Table 3.1 summarises some of the main characteristics at the catchment scale.

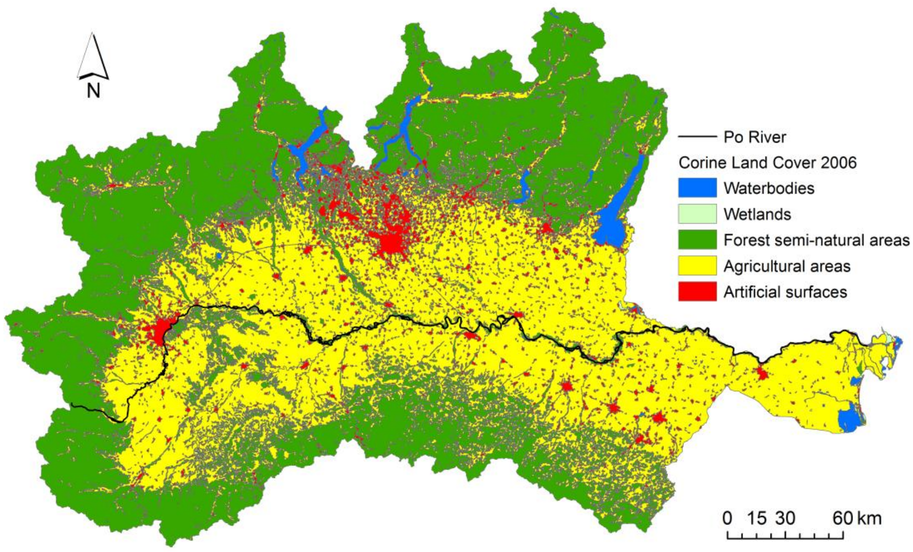

Figure 3.8 Landuse of the Po River catchment according to the Corine Land Cover of level 1 (2006).

Table 3.1 Summary of the Po River characteristics at the catchment scale.

Feature	Value
Catchment area (km^2)	71000
Mean catchment elevation (m)	736
Mean annual discharge (m^3/s)	1540
Maximum discharge (m^3/s)	> 10000
Mean annual precipitation (cm)	124.3
Landuse (% of the catchment)	
Waterbodies	2
Wetlands	0.1
Forests and semi-natural areas	44.9
Agricultural areas	46.6
Artificial surfaces	6.4

Landscape units

Mainly based on the information on physiographic characteristics and hydrogeology of the catchment, 6 landscape units (LU) have been identified (Figure 3.9; Table 3.2).

Landscape unit 1: Mountains areas (Alps)

Highest parts of the Alpine chain (above 1500 m a.s.l.) mainly characterized by crystalline rocks which dominate in the western part and mixed rocks (i.e. crystalline and with some impermeable sedimentary rocks) in the eastern parts. It is dominated by forested and semi-natural areas.

Landscape unit 2: Mountain -hilly areas (Pre-Alps)

Mountain and hilly areas (above 300 m a.s.l. up to 1500 m a.s.l.) along the Alpine chain characterised by crystalline rocks in the western part and mixed rocks (i.e. crystalline and sedimentary) in the eastern part with dominance of calcareous rocks. It also includes tertiary deposits (fluvial and glacial) of coarse and highly permeable material in the hilly areas. As LU1, it is dominated by forested and semi-natural areas in the higher parts but some agricultural activities are also present in the more hilly areas.

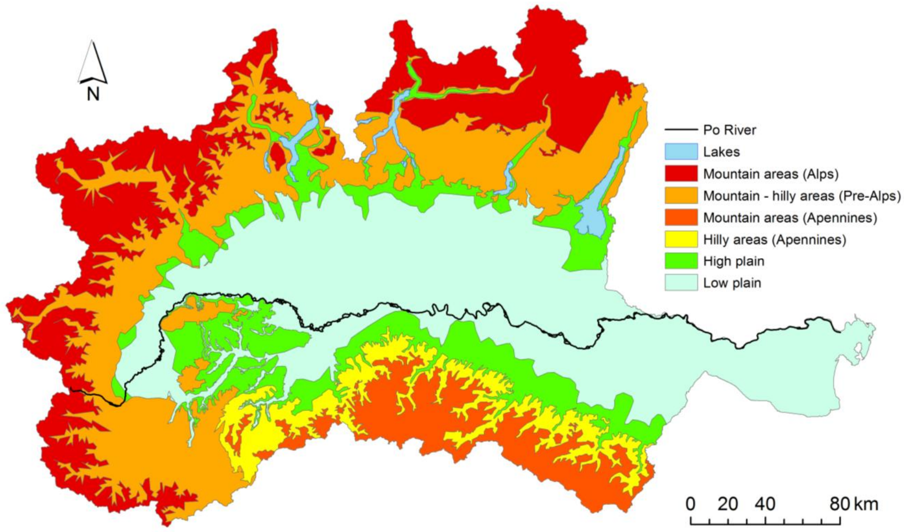

Figure 3.9 Landscape units in the Po River catchment.

Landscape unit 3: Mountain areas (Apennines)

Mountain areas (from 600 m a.s.l. up to 2000 m a.s.l.) is characterized by mixed rocks (i.e. flysch, limestones and impermeable sedimentary rocks, e.g. marls and clays, and some crystalline rocks in the western part). It is dominated by forested and semi-natural areas.

Landscape unit 4: Hilly areas (Apennines)

Mountain areas (always below 600 m a.s.l. but above 300 m a.s.l.), which composition mainly reflects those of LU3, but with dominance of flysch in the western part and sedimentary rocks (sands and impermeable rocks) in the eastern part. As LU3, it is characterised by forested and semi-natural areas but also some agricultural activities.

The Po Plain can be divided into two different areas with different characteristics in terms of altitude, geology but also vegetation and landuse: the high and the low plain.

Landscape unit 5: High plain

It includes the piedmont areas both of the Alps and the Apennines. It is characterised by slopes higher than 0.15 % (Castiglioni and Pellegrini 2001) and coarse, permeable sediment. It also includes the planes around the big glacial lakes below the Alps. It is characterised by mixed farming, such as orchards, vineyards, corn fields and vegetables.

Landscape unit 6: Low plain

It includes lowland areas where the slope is in general lower than 0.15 % (Castiglioni and Pellegrini 2001). It is characterised by fine impermeable sediment (fine sand, silt and clay). It is dominated by intensive farming (e.g. rice fields, pastures, corn fields, etc.). Main cities and industrial sites are mainly present in this area.

The following paragraphs are mainly focussed on the main alluvial course of the Po River which flow through the low plain of landscape unit 6.

Table 3.2 Summary of the Po River characteristics at the landscape unit scale.

LU	Name	Elevation	Short description	Landuse
1	*Mountain areas (Alps)*	Above 1500 m a.s.l.	High Alpine areas; dominated by crystalline rocks (mainly in the western part)	Forest and semi-natural areas

LU	Name	Elevation	Short description	Landuse
2	*Mountain - hilly areas* *(Alps)*	300-1500 m a.s.l.	Mountain and hilly alpine areas, characterised by crystalline rocks, which dominate in the west, and sedimentary (calcareous) rocks, which dominate in the east. Significant presence of fluvial and glacial deposits	Forest and semi-natural areas and agriculture
3	*Mountain areas* *(Apennines)*	600-2000 m a.s.l.	Mountain Apennine areas, dominated by flysch, limestones, marls and clays	Forest and semi-natural areas
4	*Hilly areas* *(Apennines)*	Up to 600 m a.s.l.	Hilly areas of the Apennines. Dominance of flysch in the west and sandstones, clays and marls in the east	Forest, semi-natural areas and agriculture
5	*High plain*	Always below 300 m a.s.l.	Piedmont areas of both Alps and Apennines which slope is higher than 15 %, characterised by coarse and permeable substrate	Mixed agricultural areas
6	*Low plain*	In general below 200 m a.s.l.	Low plain areas which slope is lower than 15 %, characterised by fine and impermeable substrate	Intensive farming, industrial sites and urban areas

3.2 Historical conditions and human impacts

The Po River and its plain have been modified since ancient time, contemporary to the human colonisation of the Italian territory. Thus, to determine an historical/reference situation for the Po River is rather complex.

Significant impacts on catchment and fluvial systems already began in the Neolithic age with the development of human activities (i.e. the introduction of livestock and agriculture) (Gumiero et al. 2009; Marchetti 2001). However, human impact on the Po Plain started to equal or even be more important than other natural factors (e.g. climate, tectonics, vegetation, etc.) during the roman age. In this period the dramatic increase in agricultural development and deforestation severely impacted sediment transport and caused the pro-gradation of the Adriatic coastline (Marchetti 2002).

The first construction of levees along major cities, of canals, aqueducts, irrigation systems, land drainage systems and land reclamation, also date back to the Roman period (Gumiero et al. 2009). Since then human modifications became more and more intensive.

Beginning in the 12th century, a series of canals were constructed in the central Po Plain (*Navigli*) for irrigation and navigation between major cities (Milan, Turin, Bologna, Venice), followed by an extensive hydraulic management of the valley floor (e.g. river diversions, flow regulation, meander cut-offs, levees, land reclamation) aiming at flood protection, navigation, agricultural purposes and urban development (Gumiero et al. 2009), that continued until today.

In the last century, the abandonment of the mountainous areas and consequent reafforestation, the artificial channel control in the mountain sectors and the in-channel sediment mining (now illegal but very intense in the 1960s and 1970s) are causing channel incision and narrowing along the Po River and its tributaries, as well as along large sectors of the Adriatic coast (Figures 3.10 and 3.11; Table 3.3; Marchetti 2002; Surian and Rinaldi 2003; Rinaldi et al. 2010).

Additionally to these historical human impacts, the relative recent history of the Po River has also been influenced by natural changes. For instance, Braga and Gervasoni (1989) showed that neotectonic events before the 16th century (i.e. the dramatic change in the course of the Sesia river, a left side tributary) and during the 19th (i.e. vertical movement of the ground) and 20th (i.e. raising of the external margin of the Apennine chain) centuries caused some significant geomorphic changes to the Po River course, where the most evident is the northward migration of the Po River bed.

It has been shown that, even if the Po River catchment has been impacted by human activities since ancient time, the great part of geomorphic adjustments along its main course (i.e. channel incision and narrowing, reduction of the channel length and changes in the channel pattern; Surian and Rinaldi 2003; Rinaldi et al. 2010) underwent during the last 150 years, as summarised in Table 3, as consequence of: hydraulic works and river engineering (channelization, embankments, etc.) for land reclamation, flood protection and navigation; channel sediment mining, mainly after the 1950s (see Figure 3.10); modification of the flood regime (causing an increase in the flood magnitude and frequencies); interventions at the catchment scale (reafforestation and torrential control works) (Marchetti 2002; Surian and Rinaldi 2003; Rinaldi et al. 2010).

Concerning the channel pattern and river types, the main course of the Po River along the low plain was characterised, before the beginning of the 19th century, by a multi-thread channel pattern in its upstream portion, approximately up to the confluence with the Ticino River, and by a dominant single-thread pattern in the downstream part, including the following river types (see Gurnell et al. 2014, Rinaldi et al. 2015 for further details on river types): gravel-bed braided and wandering morphologies dominated in the upstream part (river types 8, 9 and 11); mixed (fine gravel and sand) and then sand-bed meandering reaches with occasional braiding dominated the downstream part up to the river delta (river types 14 and 18) (Pellegrini 2007).

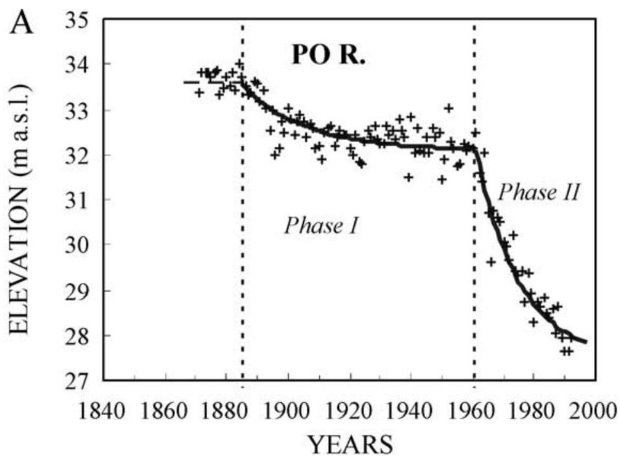

Figure 3.10 Trends of bed-level adjustments. Po River: minimum annual river stage at the gauging station of Cremona . Horizontal hatched line: trend of stable (dynamic equilibrium) conditions before incision; continuous curves: fitting exponential decay functions. Extracted from Surian and Rinaldi (2003).

During the main human interventions of the 19th century the channel pattern of the Po River changed as follows (Lanzoni 2012): in the upstream part, the dominant multi-thread channel pattern changed towards transitional (wandering; river type 11) and single-thread (sinuous and pseudomeandering; river types 12 and 13, respectively) morphologies; in the downstream part, the dominant meandering channel pattern changed towards sinuous and straight morphologies (river types 13 and 17, respectively), including the former braided sectors.

Table 3.3 Recent channel adjustments (about last 150-200 years) along the main course of the Po River and related causes and effects. Modified from Surian and Rinaldi (2003).

Geomorphic adjustments	Temporal range of geomorphic changes	Causes	Temporal range of human impacts (pressures)	Effects on structures and environment
Channel shifting	1822 - 1989	Hydraulic works		
Channel narrowing; reduction of sinuosity	1920s - 1950s	River engineering	Since 1930s	
Incision (1-6 m); channel narrowing; reduction of channel length; meander cutoff; changes in channel pattern (from multi-thread to transitional and single-thread in the upstream part; from meandering to sinuous and straight in the downstream part)	Since 1960s	Changes in flood regime; sediment mining; channelization and embankments; intervention at catchment scale	Started during Roman times; intense and widespread since 1950s	Undermining of bank-protections and bridges; loss of groundwater resources; loss of agricultural land; increase of flow velocity

Figure 3.11 Bridge piles on the Po River (Boretto): evidence of channel incision. Extracted from Bertolo et al. 2009.

3.3 Drivers: socio economic functions

The Po River catchment and its plain represent one of the most productive area of Italy, contributing for the 40 % to the Internal Gross Product.

Here is located a great part of the Italian industries (37 %) and of the national agricultural activities (35 %; Figure 3.12) as well as most of the national livestock activities (55 %). The tertiary sector is also well developed (Gumiero et al. 2009). Thus, it represents an important area for the national economy. Additionally, almost one third of the Italian population lives in the Po catchment, where the highest population densities are found in the plain and around the main cities (i.e. mainly Milan and Turin).

The water demand from both surface and groundwater resources is high for a total of 20.5 billion of m³/year (i.e.14.5 and 6 billion of m³/year, respectively), where 12 % is used as drinking water (5 % and 80 % from surface and groundwater, respectively; 15 % from mountain springs), 7 % for industrial activities (power plant excluded) and 81 % for irrigation purposes (83% and 17 % from surface and groundwater, respectively). The Po basin also hosts several hydro and thermal power plants (i.e. 40 % and 43 % of the national park, respectively) (Autorità di Bacino del Fiume Po 2006).

Extended flood protection measures are also present, increasing downstream (Figure 3.13).

As stated in section 2, most of these activities are present since ancient time, but their greatest intensity correspond to the last two centuries. The commercial navigation along the Po river, even if widespread in the past, is today limited to the area of Cremona, near Piacenza (Gumiero et al. 2009).

Figure 3.12 Rice fields in the Po Plain near Vercelli (source: www.naturamediterraneo.com).

Table 3.4 Summary of drivers and related pressures occurred in the Po catchment over time (information is taken from Gumiero et al. 2009).

Drivers	Time range	Period of maximum intensity	Related pressures (main)
Agriculture	Neolithic - today	7th century B.C.; today	Deforestation; flow regulation
Livestock	Neolithic - today	19th century-today	Deforestation
Urbanisation	Middle-age - today	19th century - today	Deforestation; sediment mining; channelization; embankments; flow regulation; flood protection measures
Water demand (irrigation, drinking,	6th century B.C. - today	19th century - today	Channelization; land reclamation; flow regulation; river fragmentation

industry)			
Navigation	12th - 20th centuries		Channelization; flow regulation; river fragmentation
Industry	18th century - today	19th century - today	Flow regulation; sediment mining
Tertiary sector (private and public transport)	19th century - today	20th century - today	Sediment mining; channelization; embankments; flood protection measures; flow regulation; river fragmentation

3.4 Pressures and effects on processes

The main pressures (http://wiki.reformrivers.eu/index.php/Category:Pressures) along the Po River and its catchment are summarised below (Table 3.4; Figure 3.13, Autorità di Bacino del Fiume Po 2006).

- In the upper areas (LU1, LU2 and LU3): river fragmentation and flood protection dominate (i.e. dams, weirs, hydropower plants and water production structures), where in the Alpine areas (LU1 and LU2) these mainly supply energy needs (hydropower plants), whereas in the Apennine areas (LU3) mainly support irrigation (agriculture).
- In the hilly areas (in part LU2 and LU4): flow regulation and water abstraction (i.e. flow diversions) are the main pressures, together with generalised morphological alteration aiming at flood protection.
- In the plain areas (LU5 and LU6): morphological alteration (i.e. channelization and embankments against floods) is almost continuous, mainly along the main stem of Po River and in the downstream part of its tributaries; some water abstraction and flow regulation are also present (i.e. high density of artificial canals for irrigation purposes).

In the lowland areas several other pressures act on the river system, as for example physic-chemical pressures (i.e. nutrients and pollutants from agriculture, livestock-related, industrial activities and urban areas), as well as biological pressures related to the introduction of exogenous and invasive species (both in terms of flora and fauna) (Gumiero et al. 2009).

The morphological effects of these pressures on river processes during the last 150 years have been analysed by previous studies (see for e.g.: Marchetti 2002; Surian and Rinaldi 2003; Rinaldi et al. 2010) and are summarised in section 2 (Table 3.4).

3.5 Effects on ecology of pressures

The high water demand along Alpine and Apennine areas causes alteration of the natural flow regime which, in the lowland areas, further contributes to the lowering of the water quality, that is significantly affected by the high concentration of nutrients and pollutants from agriculture and urban areas. Additionally, the overall fluvial ecosystem of the lowland areas is altered (i.e. absence or scarce presence of riparian zones), limiting the self-purification skills of the river.

Thus, along the Po River the environmental status is mainly moderate or poor, as well as that of its main tributaries, above all those flowing across or near main urban areas (e.g. the Lambro near Milan) (Figure 3.14).

The generalised morphological alteration, as well as river continuity fragmentation and introduction of non-native species, in addition to water pollution, alteration of the hydrological regime as well as over-fishing, severely impacted fish population of the Po River and caused a reduction in the overall biodiversity (Gumiero et al. 2009).

In some prealpine lotic systems 'supra-seasonal' droughts have become a regular event, due to the presence of dams and irrigation canals, progressively changing the flow regime from perennial to intermittent, and probably causing in the near future a change (impoverishment) of the benthic communities of these areas, as well as of overall fluvial ecosystem (Gumiero et al. 2009).

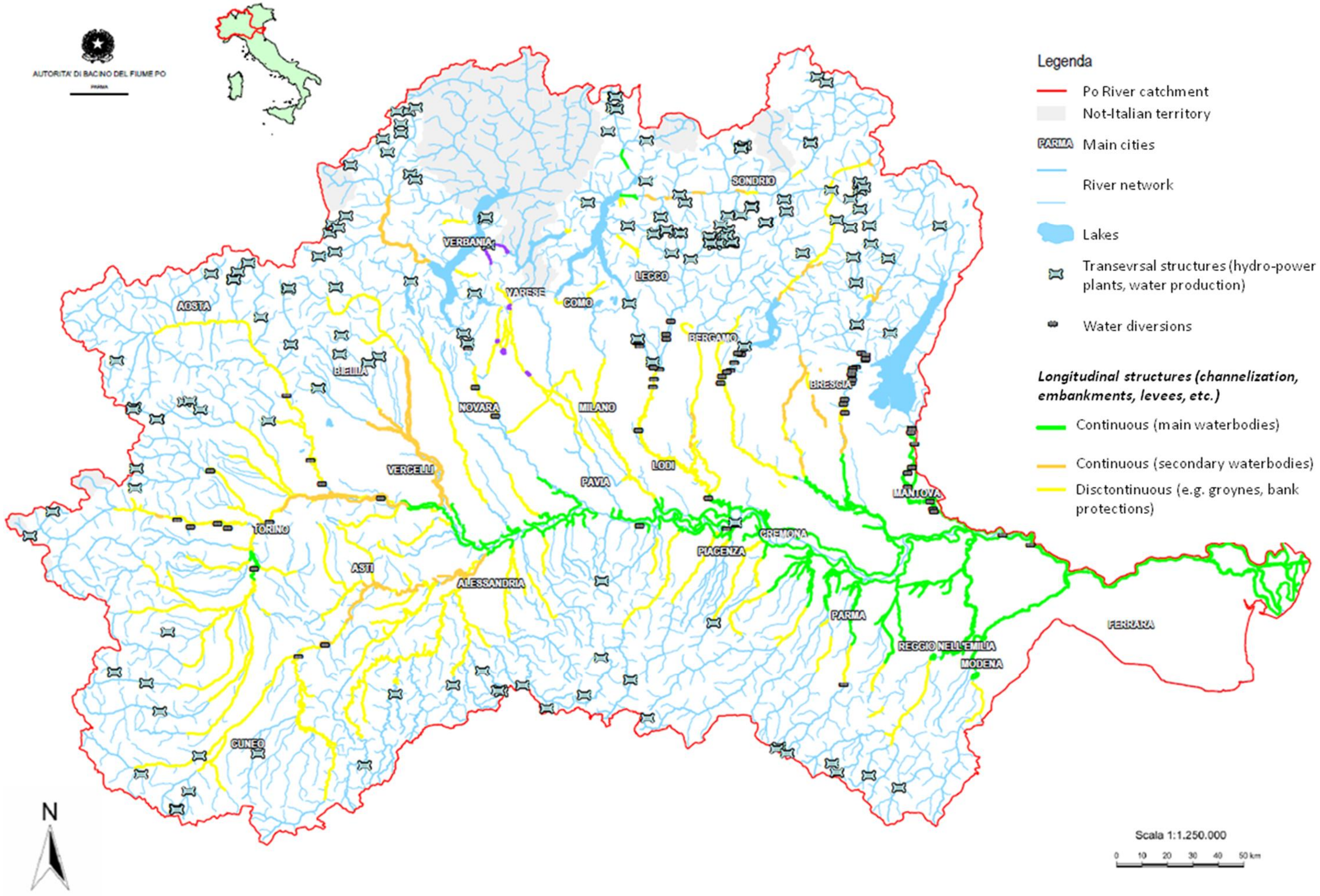

Figure 3.13 Main morphological pressures in the Po river catchment. Modified from Autorità di Bacino del Fiume Po (2006).

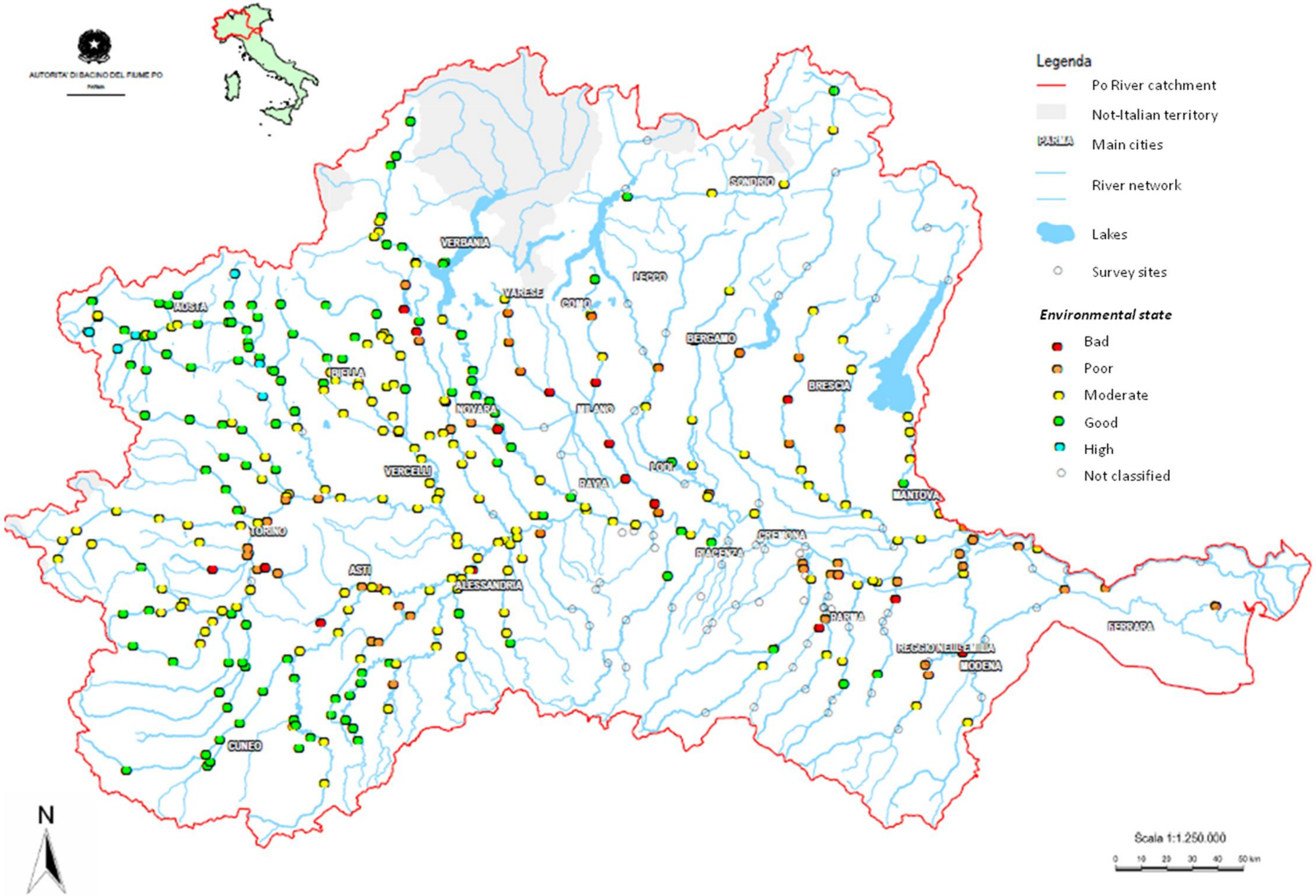

Figure 3.14 Environmental state of the Po River catchment. Modified from Autorità di Bacino del Fiume Po (2006).

3.6 Rehabilitation and mitigation measures

Within the Po River catchment are present 210 protected areas (natural or semi-natural), covering about 7 % of the total Po basin and representing 26 % of the protected lands in Italy, and where 46 out of the 210 are directly associated to river systems (Gumiero et al. 2009).

The main river rehabilitation and mitigation measures along the Po River are mainly in the form of proposal actions or guidelines for the implementation of the Integrated River Basin Management Plan developed since the 2009 in compliance with the Water Framework Directive (WFD, 2000/60/EC). They concerns:

- The '*Piano Stralcio per l'Assetto Idrogeologico*' (PAI, 2001) is one of the first tool for the sustainable management of fluvial systems in Italy; it identifies different fluvial areas having different hydraulic and hydrogeologic sensitivity, and which require different management actions.
- The River Basin Authority also provided general rules for the rehabilitation measures of the fluvial areas and according to the different PAI areas, in terms of sediment management or specific interventions of environmental rehabilitation (http://www.adbpo.it/on-multi/ADBPO/Home/Pianificazione/AttuazionedelPianodibacino/Rinaturazionedeicorsidacqua.html).
- The management of in-channel sediment, in terms of removal of no longer active bank protections or other in-channel structures, as well as the reactivation of abandoned side channels. These measures are aimed at improving the sediment flow quantity, the longitudinal connectivity, the river bed depth and width variation and the in-channel structure and substrate (Autorità di Bacino del Fiume Po 2008).
- The program of measures (Autorità di Bacino del Fiume Po 2010), which identifies all the measures that should be taken in order to achieve the objectives of the WFD.

In terms of realised measures, except some minor and local rehabilitation or mitigation interventions in some sub-catchments (e.g. Di Francesco et al. 2012; Filippi et al. 2012; Gentili and Moroni 2012; Morisi et al. 2012; Moroni et al. 2012; Puzzi et al. 2012), to date few has been done along the main stem of Po River to improve the geomorphic functionality and the ecological status.

One of the few and the biggest existing project along the Po River concerns the longitudinal continuity for fish species by the LIFE project *'Con.Flu.Po'* (Restoring connectivity in Po river basin opening migratory route for Acipenser naccarii and 10 fish species in Annex II) in order to install a fish pass for fish migration at the dam of the Serafini Island (near Piacenza), the largest island of the Po River (http://www.adbpo.it; Puzzi et al. 2012).

Another project but smaller in terms of magnitude effects concerns the re-vegetation of the riparian zone along 1.32 km^2 of a natural reserve located in a meander belt near Mantova (Boscone Island), in order to improve the natural vegetation succession (Cuizzi and Vannuccini 2012). The area was formerly an island that has been connected to the river bank because of the installation of bank protection (i.e. groynes). After that the former riparian vegetation started to change in favour of invasive exotic species. Thus, the objective of the mitigation measure was to reintroduce natural and local riparian vegetation species adapted to the new ecological and morphological conditions.

Theoretically, the 'program of measures' adopts a catchment approach. In practice, each region is then responsible of the planning and the realisation of measures, and as a result, there is a lack of an extensive catchment approach. Until now few measures have been implemented, and these are very locally focussed.

3.7 Ecological effects of measures

Concerning the fish pass of the *'Con-Flu.Po'* Life project, it will re-connect the upstream and downstream parts of the Po River catchment, since the island is located in a strategic point of the catchment itself, below the confluence with the large sub-catchment of the Ticino river, which also includes two main prealpine lakes (*Lago Maggiore* and *Lago di Lugano*) (Puzzi et al. 2012). The project is still in progress (2012-2017). Concerning the riparian zone improvement along a meander belt of the Po River (Boscone Island), the results provided useful indications for the rehabilitation of other floodplain areas along the Po River (Cuizzi and Vannuccini 2012).

3.8 General remarks or conclusions

The Po River and its catchment are of great importance both in economic and societal terms as well as in terms of environmental value.

The most significant existing pressures which mainly affect the ecology of the Po River system are: the fragmentation of the catchment because of dams and hydro-power plants; the widespread diffusion of exotic species (both for flora and fauna); and the pollution because of agriculture, urban and industrial areas.

Even if the implementation of the Integrated River Basin Management Plan (2009-2015) would include many water management (e.g. to prevent flood risk) as well as many mitigation and rehabilitation measures (e.g. recover sediment transport, improve hydromophological status, promote biodiversity, promote recreational use), very little has been done until now to effectively improve the overall environmental status of the Po River.

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4. Middle Ebro River (Spain)

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4.1 *Introduction and characterisation*

The meandering middle Ebro River has been selected as a segment case study to represent the archetypal situation of large Iberian Mediterranean rivers. River Ebro catchment lays in Northwest quarter of the Iberian Peninsula (Spain), including the Southern slope of the Pyrenees and the Southeastern end of the Cantabrian mountain range. The case study (*case study segment*) is centered in the middle river Ebro, between the rivers Aragón and Gállego, flowing across the regions of La Rioja, Navarre and Aragón (Figure 4.1). In order to make a deeper downscaling, a detailed study at a reach scale has been included. This detailed case (*case study reach*) involves a riverine protected area (Sotos de Alfaro, La Rioja) immediately downstream the mouth of river Aragón, with a few meanders that represents the processes that have been undergone at the local scale (Figure 4.1).

Mean annual rainfall range between 250 and 2200 mm with a clear positive gradient northwards and westwards. Mean annual minimum temperature fluctuates between 0ºC (Pyrenees) and 12ºC (inner drylands), and maxima range between 7 and 25ºC.

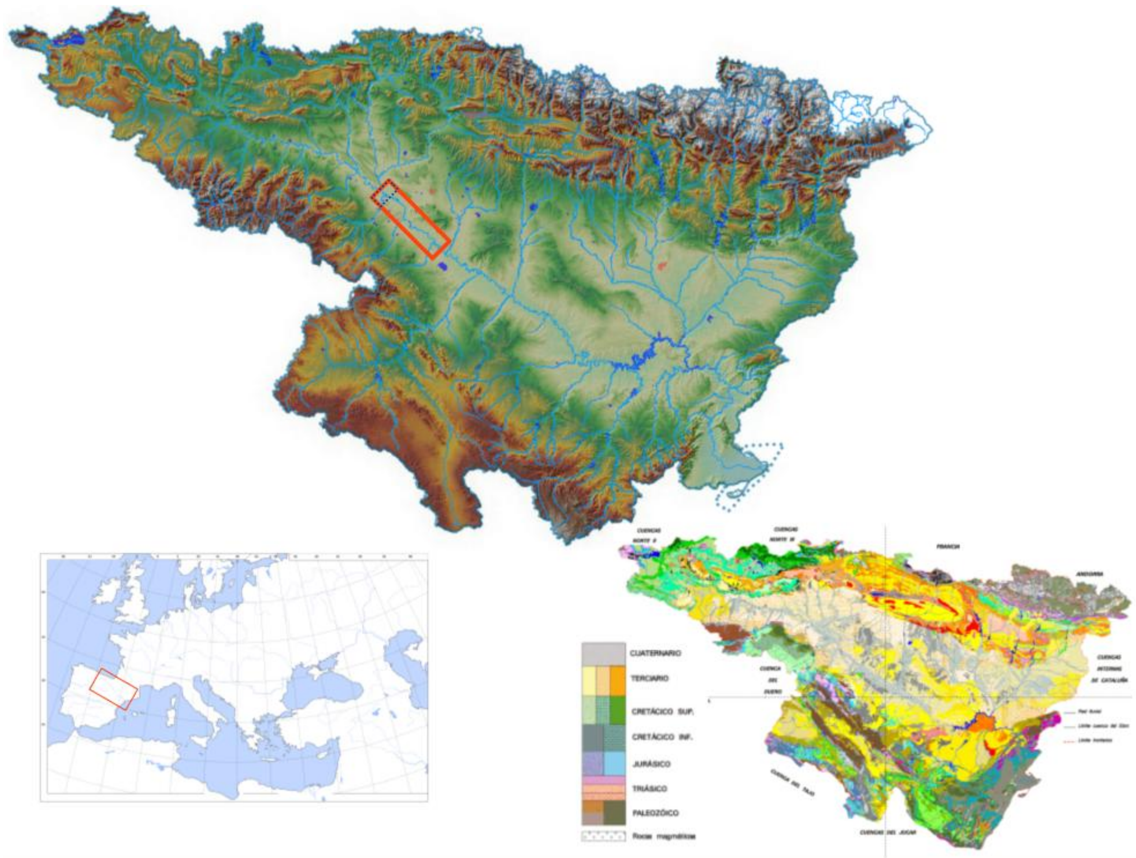

Figure 4.1. Location (thin red solid line), hypsometry and geology of the river Ebro basin; the case study at the segment scale, *case study segment*, (thick red solid line); and the detailed case study at the reach scale, *case study reach* (thick blue dashed line).

The river Ebro catchment is a sedimentary basin limited by three mountain chains originated during the Alpine Orogeny -Pyrenees, Iberian and Catalonic. It was filled by sediments produced by the erosion of those relieves during the main part of the Tertiary. At the end of the Tertiary a drastic change overcame in the development of the catchment: erosion became more important than sedimentation. The cause of this change is the evolution of a river that was developed from the Mediterranean slope through the coastal relieves and started the capture of the endorheic network of the basin. The current structure of the Ebro basin network and its sediment evacuation to the delta started from this primeval river Ebro (Baquer Barriendos *et al.* 2008).

River Ebro is the largest Mediterranean river of the Iberian Peninsula. It has a total watershed area of 85,530 km^2 and a length of 930 km. The floodplain area in its middle reaches experiences frequent flooding events, and supports the largest floodplain area (739 km^2) in the Iberian Peninsula. Its current total discharge averages 14,623 hm3 yr^{-1}. A general description of Ebro river can be found in Sabater *et al.* (2009).

The *case study segment* includes a dynamic channel that makes the river meander through nearly 350 km. It shows a sinuosity index ranging from 1.505 to 1.608, and a mean channel slope of 0.67 m km^{-1}, involving a meander belt with a mean width of 812 m. It constitutes an originally free meandering segment where the floodplain is made up of overbank deposits as vertical accretion of fine materials. It shows old abandoned meander channels of a historically active river. The convex banks are mostly made of thick sediment of easily flooded point bars. Not all the bars are tilled and thus riparian vegetation still exist in places. In comparison, the concave banks, 2 to 3 m above the stream and composed of fine materials deposited by floods, have a sparse vegetation cover, are tilled up to the edge, and have to be protected from erosion. A low mean annual rainfall (300-400 mm yr^{-1}) produces semi-arid environments in this area. This dry landscape contrasts with the relict riparian gallery forest, which is an area of great environmental importance with the riparian vegetation covering 2720 ha. Almost the entire area has been declared a Site of Community Importance for the conservation of natural habitats (European Commission, 2006). (Ollero 2010)

Aragón river and its tributary Arga river flow from their sources in the western Pyrenees significantly increasing the discharge of the Ebro river downstream its junction. In the upstream limit of the case study segment ('Castejón' gauging station), mean annual discharge reaches 230.7 m^3 s^{-1}. The lack of significant tributaries, and several diversions for irrigation purposes lower the mean annual discharge to 216.5 m^3 s^{-1} along the case study segment.

The flow regime is characterized by a total maximum in late winter (February), mainly due to Atlantic rainfall events. With a total minimum in mid-summer (August), it shows asymmetric upward and downward hydrographs. Interannual flow irregularity is less marked than in other Mediterranean rivers.

Trends of flow regime characteristics have been detected through the last century. Specifically, a negative trend in mean annual discharge, and in the number of days with a discharge lower than 30 m^3 s^{-1} (114 days during 1940s to practically disappear between 1970 and 1985), have been perceived (Frutos et al., 2004).

Flooding events occur on average 1.2 times per year, mainly in winter (Ollero, 1992). In the study segment the river overflows its banks when discharge exceeds 2,000 m^3 s^{-1} (Ollero 1990a). Highest historical flows were experienced in February 1643, September 1787, January 1871 and January 1874 (Davy, 1975). During the last century extraordinary floods were registered in March 1930 and January 1961 (maximum mean daily discharge of 4,177 and a peak flow of 4,950 m^3 s^{-1}). Over the last decades, the number of small to moderate floods has decreased because of the regulation systems. Despite such regulation, overflows occur along the free meandering stretch of the middle Ebro where agricultural use prevails. This use is quite compatible with the periodical occurrence of flooding, entailing extensive damage of different intensity, which can be compensated with indemnities. Approximately 110,000 persons inhabit floodable areas (Ollero 2010).

The *case study reach* includes the water body 447 (WFD code) of 7 km between the mouth of Aragón river (northern slope tributary) the mouth of river Alhama (southern slope tributary). It is typified as 'large Mediterranean fluvial axes', in the Ebro axis ecoregion (Gobierno de La Rioja 2006). This case study reach is located at the upstream limit of the case study segment, at an altitude of 265 m a.s.l. At this limit, the river Ebro receives the significant discharge from river Aragón (and its large tributary river Arga), and has just received its large tributary river Ega. Some of its discharge has also been diverted ('Canal de Lodosa') for irrigation purposes. At this point ('Castejón' gauging station), river Ebro drains 25,194 km2, with a specific discharge of 10.7 l s^{-1} km^{-2} (Martín Ranz & García Ruíz 1984, after Ollero 1990b). Detailed flow data of this case study reach come from the records of gauging station 'Castejón', starting form 1916 till present. Historical average annual discharge is 7282 hm^3 yr^{-1}, and the last 20 years period averages 5510,8 hm^3 yr^{-1}.

At the case study reach, the flow regime is pluvial-nival type, showing a high influence of the Cantabrian (Atlantic) storms. The oceanic pluvial influence is noticeable by the winter high flows as well as the frequency of floods. Northern slope tributaries Arga and Aragón make slightly noticeable the spring ice-melt influence. However this component is scarcely significant in the western Pyrenees due to the frequent rain storms melting the snow pack early in the season, thus not allowing long snow retention. The low water levels take place between early June until the first half of October. They can also last longer, at least till December, if oceanic rains are delayed. This is the reason why November and December are the months with the highest variability coefficient: years with intense floods are followed by others with autumn flows similar to summer flows (Ollero 1990b).

At the case study reach, the longitudinal slope is similar to average values in the medium river Ebro basin (73.9 cm km^{-1}) (Ollero, 1990a). Width ranges around 170 m (171.6m at 'Castejón' gauging station).

According to each spatial scale in the hierarchy from region to reach (REFORM Deliverable 2.1) the case study is characterised in Table 4.1.

At the region scale: it belongs to the Ebro International River Basin District, which is included in the Mediterranean(C) region; Western Mediterranean (Ca) subregion; Mediterranean Central Iberian (18); (18c) Low Aragonese, according to the Worldwide Bioclimatic Classification System (Rivas-Martínez et al. 2004).

Due to the heterogeneous nature of the different features at this large scale -the catchment includes two more ecoregions, namely: Atlantic-Central European (Bb) and Alpino-Caucasian (Bc)- it is hardly possible to state further information at the catchment or at the landscape unit scales.

At the catchment scale: the drainage area to its upstream limit is c. 25,000 km^2, which can be categorized according to WFD as 'very large >10,000 km^2'.

Table 4.1 Characterisation of the river Ebro study case according to each spatial scale in the hierarchy from region to reach (REFORM Deliverable 2.1).

REGION	River basin or district			Ebro International River Basin District
	Biogeographic region			Mediterranean(C) region; Western Mediterranean (Ca) subregion; Mediterranean Central Iberian (18); (18c) Low Aragonese; Atlantic-Central European (Bb) and Alpino-Caucasian (Bc)
CATCHMENT (SUBCATCHMENT)	Size, morphology, hydrological balance	Catchment (subcatchment) area (km 2)		85,530 km2 (25,194 km2)
		WFD catchment (subcatchment) size category		very large: > 10 000 km 2
		Catchment (subcatchment) average, maximum and minimum elevation (m)		3,352-0 masl (~2,700-260 masl)
		Relative Relief (m) and Relative Relief / Longest distance from watershed to catchment outlet (m/m)		3.68
		Catchment average annual rainfall		620 mm
		Catchment (subcatchment) average annual runoff		14,623 hm^3 yr^{-1} (5,511 hm^3 yr^{-1})
		Catchment runoff ratio (coefficient) = Average annual runoff / average annual rainfall)		0.276
	Geology, soils	Proportion of catchment where aquifers are exposed at the land surface		64%
		Proportions of catchment underlain by calcareous, siliceous, organic, mixed / other rock types		Calcareous-dolomitic (Cenomanian-Turonian) dominance and Plio-Quaternaty detritic materials.
	Land cover	Artificial surfaces		0.86%
		Agricultural areas		47.05%
		Forest and semi-natural areas		50.41%
		Wetlands		0.08%
LANDSCAPE UNIT	Water production	Rainfall		400 mm
		Surface:Groundwater		98.10%
		Land cover	urban fabric	0.43%
			industrial, commercial, transport units	0.24%
			open spaces with little or no vegetation (includes bare rock)	2.82%
			arable land	28.97%
			permanent crops	3.65%
			pastures	0.94%
			shrub and/or herbaceous vegetation	24.98%
			forests	22.61%
			Wetlands (inland)	0.04%
			large surface water bodies (inlnad marshes)	0.04%
			glaciers and perpetual snow	0.01%
	Sediment production	Potential Fine Sediment Production		340 t km^{-2} yr^{-1} (Sanz Montero 2002)
		Potential Coarse Sediment Production		
	Physical pressures on sediment regime			Resulting from flow regulation schemes, channel incision; sediment retention; flood reduction; dynamics loss. A small amount of erosion in certain locations, controlled by engineering defenses.

At the segment scale: the average annual flow is 226.92 $m^3 s^{-1}$ at 'Castejón' gauging station. The flow regime involving the whole complete time series (1948-2011) can be classified into the 'perennial flashy' type, the same as for the first 20 year period (1948-1967). However, for the last 20 years (1992-2011) it exhibits an increase in the baseflow index (BFI = 34.9) value, enough to shift it towards a 'perennial stable' type (30<BFI<50) (Table 4.2. Figure 4.2). As it will be described below, an increasing volume of reservoirs in the tributaries of river Ebro has occurred throughout the 20th century. Flow regulation for irrigation purposes seems to have therefore noticeable effect on the flow regime. It has driven a natural flashy river, with a flow regime characterised by low seasonal variability, towards an artificial stable river.

Table 4.2. Properties of the mean daily flow record used to define the hydrological regimes (REFORM Deliverable 2.1), where: ZERODAY is the number of days without channel flow in a year; FLDPRED is the maximum proportion of all floods over the fixed flood threshold that falls in one of six "60-day seasonal windows", divided by the total number of floods; FLDFREQ is the average number of floods per year having discharge higher than the mean of annual maximum daily discharge; FLDTIME is the day number of first day within the seasonal 60-day window when FLDPRED is highest (starting in January); BFI is a baseflow index calculated as the annual mean of the monthly ratio between the "minimum of the monthly discharge" and the "mean monthly discharge".

Period	ZERODAY	FLDPRED	FLDFREQ	FLDTIME	BFI	DAYCV	Hidrological class
1948-1967	0	0.26	0.95	305	21.99	116.93	Perennial flashy
1948-2011	0	0.24	1.34	335	17.82	113.91	Perennial flashy
1992-2011	0	0.26	1.55	335	34.89	114.08	Perennial Stable (but DAYCV>100)

The case study segment flows across an unconfined valley, with an average valley gradient of 0.35 ‰ and an average floodplain width ranges between 3.2 (upstream limit) and 4.5 km (downstream limit) , reaching to a maximum of 6 km (Ollero 2010, Conde *et al*. 2011).

Annual suspended sediment load at a nearby downstream reach in river Ebro for a period of moderate floods (1998-1999) has been estimated around 500,000 Tm (Roura 2004, after Balasch *et al*. 2007). Vericat & Batalla (2006) calculated an average annual suspended sediment load around 2,300,000 Tm in a year (2002-2003) with flood of magnitude Q10. In the downstream reaches of the case study segment (Balasch *et al*. 2007) found a negative sediment balance of almost 90.000 t (845 t km^{-1}).

Riparian corridor width ranges between 10 and 70 m in the detailed case study reach, with an average of 35 m in each margin.

Two main formations of riparian corridors can be currently found in the case study segment: white willow forests and hydrophyllic poplar forests. White willows forests are low density tree formations located in the river shores and dominated by *Salix alba* or *S.* x *rubens* (hybrid of *S. alba* and *S. fragilis*), and also formed by *Alnus glutinosa*, *Fraxinus* sp., *Populus alba* and *P. nigra*, which might co-dominate. The structure of the hydrophyllic poplar forests is variable. Most often they are scarcely diverse forests, lacking bush vegetation under canopy but some hydro-nitrophyllic plants, *Rubus* sp. and epiphytes attached to the logs, which are always in contact with running water or where the phreatic level reaches the surface. Hydrophyllic poplar forests are gallery formations dominated by *Populus alba*, with co-dominating *P. nigra*, *Salix alba* and *S.* x *rubens*, and *Fraxinus angustifolia*. The intermediate stratus is dominated by *Rubus ulmifolius* and *R. caesius*, with formerly abundant *Ulmus minor*. They occupy two types of riparian environments: the bottom of the valley, where the phreatic level is close to the surface; and at the very shore of the river, where they find water available all along the year. These forests can become dense formations with large size, capable to create, when well conserved, micro-environmental conditions similar to other typically riparian formations. However, most of the times they are highly altered by human activities, as sylvicultured crops, or with excessively populated intermediate strata.

Most of the currently present riparian corridors in river Ebro are relatively young, located on areas that were renewed by flood in the first half of the 20th century. Floods are a crucial factor in their structure and development. They preferably develop on lands that are flooded with a return rate of two to five years, whereas in the shores there is nothing but pioneer formations (Ollero 1993).

Shortly upstream the case study segment there is a divertion ('Canal de Lodosa') that abstracts water for irrigation purposes. There are few channel blocking structures that might disrupt longitudinal connectivity.

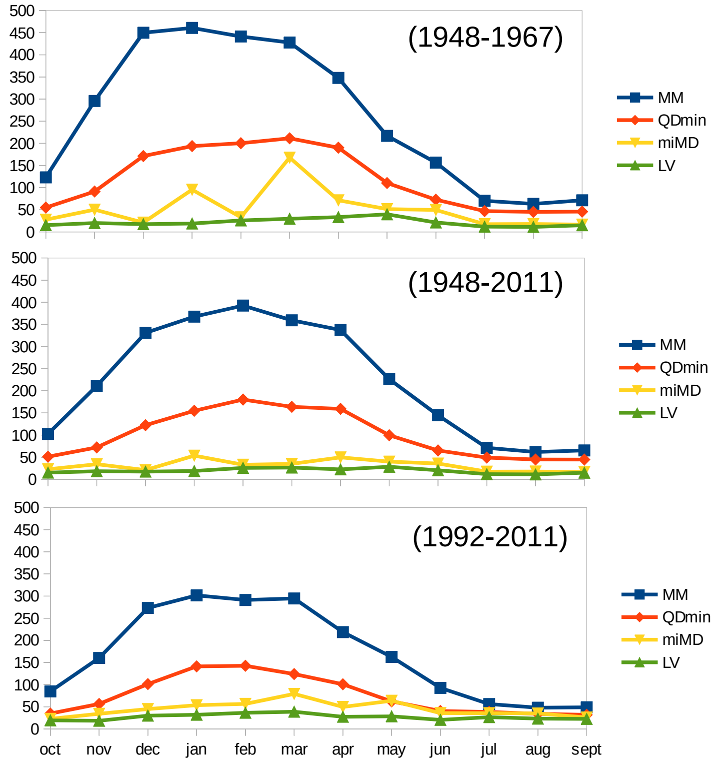

Figure 4.2. Characteristic monthly discharge ($m^3 s^{-1}$) for Ebro river at the case study segment ('Castejón' gauging station), where: MM is the mean monthly discharge; Qdmin is the mean of minimum daily discharge; miMD is the minimum of monthly discharge; and LV is the lowest of minimum daily discharge.

At the reach scale: The case study reach can be currently classified as Type 4 'unconfined single threat meandering' reach, Extended Channel Type 14(4) 'gravel-sand bed material' (A succession of marginal bank attached bars (lateral bars, point bars and scroll bars), with mid channel bars (both longitudinal and transverse bars), prevailing hydraulic units being riffles and pools in more or less regular successions along the reach.). Mean sinuosity index is 1.505, increasing to 1.608 in the downstream reaches of the case study segment. The average channel slope is 0.67 m km^{-1} and the average width of the meander belt is 812 m.

Total stream power (Ω = the rate of energy dissipation per unit downstream length): is 13145 W m^{-1} (Ω = ρ g Q S, where: Ω is in W m^{-1} , ρ is the density of water (1000 kg m^{-3}), g is acceleration due to gravity (9.8 m s^{-2}), Q is discharge (bankfull discharge ~2000 m 3 $.s^{-1}$) and S is slope (0.00067 m m^{-1}). The dominating bank and bed material in our case study reach is dominated by gravel. The case study reach is one of the few places were there still are few remnants of the former Ebro riparian corridors. This kind of formations used to occupy all the floodplain in the area. In the present riparian corridors occupy 838.7 ha, which is about a 4.5% of the whole floodplain. Riparian formations appear as thin vegetated stripes attached to the channel or like tree masses more or less isolated by crops. The best conserved riparian forests appear as dense tree formations reaching about 8-15 m high with species like *Salix alba*, *Populus nigra*, *Populus alba* and *Fraxinus angustifolia*. In the bush stratus thorn shrubs like *Rosa* sp., *Rubus* sp. or *Crataegus monogyna* can also be found. Within the forests, when they are well developed, light is scarce and thus the lowest stratus becomes poor and climbers like *Hedera helix* and *Clematis vitalba* are abundant. Gramineae are confined to cleared and open areas. There are also other nitrophyllic plants in these areas, like *Urtica*, *Sambucus, Geranium* and *Chelidonium*, since the river provides large amounts of organic debris to the riparian forest soils.

These natural woody debris like logs, branches or leaves, have increased by organic pollution from fertilizers and waste water. There are also aquatic macrophytes that can be found directly linked to the channel and gravel and sand beaches. Thus, there is *Lemna minor* and *L. giba* floating in many relatively stagnant areas like oxbows, with a maximum abundance in late summer. Also in running water, but with their roots fixed in the bottom, there is *Ranunculus peltatus* and *R. trichophyllus*. In some shores and flooded areas there is *Phragmites australis*, *Thypha angustifolia*, *T. domingensis* and *Scirpus lacustris*. Growing in the side channels and beaches there is *Polygonum persicaria* and *Paspalum paspaloides*, forming dense grasslands in the channel banks.

The margins of the river Ebro at the case study reach have suffered continuous transformations throughout the time. In an attempt to cultivate the soils and to defend them from flooding events, the original landscape has been modified. Thus, there are landscape changes like extension of adjacent croplands, poplar plantations, gravel extraction in the convex banks of several meanders, and construction of levees (mostly made by compacted materials). There are also riprap embankments, specially in the right margin, where conflicts with land owners are more frequent due to the river planform at this reach, which makes the river migrate southwards (Gobierno de La Rioja www.larioja.org)

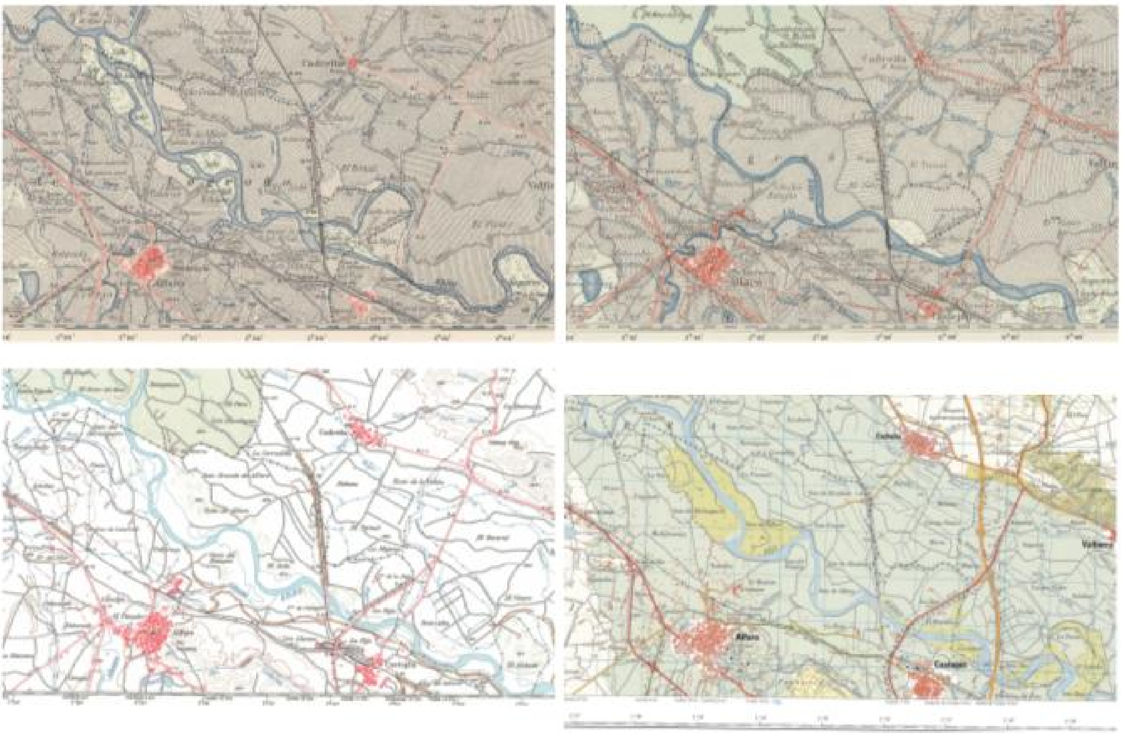

Figure 4.3. Maps of the case study reach in 1920, 1950, 1978 and 2004. (Maps: © Instituto Geográfico Nacional de España)

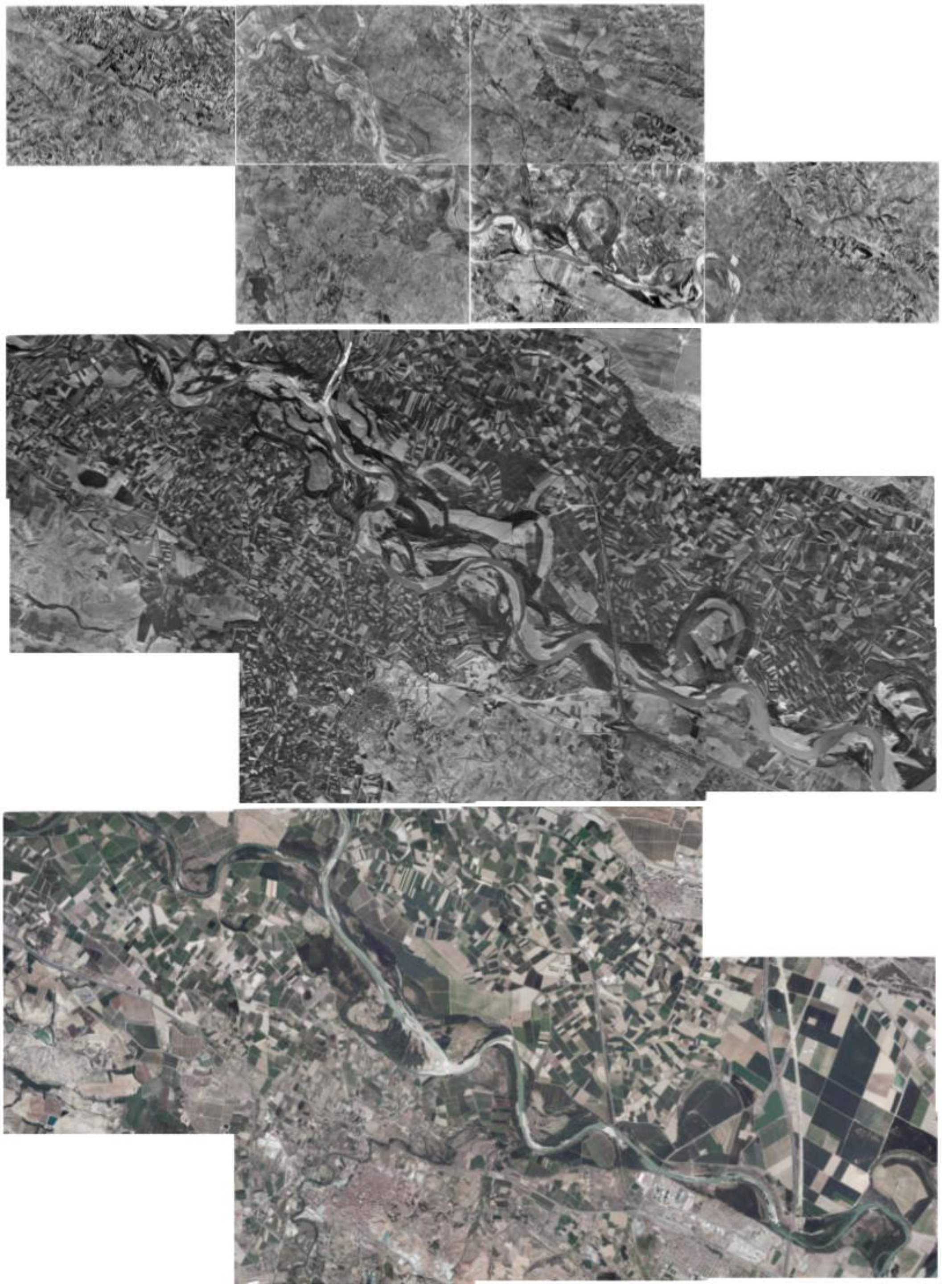

Figure 4.4. Aerial photographs of the case study reach in (a) 1927, (b) 1956 and (c) 2014.(Images:[a] Confederación Hidrográfica del Ebro; [b] and [c] PNOAS © Instituto Geográfico Nacional de España).

Figure 4.5. View of a section of geomorphic units at the case study reach (Sotos de Alfaro, Alfaro, La Rioja). (Photo: Alonso, C. 2008)

4.2 Historical situation or reference situation

Changes have occurred throughout history in river Ebro hydromorphological conditions. Cato (AD 195) calcifies river Ebro as 'big, beautiful and fish abundant' (magnus atque pulcher, pisculentus); Plinius the Elder says it is navigable from Vareia (near Logroño, upstream limit of the case study segment) to its mouth. Avienus (4th century AD) in his *Ora maritima*, described it in the same terms, saying that some foreign navigators (Phocaean Greeks, probably) used to go upstream by means of small boats, trading with the peoples of the banks (Beltrán Martínez 1961). Although literary, other ancient sources give information on the non-wadeable characteristics of river Ebro. La Chanson de Roland tell how the muslim trops falling back from Charlemagne "(...) River Ebro cuts their withdrawal. The water is there deep, fearsome, violent" (CLXXX), and illustrates the navigability of the river says below that "(...) In the river Ebro we have four thousand barges, skiffs, boats and galleys (...)" (CXCVI). Vikings go upstream the rivers Ebro, Aragón and Arga until reaching Pamplona to kidnap the king García Íñiguez in 859. The king Alfonso II of Aragón (1164-1196) extends customs duties until Gallur (downstream limit of the case study segment). About the same time navigability of the river starts being protected, since it was threatened by the construction of weirs, dams, bridges and fishing devices. In addition, the Pyrenees were highly populated during the Middle Ages, and large deforestation should have occurred in the head of the catchments, increasing the sediment yields. The importance of the navigation grows and in the 14th century a total amount of 9000 tonnes a year of goods are transported by this fluvial way, mostly concentrated between May and July, being limited during the lowest and highest water levels. The most frequent are low draught boats (40-50 Tm boats and 10-15 Tm pontoons), being towed with towropes from the shore in the upstream journey. The deterioration of the river Ebro as a boat corridor is promoted by the obstacles placed by the agricultural users. Thus, in the 19th century the river was hardly navigable up to Escatrón (downstream Zaragoza); nevertheless, there was logwood transport until the early 20th century (Gran Enciclopedia Aragonesa c. 2003).

There are no reliable large continuous flow data series going back as far as 100 years. The flow regime of the earliest 20 years period with available data (1948-1967) can be classified into the 'perennial flashy' type (Table 4.1, Figure 4.2). Since this type describes the flow regime prior to major regulation, it can be assumed as historical or near reference hydrological condition. According to historical maps and aerial photographs (Figure 4.3 and 4.4), the case study reach could be classified as Type 6 'unconfined multiple threat braided'.

In natural conditions, floods have been the main driving force for channel morphology changes in the middle river Ebro. There have been continuous changes in the channel morphology throughout history: sudden meander cut-offs produced during flood episode, and progressive concave bank erosion, producing migration of each meander (Ollero, 1992) (Figure 4.3 and 4.4).

According to the extended river typology (D 2.1) and based on historical data (maps and aerial photographs, see Figure 4.3 and 4.4), this reach was originally (early 20th century) Type 6 'unconfined multiple threat braided', and passed through a transitional stage of Type 5 'unconfined transitional wandering' in the mid-20th century. It currently can be classified as Type 4 'unconfined single threat meandering' (Table 4.3).

4.3 Drivers: socio economic functions

Until the mid 20th century, the main driver altering the natural dynamics of the river Ebro is the widespread deforestation all across the catchment due to demographic pressure in the rural environment as well as in the mountain areas. Since then, a slowing down of the river dynamics can be noticed between the 1950s and the 1980s. The drivers of these changes are related to land use changes. At the catchment scale, the increase of the irrigated lands is the direct outcome of the intensification of agricultural practices in the valley, this land use change needs an irrigation plan whose major concern is the availability of water. During the last half of the 20th century, a number of irrigation plans have produced the construction of several large dams in the headwaters of the river Ebro and its tributaries (Ibisate *et al.* 2013). At the same time, and related to these agricultural intensification programs by feedback loops, the river adjacent croplands were directly intensified by these politics but also benefited from an increase in the return period of ordinary flood events. These artificial stabilization of flow regimes was perceived as an opportunity to cheaply stabilize the riverbanks 'conquering' some of the original fluvial territory. These direct and indirect processes have led to a “control of the channel” and a invasion of the river space.

Following the flow regime stabilization, the invasion of the floodplains is guaranteed by the proliferation of embankments. This has contributed to the definitive stabilization of the riverbanks. Although levee construction potentially increases rates of bed erosion (James 1999, after Ollero 2010), in the Ebro River, each active meander has been fixed with bank protection, avoiding channel mobility (Ollero 2010).

Table 4.3. Characterisation of temporal changes in the river Ebro case study according to the extended river typology (D 2.1) and based on historical data (maps and aerial photographs).

CATCHMENT/LANDSCAPE UNIT	Land cover / Land use	Agricultural and urban development: the increase of the irrigated lands is the direct outcome of the intensification of agricultural practices in the valley, this land use change needs an irrigation plan whose major concern is the availability of water. During the last half of the 20th century, a number of irrigation plans have produced the construction of several large dams in the headwaters of the river Ebro and its tributaries. At the same time, and related to these agricultural intensification programs by feedback loops, the river adjacent croplands were directly intensified by these politics but also benefited from an increase in the return period of ordinary flood events. Progressive increase of the evapotranspiration values, higher temperatures, the increase of natural vegetation in the mountainous areas of the basin because of rural exodus, the increase in irrigated areas and in water masses dammed up in reservoirs.
	Land topography (tectonics, seismic activity and mass movements)	No significant changes.
	Rainfall and groundwater	Not significant, yet generalized, decrease in the total rainfall between 1950 and 2000.
SEGMENT	River flows and levels	Mean discharge at the mouth reduced between 1950-1985 (468.7 $m^3 s^{-1}$) and 1985-2004 (306.7 $m^3 s^{-1}$), with no significant changes in the total rainfall since 1950. Flow regime artificially regular.
	Valley setting (gradient and width)	No significant changes.
	Channel gradient - Changes to longitudinal profile	As a result of the regulation,channel incision and mature vegetation (attached to the channel).
	Sediment delivery	Sediment delivery reduced in abandoned mountain croplands with the lowest productivity; increased in abandoned terraces (more productive mountain croplands); increased in the newly developed irrigated cropland in the valley bottoms (Lasanta 2003).
	Sediment transport	Sediment retention and flood reduction progressively reduce the geomorphological dynamics and impoverish biotic processes along the fluvial system.
	Riparian corridor and Wood	Considerable and progressive decrease of the amount of surface occupied by the flooded channel and the gravel bars with no plant colonization on the floodplain. Decreased riparian vegetation , specially among the first colonizers. Width of the riparian corridor has decreased significantly between 1957 and 1998.
REACH	Planform morphology and channel migration	The reach was originally (early 20th century) Type 6 'unconfined multiple threat braided', and passed through a transitional stage of Type 5 'unconfined transitional wandering' in the mid 20th century. It currently can be classified as Type 4 'unconfined single threat meandering'. The morphology of the case study segment has evolved throughout the 20th century following three main stages: (1) wandering channel with unstable riverbanks until ca. 1950; (2) progressive degree of stabilization in the meandering channel and riverbanks until ca. 1980; and (3) restricted meandering channel and stable riverbanks.
	Channel geometry	Since 1927, the most frequent changes in the river morphology correspond to sinuosity increase, followed by downstream meander migration, combined widening and migration, chute cut-offs and neck cut-offs.
	Bed sediment calibre	Presumably reduced calibre due to the coarse sediments trapped in the headwaters reservoir system.

This agricultural intensification has also reduced the total amount of water released by the whole catchment to the sea. The mean discharge at the mouth was 468.7 $m^3 s^{-1}$ between 1950, and 1985 and 306.7 $m^3 s^{-1}$ between 1985 and 2004, with no significant changes in the total rainfall since 1950 (De Luis *et al.*, 2007, after Ollero 2010). This is mainly due to the progressive increase of the evapotranspiration values, higher temperatures, the increase of natural vegetation in the mountainous areas of the basin because of rural exodus, the increase in irrigated areas and in water masses dammed up in reservoirs (Frutos *et al.* 2004, after Ollero 2010).

This artificially stable situation is likely to be maintained since the main drivers are still acting. Although more environmental conscious, which has allowed the consideration of enviromental requirements as constraints to use, water management and agricultural politics have not changed in their fundamentals. As long as there is a promotion of the agricultural intensification by means of the declaration of new irrigated lands, instead of an effective promotion of non-irrigated crops (CHEbro 2013)[1], there wil be an increase of the demand of water, which is currently high. This lack of accuracy in the targets of water management optimization plans will be the ultimate drivers of future pressures on the river functions.

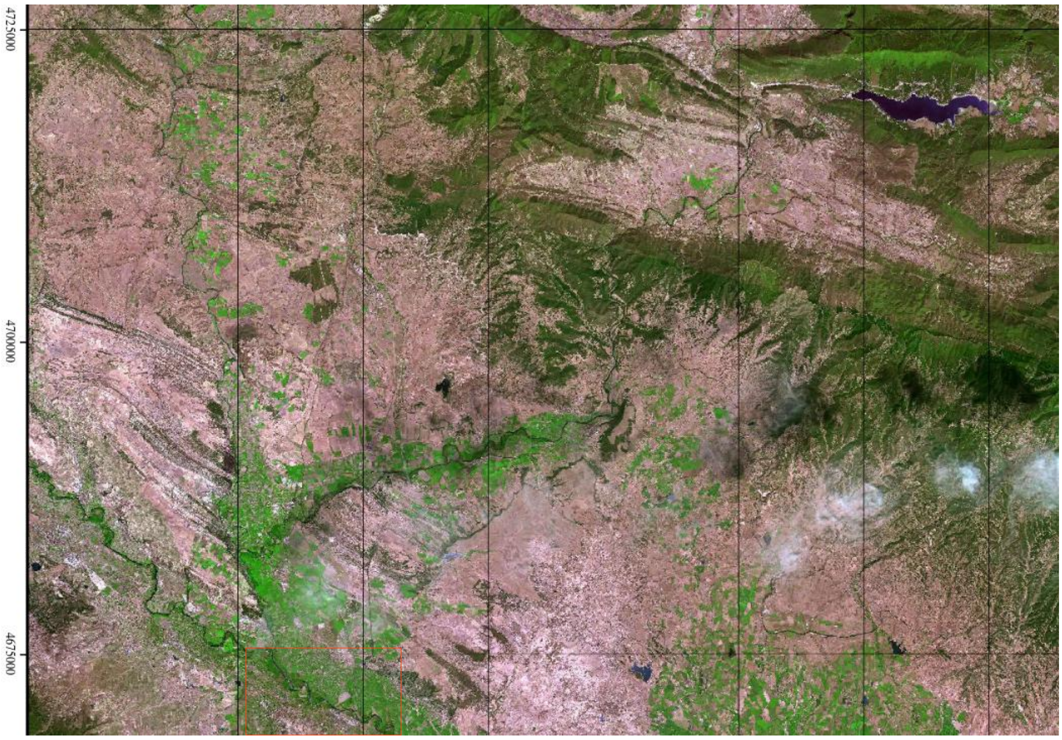

Figure 4.6. Yesa reservoir (left top corner), 447 hm^3, to be soon enlarged up to 1066 hm^3, in river Aragón; and case study reach (red rectangle) surrounded by irrigated lands (bright greenish areas). UTM coordinates. Spot5 image, PNT, Instituto Geográfico Nacional, © CNES 2010.

1 Water uses and demands in the mid-upper river Ebro: irrigation 712.66 hm3 yr-1; cattle 1.29 hm3 yr-1; urban 82.58 hm3 yr-1; industry 42.05 hm3 yr-1

4.4 Pressures and effects on processes

Current significant pressures at the sub-basin of the case study segment (Figure 4.5 and 4.6), consigned in the Ebro River Basin Management Plan 2010-2015 (Ebro RBMP 2010-15 [CHEbro 2013a]), are the following:

Point source water pollution. Spatially, the intensity of this pressure is linked to population density and industrial locations, which generally are mutually linked. Quantitatively, the main point source pressures are located in the main river channel from Miranda de Ebro (upstream the case study segment) to Zaragoza (downstream limit of the case study segment), near the cities (Pamplona, Vitoria-Gasteiz and Lleida) and medium-sized towns of the basin. However, depending on the hydrological regime of the recipient water body, moderate pressures can produce higher effect on the water body status.

Diffuse pollution. These pressures are mainly associated to the agriculture-cattle complex developed around the large irrigated areas of the left bank ('Riegos del Alto Aragón', 'Canal de Urgell', 'Canal de Aragón y Cataluña') and the main axis of river Ebro ('Canal Imperial de Aragón', 'Canal de Lodosa', 'Canal de Tauste', 'Canales del Delta'), which lay downstream the case study segment.

Surface water abstraction. All the water abstractions for consumption sums 7200 hm^3 yr^{-1}: c. 610 hm^3 for urban and industrial supply, and c. 6590 hm^3 for agriculture. The inventory of water abstractions are identified as follows:

(a) Irrigation and other agricultural uses: 3244 abstractions.

(b) Drinking water supply: 457 abstractions

(c) Hydropower (38000 hm^3 yr^{-1} turbine capacity): 458 abstractions. Additionally, 10 thermal power plants (2 conventional, 6 combined cycle and 2 nuclear) operate with cooling water from the main axis of the river Ebro.

(d) Aquaculture (non-consumptive use of 613 hm^3 yr^{-1}): 33 abstractions.

(e) Other industrial uses: 95 abstractions.

(f) Other uses (cattle supply, urban non-drinkable and others): 13 abstractions.

Groundwater abstraction. According to INTEGRA data, the main groundwater abstractions are wells for agricultural purposes (252 hm^3), drinking water supply (38 hm^3) and industrial use (46 hm^3). These numbers are the concessional volume, or legally compromised volume, which might be supposed to over-valuate the actual abstraction. Provided that the accurate value of this amount in unknown, its percentage distribution by uses and groundwater bodies can be used as a good estimate of the actual values. Agricultural use (including crops and cattle) are a 67% of the total abstraction, followed by industrial use (20%) and water supply (12%). Other uses, including recreation and other non-specified uses, are less than 1%. Regarding their geographic distribution, most of the abstractions are located in the central areas of the catchment and the Iberian Aragonese piedmont ('somontano ibérico aragonés'). Most intensively abstracted groundwater bodies are 'Miocene of Alfamén' (77), Ebro river alluvial at 'Lodosa-Tudela' (49) [which is the only one affecting the case study segment] and 'Zaragoza' (58), 'Gállego river alluvial' (57) and the 'Moncayo piedmont' (72). These five groundwater bodies are little more than 40% of the total abstractions in the catchment. The largest compromised volumes for agriculture and industrial uses are located in this geographic area.

Discharge diversions and returns. A total number of 16 flow transfers and 378 water diversions have been accounted, of which 322 are operational. Accounted transfers are all those supplying more than 20000 m^3 yr^{-1} to the recipient water body.

Hydrological regime modification. There are currently 157 reservoirs in use in the whole catchment, with a total storing capacity of 8053 hm^3 . The reservoir-stocking capacity to the case study segment is 2080 hm^3, smaller, but still high. Figure 4.7(a) shows a significant increase of the regulation capacity up to the case study segment due to two large reservoirs in the basin headwaters: Reinosa reservoir (540 hm^3 , operational since 1945) and Yesa reservoir (447 hm^3 , operational since 1960, soon it will be enlarged up to 1066 hm^3)(Ollero 2010). These devices are built for irrigation purposes. This water use stores water during the winter high flow season, and delivers it during the naturally water deficitary season, in summer. The outcome of this water management scheme lowers high flows in winter and a increses low flows in summer, stabilizing the hydrological regime (see Figure 4.7[b] and 4.7[c]) (Frutos et al., 2004). Most of the floods after 1960 have been partially eliminated by means of complex management manoeuvres of the different dams (Ollero 2010).

River fragmentation. There are 260 inventoried dams in the basin (cross-sectional structures higher than 10 m), a¡only four of them have a fish pass.

There are 2350 weirs in the basin, of which 738 are lower than 10 m and higher than 2 m. Cross-sectional lock-gates for water level control are also included in this number, as well as the obstacles produced by shallow sections below bridges. Of 738 inventoried weirs, 25 have a fish pass.

Channelisation/Cross section alterations. There are 61 channelizations longer than 500 m. There are also 28 human made meander cuttings, looseing channel stretches longer than 500 m. A total number of 30 covered channels, of which 2 are longer than 200 m. There are 1022 bank protections, of which 252 are longer than 500 m.

Other pressures. The most marked pressure is invasive alien species introduction (55 cases). Four cases of polluted sediments have also been detected.

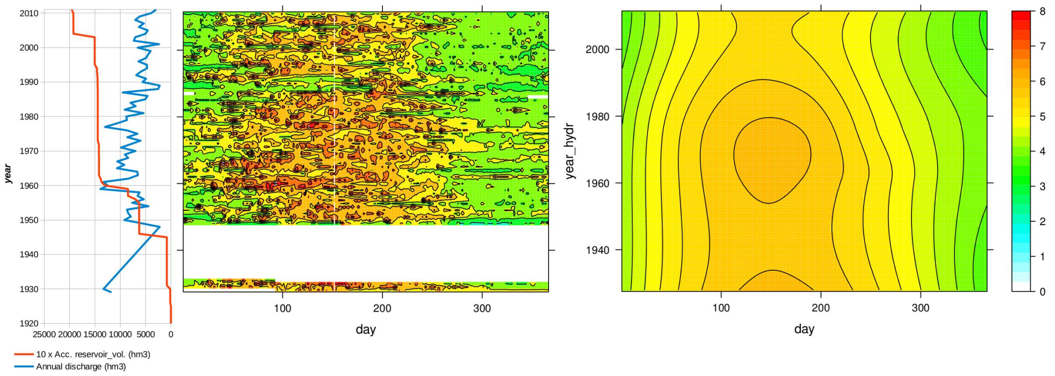

Figure 4.7. Variation of flow related variables along the measured time series at 'Castejón' gauging station (case study reach): (a) mean annual discharge (hm^3) (blue line), storing capacity (10 x hm^3) (red line) of the reservoirs to 'Castejón' gauging station, at the case study reach; (b) annual hydrographs (1st oct.-30th sept.) showing ln(mean daily flows, m^3 s^{-1}); and (c) surface of annual hydrographs show in Figure 4.7(b) smoothened by means of a polynomic function. (Data from CEDEX)

4.5 Effects on ecology of pressures

The hydrological change experienced by the middle river Ebro (case study segment) due to water abstraction (both surface and groundwater) and to flow regulation were analyzed by Magdaleno & Fernández-Yuste (2011). They showed that the most significant change was observed in th lowest flows, specifically during the driest months - August and September. There is an important increase of flow when compared to natural regime. However, contrarily to Frutos *et al.* (2004) and Ollero (2010), these authors fail to find any major modification of the geomorphically significant flow variables (magnitude, frequency and duration) of the high flow regime. An exploratory analysis of the evolution of the hydrographs (Figure 4.7[a]) shows both a decrease of high flows and an increase of low flows during the regulated period (1960-present).

As a result of the regulation, incision has been observed and the vegetation has matured, and attached itself to the channel. Sediment retention and flood reduction are progressively impoverishing the geomorphological and biotic processes along the fluvial system. (Batalla *et al.*, 2004, Ollero 2010). The formerly strong and active river has progressively lost its dynamics until the end of the century; it has no moving capacity from its current position (Magdaleno & Fernández-Yuste 2011). Only a small amount of erosion occurs in certain locations, but this is controlled by engineering defenses.

It is important to remark that all these channel changes have been natural. No channelization involving straightening or alteration of the channel path has been carried out in the case study segment. By contrast, during the 17th and 18th centuries some cut-offs were created to improve navigability. But the river planform was afterwards re-naturalized by the river itself during the 19th century (Ollero, 1992).

Regarding the floodplain, there has been a progressive and significant decrease of areas covered by water and non-vegetated gravel bars.

According to Ollero (2010), the morphology of the case study segment has evolved throughout the 20th century following three main stages: (1) wandering channel with unstable riverbanks until ca. 1950; (2) progressive degree of stabilization in the meandering channel and riverbanks until ca. 1980; and (3) restricted meandering channel and stable riverbanks.

The general status of the fish community in the middle course of river Ebro is a consequence of putting together the alterations of hydromorphological dynamics and the introduction of alien species. The habitat condition of the case study segment are those of a highly regulated Iberian Mediterranean river. This smoothened flow regime facilitates limnophyllic species, adapted to regular flow conditions in central European and North American large rivers. Iberian native species, mainly rheophyllic species adapted to high intra-annual flow variability, are out-competed by these newcomers since cannot express their competitive advantages in an artificially lentic environment.

The effects of pressures on the macroinvertebrate community of river Ebro are so dramatic that the most abundant populations of a highly threatened species, *Margaritifera auricularia* (Mollusca, Bivalvia) are located in an irrigation channel ('Canal Imperial de Aragón'), whereas its populations in the river Ebro (original habitat) are very reduced (Araujo & Ramos 1998, after Torralba 2009). All the communities observed in the Aragonese stretch of the case study segment are deeply disturbed. There is a lack of wide proportions of the communities that should be present. However, there are still two pollution-sensitive taxa, namely leptophlebiidae and heptageniidae, the latter with very low densities, whereas the former can reach densities up to 355 ind. m^{-2} (Torralba 2009).

Until recent times (1st mid of 20th century), in addition to supporting a relatively diverse stable fish community (*Anguilla anguilla*, *Achondrostoma arcasii*, *Gobio lozanoi*, *Luciobarbus graellsii*, *Parachondrostoma miegii*, *Phoxinus bigerri*, *Tinca tinca*, *Cobitis calderoni), the middle river Ebro should have worked as a corridor to connect populations of other species inhabiting tributaries (Salmo trutta*, *Barbus haasi*, *Barbatula quignardi*). Moreover, until the construction of Xerta-Tivenys weir near the mouth of the river (15th century), there should have been a profitable fishery of sturgeon (*Acipenser sturio*) (Farnós & Porrés 1999). Eels became extinct more recently, due to the construction of the Mequinenza-Rivarroj-Flix dam system (c. 1960), downstream the case study segment. Following the flow regulation experienced throughout the 20th century, limnophyllic alien species (*Esox lucius*, *Silurus glanis*, *Alburnus alburnus*, *Sander lucioperca*, *Micropterus salmoides*, *Lepomis gibbossus*, *Ameiurus melas*) were successfully introduced, increasing the originally limited non-native fish community (*Cyprinus carpio*, *Carassius* sp.) (Alonso & Gortázar 2009).

In order to get a more precise approach to the present ecological status the case study reach is hereby described. The most part of this reach is included in the surface water body coded 447 'River Ebro from the mouth of river Aragón till the mouth of Alhama stream'. According to Ebro RBMP 2010-15, this water body is in currently in 'good' status. However, it was classified as 'below good' status in a study of the same water authority cited by a prior (2006) study made by the regional government of La Rioja (Gobierno de La Rioja 2006). This draws a general picture that, if it can be classified as 'good', it might be close to a 'below good' status.

The last cited study describes the status of this surface water body as highly conditioned by the discharge of river Aragón, tributary in its left bank. This tributary has its source in the southern slope of the Pyrenees, and increases twofold the discharge of river Ebro after its junction. The sub-catchment of river Aragón is highly populated, with important agricultural and industrial activities, which lower the chemical quality of its discharge to river Ebro. On the other hand, diffuse pollution has been identified as a significant pressure in this stretch of river Ebro. All the margins but the protected area of 'Sotos de Alfaro' are occupied by irrigated croplands.

Specifically, in the southern (right) bank of the reach there is a urban wastewater point source at the wastewater treatment plant in the village of Alfaro. This plant is designed for nutrient treatment (phosphorus and nitrogen). There are also punctual morphological alterations in the form of longitudinal bank protections against floods in the village of Milagro. The control sampling site network show moderate status, with intermediate risk and probably impacted water body.

It must be noticed that this reach is classified as 'interesting' for the European mink (*Mustela lutreola*) conservation programs.

Regarding macrophyte communities, Cambra *et al*. (2013) identified 180 taxa among cormophytes (75), briophytes (52), algae (50) and lichens (3); and found that largest water bodies in the Ebro basin are the most impacted along the gradient of a synthetic impact descriptor built from 10 hydromorphological variables. In a WFD survey conducted in 2009 (Cambra *et al*. 2009) the study reach (river Ebro at Alfaro), the macrophyte community scored: IMF=8.85 (poor); IBMR=8.08 (poor); IVAM-CLM=5.5 (good); and IVAM-FBL=4.0 (moderate).

Durán (2008) assessed the ecological status of the case study reach (river Ebro at Alfaro) according to the diatoms, which scored in 2005: IPS=10.5 (moderate); IBD=9.2 (moderate); and CEE=9.7 (moderate).

4.6 Rehabilitation and mitigation measures

Ebro RBMP 2010-15 (CHEbro 2013b) propounds a program of measures to reach the 'good' ecological status of the surface water bodies. It contains 138 measures, of which 26 are referent to water supplies, 11 sewage treatment plans, 5 agro-environmental plans and 44 other types. All these measures are distributed into 22 sub-programs, the most important of which are (Table 4.4):

- Sewage and water treatment plans, specifically in the Pyrenees.

- Actuations in the context of the national river restoration strategy, for the enhancement of the morphological indicators of the river space, starting with rivers Cinca and Ebro along the duration of the RBMP (6 yr).

- Emergency plan for the control of the surface and groundwater abstractions.

- Enhancement of the stretches with point source pollution problems.

- Proposals for the re-use of urban effluents and irrigation returns.

- Plan of agro-environmental measures in irrigated croplands, reducing the nitrogen input of surface and groundwater.

- Modernization of irrigated areas, reducing the returns and increasing the efficiency.

- Implementation of ecological flow regimes in several reaches.

- Programs of licensing and revision of concessionary status.

- Emergency plans to control non-native species, specially against zebra mussel (*Dreysenia polymorfa*), and macrophytes in the large waterbodies of the catchment (Ebro and lower Segre).

- Polluted sediments treatment, specifically in Flix and Sabiñánigo.

- River longitudinal connectivity enhancement by means o (CHEbro 2013b).

Table 4.4. Resumed plan and detailed group of measures within the 'Environmental objectives' program (CHEbro 2013b).

	Program	Total number of measures	%	Measures with investment by 2010-15	%	Measures without investment by 2010-15	%	Measures with unknown investment by 2010-15	%
Program	Environmental objectives	138	49	78	57	54	39	6	4
	Demand satisfaction	118	42	57	48	50	42	11	9
	Extreme events	22	8	11	50	3	14	8	36
	Mgmnt. and governance	4	1	3	75	0	0	1	25
	Total	282	100	149	53	107	38	26	9
Groups of measures in the program of environmental objectives	Others	44	32	27	61	15	34	2	5
	Water supply	26	19	14	54	10	38	2	8
	Environmental restoration	24	17	11	46	13	54	0	0
	Irrigation	21	15	7	33	13	62	1	5
	Waste water treatment	11	8	9	82	2	18	0	0
	Point source pollution	7	5	5	71	1	14	1	14
	Agro-envirnomental plans	5	4	5	100	0	0	0	0
	Total	138	100	57	48	50	42	11	9

4.7 Ecological effects of measures

Gonzalo *et al*. (2010) evaluated the performance of the restoration measures in river Ebro across the region of La Rioja (upstream limit of the case study segment). They found that most of the applied measures sought to increase the discharge section: in 23 of 31 evaluated measures dredgings and/or sediment removals or relocations were planned, whereas in 20 measures riparian vegetation clear-cuttings and woody debris removals were done. These practices produce severe geomorphic impacts, as long as they destroy the bed naturalness, alter fluxes and modify the erosion, transport and sedimentation processes. Riverbank stabilization was observed in 10 occasions, and it completes the described measures occurring in the cleared channel. Geomorphically, it increases the above mentioned measures since it artificializes the bank morphology. In six cases riprap structures were used to stabilize the margins with highest risk of erosion, completing the above mentioned processes and increasing the geomorphic impact. In 13 occasions the measures were completed with re-vegetation by means of plantations and/or pegs. The remaining assessed measures were to some extent exceptional and addressed specific local demands.

In summary, the typical measure was a dredging and clearing aimed to increase the discharge capacity, consolidating and stabilizing with bank modifications and rip-raps the most conflictive stretches, and in some occasions 'embellishing' the results with vegetation. These sort of measures are widespread in the whole Ebro catchment as well as in all across Spain (Ollero 2008), and it can be considered as the typical measure of the water authorities on the river environment. It is a highly geomorphically and environmentally impacting measure, far from the new paradigms of river restoration, but a good response to the local and private demands. It can therefore be considered a greatly accepted measure by the public.

Most of the planned measures could have been resolved by means of less impacting practices. In general, they are spatially limited measures and the risk conditions are not especially severe. Real restoration measures should be prioritized letting the rivers work to achieve their self-correction. Only in such cases where this is not possible and when the problems are likely to increase at the short term harder solutions might be applied. In addition, dredgings and clearings are short term temporal 'solutions' that increase the discharge capacity for few years, needed to be repeated periodically.

Alternatively, according to the fundamental restoration criteria (Ollero 2007a), the following measures should be addressed:

(a) Planning of the fluvial territory, in order to reduce vulnerability, assessing case-by-case whether it is possible to remove some human activities from the channel and floodplain, seeking economic compromises with the actual stakeholders.

(b) Naturalization of flow regimes in order to keep the processes that naturally remove vegetation and mobilize sediments.

(c) Green infrastructures to stabilize banks, as long as these measures are needed, or to produce bed heterogeneity and facilitate changes in the flow direction.

(d) Burial of rip-raps and wall as long as they are considered indispensable.

(e) Reform and widening of bridges.

The human driven change of hydraulic and morphologic regimes is the ultimate cause of the observed changes in fish communities. It is therefore expectable that, as long as these drivers are acting, biotic communities will remain impacted. Whether certain thresholds leading to community shifts have been surpassed or not will be known when real effective measures are implemented, letting enough time to produce biotic responses.

4.8 General remarks or conclusions

The case study segment at the meandering middle river Ebro has been under continues severe pressures over the last 50 years, mainly due to agricultural and urban development. Since 1927, the hydrological dynamics have changed towards an artificial stabilization of flow regimes. This has led an originally multiple threat towards a single threat segment. A decrease of the flooded channel and the gravel bars with no plant colonization is the outcome at the reach scale. The massive construction of hard bank stabilizing structures has consolidated the human invasion of river space (Ollero 2010).

The currently reduced hydromorphic dynamics of middle river Ebro will only be restored by means of a highly active solution. The recuperation of the fluvial mobility space, involving the removal and displacement of present hard longitudinal structures. This will improve the current ecological status and minimize the risk of flood damages in the case study segment (Ollero *et al.* 2006; Ollero 2010).

The restoration measures often lack a holistic view of biotic and non-biotic processes and structures. Many planned measures show bias in their focus towards structural solutions or towards biological conservation (Ollero 2007b). It can therefore be concluded that one of the main drivers of the actual poor hydromorphological integrity of the free meandering Ebro reaches is the -technical, managerial and political- difficulty to approve effective measures to deal with the ultimate causes by the decision making conferences.

The wrong problem diagnosis due to the neglected fluvial processes, there is a lack of accuracy in the planned measures. These measures should take advantage of the natural river dynamics in order to achieve the desired effects on the floodplain uses and human interests. On the contrary, most of the planned measures address local problems by means of structural short term practices. The provision of a fluvial territory, where the river could freely express its dynamics, favouring longitudinal, vertical and lateral connectivities and the recuperation of natural planforms, will in the long term produce greater and more financial effective benefits (Gonzalo et al. 2010).

As Ollero *et al*. (2014) propound: “The Fluvial Territory would be, therefore, a space of sufficient width and continuity that would retain or regain the hydro-geomorphologic dynamic, obtain a continuous riverside passageway that would ensure ecological diversity (Habitats Directive, 1992/43/CE) and the bioclimatic function of the river system, comply with a good ecological state (Water Directive 2000/60/CE), laminate the avenues naturally (Flood Directive 2007/60/CE), solve management problems of floodable areas, as well as improving and consolidating the landscape around the river.”

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5. Delta Rhine (the Netherlands)

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5.1 *Introduction and Characterisation*

The river Rhine is a large European river that begins in the southeastern Swiss Alps, flows through Germany and ends in the North Sea in The Netherlands. It is the second longest river in Central and Western Europe (after the Danube), at about 1250 km with an average discharge of about 2,300 m3/s and has a catchment area of 185,260 km2 (Tockner et al., 2009), of which 20,000 km2 is situated in The Netherlands (Wolters et al., 2001). The general climate of the Rhine basis is determined by its location in a temperate climate zone characterized by frequent weather changes. The Rhine is fed by glaciers in the Alps, and further downstream by precipitation. Consequently, the upper stretches of the Rhine have their highest discharges in the early summer months, whereas the highest discharges further downstream occur during the winter months.

In this chapter, we will focus on the stretch of the Rhine in The Netherlands: the Delta Rhine[2].

Hydromorphology

At the Dutch-German border, the Rhine is a single river channel. About 10 km downstream, the river changes to a system of Rhine branches (Figure 5.1). At the Pannerdensche Kop, the river bifurcates into the river Waal and Pannerdensch Kanaal. Around 10 km further downstream, the Pannerdensch Kanaal bifurcates into the branches Neder-Rijn and IJssel.

Where the Rhine enters The Netherlands (at Lobith), the discharge varies roughly between 800 and 12,000 m^3 s^{-1}, resulting in a difference between the minimum and maximum water level of up to 8 metres (Middelkoop 1997). Typically, the highest river discharges occur in winter and the lowest in late summer and early autumn (Buijse *et al.*, 2002). During the growing season of the vegetation (May – October), periods of low water-levels may occur (Figure 5.2).

No weirs are present in the branches Waal and IJssel, whereas the lower water levels of the Neder-Rijn have become regulated after the construction of three weirs in the 1960s. The Waal and IJssel are free-flowing, and the amplitude of water level fluctuations show a gradual decline in their course downstream, from large level fluctuations in the upstream parts to reduced level fluctuations downstream (Figure 5.3). The weirs in the Neder-Rijn divide the discharge between the Neder-Rijn and IJssel, and are gradually closed when the discharge is lower than average (2,300 m^3 s^{-1}), which ensures a sufficient proportion flows into the IJssel during low flow periods (so-called ‘285 m3/s regime’). Hence, in the Neder-Rijn, the construction of weirs did not changes in the flooding regime during high discharges, but in this river stretch the natural water-level regime with occasional low river water levels has been replaced by an artificial distribution with higher minimum water levels than would be expected naturally (Figure 5.3).

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[2] The stretch of the Rhine in the Netherlands is quite often also referred to as the Lower Rhine. Here we follow the subdivision given in Rivers of Europe (Tockner et al. 2009) and use the term ‘Delta Rhine’, because the Rhine splits into three branches shortly after it enters the Netherlands.

On an annual basis, the Rhine transports 500,000 m^3 of sand and gravel, and 2,500,000 tonnes of silt. In the Rhine branches about 25% of the annual load is transported during floods, while these account for only 4% of the time (Middelkoop, 1997; ten Brinke *et al*., 2000). The suspended material consists of a relatively fine sand fraction and silt, which is a cohesive, clayey fraction with an organic component. Silt will be deposited at low flow velocities (indicatively lower than 50 cm/s), and otherwise will be eroded or remain suspended. As a result, the largest proportion of the material, and the coarsest fraction, is deposited directly along the main channel. Here a natural levee develops, which aggradates during each bank overflow. At lower flow velocities at longer distances from the main channel, silt is deposited in the floodplains during floods. On a yearly basis about 8% of the total silt load that enters The Netherlands at Lobith is trapped by the floodplains. This corresponds to 200,000 tonnes (Middelkoop, 1997; ten Brinke et al., 2000).

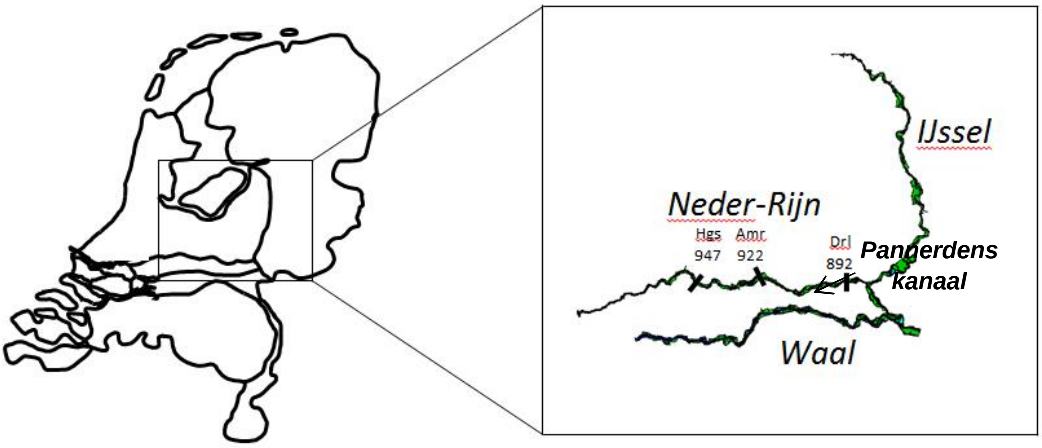

Figure 5.1. Map of the three branches of the River Rhine in The Netherlands. Hgs, Amr and Drl are the three locations with weirs; figures are river km.

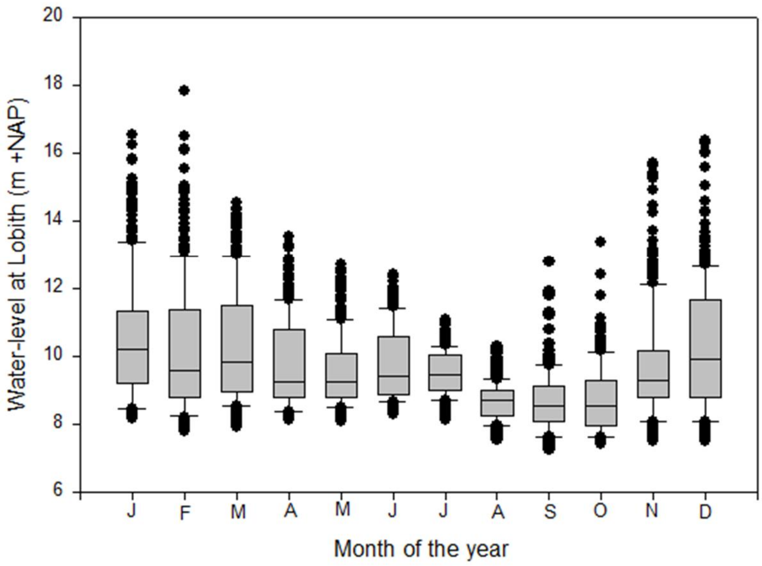

Figure 5.2. Monthly water-level of the Delta Rhine at Lobith in the period 1990–1999. Each box represents the median, 25 and 75 percentile values; the whiskers 5 and 95 percentile values. Dots indicate individual water-level measurements lower or higher than the 5 and 95 percentile values respectively.

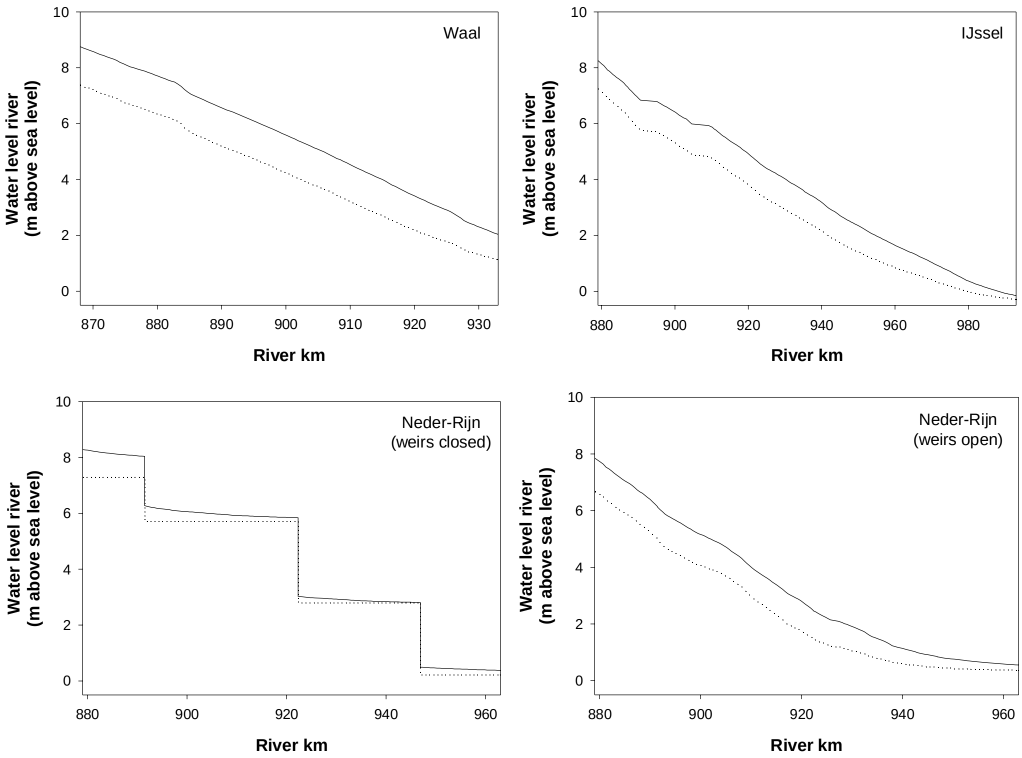

Figure 5.3. The mean and minimum water levels (m ASL) in three Rhine branches (Waal, IJssel and Neder-Rijn) for the period May–October 1990–99. For the Neder-Rijn, the mean and minimum river water levels are also shown at times when the weirs would be open (calculations based on the 1D water quantity model SOBEK).

5.2 Historical situation or reference situation

The historical state of the Delta Rhine around 1850, prior to major river normalizations, has been described by Middelkoop *et al.* (2005). We used this description as a reference of the 'near-natural' state. Note that at this time, the rivers were already embanked, the present-day morphology had largely developed, and large parts of the floodplains were used for agriculture. This reference thus is not a pristine river, but a still dynamic river system where extensive land use was largely adapted to the natural morphological patterns and processes.

The ratio of the width and depth of the main channel is a good proxy for the morphological activity of a river. Higher values of this ratio indicate stronger morphodynamical processes, and higher sandbanks in the main channel. Small islands in the main channel will only develop when the river is very width and shallow, viz. at width/depth ratios larger than 100 (Figure 5.4 and 5.5). Before 1950, this was the case for the river Waal (Figure 5.6) and Lek, but nowadays these conditions do not occur anymore along the Rhine. Alternating bars (sand depositions on the shoreline of the main channel) can also develop at width/depth ratios larger than 40. Before 1850, all river stretches of the Rhine had width-depth ratios larger than 40, nowadays only in the Bovenrijn and Waal.

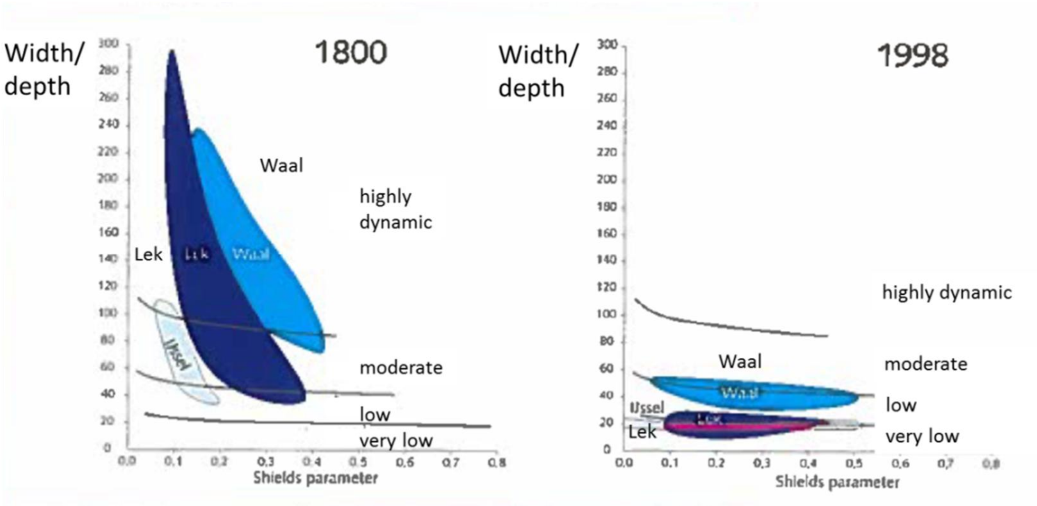

Figure 5.4. Relationship between ratio of width/depth and Shields parameter for the Waal, IJssel and Lek around 1800 and 1998.

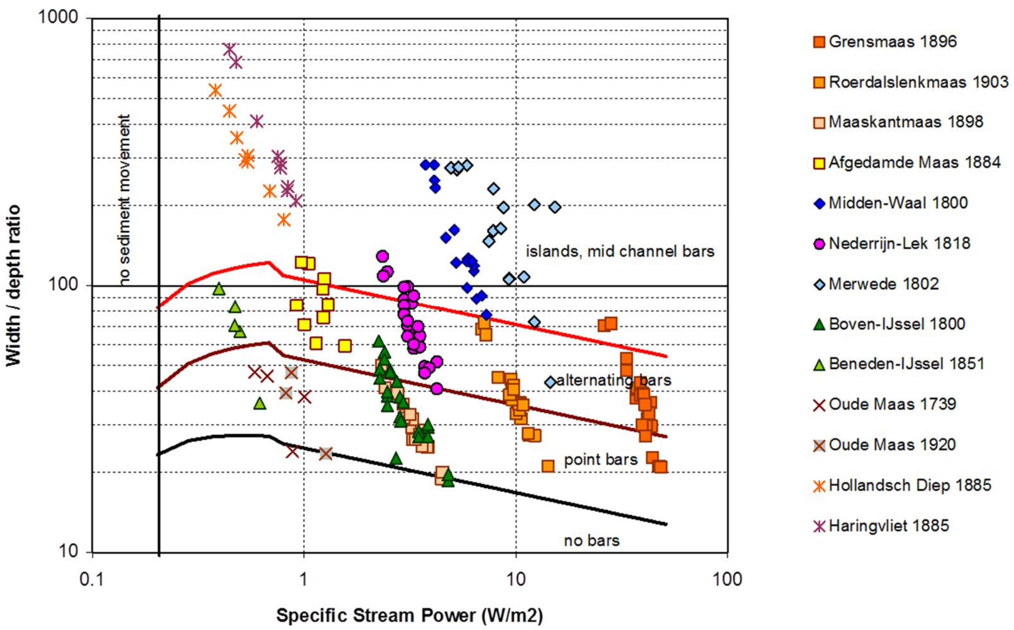

Figure 5.5. The potential to develop bars and islands in various stretches of the River Rhine and Meuse based on width/depth ratios and specific stream power in the period prior to major normalisations. (Source: Middelkoop et al. 2005)

Ecotope distribution along branches of Delta Rhine

In Middelkoop et al. (2005), the historical state is expressed in terms of ecotopes. Ecotopes are defined as more or less homogeneous landscape units, identifiable by geomorphological and hydrological characteristics, and a vegetation structure that depends on these abiotic conditions in combination with the prevailing land use. Accordingly, ecotope classification schemes for the Rhine are based on hydrodynamics, morphodynamics and (land) use dynamics (Rademakers & Wolfert, 1994). Hydrodynamics include all physical and chemical influences of water on the development of soil, vegetation and fauna, which is mostly defined in terms of average inundation duration or frequency. Morphodynamics relate to all mechanic forces acting upon soil and vegetation, which are primary controlled by current velocity, and erosion and sediment transport processes, but also by wind or human activity. Land use dynamics refers to human influences affecting soil and biota, including e.g. agricultural use, grazing intensity or constructing objects. Under uniform boundary conditions of management and in equal stage of vegetation succession, ecotopes are equivalent or geomorphological units, in that case referred to as 'physiotopes'.

In Figure 5.7, the geomorphological succession of ecotopes along the Rhine is depicted. The distribution of ecotopes along the Rhine branches does not reflect a static situation, but represents a 'snap-shot' of an ongoing succession of geomorphology, vegetation, and land use management. Human activities influenced the development of physiotopes by river training works, but human impact on ecotope succession was strongest on the floodplain where natural vegetation was removed to make place for agricultural use (pasture, arable lands, orchards, production forest, Figure 5.7). As a consequence, only at a few locations the succession could reach a climax vegetation of floodplain swamps, grasslands, softwood or hardwood floodplain forest.

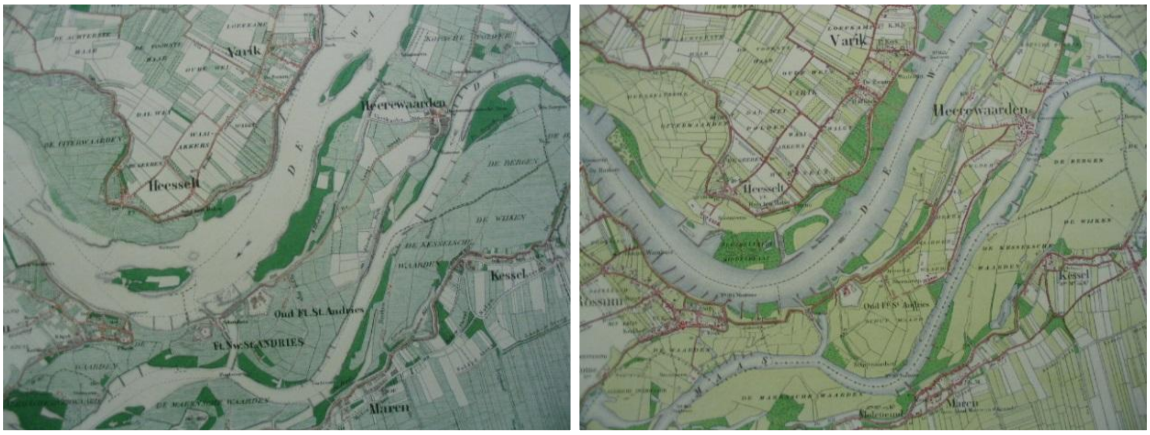

Figure 5.6. Maps of the river Waal and Meuse during 1872 (left) and 1912 (right). Please note how the main channel has been narrowed and islands disappeared in the River Waal (source: Topografische Dienst).

Around 1850, a large variation in ecotope patterns existed within the river channels and on the embanked floodplain along the longitudinal gradient of the Delta Rhine. Floodplain meadows dominated in a large part of the floodplains along the Rhine branches, especially along the upstream stretches of the Ijssel branch (Boven-IJssel). Also on along all reaches river forests occurred: softwood forest was found on young accretions along the main channel and lower parts of the floodplain, while only small areas of hardwood forest occurred on older levees and river terraces along the IJssel. Ecotopes associated to backwater channels and swales characterized the Waal, and to a lesser extent the Lek, which is the downstream part of the Neder-Rijn branch. The proportion of 'channel ecotopes' was high in the Waal and Lek, and low along the IJssel.

Major changes have occurred since 1850. The river training works have drastically decreased the morphodynamic nature of the Delta Rhine, and have considerably levelled out the natural variation in hydro-morphodynamics. Island formation cannot occur in any reach of the Delta Rhine because of the artificial reduction of the width/depth ratio. The Waal is the only reach where alternating banks still may develop. In addition, dredging practices for maintenance of the fairway channels prevents the formation of sand bars and islands. Ecotopes associated with channel migration, such as backwaters or residual channels no longer develop, because the channel banks have been fixed (Figure 5.8, 5.9). The construction of weirs has largely reduced water level variations in the Neder-Rijn, and caused a reduction of flow velocities. Consequently, sediment transport rates have decreased. Table 5.1 summarises to which extent ecotopes can still develop or naturally or can only be rejuvenate or created by human intervention in the various stretches of the three Rhine branches.

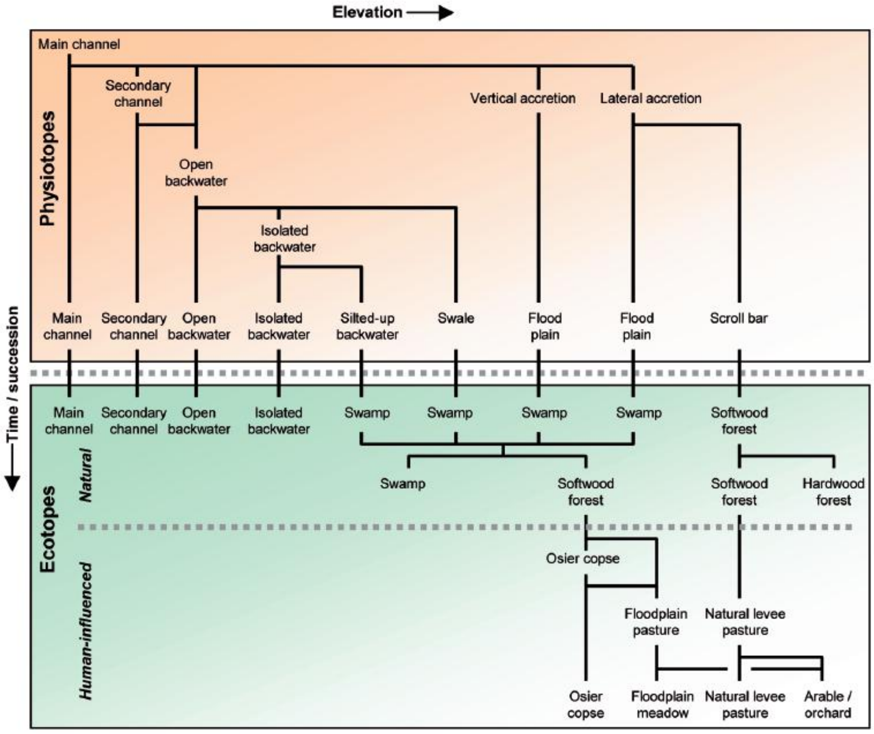

Figure 5.7. Bio-geomorphological succession scheme of the Delta Rhine derived from historical data 1600-1850 and geomorphological surveys (Source: Middelkoop et al. 2005).

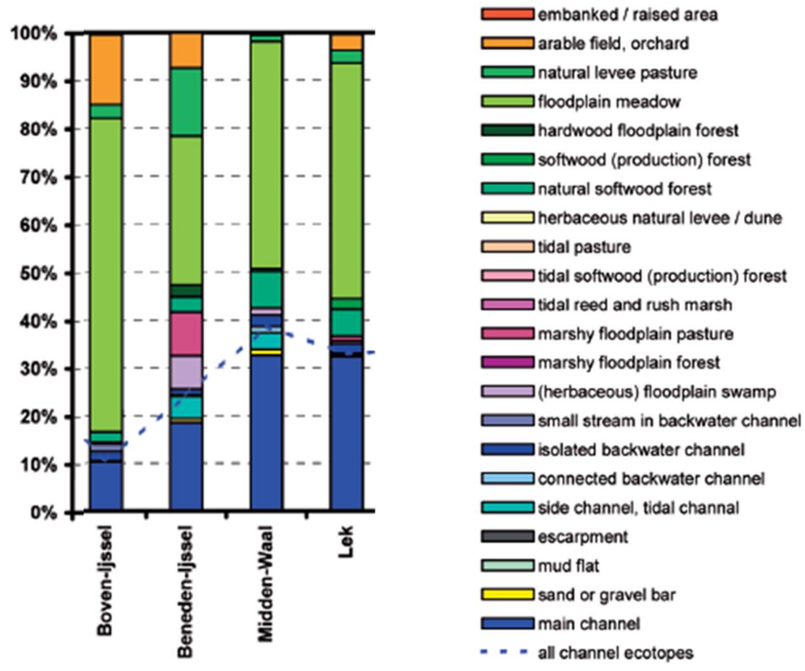

Figure 5.8. Ecotope distribution in river reaches along the Delta Rhine, situation around 1850 AD. (Source: Middelkoop et al. 2005)

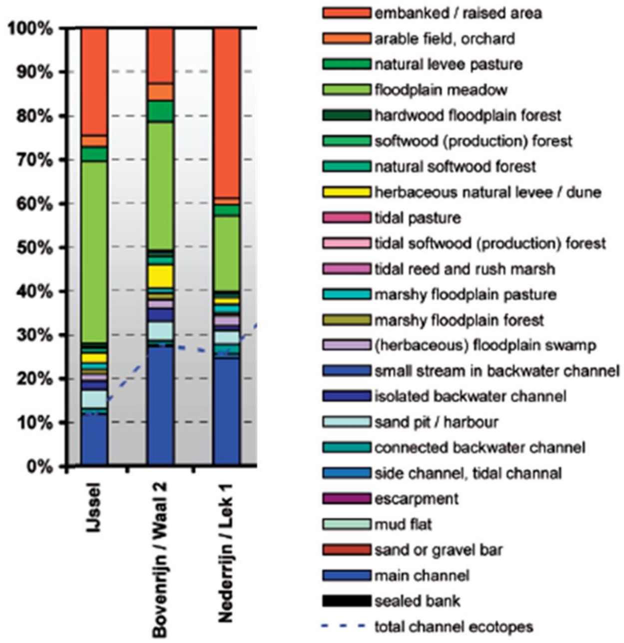

Figure 5.9. Ecotope distribution in river reaches along the Delta Rhine, present day situation (approx. 2000 AD). (Source: Middelkoop et al. 2005)

Table 5.1 Potentials for ecotopes to develop, rejuvenate or being created along river reaches of the lower Rhine and Meuse rivers (Source: Middelkoop et al. 2005)

River reach	Mud flats, sand bars	Sand and gravel bars	Dynamic islands	Shallow, wide secondary channels	Narrow, deep secondary channels	Connected backwater channels	Closed-off backwater channels	Isolated backwater channels	Residual channels	Swales	Brook channels	Tidal reed and ruch marshes	Swamp / reed marsh*	River dunes	Herbaceous natural levees	Natiral levee pastures	Softwood ofrest	Hardwood forest
Boven Rijn		rejuvenation		rejuvenation		rejuvenation	rejuvenation		rejuvenation					development	development	development	development	development
Boven Waal		rejuvenation		rejuvenation		rejuvenation	rejuvenation	conservation	conservation		development			development	development	development	development	development
Midden Waal		rejuvenation		rejuvenation		rejuvenation	rejuvenation	conservation						development	development	development	development	development
Beneden Waal		rejuvenation		rejuvenation		rejuvenation	rejuvenation						development	development	development	development	development	development
Pannerdensch. Kanaal					creation												creation	
Gestuwde Nederrijn / Lek						rejuvenation	rejuvenation	conservation			development		development		conservation	conservation	development	
Beneden Lek				rejuvenation	rejuvenation	rejuvenation	rejuvenation						development	conservation	development	conservation	development	development
Boven IJssel					rejuvenation	rejuvenation	rejuvenation		rejuvenation	conservation	development		creation		development	conservation	development	development
Midden IJssel					rejuvenation	rejuvenation	rejuvenation		conservation	conservation					development	conservation	development	conservation / development
Sallandse IJssel					rejuvenation	rejuvenation	rejuvenation				development				rejuvenation	conservation	development	conservation / development
Beneden IJssel				rejuvenation	rejuvenation	rejuvenation	rejuvenation			conservation			development		development	conservation	development	conservation / development

*Not including marshes in isolated backwater channels and residual channels

- development - rejuvenation - creation - conservation of existing ecotope

- no potential or mismatch with morphological pattern of river reach

5.3 Drivers: socio-economic functions

The main socio-economic functions of the river Rhine are flood protection, navigation, discharge regulation, water management, agriculture, drinking water, industries, sediment extraction, urban areas, infrastructure and fisheries. These drivers have resulted in a number of hydromorphological pressures along the river Rhine (Table 5.2).

Around 1400, the floodplain area of the river Rhine in The Netherlands was already strongly reduced due to a closed ring of embankments along the river stretches. During the 17th – 19th century, also minor embankments were constructed in the floodplains to facilitate agricultural use by preventing small floods. In addition, the natural riparian vegetation was cut to stimulate agriculture use of the floodplains and to prevent ice jamming. Especially from 1850 onwards, the river channel was strongly channelized and normalized for navigation purposes. Nowadays, The Netherlands is Europe's biggest inland shipping nation. Nearly half the freight shipped to and from Germany is transported by the river Waal: the busiest inland waterway in Western Europe. Today, no less than 65 per cent of the Netherlands' fresh surface waters originate from the Rhine. This water is used for various purposes, including agricultural sprinkling and 'rinsing' brackish polders with fresh water. Such rinsing takes place mainly in the western part of The Netherlands, where the groundwater tends to be brackish or saline. River water is also used for the preparation of drinkwater, some 1.28 billion cubic metres of it in 1994. Almost as much water is used for industrial purposes, excluding cooling at power stations. Water from the river IJssel additionally serves to maintain water levels in the freshwater reservoir IJsselmeer. Furthermore, the river Rhine plays a vital role in the prevention of drought in parts on The Netherlands with a large summer precipitation deficit.

Table 5.2. Relation between "Drivers" and indicators of "Pressures" along the river Rhine in The Netherlands

Drivers	Pressure
Agriculture	% Removal riparian vegetation
Agriculture, flood protection	% Water level management
Flood protection	% reduction natural inundation zone/active floodplain
Flood protection	% Embankment
Flood protection, water management	% Intern basin water transfer
Industries	Cooling water
Navigation, discharge regulation	% Channelisation
Navigation, discharge regulation	% Normalisation
Navigation, flood protection	% Bank protection
Navigation, flood protection	% Groynes
Navigation, sediment extraction	% Deepening
Navigation, water management	# weirs, sluices: passable
Navigation, water management	# weirs, sluices: not passable

5.4 Effects of pressures on hydromorphology

The historical development of the area of the river Rhine can be sketched in a number of milestones (see Table 5.3; after Wolters et al, 2001). Until approximately the year 1000 natural factors determined the development of the landscape. From this period onwards, human influence became important. The scattered constructions of embankments for protection of settlements and agricultural lands on natural levees resulted in closed rings of embankments around the year 1400. This was the beginning of a process of ever further reduction of the room for rivers (Wolters et al., 2001). During the 17th – 19th century, meanders were artificially cut-off and the discharge distribution over the Delta Rhine branches was adapted, land was reclaimed from the main river channel and minor embankments were raised to protect the floodplain from minor floods; the embanked floodplains due to being increasingly used for agriculture with meadows, arable field and orchards. Around 1850 major river training works – referred to as 'normalizations' – were carried out to improve the discharge capacity which resulted in a systematic narrowing and deepening of the main channels and the removal of islands, meanwhile preventing further lateral channel migration. During 1954 - 1971, the Neder-Rijn river were canalized by weirs, and during 1958 – 1987, the Delta Plan was carried out, which resulted in the closing of the Haringvliet sluices in October 1970 (Middelkoop et al., 2005).

In Table 5.4, the effects of the pressures on hydromorphology for the water bodies of the river Rhine in The Netherlands are summarised. All water bodies are strongly affected by removal of riparian vegetation, embankment, normalisation of the river, deepening of the main channel and construction of groynes. Based on García de Jálo et al. (2013), the effects of the most important pressures on hydromorphological processes and variables are summarized below:

Embankments, levees, lateral dikes:

- increased water flow, resulting in higher water depth during flooding and higher shear stress;
- reduced discharge to aquifer, resulting in lower groundwater levels, and – hence – decreasing water levels and droughts in oxbow lakes and other wetlands, as well as mortality of trees;

Removal of riparian vegetation

- cutting of trees has resulted in the almost absence of Large Woody Debris, as well as a strongly reduced input of particulate organic matter (POM) into the river.

Channelisation

- groynes have stabilized river banks. As a result, rejuvenation of dynamic river habitats is halted, while the vegetation succession of remaining habitats proceeds.

Channel dredging:

- riverbed incision with lower water levels, resulting in lower ground water levels, potentially leading to tree mortality and droughts in oxbow lakes and wetlands.

Table 5.3. Historical developments of embankment, normalisation and channelisation of the river Rhine

Time period	Historical developments
until ca 1000	natural river landscape
from ca 1000	building of embankments
from ca 1400	closed system of river embankments
1707	excavation of the Pannerdensch Kanaal
1850 - 1890	excavation of the Nieuwe Merwede
1868	excavation of Nieuwe Waterweg
1876	excavation of the Noordzeekanaal
1850-1875	regulation of the Waal for discharge and ice (building groynes)
1875-1916	normalisation of the Waal for shipping
1904	excavation of Bergse Maas, separation of Waal and Meuse
1911-1916	normalisation of the Boven-Merwede
1932	damming off of the Zuiderzee
1938-1952	excavation of the Amsterdam-Rijnkanaal
1954-1971	normalisation of the Nederrijn-Lek; construction of weirs
1958-1987	execution of Delta Plan, including closing of Haringvliet sluices in 1970

Table 5.4. Effects of pressures on hydromorphology of water bodies along the Rhine in The Netherlands

Pressures sensu REFORM WIKI	Pressures RBMP	Bovenrijn-Waal	IJssel	Nederrijn-Lek
Alteration of riparian vegetation	% Removal riparian vegetation	100	100	100
Artificial barriers	# Weirs, sluices: passable	0	0	3
Artificial barriers	# Weirs, sluices: not passable	0	0	0
Channelisation/cross section alteration	% Channelisation	20	30	20
Channelisation/cross section alteration	% Normalisation	100	100	100
Channelisation/cross section alteration	% Deepening	78	100	100
Channelisation/cross section alteration	% Bank protection	10	70	35
Channelisation/cross section alteration	% Groynes	90	80	70
Embankments, levees or dikes	% Reduction active floodplain	100	100	100
Embankments, levees or dikes	% Major embankments	100	85	100
Hydrological regime modification	% Water level management	0	100	100

5.5 Effects of pressures on ecology

Embankments

Embankment of the floodplains reduces the exchange of fish between the main stream of the river and floodplain water bodies. This reduces the feeding habitat for young (0+) fish and migratory fish species (Grift 2001). Additionally, the area of the inundation zone in the active floodplain will become reduced (see below).

Reduction of natural inundation zone or active floodplain

The reduction and impairment of the inundation zones in floodplains will have strong negative impact on (many different) gradients which are present in pristine conditions, especially habitats which are characteristic for low-dynamic conditions at long distances from the main channel (Buijse et al. 2002). Additionally, the interplay between inundation and temporary desiccation is strongly disrupted, which will influence physical-chemical processes. Consequently, composition and succession of macrophyte vegetation are strongly affected, resulting in a loss of species such as Water soldier (*Stratiotes aloides*) (Van den Brink, 1994; Van den Brink et al., 1996). The benthic invertebrates community is also strongly affected by the loss of gradients in abiotic conditions and – hence – in different habitats (Van den Brink et al., 1996). Especially for species that are characteristic for floating islands and other more advanced phases of aquatic vegetation succession have declined strongly. Furthermore, in remaining narrow active floodplain, the flooding water is loaded with high concentrations of suspended sediments, which deteriorate conditions for benthic invertebrates even more. For fish community, especially the conditions for limnophilic species with a high tolerance for low oxygen concentrations has deteriorated, especially for species such as Weatherfish (*Misgurnus fossilis*), Tench (*Tinca tinca*) and Crucian Carp (*Carassius carassius*) (Grift et al., 2006).

Normalisation and channelisation

During normalisation, the depth profile of the river becomes fixed and – hence – the lateral migration of the main channel stops. During channelisation, the main channel of the river is ‘straightened’ and large meanders are cut off from the main channel. Both normalisation and channelisation reduce the diversity of flow conditions and grain size of sediments and – hence – the number of characteristic riverine habitats becomes strongly reduced. In particular shallow shore zones disappear reflected by a reduced shoreline length (cf Ward et al. 1999). Furthermore the width/depth ratio reduced substantially (Figure 5.4) resulting in steeper and narrower shorelines reflected by a low % of riparian zones that is frequently inundated (Buijse et al. 2002). Consequently, the species diversity of macrophytes, macro-evertebrates and fish decreases, especially for rheophylic species that prefer highly dynamic habitats.

Groynes

Groynes prevent the lateral migration of the main channel of the river, and – hence – the natural hydromorphological processes (such as erosion and sedimentation). Consequently, the species diversity of macrophytes, benthic invertebrates and fish decreases, especially for rheophylic species that prefer highly dynamic habitats.

Deepening

Deepening results in deteriorated habitat conditions in the river channel, which reduce habitat diversity for macrophytes, benthic invertebrates and fish. Additionally, the water levels in the main channel decrease during low river discharge, with consequently lower groundwater levels and a reduction of the area of wetlands and open water in the adjacent floodplains.

Shoreline protection

As a result of shoreline protection, natural processes such as erosion and sedimentation of shorelines are halted, and natural gradients from wet to dry are disrupted. These gradients are important for macrophytes, benthic invertebrates and fish species.

Removal of riparian vegetation

Removal of riparian vegetation will result in a reduced habitat diversity in floodplains, which negatively affects biodiversity in floodplains. Riparian vegetation (such as alluvial forests) also result in a strong input of organic matter (decaying leaves) in water bodies and streams of floodplains, which has a large influence of the food web structure and the flow of energy and matter in the river system. This may influence species composition of benthic invertebrates and fish community, as well as the productivity of river systems. Furthermore, well-developed riparian vegetation can strongly stabilise sediments in floodplains, and has a large impact on the occurrence of hydromorphological processes such as erosion and sedimentation.

Weirs, sluices

Weirs and sluices that are not passable for fish and other organisms have a strong impact on the dispersal and migration of species, especially several diadromic fish species that are characteristic for the Rhine (such as Sea trout, Salmon, Allis shad, Sea Lampern and River lamprey).

Weirs and sluices that are passable for fish and other organisms still have a strong impact on upstream water levels both in the main channel and the floodplains and flow velocities in the impounded stretches. Only one of the three Rhine branches, the Neder-Rijn, is regulated by weirs (Figures 5.1 and 5.3)

Water level management

In the Neder-Rijn, the construction of weirs did not changes in the flooding regime during high discharges, but in this river stretch the natural water-level regime with occasional low river water levels has been replaced by an artificial distribution with higher minimum water levels than would be expected naturally (Figure 5.3). As a result, the groundwater levels (and – hence – water level in floodplain water bodies) are also strongly stabilized, which results in a strongly reduced amplitude of water level fluctuations in these floodplain lakes. As a result, the composition of macrophyte vegetation has changed which results in reduced species richness and altered successional pathways.

5.6 *Rehabilitation and mitigation measures*

In the RBMP's 2010-2015 for the Bovenrijn, Waal, IJssel en Neder-Rijn-, a number of measures are listed to reach the "good ecological potential" in the water bodies of the Delta Rhine (Table 5.5).

Table 5.5. Ecological rehabilitation measures that will be carried out along the Delta Rhine

Name measure REFORM wiki	Name measure RBMP or other measure programs	Nederrijn-Lek	Bovenrijn-Waal	IJssel
Set back embankments, levees, dikes	Set back major embankments			
Reconnect backwaters and wetlands	Connecting lakes to river (1 or 2-sided) km	13.8	26.5 km/113 ha	37
Remove bank fixation+non-native substrate	Development natural shores (km)	30	24.3	94.9
Lowering river banks or floodplains	Floodplain lowering (ha)	5,1	241	229
Longitudinal connectivity improvement	Reconnection of brooks to river (N)	7	-	16
Facilitate (downstream) migration	Measures to improve fish migration (N)	6	-	-
Isolation of water bodies/Restore wetlands	Development of isolated water bodies, marshes	0.9 ha/0.5 km	-	-
Retain floodwater	Retain floodwater behind minor embankments (N)		1	
Introduce large wood	Introduction of dead wood			
	Removal of contaminated sediments (ha)	-	-	2.6

From Table 5.5, it is clear that a large effort is put into measures that increase river dynamics, e.g. reconnecting water bodies to the river (one-sided or two-sided), floodplain lowering and removal of bank fixation. Far less attention has been paid to the development of low dynamic habitats in floodplains, such as marshes and isolated, semi-stagnant water bodies, which origins from the fact that the WFD is focussed to improve conditions in the main channel merely.

5.7 Ecological effects of measures

Reconnecting lakes to rivers: side channels

Along the Delta Rhine in The Netherlands, several side channels have been excavated in the floodplains. This has been beneficial for fish (Grift 2001) and benthic invertebrates (Jans et al., 2004), while aquatic macrophytes did only colonize side channels along downstream river sections with small amplitude of water level fluctuations during the growing season. Characteristic species are *Potamogeton nodusus*, *P. perfoliatus*, *P. pectinatus*, and *Myriophyllum spicatum*. In more upstream river sections, the amplitude of the water level in the main channel (and – hence – in the permanently connected side channels) was too large for successful establishment of aquatic macrophytes (Van Geest & Teurlincx, 2014).

Already within a few years, these side channels have been colonized by a large number of macro-evertebrate species. The species diversity of the side channels is much higher than in the groyne fields of the main channel. In the slow flowing parts of the side channels significantly less non-native species occur than in the main river bed. From the (benthic invertebrate) target species however, only a small proportion were discovered (Jans et al., 2004). The absence of other target species can largely be attributed to the lacking of specific habitats e.g. gravel, large wood and aquatic vegetation (Jans et al., 2004). Additionally, the variable flow regime in the side channels due to water displacement of passing ships may be a problem (Klink et al., 2014). The sediment type, the water depth, the flow velocity, the morphodynamics, the organic matter content and the soil chemistry together determine the species composition of the macro-evertebrate community (Jans et al., 2004).

Side channels do have a higher fish species diversity and density than existing habitats in the main channel. Hence, these channels have an important nursery function for riverine fish (Grift 2001; Dorenbosch et al., 2014). Recently created side channels along the Delta Rhine function as nursery areas for rheophilic fish species (Ide *Leuciscus idus*, Gudgeon *Gobio gobio*, Barbel *Barbus barbus*, and Asp *Aspius aspius*) of which densities of juveniles peak in summer (Grift, 2001). Side channels may also function as spawning areas for Ide and Gudgeon, but this could not be demonstrated. For lithophylic species (Barbel and Asp) they do not function as spawning areas since suitable substrate lacks in the Delta Rhine as a whole and consequently also in the side channels (Grift, 2001).

Reconnecting lakes to rivers: one-sided channels

Over de past decades, a number of floodplain lakes and oxbows have been connected to the main channel. These lakes are connected only at the downstream end to the river. So far, these lakes have not been colonized by aquatic vegetation, also along river trajects with small amplitude of water-level fluctuations during the growing season. The absence of colonisation by macrophytes may be caused by a large water depth, as well as effects of waves caused by navigation. Also the benthic invertebrate composition is composed of eurytopic species which are characteristic for standing waters and are able to cope with high sediment rates of clay particles.

These water bodies serve as an important nursery area for rheophylic fish (Ide *Leuciscus idus*, Gudgeon *Gobio gobio*, Barbel *Barbus barbus*, and Asp *Aspius aspius*), although densities of these species are generally lower than in (permanently flowing) side channels (Grift 2001; Dorenbosch et al., 2014).

Measure that improve fish migration

All three weirs in the Neder-Rijn branches do have a fish pass, which all function well (Winter 2010; Figure 5.10). The fish passes improved connectivity for fish very much being passable for all species and size classes, but did not have a beneficial effect on other hydromorphological conditions.

Figure 5.10 The fish pass near Hagestein in the Neder-Rijn. Monitoring showed that among 38 fish species numerous diadromous lampreys migrated through this fish pass. (Photos: Tom Buijse)

Development of isolated water bodies and marshes

During past decades, a number of lakes and ponds have been excavated in the floodplains along the Delta Rhine. Such created or rehabilitated lakes were readily colonized by various submerged macrophytes in the years after excavation. In the first four years, pioneer species such as *Chara vulgaris*, *Potamogeton pusillus*, and *Elodea nuttallii* dominated these lakes. Remarkably, after this first stage of macrophyte dominance, a large proportion of the excavated lakes lost their aquatic vegetation within a few years. Only lakes that were small (< 1-2 ha) and shallow (< 1.5-2 m) remained vegetated by submerged macrophytes (Van Geest, 2005).

Floodplain lake morphometry, as well as amplitude of water-level fluctuations during non-flooded conditions, strongly determined cover and composition of aquatic vegetation. During non-flooded conditions along the Rhine, lake water-level fluctuations are largely driven by groundwater connection to the river. Hence, water-level fluctuations are largest in lakes close to the main channel in strongly fluctuating sectors of the river and smallest in more remote lakes. Additionally, water-level fluctuations are usually small in old lakes, mainly due to reduced groundwater hydraulic conductivity resulting from accumulated cohesive clay and silt on the bottom. The reduced amplitude of water-level fluctuations with lake age has a strong impact on macrophyte succession in floodplain lakes from desiccation-tolerant species (e.g. *Chara* spp.) in young lakes to desiccation-sensitive species (e.g. *Nuphar lutea,* Figure 5.11) in old lakes (Van Geest, 2005).

Floodplain lakes with abundant vegetation, which inundate less than 20 days per year have low fish species richness, but provide suitable habitat for the reproduction of limnophilic species such as Tench (*Tinca tinca*), Rudd (*Rutilus erythrophtalmus*) and Crucian carp (*Carassius carassius*) (Grift et al. 2006; Figure 5.11). The proportion of limnophilic species in these lakes is, however, outnumbered by eurytopic species such as Bream (Abramis brama). Some limnophylic species such as weatherfish (*Misgurnus fossilis*) and Ten-spined stickleback (*Pungitius pungitius*) were extremely rare, suggesting that most remote and seldom flooded lakes have disappeared completely from the floodplains along the Delta Rhine.

Figure 5.11 Floodplain lakes which inundate less than 20 days per year harbour limnophilic fish species such as tench (Photos: Tom Buijse)

Retain flooding water behind minor embankments

In 2008 and 2009, a seasonal inundated floodplain was created by means of retention of river water behind a minor embankment. As a result, the area of temporarily flooded marshes and meadows increased strongly. The community of breeding birds responded strongly with several pairs of (Red listed and N2000) species such as Bittern, Crake, Garganey, Little grebe, Snipe and Shoveler. Also the densities of macro-evertebrates, larvae of newts and 0+ fish increased strongly, which served as a food source for birds.

Introduction of large wood

In December 2013, a pilot study was carried out along the river Neder-Rijn, to investigate the contribution of large dead wood to achieve the goals of the Water Framework Directive (WFD). The preliminary results of this first year of monitoring indicate that the first phase of colonization is prosperous. On the shallow locations, especially near the branches, high concentrations of juvenile fish were found. The fish community in the groyne fields is dominated by the invasive non-native Round goby (*Neogobius melanostomus*). The fish community around the trees however is composed more evenly, and consists of many more native species, whereby biodiversity is higher. Fish use the trees for shelter and to feed, and there are also strong indications that they use the dead trees as a spawning habitat. For benthic invertebrates on dead trees, high numbers of characteristic riverine species were found, such as caddisflies (*Trichoptera*) and Chironomidae (*Diptera*). These species are currently missing on the with rip-rap protected shores in the river. Potentially confounding factors for the future are massive colonisation of the dead trees by dreissenid mossels and subsequent invasion by *Chelicorophium* species, which makest the habitat unsuitable for characteristic riverine species.

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6. Middle Vistula River (Poland)

Authors: Marek Giełczewski, Tomasz Okruszko, Zbigniew Popek, Mateusz Stelmaszczyk & Michał Wasilewicz (WULS)

6.1 General characteristics of Vistula river

Vistula is the longest and largest river in Poland, and the second largest in terms of river basins in the catchment area of the Baltic Sea (after Neva). It flows generally from south to north through the mountains and foothills of southern Poland and across the lowland areas of the great North European Plain, ending in a delta estuary that enters the Baltic Sea near the port of Gdańsk (Figure 6.1). Vistula river basin is divided into three major subbasins: the upper, middle and lower. These basins are determined by the major tributaries of the Vistula, ie. the San and the Bug. The Vistula is connected with the Oder drainage area by the Bydgoszcz Channel. Eastward the Narew and Bug rivers and the Dnieper–Bug Channel link it with the vast inland waterway systems of Belarus, Ukraine, and Russia.

Figure 6.1. Vistula River watershed in Poland, Ukraine and Belarus.

The source of the Vistula is found about 24 kilometers south of Bielsko-Biała, on the western slope of Barania Góra in the Silesian Beskids (western part of Carpathian Mountains) were the river is formed from two sources: White Little Vistula (Biała Wisełka) at an altitude of 1,080 m and the Black Little Vistula (Czarna Wisełka) at an altitude of 1107 m. The length of the Vistula River from source of Black Little Vistula to the mouth is about 1048 km, and from White Little Vistula about 1045 km. Vistula basin area is 194.7 thousand km^2 (in Poland 168.7 thousand km^2). The average altitude of the Vistula basin is 270 metres above sea level. In addition, the majority of river basin (55%) is located at heights of 100 to 200 m above sea level, and over 3/4 of the river basin ranges from 100 to 300 metres. The highest point of the river basin lies at 2655 metres (Gerlach Peak in the Tatra mountains).

One of the features of the river basin of the Vistula is its asymmetry—in great measure resulting from the tilting direction of the Central-European Lowland toward the north-west, the direction of the flow of glacial waters, as well as considerable predisposition of its older base. The asymmetry of the river basin (right-hand to left-hand side) is 73–27%.

The average discharge measured at the mouth of the river equals of 1951-1990 m^3/s, in the lower basin 1090 m^3/s, in the middle basin of 449 m^3/s. The average width of the riverbed of the Vistula River in Ustroń (headwaters) does not exceed 40 meters, 80-150 m in Krakow, 200-300 m in Tarnobrzeg, 500-800 m in Dęblin, and 700-900 m in Warsaw. The Vistula channel slope is gentle, average slope equals 1.01 ‰, generally slope depends on the river reach and is in a range of 0.4 to tens ‰.

Vistula River basin is located in the impact area of continental and oceanic forces that shape climate. Over the Polish territory three air masses meet: polar, arctic and tropic air. These masses depending on the humidity, temperature and age in a specific way affect shaping of the weather. Generally, the area is dominated by maritime polar air mass with a significant influence of continental polar air. The highest annual sums of precipitation in the Vistula basin are present in mountain areas, where locally exceed 1100 mm, the lowest annual rainfall is observed on the river reach from the Bug river junction with Vistula to the Płock city, not exceeding 500 mm. Most of the basin is characterized by annual precipitation in the range of 500-700 mm. The lowest average annual air temperature on the Vistula River basin are observed in mountainous area, locally even below 5°C. Generally, the basin is dominated by the average annual air temperature in the range of 7-9°C. The average annual minimum temperatures in the Vistula basin are at a level of -12 to -10°C. The average annual maximum temperatures are at the level of 25 to 28°C.

At present the land use in the Vistula basin is characterized by: 48.8% arable land, 26.4% forest, 15.7% grassland, 1.4% orchards and 7.7% other categories. The Vistula basin is populated by 22 million peoples, about 60% of whom are concentrated in urbanized agglomerations. The rest are farmers.

The Vistula case study reach (beginning at Warsaw, 488 km of river – to Płock city, 632 km)

Case study reach is located between 488 kilometerof river located in the vicinity of Warsaw, and a 632 kilometer located in the vicinity of Płock (Fig. 6.1). This 144 km long reach is located in the Toruń-Eberswalde Urstromtal, with an average width of 20 km. This section covers the lower subbasin of the Vistula River, from the mouth of Narew to Włocławek Reservoir, which is reservoir of dam in Włoclawek. The most important watercourses affecting the Vistula in case study reach are the right bank tributaries: Narew and Skrwa, and left bank Bzura. It is estimated that the Narew brings to the Vistula River about 328 m^3/s of water, and Bzura approximately 25.5 m^3/s.

In terms of physiographic area is located in two basins: Warsaw and Płock. Warsaw Basin is the lowest part of the Central Mazovian Plain area with an average elevation of about 68 m above sea level, which is an extension of the Vistula river valley near the Narew junction area. The surface of this area is approximately 1716 km^2. Warsaw Basin turns in Płock Basin forming part of Toruń-Eberswalde Urstromtal of an area of approximately 850 km^2.

One of the water gauges located on the the Vistula River is "Warsaw-Port" water gauge located in Warsaw on 513.3 km of river were Vistula is 300 wide and catchment area equals 84,696 km^2. Altitude of the base of water gauge is located on 76.08 m a.s.l., and equals the minimum water level 56 cm. Lowest observed water level on this water gauge is 68 cm (min. observed discharge – 68,2m^3/s), the highest water level equal to 780 cm (max. discharge – 5860 m^3/s), and the mean water level from multi-year period (19921-2002) equals 235 cm (mean discharge – 536 m^3/s) (Figure 6.2).

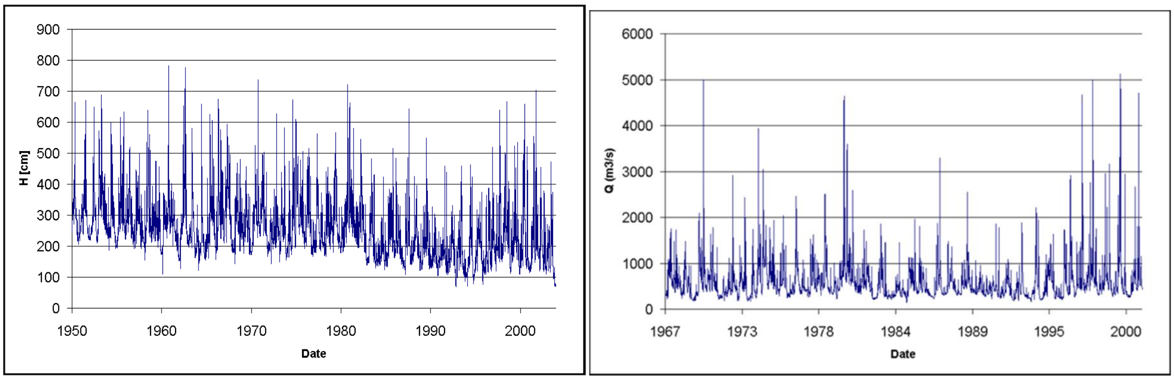

Fig. 6.2. Water level (left figure) and discharge (right figure) of Vistula River as observed at the water gauge Warsaw for the period 1950-2002.

Case study reach of the Vistula is under the influence of two flood protection reservoirs, they are: Zegrze Reservoir (Zegrze Lake) located just north of Warsaw, on the lower course of the Narew river and Włocławek Reservoir located on the Vistula River in the vicinity of Płock. Zegrze Reservoir has a total capacity of 94.3 million m^3 and an area of approximately 30 km^2. Włocławek Reservoir has a total capacity of 408 million m^3 and a surface area of 70.4 km^2.

Case study reach of the Vistula is strongly linked to neighboring regions, surrounded by uphill areas with highly developed urban centers, where low forest cover is present simultaneously with a high proportion on agricultural land, with lead to intensified runoff from adjacent areas to the Vistula River. On the other hand, this area relatively biodiverse with valuable nature elements is an essential part of the ecological network, as a kind of biological reservoir increasing stability of ecosystems located in the neighboring areas.

6.2 Historical background

General characteristics of the riverbed morphology

The Middle Vistula River has the nature of a braided river, where permanent islands and temporarily occurring sandy fluvial deposits divide the riverbed into river branches (Figure 6.3). The main current of a braided river is sinuous and frequently changes its location (Figure 6.4). The bed morphology of a braided river is determined by the absence of stable flow throughout a hydrological year as well as by the intense bed load transport. According to Schumm (1971), the main factor determining the development of a braided river is the share of the bed load higher than 11% in the total volume of the sediment, i.e. the suspended load and the bed load. According to the research conducted by Skibinski (1994), the Vistula River in Warsaw carries on average approximately 500,000 m^3 of bed load a year, which constitutes approximately 35% of the total load volume carried by the Vistula River in this cross-section.

During high flows the transport capacity of the river increases, which results in the severe riverbed erosion. During mean and low flows, which prevail in a hydrological year, the transport capacity of the river decreases, which causes intense deposition of the carried material in the form of channel bars and point bars. These bars can move downstream or occupy a permanent location for a longer time.

A natural factor that significantly influences the riverbed morphology is the geology of the channel zone, in particular when on the riverbed or right under the riverbed there occur contemporary depositional structures composed of the erosion-resistant material: Pleistocene silty deposits, glacial tills, residual pavements made up of gravel, pebbles and boulders (Falkowski 2006). The sections of the riverbed upstream from the residual lags are the zones of intense sedimentation and the sections downstream from them are the zones of erosion.

Figure 6.3. Typical morphology of braided river (left side - Halcrow 2013)

Among the anthropogenic factors that are critical in the development of the riverbed morphology are flood embankments and river regulation works. The valley of the Vistula River is protected by the flood embankments on the almost entire analyzed distance. The only exceptions are the sections of the Vistula River in the center of Warsaw and in the vicinity of Wyszogrod, where the present-day riverbed runs along the banks of the terrace composed of erosion-resistant material, mainly Quaternary glacial tills (Starkel et al. 2007).

The regulation structures on the analyzed section of the Vistula River occur only locally and comprise short sections of the river. Frequently, the regulatory works have been done on one bank only (one-sided regulation) or there have been erected single regulation structures. The only exception is the section of the river in the City of Warsaw, where a complete, two-sided riverbed regulation has been conducted over the distance of 20 kilometers (km 501.5 – 521.5). The remaining part of the riverbed maintains a natural character as the river training works conducted locally have not been very extensive and thus have had only negligible influence on the bed morphology of the braided river. The sections of the river where some regulation structures were developed in the past but have since become destroyed can be considered natural as well. The present condition of the riverbed in these sections of the river and the pattern of the riverbed processes are the evidence of the river self-restoration.

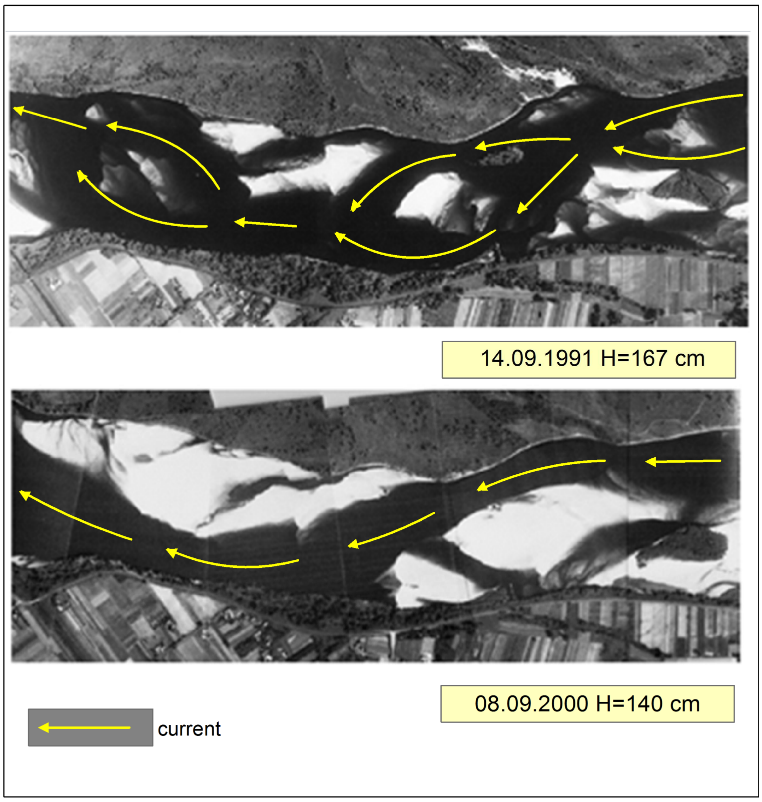

Figure 6.4. Changes of the riverbed sandy forms configuration upstream Warsaw on the Vistula River nature reserve "Wyspy Swiderskie" section in km 491-495, modified (Dobrowolski and Glowacka 2002).

The morphological changes of the riverbed in the 19th and 20th century

An analysis of morphological changes of the channel planform which have occurred during the last 200 years has been carried out on the section from Warsaw (512 km) to Plock (632 km). For the investigations a digital map was used developed using ArcView programme on the basis of 4 archival topographic maps from 19th and 20th century: 2 maps elaborated in the 19th century and 2 maps in 20th century (Kowalska 2001, Zelazo et al. 2002). The oldest map was issued in black-white coloring and in the scale of 1:126000 in 1839. The next map in 3 colours, in the scale of 1:84000 was created on the basis of area surveys conducted in the years 1887-1903. The maps created in 20th century are presented in full color and scale of 1:100 000. For the needs of the analysis there were used map sheets issued in the years of 1924 – 1925 and 1932 – 1934, and also contemporary maps prepared in the 80s. The availability of maps, technical state of the sheets and accuracy of topographic projection were taken into consideration in the selection process.

Registered maps were used for creation of different layers corresponding to specified topographic and environmental objects (Table 6.1).

The analysis of the digital map indicates changes in planform of the river as well as in management of the river valley during last 200 years. Table 6.2 there presents plant cover of the valley surface. There is a characteristic decline in forests area till the beginning of the 20th century and significant increase in this area in the second half of the 20th century. There is also noticeable decline in brushwood area and simultaneous increase in the area of meadows.

Construction of the embankments (Table 6.2) was an essential factor changing the plant cover of the area. The embankments allowed for transformation of areas previously flooded and covered with brushwood and riparian forests into agricultural land. It can be assumed that the changes in management of the valley also influenced changes in its retaining capacity and conditions of flow of high waters, and at the same time had influence on the shaping of the Vistula riverbed.

Table 6.3 presents areas of the Vistula riverbed and islands as well as the length of the embankments in particular periods. Changes in the area of the riverbed achieve +/- 5 – 10% but a distinct trend of these changes is not noticeable. More significant differences occurred in the total area of islands. A very large area (about 25% of the riverbed area) was covered by islands at the beginning of the 19th century. During the next periods the area of islands decreased significantly only to increase distinctly at the end of the 20th century. It can be explained by the influence of the embankments (the end of the 19th century and the beginning of the 20th century) and of river training works carried out in order to improve navigation conditions. The increase in the area of islands at the end of the 20th century is probably the effect of the increase in the sediment transport from upstream situated, regulated and eroded, section of the Vistula River in the region of Warsaw, and also the result of limitation of regulation and maintenance works. The area of islands at the end of the 20th century achieved 25% of the area of the bed, that is it approached the state from before 200 years.

Special attention should be paid to a distinct change in the proportion of the area of overgrown islands (bushes and trees) to sandy islands (Table 6.3). Sandy islands, are considered places of great importance for rare species of birds, and they are subject of special care by nature scientists. At the beginning of the 19th century sandy islands constituted over 56% of the total area of islands and at the end of the 20th century it was only 7.7%. The reasons for such radical changes can be sought in the change of the regime of water flows including the decrease in the frequency and size of floods in the 20th century resulting from the construction of the embankments. Other factors include the influence of the regulation developments on the stability of mobile sandy outwashes and of the closing of side ramifications of the bed, which stimulated better conditions for natural succession of flora.

The detailed analysis of planform of the Vistula River channel on maps from various periods indicates a big dynamics of hydromorphological processes. Changes in planform of the riverbed and of islands occur in the whole analyzed section. However, the art of these changes and their extent is differentiated along the run of the river and to a large degree is connected with the regulation works conducted. Here it can be distinguished:

- sections on which there was conducted systematic regulation of the river – two-sided development of the banks with river training structures, obtaining a constant width of the bed in this way,
- sections on which there were conducted local regulation works, for example closings of river arms, revetments of banks, one-sided systems of groins or longitudinal dikes,
- sections on which there were not conducted regulation works in the riverbed.

An example of a wholly regulated section is the fragment of the Vistula within the boundaries of Warsaw and areas downstream from the city. Figure 6.5 shows the section Zeran – Boza Wola, on which systematic regulation was carried out to the city of Jablonna. In the 19th century the bed on this section was characterized by differentiated line of banks and occurrence of many islands (Figure 6.5 a and b). As a result of regulation works carried out at the beginning of 20th century the shape of the bed was unified and islands were removed (Figure 6.5 c). However, at the end of the 20th century a greater differentiation of the riverbed on the section regulated earlier can be seen again (Figure 6.5 d). The reason for the reconstruction of the riverbed morphology is the limitation or discontinuation of the maintenance works of river training structures.

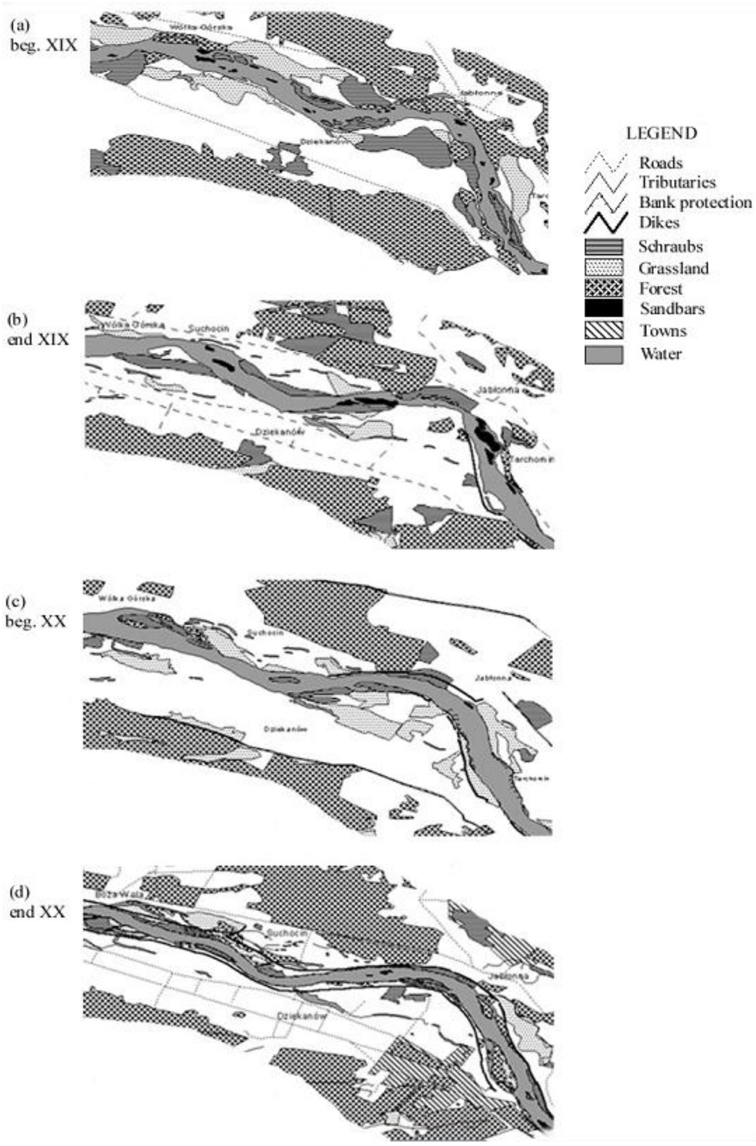

Figure 6.5. Changes in the Vistula riverbed on the reach Zeran – Boza Wola (km 525-545) in XIX (a,b) and XX (c,d) centuries (Zelazo et al. 2002).

On sections where local regulation works were executed on one bank the riverbed is characterized by significantly greater irregularity and occurrence of sandy outwashes and stable islands (Figure 6.6). Conditions of water flow and navigation here are less advantageous than on regulated sections. However, thanks to numerous bed structures and irregularities of banks a large differentiation of abiotic conditions has been created, which influences high natural values of the river.

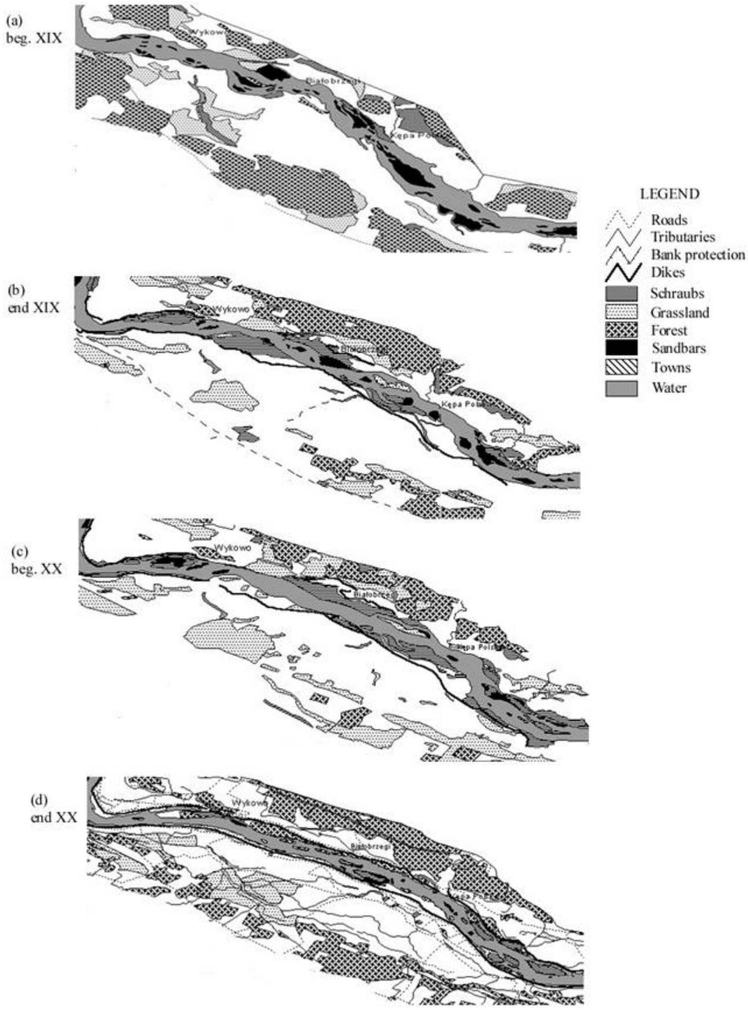

Figure 6.6. Changes in the Vistula riverbed on the reach Rakowo – Kepa Polska (km 598-622) in XIX (a,b) and XX (c,d) centuries (Zelazo et al. 2002)

The morphological changes of the riverbed in Warsaw

Thanks to its beneficial geographical location the Vistula River was for a long time used as a transport waterway. However, for historical, political and economic reasons, while other large European rivers – the Oder, Elbe and Rein – were being adapted for their role as waterways, the Vistula River was spared such activities. There were only fragmentary protective regulations performed in order to protect the river banks from erosion.

In the Vistula's Warsaw section the present-day riverbed morphology differs from the one characteristic of a braided river to be seen on the map from 1808 (Figure 6.7). In the 19^{th} and 20^{th} centuries the Vistula's riverbed was under powerful anthropogenic impact and was frequently transformed as a result of the river regulation and construction of the flood embankments. The first river training plan of the Vistula River was prepared by engineer Kostanecki in 1873 (Zelazo et al. 1998). In the years 1884 – 1889 regulation works were conducted according to this design in the area of the water intake for the Warsaw waterworks (Figure 6.8).

Figure 6.7. The Vistula riverbed on the map of Warsaw in1808, modified (www.polona.pl).

Figure 6.8. The project of the Vistula River training works made by Kostanecki in 1873, executed by Lindley in 1884 – 1889 as a part of the water supply infrastructure project in Warsaw (Damiecki i in. 2008).

By 1910 the riverbed of the Vistula had been regulated in the section from Wilanow to the Kierbedz Bridge, which is 11.3 km long. The planform of the Vistula that was formed at that time and had the width of the mean-water channel equal to 340 m remained unchanged until the 50s of the 20th century. In the years 1960 – 1970 the planform was significantly corrected and as a consequence the mean-water channel was developed with the system of groins and longitudinal dikes, which resulted in its narrowing by approximately 35% decreasing to the width of 220 m (Figure 6.9, 6.10).

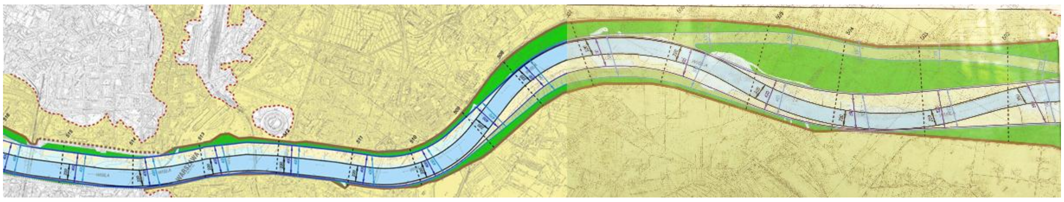

Figure 6.9. The Vistula River training works in project from 1960, executed in the 1970s of the XX century (Damiecki et al. 2008)

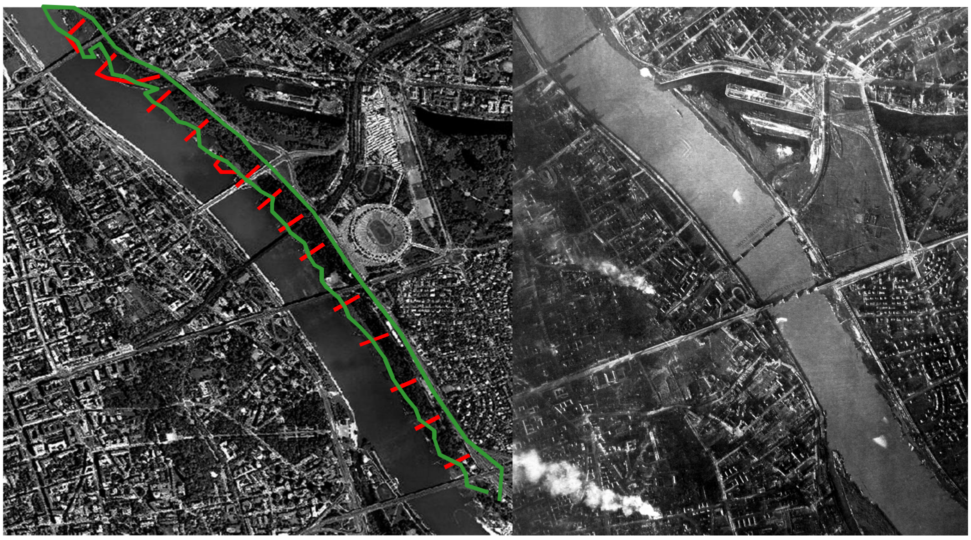

Figure 6.10. Aerial view of the Vistula riverbed in the city of Warsaw: left:in 1944 during the Warsaw Uprising in World War II, right: in 2006: red colour indicate location of goynes, green colour – area of sediment deposition and overgrow by high vegetation (Damiecki et al. 2008).

The flood embankments in Warsaw were constracted in a less systematic way and over a longer period. The first section of the embankments was built on the left side of the Vistula in the area of the center of Warsaw, probably in the mid-19th century. In the following years of the 19th century until the 70s of the 20th century the length of the embankments within the city borders increased steadily. The present-day space between the embankments in the Warsaw section of the Vistula (km 501 – 521) is shown in the Figure 6.11, where it is visible how the high-water channel gets narrowed from 1500 m upstream from Warsaw (km 501) to the mere 470-480 m in km 510-514, i.e. at the city center section of the Vistula River.

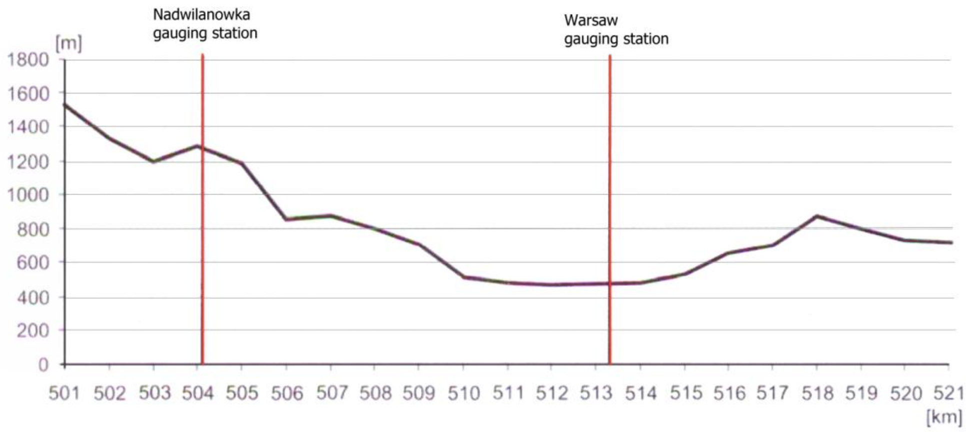

Figure 6.11. The flood channel width limited by embankment on the Vistula River reach near Warsaw (Magnuszewski 2013)

Short-term morphological changes of the Vistula riverbed

Based on the analysis of archival material from 1972-2009, a characteristic of riverbed changes was obtained for the Vistula riverbed of about 33 km long, located between Czerwinsk (km 576) and Kepa Polska (km 609) (Popek and Wasilewicz 2015). For the investigations archival cartographic materials were used from 1972 -1992 (three topographic maps), as well as a digital situation-elevation map from 2003 and orthophotomap from 2009. A total of 34 profiles were determined in the examined section of the Vistula River. The following morphological parameters of the riverbed were analyzed: width, length, and location of the riverbanks, abundance and area of islands, as well as their percentage in the total riverbed area. The data also allowed to calculate geometric centers of islands (gravity centers), which have been generated automatically in ArcGIS software by the function of converting polygons to point objects.

The average width of the Vistula riverbed within the studied section was the biggest in 1972-1974 and was around 1130 m (Table 6.4). In the following years, the average width decreased to about 1116 m in 1992. Floods in 1997-2001 caused an increase in the average riverbed width by 2 m in 2003. The riverbed width were reduced again up to 1094 m in 2009. It was affected by the accumulation of material near the riverbanks, which resulted in a part of point bars and islands merging with the banks thereby creating a cutoff side of riverbed.

Table 6.1. Specification of layers of the digital map (Kowalska 2001)

No.	Description of layer	Year of elaboration of map			
		Beginning of 19th cent.	End of 19th cent.	Beginning of 20th cent.	End of 20th cent
1	Planform of river bed	+	+	+	+
2	Islands in the river	+	+	+	+
3	Tributaries	+	+	+	+
4	Valley lakes	+	+	+	+
5	Bank protections		+	+	+
6	Embankments		+	+	+
7	Navigation havens		+	+	+
8	Forests	+	+	+	+
9	Meadows	+	+	+	+
10	Brushwood	+	+	+	+
11	Parks and coppices				+
12	Main roads	+	+	+	+
13	Bridges	+	+	+	+
14	Railway lines	+	+	+	+
15	Electricity supply lines				+
16	Navigation lines				+
17	Canoe routes				+
18	Water-gauging stations				+

The effect of accumulation process and erosion on changes in the riverbed morphology is also visible in the length of the riverbanks (Table 6.5). The outline of the riverbanks of the test section varied significantly in 1972, there were numerous bays and embankment fluvial deposits. This is reflected in the length of the riverbanks, which for the left bank was then the longest and amounted to about 40 km, while at the same time, the right bank was shorter by almost 3 km. In 1982 both banks of the river were shortened. Changing the length of the right bank (by approximately 1.3 km) was caused by the disappearance of two river branches. In the following period (1982-2003), there was generally a gradual increase in the length of both banks. In the next period the accumulated material buried narrow river branches causing the merging of numerous coastal islands with the left bank thus in 2009 its length was decreased up to 36.6 km. The right bank of the river was 37.3 km long, so its length was almost the same as in the early 70s of the 20th century.

Table 6.2. Percentage share of types of vegetation mantle in covering of valley surface (Zelazo et al. 2002).

Type of vegetation mantle	Share in valley surface (in %) in various periods			
	Beginning of 19th century	End of 19th century	Beginning of 20th century	End of 20th century
Forests	38,7	22,0	18,5	29,2
Meadows	11,5	14,3	19,4	12,7
Brushwood	6,8	4,3	2,7	2,5

Table 6.3. Basic morphological characteristics of analysed reach (Zelazo et al. 2002).

Art of map	Area of river bed	Area of islands		Overgrown islands	Sandy islands	Embankments [km]	
	[km^2]	[km^2]	[%]	[%]	[%]	Left bank	Right bank
Beginning of 19th century	100,4	24,7	24,6	43,8	56,2	-	-
End of 19th century	95,3	16,3	17,1	55,6	44,4	42,3	9,3
Beginning of 20th century	106,0	15,5	14,6	80,3	19,7	56,2	25,3
End of 20th century	98,9	24,1	24,4	92,3	7,7	102,4	75,0

The analyzed section of the Vistula River is characterized by the presence of a large number of islands and fixed fluvial deposits (Table 6.6). In 1974 there were 106 islands of the total area of 14 km^2, which accounted for approximately 39.2% of the main riverbed area. In 1982 and 1992, there was a smaller number of deposit forms in the Vistula riverbed and their area, as compared to 1974, decreased to an average of about 11.9 km^2 in 1992. The percentage of the channel bars area in both these years was more or less similar and averaged about 35 % of the total riverbed area. In the years 2003-2009, an increase in the number of islands up to 147 and their area to 12.1 km^2, was observed. The space occupied by persistent islands accounted for 36% of the Vistula riverbed in 2009.

Table 6.4. The water stages at Wyszogrod gauge station during realization of cartographic materials and results of analysis of the riverbed average width's changes on the Vistula River reach Czerwinsk - Kepa Polska (Popek & Wasilewicz 2015).

Year	Water stage (cm)	Average riverbed width in 34 transverse profiles (m) in the given year	Changes in following period
1974	240	1129	-
1982	245	1119	-10
1992	245	1116	-3
2003	247	1118	2
2009	250	1094	-24

Table 6.5. Length of the riverbanks on the Vistula River reach Czerwinsk - Kepa Polska (Popek & Wasilewicz 2015).

Year	Length of the riverbanks (km)		Changes of riverbanks length's in the following period (km)	
	Left bank	Right bank	Left bank	Right bank
1974	40.0	37.1	-	-
1982	35.5	35.8	-4.5	-1.3
1992	38.1	36.8	2.6	1.0
2003	37.4	38.2	-0.7	1.4
2009	36.6	37.3	-0.8	-0.9

Table 6.6. Number of islands, their area and percentage portion in total riverbed area on the Vistula River reach Czerwinsk - Kepa Polska (Popek & Wasilewicz 2015)

Year	Number of islands	Islands area (km^2)	Total riverbed area (km^2)	Portion of islands in riverbed area (%)
1974	106	14.01	35.75	39.2
1982	84	12.11	34.68	34.9
1992	86	11.86	34.31	34.6
2003	124	9.87	34.48	28.6
2009	147	12.11	33.86	35.8

Interesting observations relate to changes in the position of islands within the Vistula riverbed. Two island types can be distinguished: permanent islands with high vegetation as well as sandy fluvial deposits. These structures differ significantly in their change of shapes and rate of movement in the riverbed. Research carried out by other authors (Babinski 1992, Dobrowolski & Glowacka 2002) indicate that sandy channel bars move at a rate dependent on hydrological conditions. In the case of increasing flow by approximately 30% (about 1 m upstream from the mean water level), more than twofold increase in the movement rate of the channel bars head from about 0.7-1.0 $m \cdot day^{-1}$ to more than 2.0 $m \cdot day^{-1}$, occurs (Babinski 1992). Channel bars are more stable structures. The majority of stable islands analyzed in details have been present at least for 200 years. This can be seen when comparing the old cartographic materials such as the map from 1888 (Figure 6.12).

The example of shape end gravity center of islands changes in period 1974-2009 is shown on Figure 6.13. On the Vistula River section in km 596-602 there are three stable islands: Kepa Stobieckiego, Kepa Suchodolska and Kepa Antoninska. The largest island Kepa Antoninska had its area reduced from 0.74 km^2 to 0.56 km^2 in 35-year period. The geometric center of the island was slightly shifted by 34 m in the direction of the main stream of the river. Two smaller islands located at the height of Kepa Antoninska head in the left part of the Vistula riverbed, significantly increased their surface in 1974-2009, and their geometric centers were shifted respectively by 135 and 200 m upstream. In the case of Kepa Suchodolska there were no observed significant changes of the island area but the geometric center was shifted by 68 m to the left river bank direction. Kepa Suchodolska island was characterized by the greatest stability - within 35 years its area decreased only by about 4% and the geometric center was moved by 19 m.

Figure 6.12. The Vistula River section between Wyszogrod and Zakrzewo in 1880 on "The new topographic map of west Russia in scale 1:84 000" - sheet XXII-7

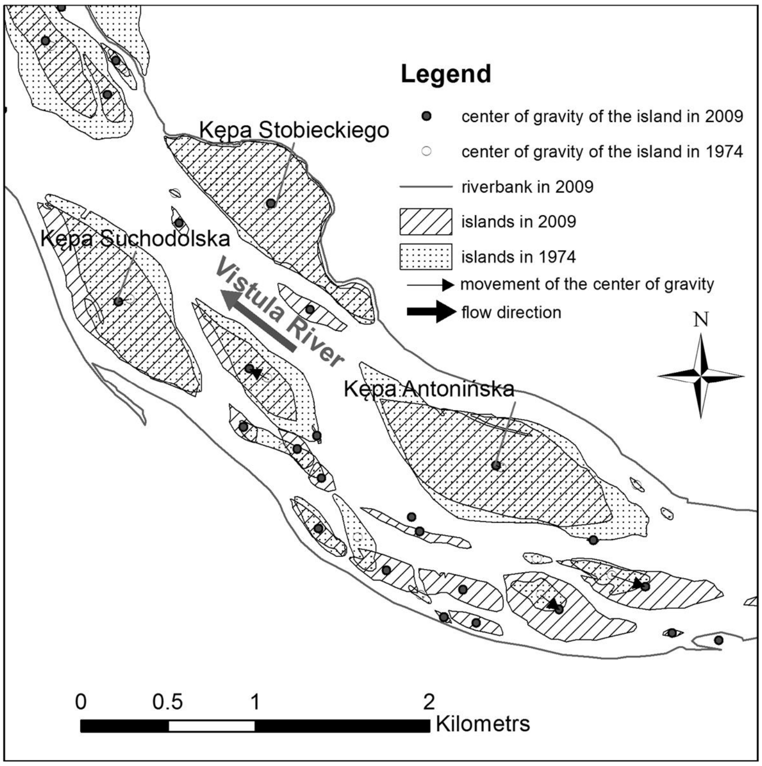

Figure 6.13. Changes of shape and gravity centre of islands on the Vistula River reach km 596-602 (Popek and Wasilewicz 2014)

6.3 *Drivers: socio economic functions / activities*

Source of water

The Vistula River is the main source of water for purposes of exploitation of Warsaw water supply network via central water treatment plants as well as for industrial purposes. Water drown from the Vistula River covers ca. 70% of demand for water by the city, which total volume in 2013 amounted to ca. 104 million $m^3 \cdot y^{-1}$. Besides this for industrial purposes from plant's own intake was drown 170 million $m^3 \cdot y^{-1}$ (Environment 2014).

Water for municipal purposes is drown from the Vistula River by infiltration intakes provided with wells and drains located in alluvial layer under the bottom of the river, whose total length equals almost 10 km. Out of the seven infiltration intakes of the Vistula waters, two on-shore intakes are located on the right bank of the river and four – on the left bank. The main seventh intake – called "Fat Kate" – is located in the river's current (Figure 6.14). Each of the on-shore intakes is equipped with 6-8 drains. The "Fat Kate" is the biggest infiltration well in Europe, water is drown here via 15 drains, 100-180 m long each, spaced radially under bottom of the Vistula River.

Figure 6.14. View of the „Fat Kate" water intake (www.mpwik.pl/o-firmie/galeria, access: 03.07.2015)

Sewage receiver of treated wastewater

Municipal and industrial treated wastewater discharged into the Vistula River in Warsaw reached in 2013 the total volume ca. 107 million $m^3 \cdot y^{-1}$ (Environment 2014). In this volume ca. 100 million $m^3 \cdot y^{-1}$ of wastewater was treated with increased biogenic substance removal.

Two municipal sewage treatment plants are located in Warsaw. The biggest one – called "Czajka" – may treat daily up to 435 thousand $m^3 \cdot d^{-1}$ of wastewater, and another – called "Poludnie" – up to 110 thousand $m^3 \cdot d^{-1}$ (www.mpwik.pl, access: 07.07.2015). In both sewage treatment plants are used very modern technologies which satisfied the quality criteria for wastewater discharged into surface waters, defined in the Regulation of the Minister of Environment.

Waterway

The most important significance of the Vistula River as a waterway for the transportation of bulk goods occurred during the period from the fourteenth to the end of the eighteenth century (Mielczarski 1982). The Vistula River together with a network of tributaries combined center and south of the country with Gdansk - the principal Polish seaport at that time. For the "golden age" of the Vistula waterway is considered to run a period of about 300 years (1466-1772), in which the Polish Kingdom took complete control of the Vistula river mouth in Gdansk. The largest amounts of goods transporting by water to Gdansk were recorded at the end of the sixteenth century and early seventeenth century. This was mainly grain and other agricultural products, potash, ship timber and tar. At that time Gdansk was the main source of supply of Western Europe in these products, and Poland was described as "the fertile granary of Europe and provider of marine construction materials". Vistula was then the most important inland waterway in the world. The number of transports, which was reported on the river during that period, was recorded on the Rhine two centuries later.

Intensive water transport has contributed to the growth of many cities located on the Vistula river, including, i.e. Warsaw, which became an important center of trade and transshipment.

The collapse of the Polish Kingdom caused that the Vistula in the late eighteenth century was part of the three occupying countries: Upper Vistula had belonged to Austria, Middle Vistula to Russia and Lower Vistula to Prussia. These countries were not interested in economic development in the area of former Poland, which caused decreasing of importance of the Vistula as a waterway. The difficult conditions of navigation in the natural riverbed of Vistula has contributed to it as well. After the innovation of mechanical drive of ships it has become necessary, as in many rivers in Europe to carry out systematic river training works over the entire length of the river. That had not happened, so the Middle Vistula River still has the character of a natural braided river, which significantly limits its importance as a waterway.

Currently, The Middle Vistula is a waterway of regional importance, class IB, with limits for ships: maximum length 41 m, maximum draft 1.4 m, load capacity of 180 tons (www.rzgw.gov.pl, access 07.07.2015). Valid parameters make river practically inaccessible for navigation by freight ships, especially near Warsaw. It is possible only to navigate on small vessels.

Source of sand and gravel

For centuries the Vistula riverbed was a valuable source of good quality sand and gravel, harvested for construction purposes. Exploitation of bed sediments in Warsaw was particularly intense after the end of the World War II during the reconstruction of the city (the left-bank part of the city was destroyed in 84%). In the years 1968-2000 the extraction of sand decreased, although its amount was still high and ranged from approx. 250 to 1 500 thousand m^3 per year (Zelazo et al. 1998, Zelazo & Popek 2000, Zelazinski et al. 2005).

Natural environment

Warsaw is a unique place among European capitals thanks to the nature of Vistula River. The Natura 2000 site "Middle Vistula Valley" (PLB140004) is within the city limits. It is a Special Protection Area for bird, including the section of the Vistula riverbed with the area between the embankments, of 252 km long, situated between the towns of Puławy (km 379) and Plock (km 631) (RDOS 2014)

"Middle Vistula Valley" is a very important refuge for waterfowl, providing breeding sites for 40-50 species of birds, of which 26 species is the subject of the protection of Natura 2000 site. It is the most important breeding ground for common gull (*Larus canus*) and little tern (*Sternula albifrons*) in Poland, and one of the most important for common tern (*Sterna hirundo*). It is nesting place for many rare species of birds such as oystercatcher (*Haematopus ostralegus*) and shoveler (*Spatula clypeata)*. The area is of great importance as a migration corridor of birds – mallards (*Anas platyrhynchos*), common heron (*Ardea cinerea*) and black stork (*Ciconia nigra*), as well as a place of refuge for species of wintering birds – goldeneye (*Bucephala clangula*), mergansers (*Mergus merganser*) and smew (*Mergellus albellus*). An acquired part of the "Middle Vistula Valley" site have been strictly protected in 14 nature reserves in order to maintain the refuge of breeding rare and endangered species of birds.

In the Natura 2000 site "Middle Vistula Valley" there are many valuable habitats for birds, characteristic of the valleys of large natural lowland rivers, of which the most important are:

- sandy islands and channel bars,
- steep banks of the river and permanent islands,
- floodplains of diverse vegetation (grass, willow scrub, riparian forests)
- oxbow lakes and swampy areas.

Many of the Vistula reaches has areas neighbored to the Natura 2000 site for the most part not subject to any forms of nature protection, on which, however, are valuable habitats such as meadows, bogs, alluvial forests and swamps, pine and mixed forests. Especially valuable natural area is Kampinos National Park - a UNESCO World Biosphere Reservation, directly bordering to the Vistula River valley. The area of Park is a home to 16 500 animal species, including 226 under protection and 200 bird varieties, as well as 1 300 plant species.

<u>Recreation</u>

The high natural and landscape values of the Vistula River make it an attractive place for recreation of Warsaw residents and tourists visiting the city. In the summer time there are available regular cruises by ships of Warsaw Tourist Lines. It is possible to enjoy the city's beaches (Figure 6.15), yachting and rowing marinas. On both sides of the river are bike and walking paths, parkland, as well as catering facilities and car parks.

Figure 6.15. City beach in Warsaw (www.nasza-warszawa.pl, access; 07.07.2015)

<u>Flood protection</u>

Floods on the Middle Vistula River are caused by the three types of factors (Niedbala et al. 2012):

- Rain - especially heavy rainfall in the catchment area of Upper Vistula section - as a result flood waves causing the threat of flooding along water courses are formed;

– Thaw - due to snow thawing, often "enhanced" by rainfall, which increases the danger of the flood. These types of floods frequently occur in the basin of the Bug and Narew, These rivers reach the Vistula downstream of Warsaw;

– ice jam - caused inhibition of the runoff and rising up the slush ice in time the river is going to freeze or during the spring thaw when ice floes are flowing. The braided river morphology increases the risk of ice jam flood on the analyzed section of the Vistula river. It happens quite often - especially on the section downstream the Narew tributary (Figure 6.16).

The whole valley of the Vistula River on the analyzed section is protected by embankments, of which the total length is approx. 222 km (Borys 2011). The embankments of the highest class (class I) are located in Warsaw, while on the section outside the city there are embankments of class II.

Figure 6.16. Ice-jam on the Vistula near Płock (04.03.2010) – damaged embankment at km 597

According to Polish regulations (Regulation of the Minister of Environmental Protection, Natural Resources and Forestry, 1996) embankments of Class I must ensure flood protection for the maximal design discharge $Q_{p\ =\ 0.5\%}$ (0.5% probability of occurring = 200-year return flood flow) with a safety margin of 1.3 m and the control discharge $Q_{p\ =\ 0.1\%}$ (1000-year return flood flow) with a safety margin of 0.3 m. Requirements for Class II shafts are as follows: design discharge $Q_{p\ =\ 1\%}$ (100-years flood flow) and headroom 1.0 m, control discharge $Q_{p\ =\ 0.3\%}$ (333-years flood flow) and a safety margin of 0.3 m.

The embankments of Vistula meet requirements above-mentioned, but the bigger problem is their technical condition - in some sections there is a threat to the stability of the embankments during the floods, caused by the low compaction of soil and uncontrolled seepage conditions through or under the embankment. Approximately 31% (69 km) of the embankments along the analyzed section of the Vistula needs to be modernized, including 8 km located in Warsaw (Borys 2011).

Very large potential danger of flooding occurs mainly in Warsaw as a result of the intensive development of the Vistula River valley (KZGW 2015). The area within the 100-year flood flow is estimated to about 125 km^2 (Figure 6.17). During the last high flood in May 2010 (Figure 6.18) in several places of Warsaw (marked on the map – Figure 6.17) were dangerous seepage through or under the embankment, but the flood damages did not happen (Kuźniar 2011). However the flood damages were noticed downstream, in the region of Plock. The left-sided part of the Vistula River valley has been flooded on the surface of approx. 56 km^2 after a breakdown of embankment at km 609 (Figure 6.19).

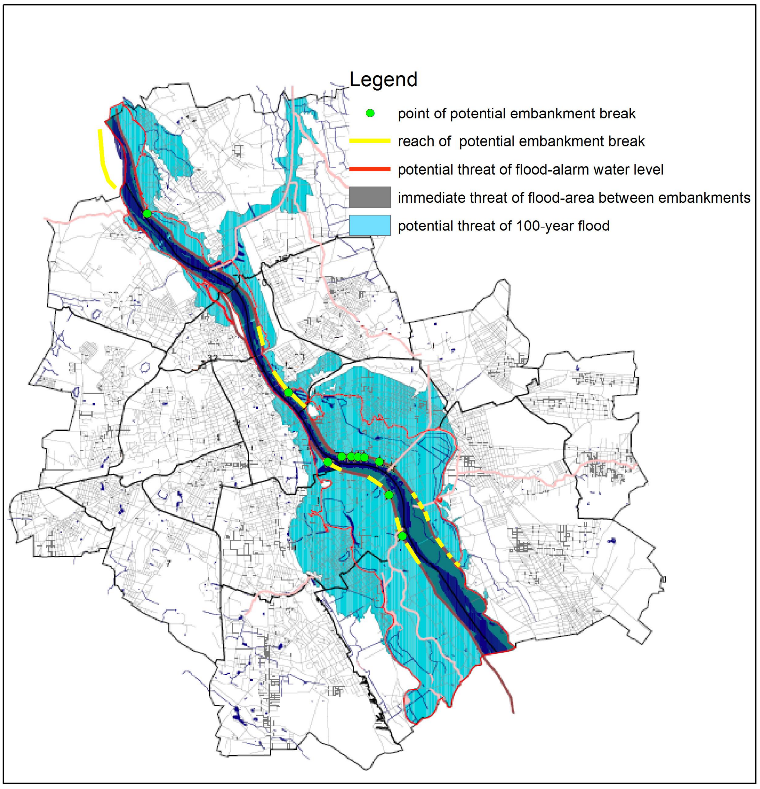

Figure 6.17. Flood risk area on Vistula valley in Warsaw (Eco-physiographic study for Spatial Development Conditions and Directions Study of Warsaw).

Figure 6.18. Views of the Vistula River on 22.05.2010 during the peak water stage 780 cm (21 cm below the stage of 100-year flood): left picture shows view of the „Fat Kate" water intake (km 511), right picture shows the Slasko-Dabrowski Bridge (km 515).

Figure 6.19. Flood in the Vistula valley near Płock in May 2010.

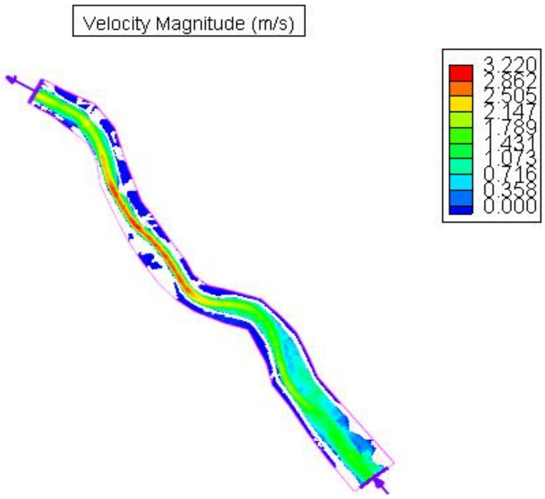

Figure 6.20. Variability of flow velocity during the 100-year flood flow on the Vistula River section in Warsaw – results of CCHE2D hydrodynamic model calculation used for discharge $Q_{p=1\%}$ = 7214 $m^3 \cdot s^{-1}$ (Magnuszewski et al. 2008)

6.1 Current pressures and effects on processes

The biggest changes in the naturalness of the riverbed morphology occur in Warsaw, on the city section of the Vistula River. A high concentrated flow and a significant increase of the current velocity, especially during a flood flows (Figure 6.20), occurred as a result of the narrowing space between the embankments, from 1500 m upstream Warsaw to 470-480 m on the city section (Figure 6.11). In addition, the system of groins and longitudinal dikes has limited a part of riverbed leading the mean and low flows (Figure 6.9, 6.10). In the last 50 years, there has been changed the flow conditions as a result of hydrotechnical constructions. The lowering of the Vistula riverbed has occurred and resulted in decreasing of water levels during low flows for approx. 2 m (Figure 6.21). Paradoxically, the navigation conditions have not been improved by the river control as it was assumed. As a result of the riverbed erosion a natural thresholds (residual lags) composed of the erosion-resistant material were occurred (Figure 6.22), that make shipping at low water levels unavailable (Falkowski 2009, Falkowski & Ostrowski 2012).

Also the excessive dredging of sand and gravel from the Vistula riverbed is mentioned by many authors (Skibinski 1963, Zelazo et al. 1998, Popek & Zelazo 2000, Zelazinski et al. 2006) as an important factor of the bottom erosion (Figure 6.23). It should be emphasized that erosion of the riverbed did not result in an increase of the maximum capacity of the river. The stage - discharge curve (Figure 6.21) in the maximum flow zone has not changed, despite down-cutting, because of the river sediment accumulation process in the spaces between the groynes (Figure 6.24). As a result the cross-section area of the riverbed stayed unchanged. In addition, the increase of flow in the current zone of the river, was also "balanced" by a smaller channel capacity in a flood terrace, caused by increasing of flow resistance after the groynes construction, as well as by high vegetation growth (Figure 6.24).

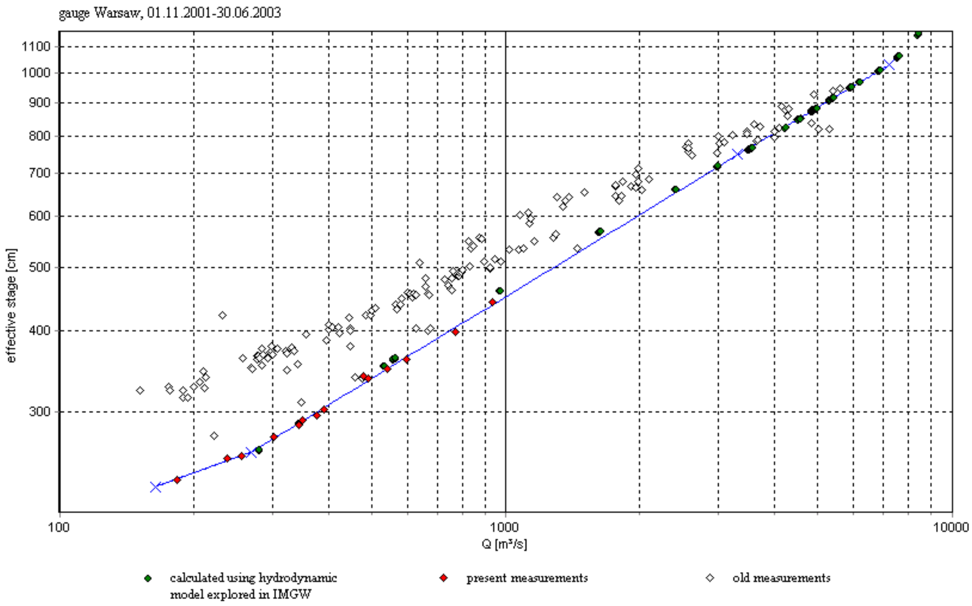

Figure 6.21. Stage - discharge curve for the Warsaw gauge station, located in km 513 (Zelazinski et al. 2005)

Figure 6.22. View of the Vistula riverbed in Warsaw at low water level - partially uncovered the natural thresholds (culminations of alluvia basement) covered by residual gravel and bolders: a) at km 514, b) at km 517.

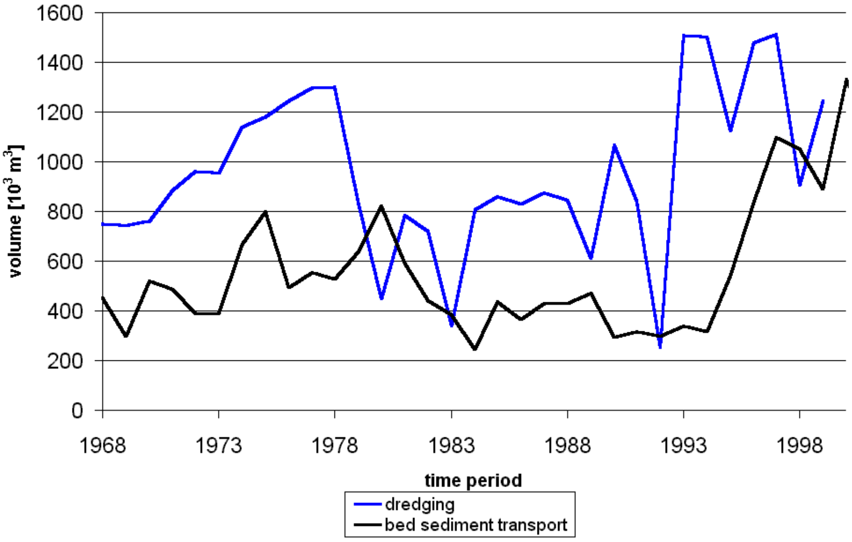

Figure 6.23. Comparison of dredged sand volume with the volume of computed bed-material sediment transport in the Vistula River in period 1968-2000 (Zelazinski et al. 2005)

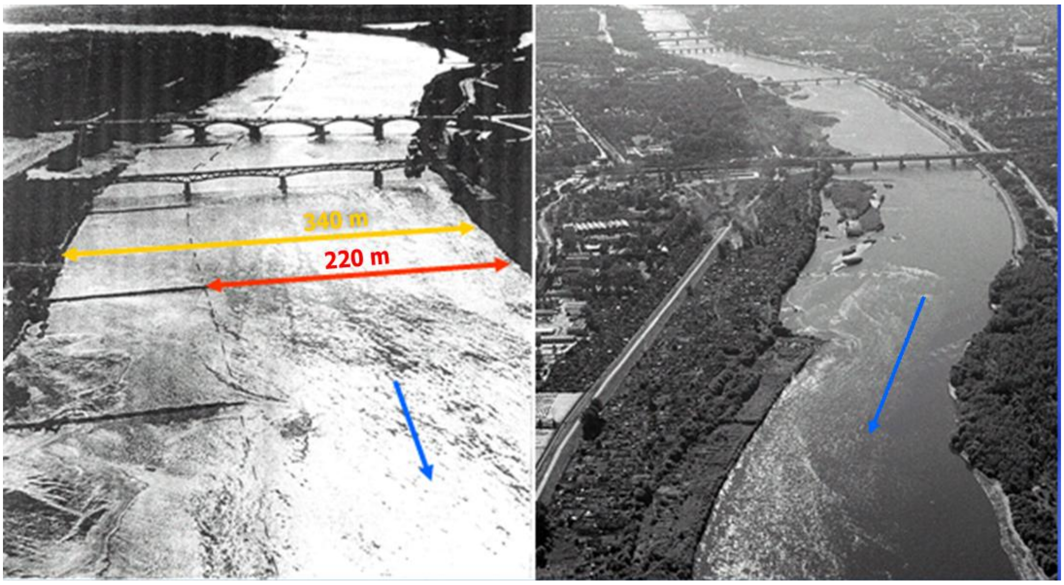

Figure 6.24. River training works in the Vistula riverbed in Warsaw. The left part: Aerial view of the groins system in 1964 - after completion of the project. The right part: Aerial view of the riverbed in 2006 – spaces between groins filled by sediments and covered by high vegetation.

The interesting results of the research should be mentioned here, which aim was to determine the impact of the aforementioned factors on the erosion process of the Vistula riverbed in Warsaw (Zelazinski et al. 2005). Simulations based on daily water levels and flows in the period 1967-2002, observed in the gauging stations (Figure 6.2): Nadwilanowka (km 504) and Warsaw (km 513), as well as data of the sediment volume dredged from the Vistula riverbed in the Warsaw area, The authors noticed the average elevation bottom changes in 152 cross sections, located at a distance of 91 km, i.e. between the mouth of the Pilica tributary (km 458) and the mouth of the Narew tributary (km 549). The one-dimensional hydrodynamic model CCHE1D was used for numerical calculations. The simulation estimated the importance of the narrowing of the channel by river training structures at 30-40% in the bottom erosion process. Sand and gravel dredging, the size of which, as mentioned earlier, significantly exceeded the volume of bed load from upstream the river occurred the main agent - 60-70% of the importance (Figure 6.23).

Riverbed along the rest of the sections retains the braided river with the typical morphological characteristics and their temporal and spatial variability. High naturalness of riverbed is observed also in sections where river training works have a local range or were made 50-60 years ago (Zelazo et al. 1998, Kuzniar et al., 2002). However, not always the naturalness of morphological processes and specific flow conditions shaped by them should be considered as a desirable river attribute, taking into account both the requirements of environmental protection (Popek 2007), as well as economic conditions and the need for flood protection (Magnuszewski 2013).

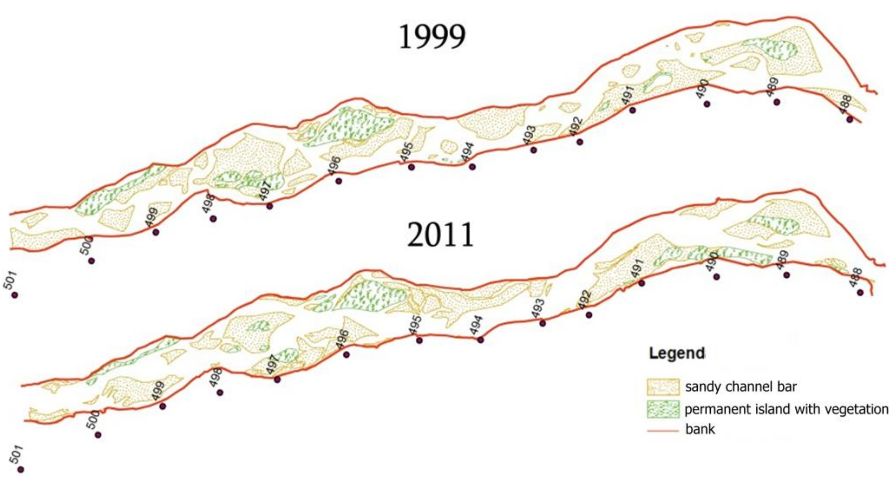

Figure 6.25. Planform of the Vistula riverbed in 1999 and 2011, section of km 488 - 501: area of the nature reserves „Wyspy Swiderskie" and „Wyspy Zawadowskie"

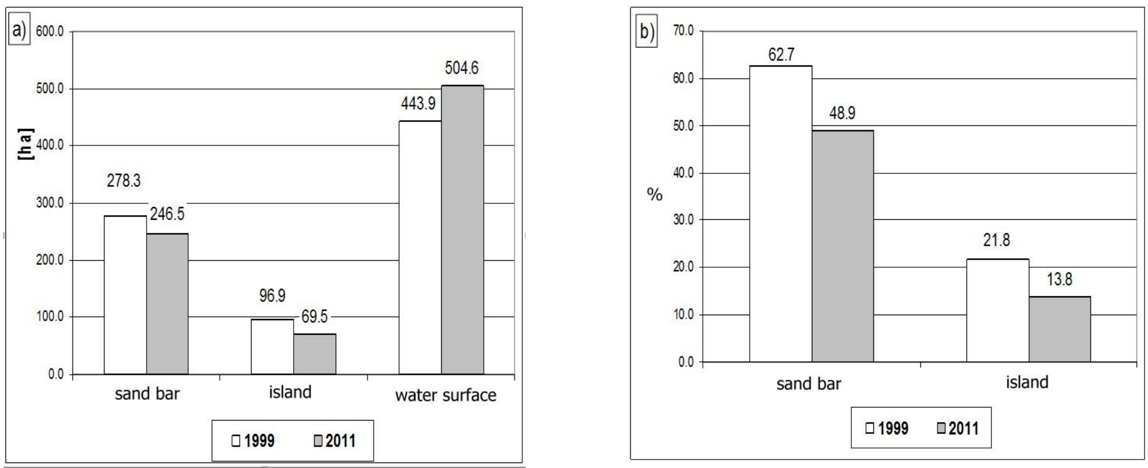

Figure 6.26. Changes of islands and channel bars area in of the Vistula riverbed in 1999 and 2011, section of km 488 - 501: area of the nature reserves „Wyspy Swiderskie" and „Wyspy Zawadowskie": a) area [ha] of permanent islands, channel bars and water surface, b) area of permanent islands and channel bars as the percentage of water surface.

The results of detailed studies carried out on two selected sections of the Vistula River could serve as an example. Both of them are located in the area of nature reserves: at km 488-501 - "Wyspy Swiderskie" and "Wyspy Zawadowskie" and at km 596-602 "Kepa Rakowska" and "Kepa Antoninska" (Popek and Wasilewicz 2013). The goal of protection in these reserves are, i.e. breeding habitats for wader birds or constantly renewing and changing its position sandy channel bars, sticking out the water table during the mean flows or lower. Long lasting periods of low flows causes that sandy channel bars are gradually becoming overgrown and no longer serve as a breeding habitats.

Vistula riverbed in the section of reserves "Wyspy Swiderskie" and "Wyspy Zawadowskie" is completely natural. The planform of the river in 1999 and in 2011 is presented in Figure 6.25, while the results of changes analysis of the surface of sandy channel bars and permanent vegetated islands in Figure 6.26. In 2011, surface of sandy bars was lower by 13.8% than in 1999, which is probably caused in part by the different water levels in time of shooting satellite images.

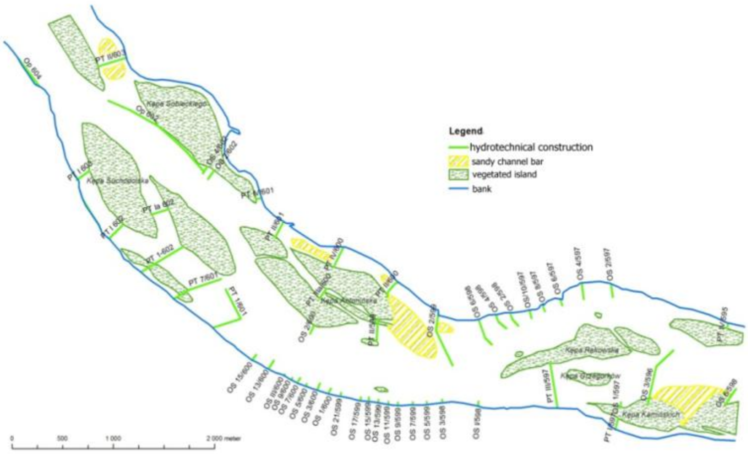

Figure 6.27. Planform of the Vistula riverbed and location of the hydrotechnical constructions in 1961 section of km 596-602: area of the nature reserves „Kepa Rakowska" i „Kepa Antoninska" (Popek et al. 2009)

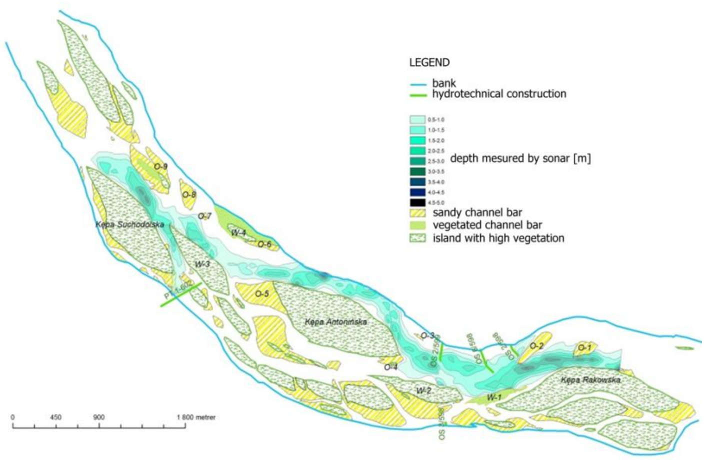

Figure 6.28. Planform of the Vistula riverbed and location of the hydrotechnical constructions in 2009, section of km 596-602: area of the nature reserves „Kepa Rakowska" i „Kepa Antoninska" (Popek et al. 2009)

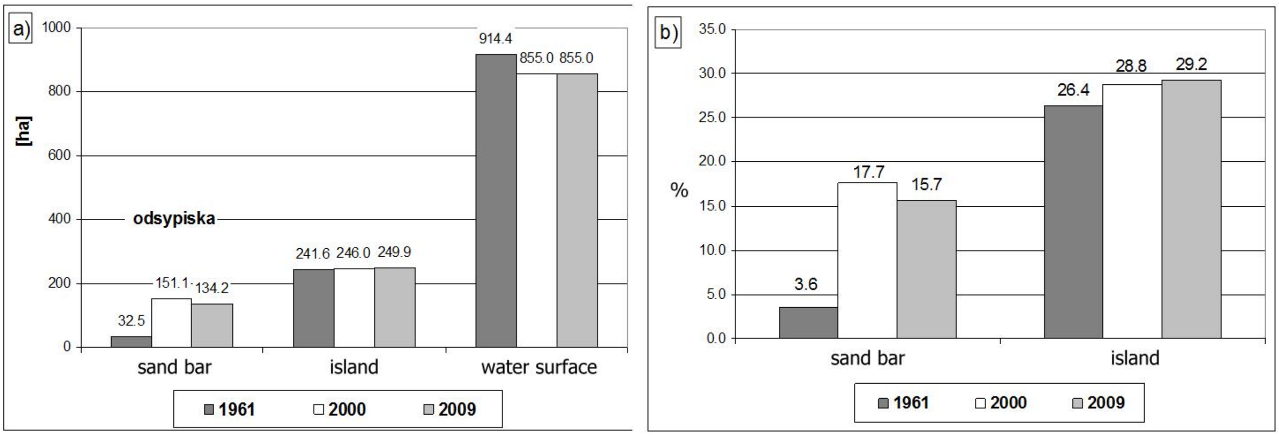

Figure 6.29. Changes of islands and channel bars area in of the Vistula riverbed in 1961, 2000 and 2009, section of km 596-602: area of the nature reserves „Kepa Rakowska" i „Kepa Antoninska" (Popek et al. 2009). a) area [ha] of permanent islands, channel bars and water surface, b) area of permanent islands and channel bars as the percentage of water surface.

A more clear morphological changes of the Vistula riverbed could be found on the river section in the region of reserves "Kepa Rakowska" and "Kepa Antoninska". The river work in this section was done at the beginning of the 60s of the twentieth century. The planform of the riverbed and thelocation of the hydrotechnical structures in 1961 and 2009 is shown in Figure 6.27 and 6.28. Comparing the two figures can be noted that the hydrotechnical structures were almost completely destroyed or filled with sand, causing switching the current to right branch of the Vistula - a much narrower than the left one. The left branch of the river experienced intense accumulation of sand and some newly formed islands has been overgrown. This caused significant changes in the area of sandy bars and permanent islands (Figure 6.29a). In the period of 1961-2009 the sandy bars area increased from 3.6% to 15.7%, and the solid islands area - from 26.4% to 29.2% (Fig. 4.10b). In the shorter term, 2000-2009, with the same surface of the water, sandy bars area decreased by 2%, while the area of vegetated islands increased by 0.4% (Figure 6.29b). The changes observed in the last period should be considered ecologically adverse because if the sandy bars area decreasing – it means that the valuable natural habitats shrinking. Ornithological studies have shown that disappear gradually also other important habitats located on the flood terrace - the surface of open sandy areas decreases as a result of intensive overgrowing (Halcrow 2012).

Excessive overgrowing trough high vegetation and the adverse morphological changes observed in the riverbed of Vistula, affect not only the natural habitats, but also cause deterioration of flood flows conditions and increase the risk of the formation of ice jams and slush ice jam (Brikman et al. 2000 Falkowski & Popek 2000 Grzes 2011). There is a section of the Vistula River from the mouth of Narew River to Plock, where the biggest risk of flood is occurring, as a result of the morphological riverbed condition (KZGW 2015).

As a result of the sediments accumulation and the succession of high vegetation on this section in the last 20-30 years has been observed steadily deterioration of flood flows conditions (Popek & Wasilewicz 2013). The evidence on the effect of the above factors can be found in the observations (Table 6.7) of the Kepa Polska gauging station. This station lies 4.5 km downstream the analyzed section of the Vistula River, in the area of nature reserves "Kepa Rakowska" and "Kepa Antoninska". Data in Table 6.7 show the water level and the corresponding peak flow discharge during the biggest rainfall floods in the period 1980-2010. From this study it can be noticed that in 2001, despite higher by 8 cm water level than in 1980, the peak flow discharge was 1060 $m^3 \cdot s^{-1}$ lower. However, from a comparison of data from 1980 and 2010 it shows that on 10 June 2010, with higher water levels by as much as 50 cm than in 1980, the peak flow discharge was just 320 $m^3 \cdot s^{-1}$ higher than in 1980. It is worth recalling that three weeks earlier, on 23 May 2010 the embankment had been interrupted at km 609, i.e. at the site located just 2.5 km below the gauging station Kepa Polska. After this accident 5600 hectares of agricultural land and 21 villages was flooding in the area of the left side of the Vistula River valley. The risk of flooding on this section of the river valley is very high, if taking into account the fact that the previous flood occurred at the turn of the year 1980/81 - it was a flood caused by a slush ice jam.

Table 6.7. The peak water stages (H_{max}) and discharges (Q_{max}) during the rainfall floods in the gauging station Kępa Polska, km 606.5 (Niedbala et al. 2012)

Date of flood wave peak	H_{max} (cm)	Q_{max} ($m^3 \cdot s^{-1}$)
30.07.1980	610	5520
16.07.1997	562	3920
01.08.2001	618	4460
23.05.2010	739	6965
10.06.2010	660	5840

The examples mentioned above clearly show the need to maintain a proper state of the Vistula riverbed, taking into account both its natural as well as economic functions. This means the necessity of compromise is required to take activity consistent with the idea of sustainable development (Zelazo et al. 1998 Kuzniar et al. 2002, Wierzbicki 2003, Zelazo et a. 2004). It is strongly recommended to tend the high vegetation and to keep the local river training and dredging works in the riverbed to ensure:

- proper capacity of the main channel and the inter-embankment area
- embankments safety,
- infrastructure safety (water intake, sewage, bridges, harbors, ports, etc.)
- the possibility of local navigation needed to maintain river (for river trainig structures renovation, ice breaking, etc.) and recreational navigation,
- protection or restoration of natural and landscape values of the rivers,
- opportunities for tourism and recreation.

6.2 *Effects on ecology of pressures*

Ecological values of the river environment generally increase in proportion to:

- the morphological diversity of the riverbed,
- increasing the width and surface diversion of the inter-embankment space,
- structure and type of vegetation cover.

However, the occurrence of the hydrotechnical structures in the riverbed, the infrastructure facilities and other anthropogenic objects, always limit the natural values of the river (Figure 6.30).

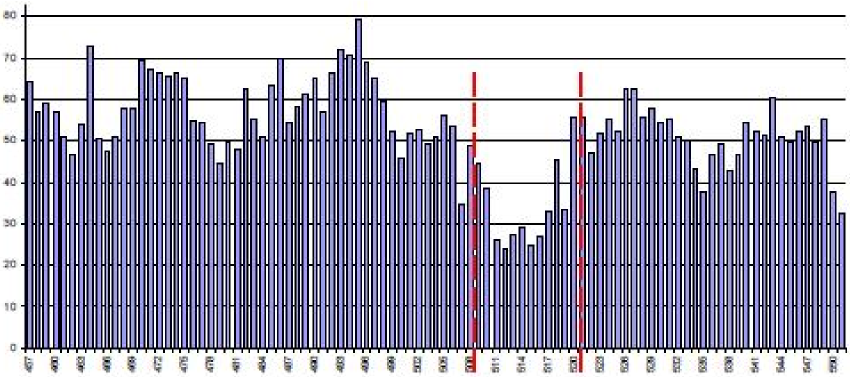

Figure 6.30. Natural valorization of the Vistula River section near Warsaw with marked section in the city center (Matuszkiewicz 1998).

Monitoring of birds occurring in the Warsaw region (km 497-538) in the Natura 2000 site "Middle Vistula Valley" has been a good example of it (Elas 2012). The objects of protection in this area are i.e. species of breeding birds requiring the presence of the sandy channel bars, with no vegetation. The most important for the Natura 2000 site is to protect breeding species of birds, associated with the current of the river: little tern (Sternula albifrons), common tern (Sterna hirundo), common gull (Larus canus) and black-headed gull (Larus ridibndus). Habitat preferences of these species, determined by the spring monitoring of 2012, is shown in Figure 6.31.

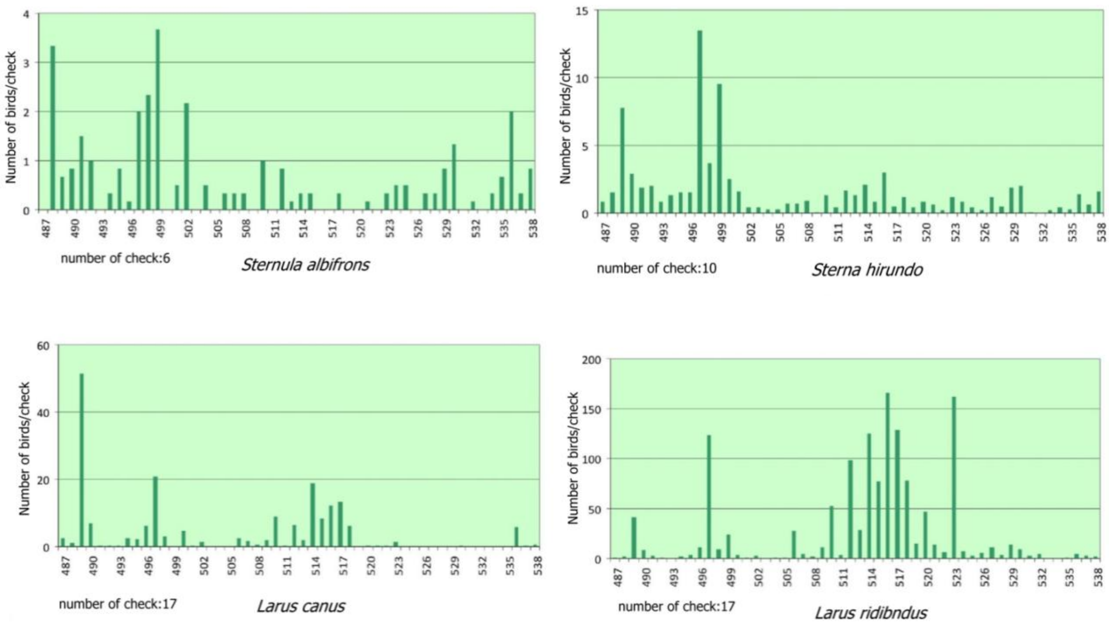

Figure 6.31. Habitat preferences of wader birds species on the section of the Vistula near Warsaw (km 487-538) in the migration season, spring 2012

Looking at this figure, it has been clear that for the most modified section of river (City of Warsaw section in km 511-517) recorded number of birds was generally less than in the sections upstream and downstream the town. The exception is the black-headed gull (Figure 6.31), for which an important place of the feeding are outlets of sewage treatment plants. Other species of birds more prefer section of the Vistula upstream Warsaw, and in particular a part of nature reserves „Wyspy Swiderskie " and "Wyspy Zawadowskie" (km 488-501). However, in the nature reserve "Lawice Kielpinskie", at km 527-538, downstream Warsaw, there has been much less number of observed birds in the spring. In contrast, much worse results were obtained in the case of an inventory of wader birds.

The presence of four breeding colonies revealed in the study area in 2012 - all were located in nature reserves upstream of Warsaw (Table 6.8). The breeding colonies were located in nature reserve "Lawice Kielpinskie" even in the beginning of twenty-first century. However, the overgrowing of islands and the small number of new sandy shoals, led to the complete disappearance of birds from this area a few years ago.

The most numerous breeding species in 2012 was a black-headed gull - in 3 colonies was approx. 500 pairs (Table 6.8). However, the number of breeding pairs was reduced considerably compared to previous years. In the mid-90s of the twentieth century there was a colony of 2500 pairs population located at km 490, and a few years later the same large colony was established at km 497. In the case of the species little tern it was counted 39 breeding pairs. It is also a number less than noticed in 2010 (60 pairs), but comparable with the number of the 1990s. In 2012, it was confirmed the occurrence of a number of 190 pairs of common tern, while the single largest colony in the study area had 180 pairs in 1998. The smallest population number of gray gulls was in 2012 - 56 breeding pairs. In the “Wyspy Zawadowskie” nature reserve it was counted 120 pairs of this species in 2009, and approx. 200 pairs in 1998.

Table 6.8. The number of breeding pairs of birds in selected colonies in 2012 (Elas 2012)

Km of river	Sternula albifrons	Sterna hirundo	Larus canus	Larus ridibundus
490	12	57	44	0
496	1	21	5	44
497	6	19	7	150
500	20	90	0	300

Table 6.9. The number of breeding pairs of birds in 2012 and 2013 on analyzed section of Vistula river, on the whole Natura 2000 reserve „Dolina Środkowej Wisły” and in Poland (Elas 2012)

Species	2012	2013	area of Natura 2000 reserve	Poland
Sternula albifrons	39	44-79	420-539	900
Sterna hirundo	188	142-410	1 400-1 728	4 000-4 500
Larus canus	56	77-95	707-814	2 300-2 600
Larus ridibundus	494	1 080-1 133	10 190-11 195	80 000-90 000

It can be observed an evident increase in the number of breeding birds tested according to the inventory done in 2013 (Table 6.9) About 10-15% share of the breeding birds population present on the entire area of Natura 2000 " Middle Vistula Valley" was observed on the monitored section of the river. This is a significant density, because the breeding is taking place in only 4 habitats, located at a distance of 10 km, which accounts for approx. 4% of the length (252 km is the total length of the river valley considered as the Natura 2000 site).

The types of habitats found in the Vistula valley are related to 11 plant communities (Matuszkiewicz 1999). The most valuable plant communities of it include: *Ficario-Ulmetum* riparian and *Salici-Populetum* riparian, flooded grassland and pastures, riparian herbaceous. The area of the Vistula River valley has been rich with 1013 vascular plants species, of which 433 are present in the inter-embankment area.

6.3 Rehabilitation and mitigation measures

Concept of right river bank management at Warsaw agglomeration – Vistula Nature Park

Conceptual design of the Vistula Nature Park located on the right bank of the river in Warsaw, was developed in 2008 by a team of researchers Warsaw University of Life Sciences under the chairmanship of professor Damiecki (Damiecki et al. 2008). Creating the Vistula Nature Park was expected to achieve the following objectives:

- improving flood safety conditions of the city,
- improving the conditions of conservation, in particular, protected birds in the Natura 2000 site „Middle Vistula Valley"
- providing attractive recreation places,
- improving navigation conditions,
- improving conditions for water sports.

The authors proposed a number of solutions that include the development programs of the Vistula, contained in Warsaw Development Strategy until 2020 (http://bip.warszawa.pl, access: 07/09/2015):

- *Development of the Vistula Valley and usefulness of it for locals and tourists*, highlighting the natural beauty of the Vistula valley in Warsaw and presenting the program of development activities, such as the creation of beaches, swimming pools and shipping services. Specific objectives include:
  - restoration of the old tradition of sailing on the Vistula River,
  - construction the weir on the Vistula River, in the northern part of Warsaw, in order to improve the conditions of navigation, water recreation and the natural environment,
  - building a modern marina for the seasonal passenger ships and support for the revitalization programs of Warsaw ports, harbors and quays.
- *Opening of the city on the Vistula River*, which will result in better use of natural and landscape conditions of the river, including i.e. the use of its banks as a recreational areas with the preservation of the natural vegetation.

Important indications of the Vistula River development are also included in another planning document. "*Study on the commune's land use conditions and directions of the Capital City Warsaw*" (http://bip.warszawa.pl, access: 07/09/2015) indicates the role of the Vistula, as an essential element of the natural system and landscape of Warsaw: "*Vistula with green areas as an example of harmonizing the values of cultural and natural landscape by emphasizing the role of the river in the spatial structure of the city and an attractive riverside development according to the requirements of the environment protection and cultural heritage*".

The variants of the Vistula Nature Park proposed in the conceptual project take into account the need of reducing negative impacts of the riverbed erosion caused mainly by dredging, river training structures, narrow flood flow channel as well as excessive overgrowing of the inter-embankment area. Technical measures should lead to the enlargement of the riverbed and the differentiation of banks, as well as creating the conditions for the formation of islands and sandy bars and shoals. Restoration of the braided character of the riverbed will improve the natural conditions of the river ecosystem, and build up especially the functions of habitat for migratory and breeding birds of the Vistula River section in Warsaw. The city section of the river will start then to connect the areas lying downstream and upstream, which have a much higher nature value. Reconstruction of the riverbed will also allow spontaneous process of creating natural beaches and open the riparian zone of the river for recreation. These actions will increase the attractiveness of the Vistula River for locals, at the same time reduce the recreational pressures on faunal reserves along the Vistula River. In addition, cleaning and maintenance of vegetation in a flood terraces will improve water flow condition and increase the capacity of the riverbed.

Figure 6.32. The Vistula River Park – conception of reconstruction of goyne's system located on right bank of the river between two bridges: Lazienkowski and Poniatowski (Damiecki et al. 2008)

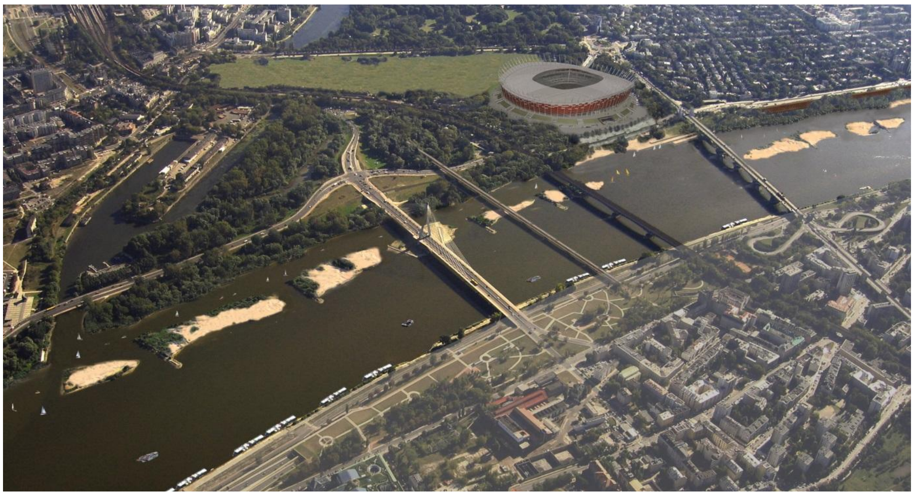

Figure 6.33. Visualisation of regulation works reconstruction project and dam up the river – view on the section between National Stadium and Praski Harbour (Damiecki et al. 2008)

In one of the options of the Vistula Nature Park project the authors proposed (Figure 6.32):

- cut off from the bank or lowering the top of the groynes to form the narrow branch of the riverbed along the right bank,
- creation the islands, stabilized by abandoned parts of groynes,
- creation of beaches and recreational areas by the silt removing and maintenance of the vegetation (partial removal of shrubs and invasive species of trees).

An integral element of the concept was the proposal to build a shell-type weir at km 520, which, through periodic water level increasing allowed to sail passenger ships, so far impossible at low water levels. The visualization of the redeveloped part of the Vistula with an increased water level were shown in Figure 6.33.

So far, none of the options of the Vistula Nature Park project has not been fully implemented, in particular hydrotechnical issue. By contrast it was executed very important part of the project for improving the recreation conditions: it has been created beaches and bathing, hiking and cycling paths. It has been also carried out comprehensive shaping of high vegetation on the right bank of the Vistula River and silts were removed with the local ground level correction of the flood terrace.

Program Life+ - Habitat protection of main bird species in the Middle Vistula River valley in conditions of high anthropogenic pressure in Warsaw agglomeration

The project is implemented by Warsaw City Hall and Warsaw Society of Bird Protection (www.wislawarszawa.pl, access: 09.07.2015). The main project’s objectives are as following:

– Breeding colonies restoration of priority species of waders, gulls and terns on the Special Protection Area (SPA) Nature 2000 “Middle Vistula Valley” within the Warsaw borders;

– The improvement of internal cohesion of the SPA Nature 2000 site by restoration of habitats characteristic for braided rivers like middle-stream of the Vistula River within the Warsaw borders;

– Assurance in improvement of protection quality in the SPA Nature 2000 by means of rising up ecological knowledge citizens of Warsaw in area of threatened bird species protection, throughout shifting they land-use behavior in SPA Nature 2000, and engaging in protection actions for birds and habitats in the Vistula River Valley.

The main expected project’s results:

– New stable islands and floating islands created on Vistula river. The number of shoals and shallows on the riverbanks of the riverbed increased. Thanks to those the habitat conditions will be created, that will increase the effectiveness of bird broods, create new fish spawning areas – creating main food for birds, on which the projects focuses, and will increase the feeding area for terns, gulls and other bird species.

– Artificial islands create stability of Little Tern and Common Tern population in the project’s area – their presence will lead to creation of new stable colonies of waders, which will fill in the gap on the river within Warsaw borders in SPA Natura 2000 area.

– The number of random disturbance of birds will decrease thanks to designation of access points for Warsaw citizens, the restrictions of access in other places and implemented information campaigns.

– The conditions of conservation of at least 100 bird species inhabiting the project’s area will be better, also the integrity of the area thanks to implementation of concrete conservation actions.

– Simultaneous bird monitoring schemes conducted by traditional method and by methods supported by teleinformatics technology will increase the effectiveness of project actions.

– The project will contribute to the propagation of bird conservation in area neighboring with big cities and will depict possibilities of improvement of biodiversity in big, lowland river valleys.

Investment actions regarding wading birds habitat protection and restoration are included:

- Constructing of at least: 1 stable island, 2 sandy shoals and 4 artificial floating islands by adaptation 120 t barge. The surface of stable, periodical and floating islands will be adapted for birds to start and successfully finish the breeds.
- Exposure of sandy riverbanks overgrown with bushes within the city and on the area where the islands and sandy shoals will be created, then initial stadiums of natural succession will be sustained. Thanks to this sandy riverbanks will be restored, which will potentially become a place for birds to rest during migration or feeding, especially within the city.

The bird monitoring results shown absence of nesting places for bird species, connected with sand's islands located into riverbed, on the Vistula River reach down to Warsaw border (Elas 2012). In the frame of project are planned to use active measures in order to creation a nesting places, as well as a places for bird to rest during migration or feeding. One of the place planned to restoration there are islands located on the „Lawice Kielpinskie" nature reserve area in km 527-538. The scope of measures used over there included creating of sandy shoals on total area 7 hectares and removing jointly 8.7 hectares of forest and bushes from overgrown islands (Figure 6.34).

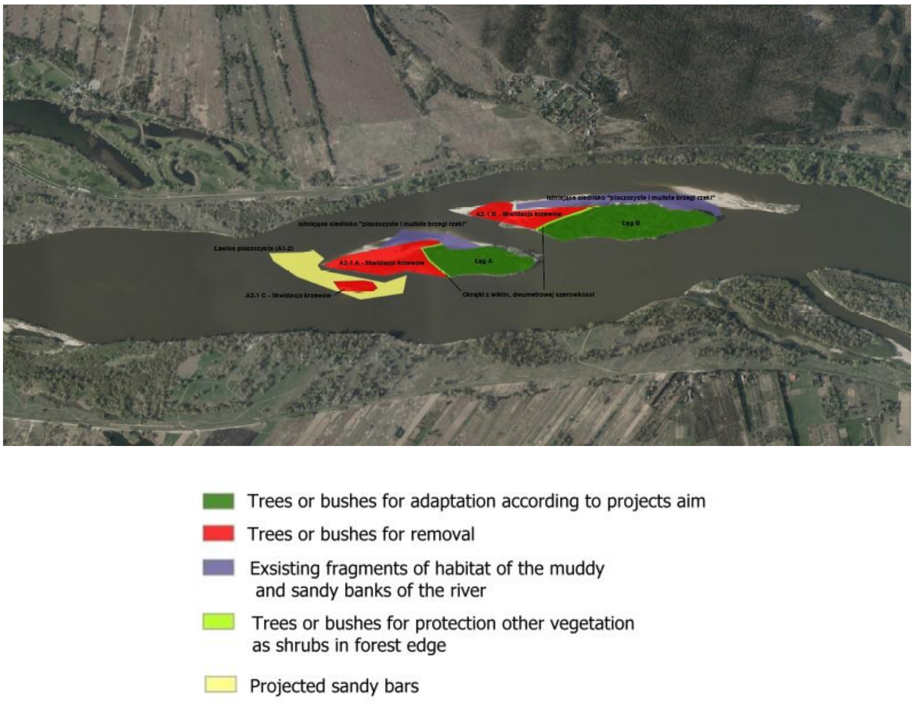

Figure 6.34. The scope of measures planned to use for restoration island on the „Lawice Kielpinskie" nature reserve area in km 527-538 (Halcrow 2013)

The project's site is located in the center of the big city. Due to the fact, it is essential to implement actions concerning avoidance of unfavorable impacts of human presence, that can threaten the animals and natural habitats. Close neighborhood of protected area Natura 2000 network and Warsaw community demands on rational access to the river for recreation. Within the city area the project plans to:

- Use different types of fences, ditches, boards, signs to protect chosen parts of the project area from people and predators;
- Make the area available in specific places, instead of free penetration of the whole area, through location of parking places, educational paths, access points for the beaches, where educational pavilions, viewing towers and picnic infrastructure will be placed.

Permanent monitoring is essential for checking the real effects of implemented project actions aimed at bird protection. Thanks to monitoring results it is possible for example show trends in numbers of birds nesting in the area, its causes and analyses impact of different factors on birdlife. In the project two parallel complementary monitoring schemes and three reports are foreseen:

- Traditional birds and habitats monitoring, implemented as systematic observations by ornithologists according to chosen methodology on the whole project area, consisting of the research in the riverbed and in area between embankments covered with riparian forests and bushes;
- Habitat monitoring and monitoring of chosen bird colonies on line, with use of video and data transfer technologies.

Demonstrative and innovative character of the project and its implementation on the area of the city of Warsaw demands many informative, educational and promotional actions. Those actions will be prepared in a form of big social campaign and will aim at raising public awareness and good pro-ecological habits among Warsaw citizens, popularization of knowledge about birds and nature at the Vistula river, propagation of the idea of Natura 2000 network and discovery of values within the project's area.

Restoration of flooding meadows on Warsaw reach of SPA Nature 2000 "Middle Vistula Valley"

The project is implemented by Warsaw City Hall and University of Warsaw, Biological and Chemical Research Center, Ecosystems Protection and Restoration Team (www.wislawarszawa.pl, access 09.07.2015). The aim of the project is to restore the proper state of habitats and species refuges of selected areas of the Warsaw part of the Vistula River Valley by reducing the invasive plant species of alien origin: *Solidago Canadensis*, *Solidago gigantea* and *Acer negundo*. The area of operation covered approximately 70 hectares along the Vistula River.

The main result of the project will be recreation a half-open, partially wooded landscape with species-rich grassland habitats on flooded habitats of the Vistula inter-embankment area, especially meadows protected by Habitats Directive: *Cnidion dubii* meadows, *Arrhenatherion elatioris* meadows, *Molinion caeruleae* meadows and *Koelerion glaucae* grasslands.

The main action in the areas selected for the project will be mowing of the neglected meadows. In some places, it will be needed to sow seeds collected in the meadows in better condition, along valley of the Vistula River and its tributaries Bug River and Pilica River.

The project is planned to obtain:

- Limitation of alien invasive plants species;
- Proper species composition of floodplain meadows;
- The increase biodiversity, including the animals, often of rare and endangered species of insects, amphibians, reptiles, birds, small and large mammals;
- Reducing the CO2 emissions - biomass formed after mowing of Solidago sp. will be converted to "green fuel";
- The mown grass and herb from restituted meadows will be used by the Warsaw Zoo, as animal feed;
- In the social dimension - improving the aesthetics of the landscape, raising ecological awareness of inhabitants of Warsaw.

6.4 Ecological effects of measures

Two projects of restoration, which have been presented in item 6.2 and 6.3, are currently implemented on the analyzed reach of the Middle Vistula River. So, the final ecological impacts of measures are unknown at present. However, taking into consideration a limited extent of both projects it must be assumed that effect will have a local significance in habitat improvement mainly for bird population and should be irrelevant for overall ecological status of the river.

6.5 General remarks or conclusions

The Middle Vistula River belong to the Nature 2000 network is the best proven of high status of river environment in general. However, it not means that a restoration measures are unnecessary, especially on the river reach in Warsaw. On the other hand, constant care should be undertaken, that freely flowing river does not create hazard to flood embankments, bridges, water uptakes, sewage dumps, etc. is necessary. Economic needs and necessity of providing adequate flood protection require carrying out of the appropriate maintenance works and supplementation of the existing river regulation structures, which should also take into consideration high environmental value the Vistula River. Technical activities planned in the river channel should not excessively harm the ecologic stability of the ecosystem created by the river channel and flood areas. The basic rule for designing these structures should be creation of local protective measures, and not the desire to change the river flow conditions on the longer distances.

It should be emphasized that ecological status of analyzed the Vistula River reach is currently defined as “poor” (V class on 3 river section) and “weak” (IV class on 1 river section). However, the main impact on this ecological status have a poor quality of bentos macroinvertebrate and some water contaminations (aluminium, cadmium and benzol). The other element of ecological status assessment, such as hydromorphological and physico-chemical elements, are defined as “very good” (I class) and “good” (II class). Therefore achieving at list a “good” ecological status in the future will need, first of all, a numerous mitigation measures undertaken for water quality improvement.

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7. Lower Danube and Danube Delta (Romania)

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7.1 Introduction and Characterisation

The Danube River is the world's most international river basin as it includes the territories of 19 countries and is home to 83 million people. The main characteristics of the Danube are summarized in Table 7.1. The length of the river is almost 2,900 km from source to mouth. The Lower Danube is represented by the last 942 km of the river before flowing in the Black Sea (Figure 7.1).

Figure 7.1. The Danube River basin and its Lower Danube section

Danube Delta

The case study which is presented in this chapter is the Danube Delta. This area has a continental-temperate climate, with some marine influences. On the basis of landforms, morphometric and hydrographic characteristics, the Danube Delta is dived in two main subunits: the fluvial delta (49% of surface area of delta), and the fluvio-marine delta (51%). The fluvial delta represents the oldest part of the delta, which is situated more upstream than the fluvio-marine part, which is situated near the Black Sea. The Danube Delta is a very low flat plain, lying 0,52 m above Mean Black Sea Level Sulina with a general gradient of 0,006 m/km. Compared to the Black Sea level, only 20% of the Delta area is below 0 meter.

Table 7.1 General charactericties of the Danube (www.icpdr.org)

Basin (km2)	801,463
District	807,827
Length (km)	2,857
Discharge (m3/s)	6,500
Altitude source (m)	1241

7.2 Historical situation or reference situation

The pristine state of the Danube Delta from hydromorphological point of view before first intervention for navigation improvement is available thanks to the European Danube Commission (Hartley, 1887; Figure 7.2).

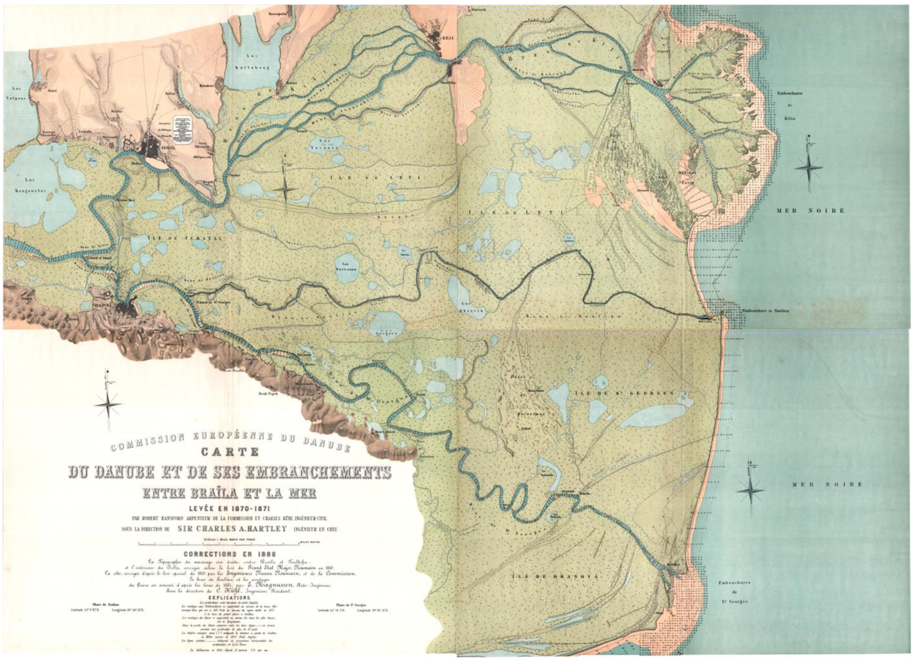


Figure 7.2 Danube Delta pristine status, 1887

Table 7.2 Major drivers and pressures in the Danube basin (Source: www.icpdr.org, Oostenberg et al. 1999)

Driver	Pressure	State
Power generation	Dams, water level management	Hydrological alterations, River/habitat continuity interruption
Flood protection	Dams, Embankment, groynes, channelization	Disconnection of adjacent floodplain/wetlands, Reduction natural inundation zone
Navigation	Bank protection, deepening, groynes, channelization, weirs/sluices,	River straightening, Disconnection of adjacent floodplain/wetlands, Hydrological alterations
Fisheries	Construction/enlarging channels in Danube Delta; embankments	Hydrological alterations, Disconnection of adjacent floodplain/wetlands
Reed culture	Construction/enlarging channels in Danube Delta	Hydrological alterations
Agriculture	Embankments	Hydrological alterations, Disconnection of adjacent floodplain/wetlands

7.1 Drivers: socio economic functions

In the Lower Danube, the main drivers have been power generation, flood protection and navigation (Table 7.2). For power generation, the dams Iron Gate I en II were constructed (completed in resp. 1971 and 1984), which regulated river water levels and interrupted migration routes for migratory fish species. Flood protection resulted in the construction of embankments, dams, and groynes, as well as channelization of the river channel. For navigation, river banks were protected and groynes were constructed, the main channel was deepened and weirs and sluices were constructed.

In the Danube Delta, the main pressures are navigation, agriculture, reed exploitation, fisheries and forestry (Table 7.2). Improved conditions, for a modern navigation system were created by shortening and deepening of the one of the river branches (Sulina) in the delta. For fisheries, internal channels were builded or enlarged, to improve water quality and accordingly to increase fish yields. For reed production, a network of channels and earth platforms were created. Many areas were embanked and leveled for the use of commercial fish farming. Additionally, many areas were embanked for agricultural production (Oosterberg et al., 1999).

7.2 *Effects of pressures on hydromorphology and ecology*

Effects of Irongate I and II

The construction of the Irongate dams started in 1964. In 1972 the Iron Gate I Dam was opened, followed by Iron Gate II Dam, in 1984, along with two hydroelectric power stations and two sluices. The building of barrages at Iron Gate I in 1970 at km 943 and Iron Gate II in 1984 at km 863 has shortened the migration route for sturgeons *(Huso huso, Acipenser guldenstaedti, Acipenser stellatus; (Bacalbasa, 1989)*. As a result, the catch of sturgeon declined strongly after completion of these dams (Figure 7.3).

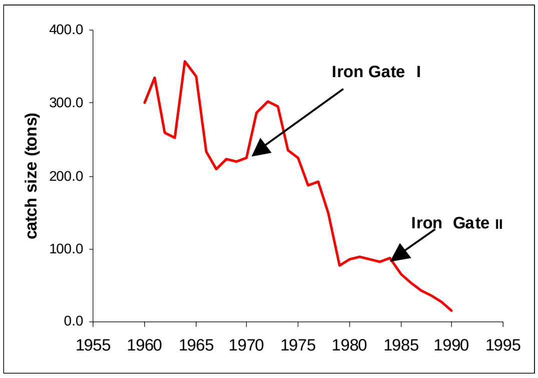


Figure 7.3 The decline and collapse of sturgeon fishery after building of Iron gate I and Iron gate II barrages.

Additionally, the construction of these dams gave the valley of the Danube below Belgrade the nature of a reservoir, and caused a 35 m rise in the water level of the river near the dam. Consequently, the current velocity of the water declined strongly, which – together with the disruption of migration routes for fish (see above) – resulted in a dramatic reduction in number of the fish species. Also, the dominant species shifted from rheophilic (*Barbus barbus, Acipenser ruthenus, Leuciscus idus*) to eurytopic *(Rutilus rutilus, Abramis brama, Stizostedion lucioperca*). This shift occurred already within four years after impounded by Iron dam I (Bacalbasa, 1991).

Lower Danube

Along the Lower Danube, the area of floodplains has strongly been reduced due to the constructions of embankments. The natural The Lower Danube floodplain without Danube Delta exceeded 500,000 ha. By 1976, 85% of this area was embanked and disconnected from the river (Table 7.3; Figure 7.4). Also the ratio river length (km) to floodplain area (ha) was reduced from 1:612 to 1:118 (Bacalbasa 1989). These reductions were largely due to the expansion of agricultural uses and river engineering works for flood control, navigation and power generation. As a result, the fish populations decreased strongly, and the decline of the fisheries indicates the response of fish population to this habitat loss (Figure 7.5).

Table 7.3 Danube River floodplain distruction by embankments (Schneider, 2002)

	Morphological floodplain (km^2)	Recent floodplain (km^2)	Loss (%)
Upper Danube	1,762	95	95
Middle Danube	8,161	2,2002	75
Lower Danube	7,862	2,200	72
Danube Delta	5,402	3,799	30

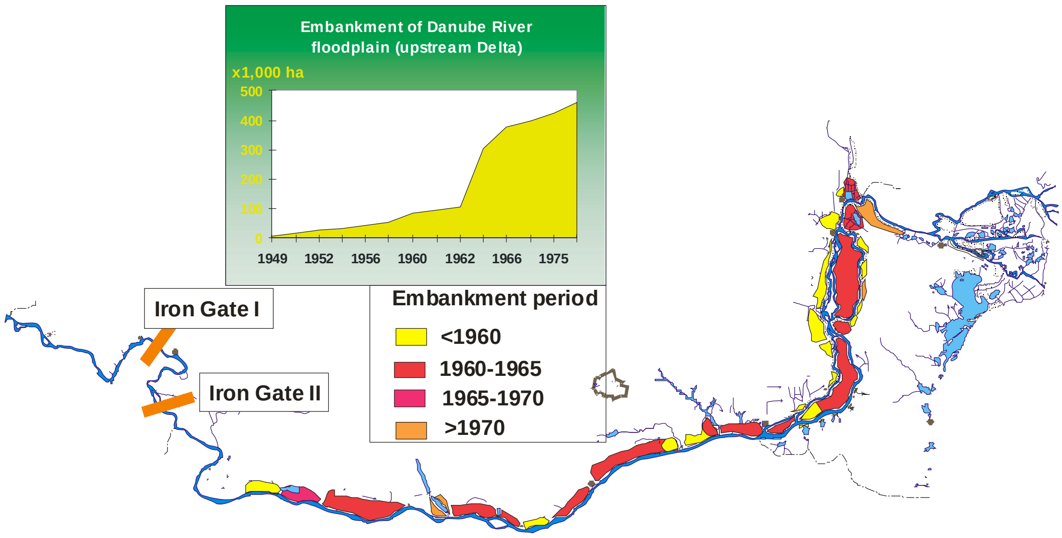


Figure 7.4 The main hydromorphological changes in the Lower Danube, upstream Danube Delta: floodplain embankments and impoundments at Iron Gate I and II (Schiemer et al. 2004).

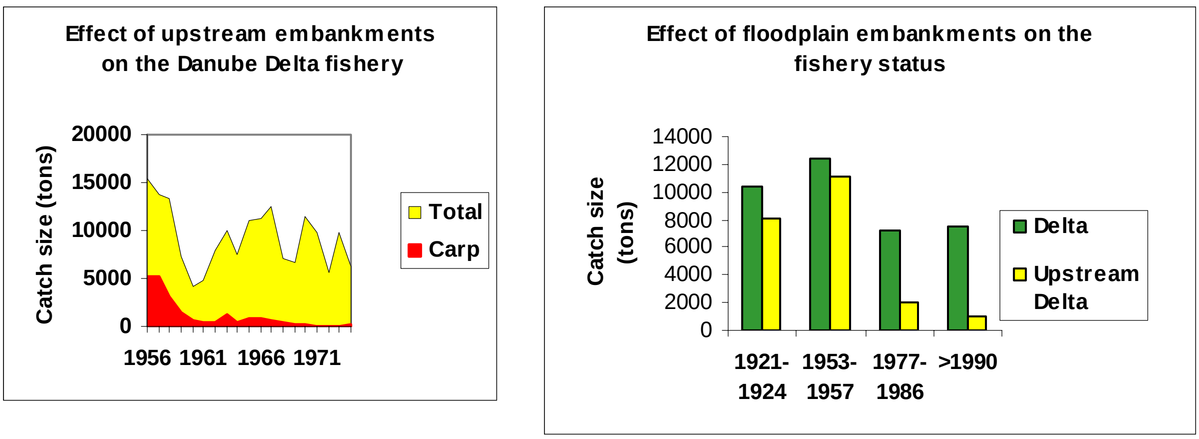


Figure 7.5 Effects of embankments in the Danube floodplain on the capture fishery

Danube Delta

The Danube delta is still in a rather pristine state despite significant human impact during the twentieth century. The main human impacts on the system include engineering to enhance navigation and fish production, and the reclamation of some 20% of the area for agriculture and fish ponds.

The human interventions are consequences of different land-use policies, which changed the pristine feature (Figure 7.6). In the end of the 19th century, measures were taken to improve the navigability of the middle arm of the delta, without major impact on the other delta's functions. During 1903-1960, in so called "capture fishery period", new channels have been built or the older natural ones have been enlarged to activate water circulation inside the delta, aiming to improve fish production function. A more intensive campaign of hydrotechnics works has been undertaken during 1960-1970, so called ''reed period", in order to increase reed production and to facilitate reed harvesting and transport to cellulose factory. Besides the channels, the first large areas have been dammed to regulate and optimize the water level, as a key factor for the reed beds development. The "fish culture period", during 1971-1980, followed by the "agriculture period", mostly during 1983 - 1989, altered the network of water courses. By the early 1980s, the total length of man-made canals equialled the length of natural or partially modified water courses (Buijse et al., 2002). The dammed areas increased from 24,000 ha to 97,000 ha and have cut off from the Danube river pulse system.

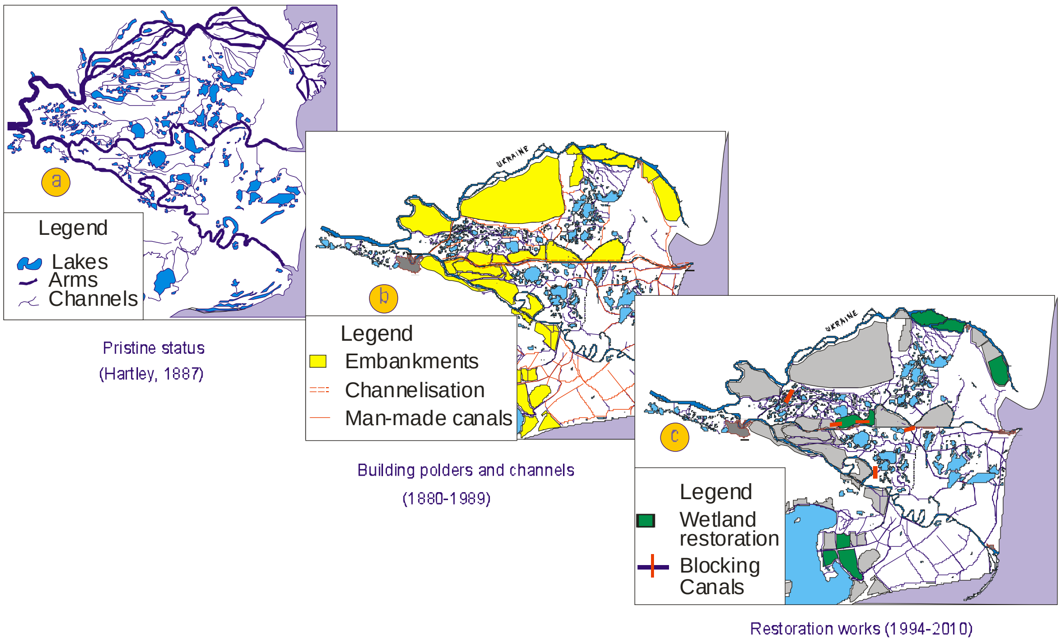


Figure 7.6. Stages in the recent Danube Delta history

As a result of dredging new canals, the total length of canals in the Romanian delta increased from 1743 km to 3496 km (Gastescu et al. 1983) and the water discharge from Danube river to delta wetlands increased from 167 m^3/s before 1900 to 309 m^3/s during 1921-1950 and 620 m^3/s during 1980-1989 (Bondar 1994).

The Danube river water discharge to the delta's wetlands, increased from 167 m^3/s before 1900 to 309 m^3/s in 1921-1950 period, 359 m^3/s in 1971-1980 period and 620 m^3/s in 1980 –1989 period (Figure 7.7; Bondar 1994). The nutrients inflow from Danube to its delta increased even more times than the water discharge owing to increasing pollution of the river (Staras 2001) As a result of eutrophication, the response of fish community was typical for European temperate waters (Ligtvoet & Grimm 1992): reduction of number of species and proliferation of those species with more eurytopic habitat requirements.

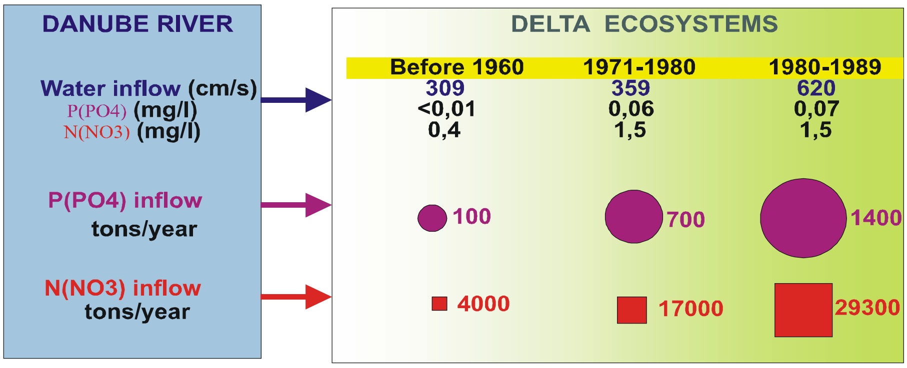


Figure 7.7 Changes in water and nutrients exchange between river and delta

The effects of habitat loss were reflected by statistical data of commercial fish yields. The cyprinid fish species have been mostly affected after 1973 (Figure 7.8 and 7.9). After this year, the areas of embankments increased from 24,000 ha to 100,000 hectares. Most of these embanked areas used to be seasonally flooded and were previously used for spawning and nursing by fish (Figure 7.8 and 7.9).

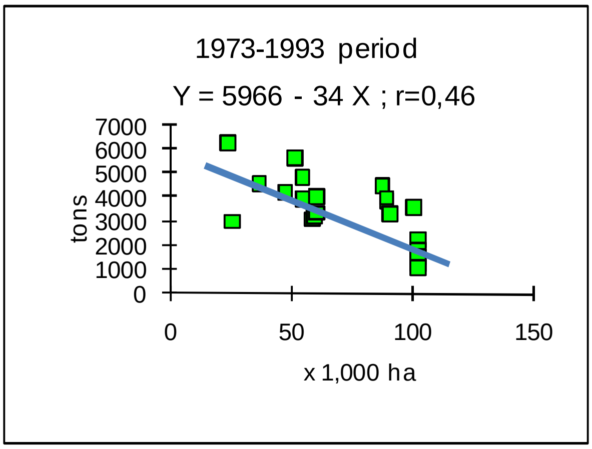


Figure 7.8 The impact of embankments on Cyprinids yields (Staras 1998).

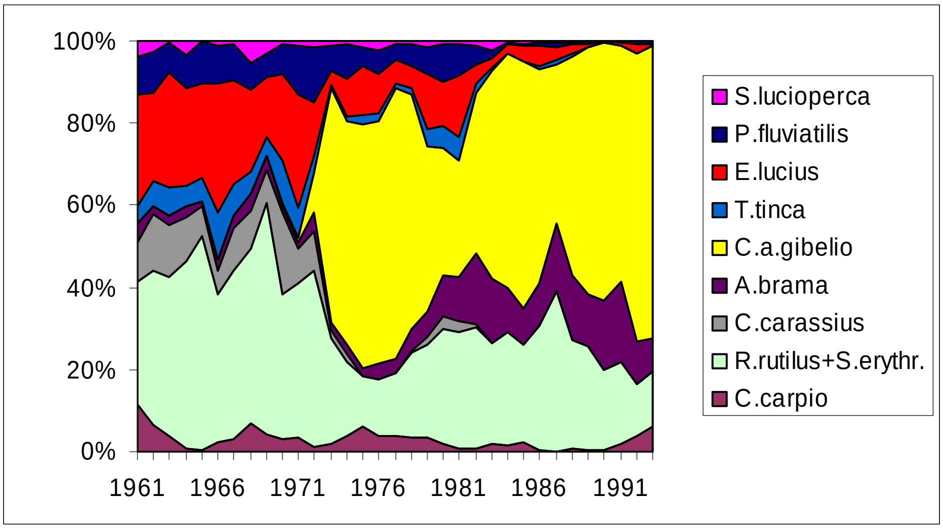


Figure 7.9 Changing of fish community structure in commercial catches (Navodaru et al. 2002).

Another example of the fast response of fish population to interruption of lateral connectivity is the case of building an artificial barrier in the Danube Delta between Danube river and Uzlina lake in 2001, in order to prevent siltation (Navodaru et al. 2005). As a result of the construction of this barrier, a rapid shift from rheophilic/eurytopic to eurytopic-limnophilic species occurred and a decrease of fish biomass was recorded in 2002 compared to 2001 (Figure 7.10), especially for lakes close to the barrier.

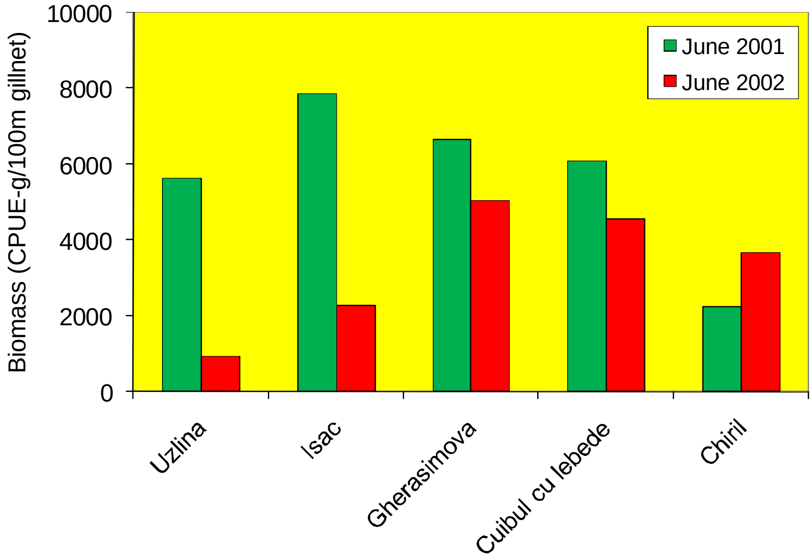


Figure 7.10 Fish biomass before and after building of an artificial barrier in five floodplain lakes.

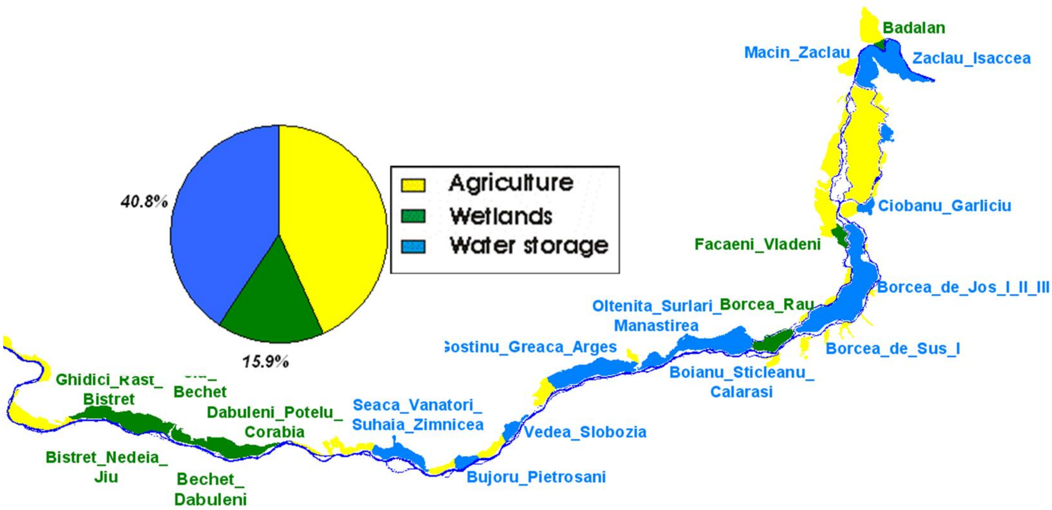


Figure 7.11. Measures along the Lower Danube

7.1 Rehabilitation and mitigation measures

Danube

Significant restoration efforts and measures will be carried out. In 2009, 95 wetlands/floodplains (covering 612,745 ha) with the potential to be re-connected to the Danube River and its tributaries were identified. Of this, the Joint Program of Measures (JPM) indicated that 11 wetlands/floodplains (62,300 ha) should be reconnected by 2015.

Additionally, the JPM indicates that, by 2015, 108 fish migration aids will be constructed. The remaining interruptions will be addressed in the next WFD cycles 2015-2021 and 2021-2027.

According to the 1st Management Plan (2009), along the Lower Danube an area of 15,9% of embankments will be reverted to permanent wetlands and 40,8% of it has been designated as alternative use for water storage and agriculture (Figure 7.11).

Danube Delta

During the past two decades, several rehabilitation projects have been carried out in the Danube Delta (Figure 7.12). Many of these projects were planned or achieved without prior knowledge of their potential for success or failure even they benefit from a consideration of river ecosystem concepts (Buijse et al., 2002). The existing guidelines have been developed mainly after 2000 and mostly for restoration of the longitudinal connectivity (www.ecrr.org).

Babina and Cernofca

Babina (2100 ha; 45.424763^{0}N; 29.411763^{0}E)) and Cernofca (1580 ha; 45.402668^{0}N; 29.495029^{0}E) as pilot projects did not benefit from a past experience on floodplain restoration. Their areas, drained for agriculture in 1985-1989, have been reconnected to Danube River in 1994 and 1996 simply by opening the surrounding dykes and allow natural processes to develop naturally under the river pulse regime, following the principle ,,let the river do the work" (Stanford et al., 1996). The openings locations correspond as much as possible to those existing before embankments, indicated by historical maps but their transversal profiles have been designed to assure an average water level of 100 cm over a longest possible period and a permanent water circulation (Schneider et al. 1997).

Popina and Fortuna

The first two projects were followed by Popina project (3600 ha; 45.29324^{0}N; 29.64420^0 E) which was implemented two phase during 1990-2000 and Fortuna (2115 ha; 45.1912318^0 N; 29.1481018^0 E) implemented in 2000. Their objective was the restoration of connectivity with Danube River for biodiversity conservation purpose in general and the methodological approach was similar (Schneider et al. 1997).

Holbina –Dunavat

Holbina –Dunavat project (44.893336^{0}N; 29.122695^{0}E) is an abandoned fish farm with an area of 5630 ha. Its status in 2005 was an area of 4360 ha connected to the natural system by breaches in the surrounding dyke, made by fishermen for access or by wave erosion with a total wet surface of about 10 m^2 whereas an area of 1270 ha remained isolated. The Holbina-Dunavat project had as specific objective to protect and maintain populations of species and habitats with mesotrophic character with high ecological values (Baboianu & Goriup, 1995; Drost et al., 1996; Drost et al., 2002).

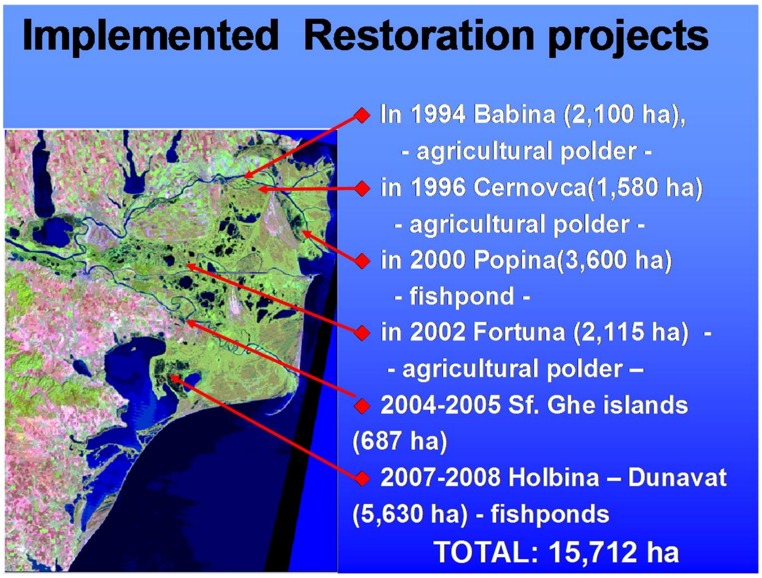
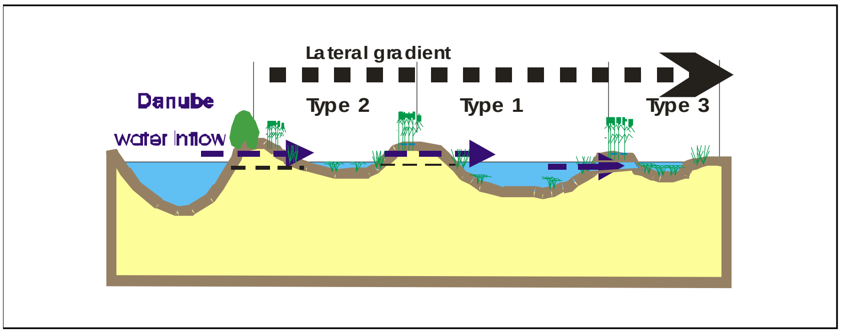


Figure 7.12. Implemented rehabilitation and mitigation measures in the Danube Delta

7.2 Ecological effects of measures

In the mid-1990's, a study was initiated to assess the present state of the lakes in the Danube Delta (Oosterberg et al., 2000; Buijse et al., 2002). Classification of the lakes forms the scientific basis for managing the delta in the future and provides a reference for heavily degraded systems elsewhere in Europe. Five main criteria were used to classfify the Danube delta lakes. Hydrogeomorphology and water quality were considered as the main controlling factors for aquatic communities, and the composition and abundance of plankton, aquatic vegetation and the fish community served as indicators of the trophic state. Based on these criteria, three principal lake types were identified in the Danube delta (Figure 7.13): (1) large turbid lakes locaties at the deeper parts of the former marine lagoon, characterised by a co-dominance of both still-water fish and fish species occurring in both standing and running water; (2) mostly clear lakes of medium size strongly influenced by river flow, colonised by dense stands of Potamogeton trichoides and filamentous algae, and characterised by a fish community indifferent to flow velocity; (3) isolated and shallow lakes with floating reed beds and peat accumulations, dense carpets of Nitellopsis obtusa and a 'black fish' community (e.g. tench, Tinca tinca, and Crussian carp, Carassius carassius). Increased inputs of nutrients and sediments to the delta lakes have recently shifted the relative proportion of lake types, with types 1 and 3 more severely affected (Oostenberg et al., 2000).

In the Danube Delta, the methodological approach evolved from empirical-experimental in the case of the large first floodplain restoration projects Babina and Cernofca implemented in 1994-1996 to a more process-based approach in the case of Holbina-Dunavat project, fully implemented by 2000. Out of six implemented restoration projects (Figure 7.12), the most relevant data on the effect of restoring lateral connectivity in the large rivers floodplain are from Babina and Holbina-Dunavat implemented projects. Below, the results of these projects are discussed.



	Type 2	Type 1	Type 3
Water residence time	Low	Intermediate	High
Ptotal (summer av. mg/l)	0.10-0.15	0.10-0.15	0.10-0.15
Transparency	clear	turbid	clear
Vegetation abundence	High	Low	High
Phytoplancton abundence	Low	High	Low
Zooplancton abundence	Low	High	Low
Fish composition	Euritopic	Intermediate	Black fish

Figure 7.13 The responses of biota to the lateral hydrologic/connectivity gradient in the Danube Delta (Source; Oosterberg et al. 2000)

Babina and Cernofca

The surrounding man-made dyke has changed the natural sedimentary processes. It does not allow the natural flow over natural ring levee during high flow. The water and sediments flow into the former polder through openings at low, medium and high levels as well. Thus the sedimentation rate inside restoration area proved to be very high due to the proximity of the Danube River and sediment removal works were needed after 9 years of restored connectivity, starting from 2003.

b) Hydromorphology of water inlets/outlets, Babina project

The evolution of the cross section of the water inlet and outlet between 1994-2010 showed a continuous reduction of the inlet section (Figure 7.14) and a slight erosion at the water outlet (Figure 7.15).

The constructed inflows become blocked by sediments by 2010 and function only during high water stages. Their role at low and medium water levels was taken over by water outlets with reversible flow character.

c) Water chemistry

Nutrient content is one of the key controlling factors of the ecological status. The results of the post-project monitoring of total phosphorous content for Babina project during 1997-2001 are shown in Table 7.4.

The results of phosphorous content monitoring in Babina restoration area has shown a common pattern occurring in the Danube Delta lakes: low content in spring and late outumn and high content in summer. This is because the most part of Babina restoration area is covered by reed beds. The main process that is responsible for the retention of phosphorus inside the reedbed is the sedimentation of the solids that are suspended in the river water during spring flood. The processes that are responsible for the release of phosphorus from sediments in summer are the anaerobic conditions and the microbial decay of reed.

The river nitrogen concentrations are somewhat higher in autumn and winter due to agricultural runoff. The main processes that are responsible for the Nitrogen removal inside the reedbed are denitrification and nitrification. This pattern is similar to the natural areas in the Danube Delta (Oosterberg et al., 1998; Oosterberg et al., 2000; Coops et al., 2008)

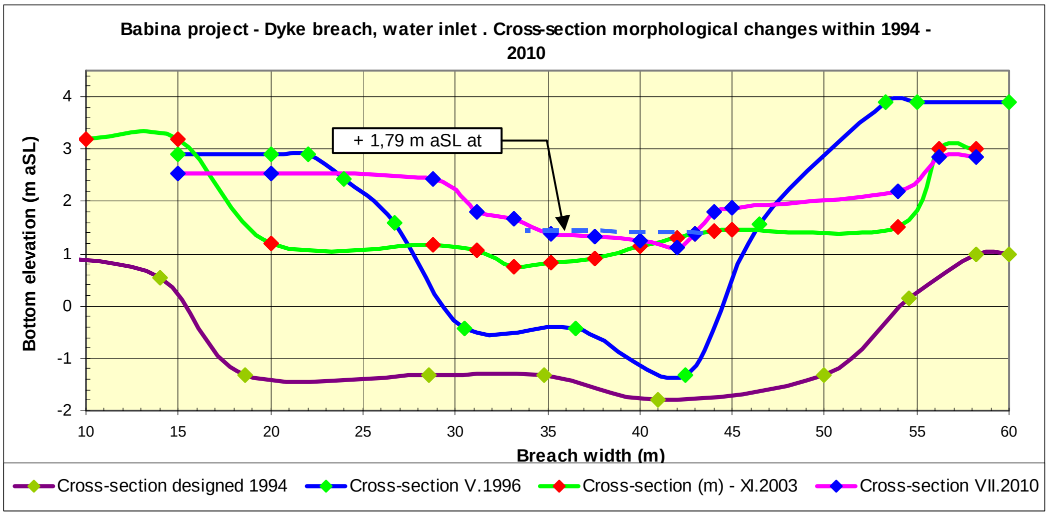


Figure 7.14 Sedimentation process at the water inlet cross-sections, Babina project

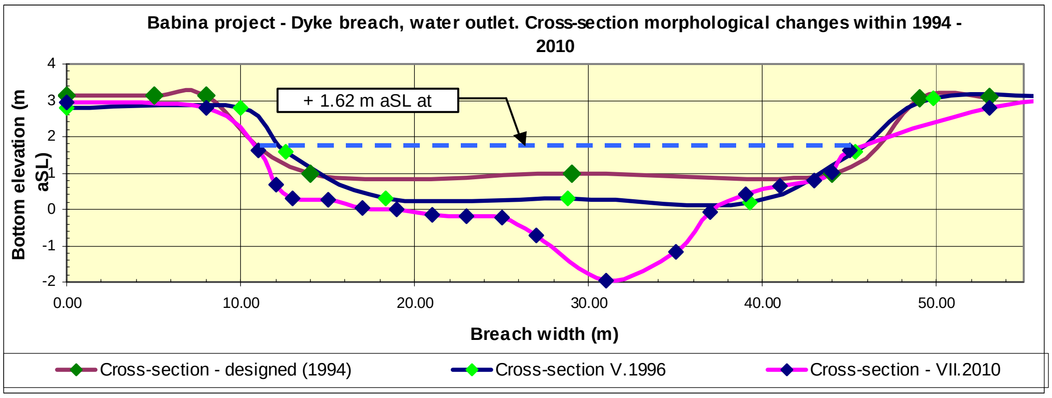


Figure 7.15 Sedimentation process at the water outlet cross-sections, Babina project

Table 7.4 The results of the post-project monitoring of phosphorous content, Babina project. Ba 1, Ba 6: sampling sites outside restoration area (Danube River); Ba 2, Ba3, Ba4, Ba5: sampling sites inside restoration area; n.d.: no data

			Pt (mg/l)						
site	Lat N	Long E	Aug-97	Jun-98	Jun-99	Jun-00	Oct-00	Jul-01	Oct-01
Ba 1	45.42747	29.36059	0.321	0.064	0.135	0.022	0.057	0.109	0.167
Ba 2	45.42670	29.36856	0.140	0.109	0.042	0.022	0.019	0.208	0.097
Ba 3	45.42646	29.37777	0.160	0.126	0.047	0.018	0.019	0.189	n.d.
Ba 4	45.41103	29.44930	0.137	0.072	n.d.	0.019	0.008	0.094	0.229
Ba 5	45.42502	29.44110	0.111	0.095	0.034	0.019	0.027	0.652	0.061
Ba 6	45.43770	29.41123	0.111	0.070	0.045	0.019	0.014	n.d.	n.d.
Ba 7	45.41830	29.39519	0.263	0.103	0.08	0.028	0.023	0.186	0.131

Macrophytes

The colonization process of aquatic vegetation in Babina evolved from 4 species in 1994 to 38 species in 2005, including protected *Aldrovanda vesiculosa* and *Utricularia vulgaris*, which was considered as remarkable (Schneider et al. 2008).

Fish

The published (Navodaru et al., 2008) and additional monitoring data on fish species composition and ecological guilds in Babina-Cernofca area before (1963) and after restoration works (1994-1996) are relevant for restoration of the lateral connectivity and ecological functions of the floodplain lakes as habitat for fish spawning, nursing and growing (Table 7.5).

The presence of adults of reophilic species *Barbus barbus, Aspius aspius, Leuciscus idus* and larvae of migratory *Alosa tanaica* in Babina in early June indicates that this area is used by these species for spawning. The numerical abundance of fish fauna by size groups in 1997, after 3 years of restoration indicates the area is actively used for all life development stages (Figure 7.16).

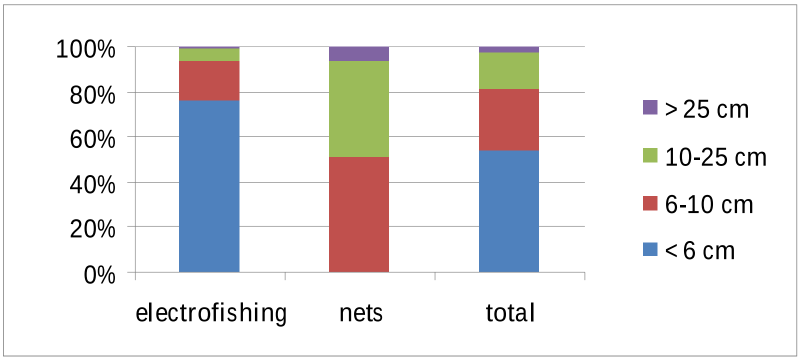


Figure 7.16. Numerical abundance of fish fauna by size groups, Babina project in 1997.

A monitoring campaign in 1998 in Babina area (Navodaru et al., 2005) revealed a differentiation of the habitat types and fish community structures induced by the gradient of connectivity and water clarity with the Danube river (Figure 7.17).

The presence/preference of limnophilic *Rhodeus amarus* or *Scardinius erythrophthalmus* in turbid water habitats (Figure 7.17) is somehow contradictory because is different from the general pattern in the Danube Delta and could indicate a still unstable system or a sudden increase of water level in Danube River and turbidity inside restoration area before sampling.

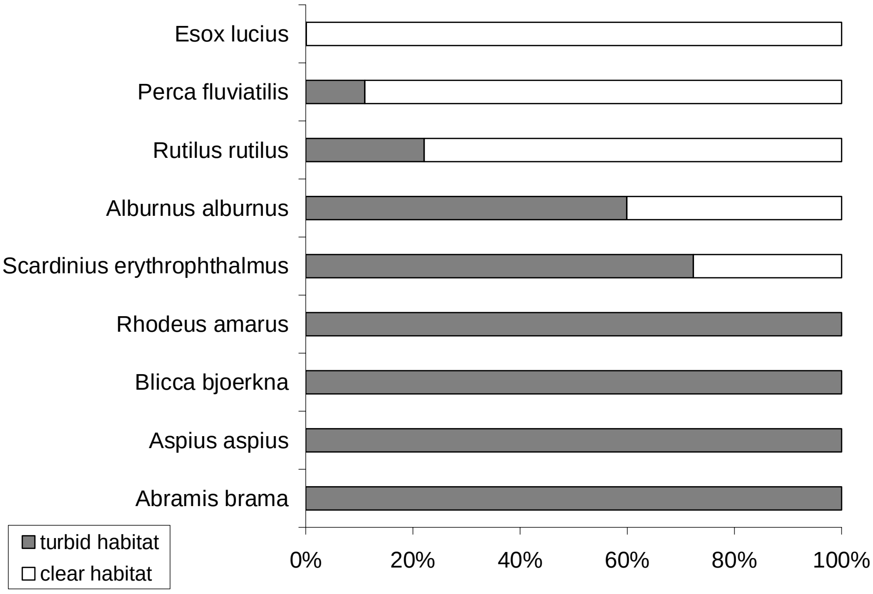


Figure 7.17 Distribution of relative biomass of dominant fish species over habitat types in Babina area, based on gillnet sampling in 1998.

Table 7.5. Evolution of fish diversity in the restored Babina and Cernofca areas and characterization of ecological guilds (after Banarescu, 1964; Schiemer & Waidbacher, 1992; Guti, 1993)

	Species name	English name	Babina 1963	Babina 1994 - 1996	Babina 1997 y, ad.	Babina 1997 lrv.	Babina 1998 y, ad.	Babina 1999 lrv	Babina 2001 y, ad.	Babina 2013 y.ad	Cernovca 1998 y, ad.	Cernovca 1996-2001 lrv.	Ecological guilds: Preference for current	Ecological guilds: Reproductive guild	Ecological guilds: Origin
1	*Abramis brama*	bream	+	+	+	+	+	+					Eu	f	n
2	*Alburnus alburnus*	bleak		+	+	+	+	+	+	+	+	+	Eu	f	n
3	*Alosa tanaica*	caspian shad		+				+					M	p	n
4	*Aspius aspius*	asp	+				+		+				Rh	f	n
5	*Barbus barbus (fluviatilis)*	barbel	+	+									Rh	li,ps	n
6	*Blicca bjoerkna*	white bream	+	+	+	+	+	+	+		+		Eu	f	n
7	*Carassius carasius*	crucian carp	+	+	+								L	f	n
8	*Carassius auratus gibelio*	giebel carp			+		+		+	+	+	+	Eu	f	e
9	*Cobitis danubialis*	spined loach			+		+			+	+	+	Eu	ps	n
10	*Cyprinus carpio*	carp	+	+			+		+	+	+		Eu	f	n
11	*Esox lucius*	pike	+	+	+		+		+	+	+		Eu	f	n
12	*Gobius sp.*	goby					+						Eu	ps, li	n
13	*Gymnocephalus cernuus*	ruffe		+	+		+		+		+		Eu	f	n
14	*Hypophthalmichthys molitrix*	silver carp		+			+						Eu	p	e
15	*Knipowitschia caucasica*				0			+				+	Eu	ps, li	n
16	*Lepomis gibbosus*	pumpkinseed		+	+		+		+		+		L	c	e
17	*Leucaspius delineatus*	sunbleak			+	+	+	+		+	+	+	L	f	n
18	*Petroleuciscus borysthenicus*	blak sea chub							+				L	f	n
19	*Leuciscus idus*	ide	+	+					+				Rh	f	n
20	*Misgurnus fossilis*	weatherfish			+				+		+		L	f	n
21	*Perca fluviatilis*	perch	+	+	+	+	+		+		+		Eu	f,li	n
22	*Proterorhinus marmoratus*	tube-nosed goby			+		+	+			+	+	Eu	f	n
23	*Pseudorasbora parva*	false harlequin		+						+			Eu	li/ps	e
24	*Pungitus platygaster*	ninespine stickleback			+			+					L	c	n
25	*Perccottus glenii*									+			L		e
26	*Rhodeus sericeus amarus*	bitterling			+	+	+	+	+			+	L	o	n
27	*Rutilus rutilus c.*	roach	+	+	+		+	+	+	+	+		Eu	f	n
28	*Scardinius erythrophthalmus*	rudd	+	+	+	+	+	+	+		+		L	f	n
29	*Silurus glanis*	wels	+	+	+								Eu	f	n
30	*Stizostedion lucioperca*	pikeperch	+	+									Eu	f	n
31	*Syngnathus abaster*	black-striped pipefish						+					L	ot	n
32	*Tinca tinca*	tench			+		+		+				L	f	n
33	*Umbra krameri*									+			L		n
	Total		13	18	20	7	19	12	16	10	14				

Abreviations

Stage: y=young, ad.=adult, lrv.=larvae

Current preference: M=migratory; Rh=rheophilic; Eu=eurithopic; L=limnophilic

Origin: n=native, e=exotic

Reproductive: f=phytophilic, ps=psammophilic, li=lithophilic, o=ostracophilic, p=pelagophilic, c=nests, ot=other

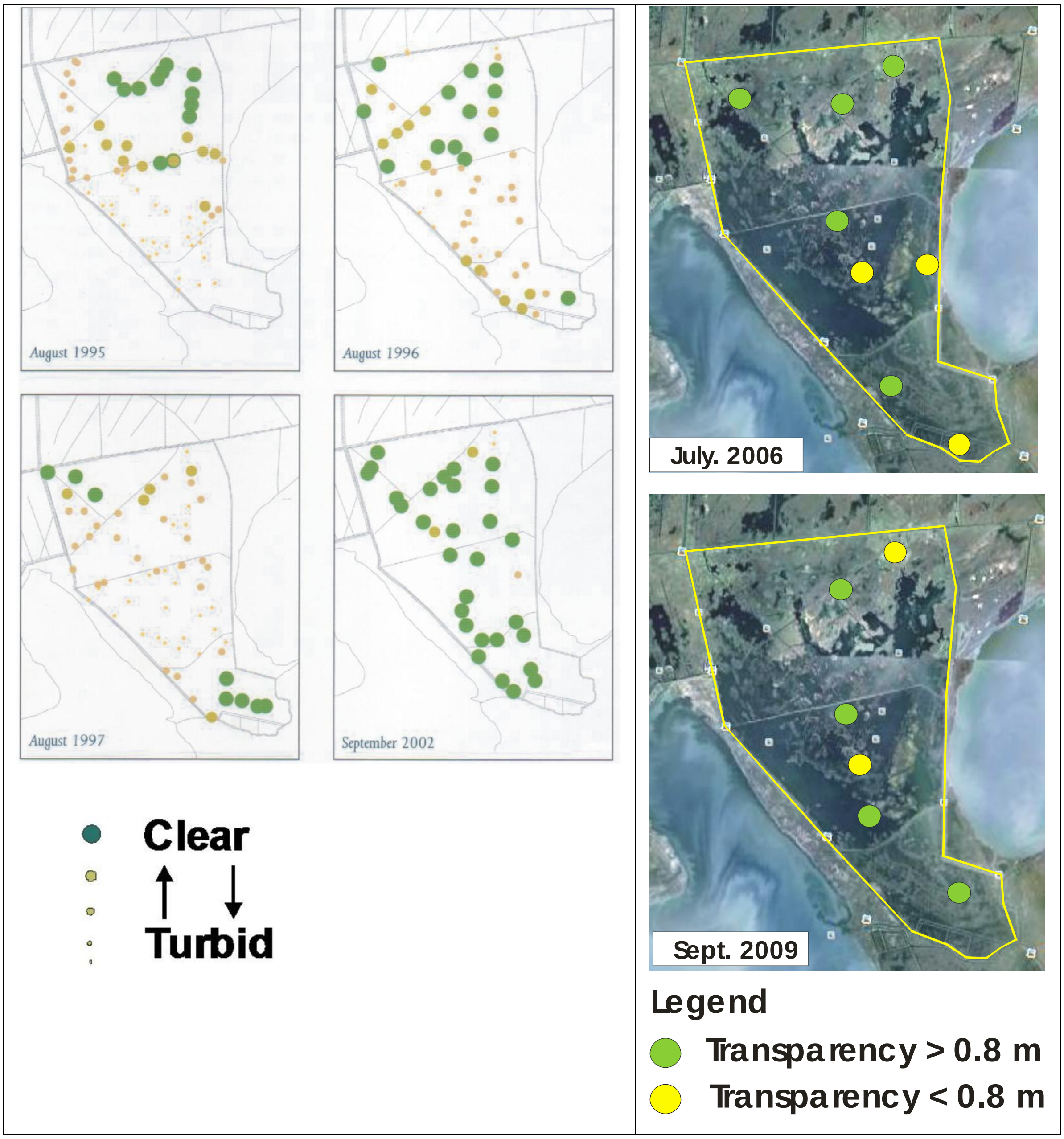


Figure 7.18. Changes in water transparency in restoration project Holbina –Dunavat during 1995 – 2002; see text for explanation (Source: Drost et al., 2002; Tudor, 2011)

Holbina –Dunavat

The project was implemented gradually during 1996-2000 in parallel with monitoring and research works aiming to assess the evolution of trophic status. A mixture clear and turbid water habitats were recorded in 1995-1996, with a clear trend of reduced area with high water clarity by 1997 (Figure 7.19). The residence time of water in Holbina was calculated to be 40-50 days during period of high flood (spring-early summer) and up to 200 days during low discharge (late summer-autumn). The large breaches were almost blocked between 1996-2000 in order to prevent further nutrient inputs and replaced since 2000-2001 with very small four openings with a total wet surface of 2 m^2 (0.5 m^2 each), aiming to increasing of residence time during high flood period and to enlarge the clear water areas (water of lake type 3 character in the typology of Oosterberg et al., 2000). The system has reverted to a clear water state by 2002 (Drost et al., 2002), and keep this character until present (Figure 7.18; Tudor et al., 2011). This project creates jobs and a sustainable tourism activity with positive effects on local community.

Macrophytes

According to Tudor et al. (2011) the number of recorded species of macrophytes from Holbina-Dunavat area in 2006 was 32, comparable with type 3 lake of Oosterberg et al. typology (2000).

Fish

The evolution of the fish species composition in Holbina-Dunavat restoration area shows a slight trend of decreasing the number of eurytopic sp. as *Cyprinus c., Stizostedion* l. in favour of limnophilic such as *Petroleuciscus borysthenicus, Lepomis gibbosus, Carassius carassius, Umbra krameri* (Table 7.6). This could be explained by increasing of residence time and high transparency area following implemented measures since 2000-2001 (Tudor et al, 2011), as discussed in previous paragraph.

Table 7.6. Evolution of fish diversity in the restored Holbina-Dunavat area and characterization of ecological guilds (after Banarescu 1964; Schiemer & Waidbacher 1992; Guti 1993)

			Jun-96	Oct-96	Jun-07	May-10	Ecological guilds		
							Preference for current	Reproductive guild	Origin
	Species name	English name							
1	*Abramis brama*	bream	1	1		1	Eu	f	n
2	*Alburnus alburnus*	bleak	1	1	1	1	Eu	f	n
3	*Alosa tanaica*	caspian shad	1				M	p	n
4	*Aspius aspius*	asp	1	1	1	1	Rh	f	n
5	*Blicca bjoerkna*	white bream	1	1	1	1	Eu	f	n
6	*Carassius carassius*	crucian carp			1	1	L	f	n
7	*Carassius gibelio*	giebel carp	1	1		1	Eu	f	e
8	*Cobitis sp.*	spined loach	1	1	1	1	Rh	ps	n
9	*Cyprinus carpio*	carp	1				Eu	f	n
10	*Esox lucius*	pike	1	1	1	1	Eu	f	n
11	*Gobius sp.*	goby	1	1			Eu	ps, li	n
12	*Gymnocephalus cernuus*	ruffe	1	1			Eu	f	n
13	*Lepomis gibbosus*	pumpkinseed			1	1	L	c	e
14	*Leucaspius delineatus*	sunbleak	1		1	1	L	f	n
15	*Misgurnus fossilis*	weatherfish		1			L	f	n
16	*Perca fluviatilis*	perch	1	1	1	1	Eu	f, li	n
17	*Petroleuciscus borysthenicus*	black sea chub			1	1	L	f	n
18	*Proterorhinus marmoratus*	tube-nosed goby			1	1	Eu	f	n
19	*Pungitus platygaster*	ninespine stickleback		1			L	c	n
20	*Rhodeus sericeus amarus*	bitterling	1	1	1	1	L	o	n
21	*Rutilus rutilus c.*	roach	1	1	1	1	Eu	f	n
22	*Scardinius erythrophthalmus*	rudd	1	1	1	1	L	f	n
23	*Silurus glanis*	wels	1		1	1	Eu	f	n
24	*Stizostedion lucioperca*	pikeperch	1	1			Eu	f	n
25	*Syngnathus abaster*	shore pipefish			1		L	ot	n
26	*Tinca tinca*	tench	1	1	1	1	L	f	n
27	*Umbra krameri*	european mud-minnow				1	L	f	n
	Total		19	17	17	19			

y=young, ad.=adult, lrv.=larvae

M=migratory; Rh=rheophilic; E=eurithopic; L=limnophilic

n=native, e=exotic

f=phytophilic, ps=psammophilic, li=lithophilic, o=ostracophilic, p=pelagophilic, c=nests, ot=other.

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8. Synthesis

Characteristics of rivers case studies

In this report, six case studies have been described that are spread across Europe. These case studies are representatieve of various European conditions with regard to climate, hydromorphological characteristics and catchment size (Table 8.1). The case studies are situated in six countries, viz. England (the river Trent), Italy (Po), Spain (Ebro), The Netherlands (Delta Rhine), Poland (Middle Vistula) and Romania (Lower Danube). All these rivers can be characterized as large rivers (viz. catchment area larger than 10,000 km^2), although they differed strongly in climatic zone, river length, catchment size, discharge, slope and river style. The results of these studies can be extrapolated to other areas in Europe.

Table 8.1. General characteristics of the case studies of large rivers in this report

	Trent	Delta Rhine	Po	Ebro	Vistula	Danube (Delta)
Country	Great Britain	The Netherlands	Italy	Italy	Poland	Romania
Climate	Atlantic	Atlantic	Alpine Continental	Mediterranean	Continental	Continental
Length (km)	275	1250	650	930	1048	2857
Catchment (km2)	10466	185260	74000	85530	194700	801463
Discharge (m3/s)	28,5	2200	1540	462	1046	6500

Historical/reference state

In an ideal world, one may want to restore rivers as close to what one perceives as a reference or “pristine state.” Identification of such states requires knowledge about previous human impacts. In general, there is a lack of information and knowledge about historical land use and associated effects on hydromorphology and ecology. The case studies have shown that many rivers have changed their river types and hydrological regimes over the past, and – hence - it is difficult to choose a reference state. Moreover, the effects of humans are much more influential now than ever before, and pristine ecosystems states are therefore unrealistic targets for restoration. Consequently, it is not self-evident that restoration should try to mimic attributes of previous river ecosystems. Hughes et al. (2007) gives a number of reasons for caution with respect to use of reference systems. Below, these reasons are given and the results of the case studies are discussed within this context.

References systems or historical data of rivers should be used with caution for the determination of goals for river rehabilitation (Hughes et al., 2007), because:

1. Often there are no suitable reference systems to mimic

   Especially in Europe, the effects of humans on rivers started already many centuries ago e.g. by the construction of embankments. Consequently, there are no examples left of reference systems that could be used as templates for other rivers. Indeed, all case studies in this report use historical data for the construction of the reference state, and – hence - no other contemporary rivers have been used for a reference. Also for the historical date, there is a lack of knowledge about the relation between changes in land use and hydromorphological processes. Descriptions of reference conditions in terms of community composition are even scarcer, and often anecdotal, or based on data for one biotic group (often historical data of fish catches).

2. Many properties of the catchment have changed since the time period chosen for a historic reference system

   For the Delta Rhine, the construction of embankments started already around 1100, while in Italy, the Romans exerted already a strong influence on rivers. The river Trent has shown different phases during the past centuries (viz. braiding and stable anastomosing), which could be linked to cover of forest in the floodplains. Additionally, the flooding area has been strongly reduced due to the construction of embankments. As a result, the amplitude of water-level fluctuations (and other river-related processes) has strongly increased in the remaining fragments of floodplains, which have a strong effect on various hydromorphological processes, as well as species composition of floodplain systems.

3. Changes in climate and species composition have been continuous throughout the Holocene

   Many properties of the catchment have changed over time. These changes may be attributed to human intervention (see above and paragraph 8.3), but may also be the result of changes in climate over the past centuries in Europe. Although it is difficult to produce correlations between climate change and detailed changes in fluvial systems (Patton & Baker, 1980), there is nevertheless evidence of alternating phases of stability and high flood activity in many rivers in temperate zones during the Holocene (Starkel 1991a). There is clear evidence that the climate varied continuously through the interglacial periods, and, for this reason, trying to restore to a previously existing natural ecosystem is not necessarily a sustainable or realistic approach.

4. Expected climate change in the future is of uncertain magnitude

   It is highly likely that climate change in the future will affect runoff patterns and hydrological regimes of rivers, thereby changing conditions for biota. Hence, a static view of species composition in floodplains is not appropriate. Overall, there seems to be a trend for increased variability of precipitation and evapotranspiration between seasons. Coping with this increased variability will be one of the many challenges that river managers have to take into account in river rehabilitation projects.

5. Non-native species cannot be avoided

   In many river systems, the presence of alien or non-native species has increased over time. The reasons for this are various but are associated with decreased geomorphological activity and increase human disturbance. Also for the case studies in this report, there has been an increase of introduced species (e.g. giebel carp in the Danube Delta). The occurrence of some alien species may even influence geomorphological patterns of river flow.

6. Landscape context of a particular location changes through time.

   In any single location, plant succession occurs, disturbances at many scales and of many types exert an influence, and habitats are modified and created. At the landscape level, there is effectively a mobile mosaic of habitats with many variable lag effects between disturbance processes and the response by both the abiotic components and the species of that landscape. Ideally, river restoration should take place at a spatial scale that allows this mobile mosaic to continue to exist, with the understanding that it will adjust itself over the longer time to climate and other changes. In practise, restoration takes often place on a much smaller spatial scale, and restoration of a small area within a larger mobile habitat mosaic is not possible. This will result in an altered (often impoverished) species composition compared to reference conditions, e.g. because propagules are no longer avaible in the seed bank or from previous upstream sources for plant regeneration.

Drivers and pressures

Between the case studies, there are large differences in drivers and associated pressures (Table 8.2). Both flood protection and navigation are important drivers for the occurrence of many pressures. The rivers Trent, Po, Ebro and Delta Rhine have a large number of drives and associated pressures, while the case studies of the Danube Delta and middle Vistula are less impacted. For the majority of the case studies no information was available regarding the extent of drivers and pressures. Therefore, we will discuss the time line of the occurrence of different drivers and pressures only in qualitative form.

The primairy drivers for early regulation of all rivers in our study were flood protection and agriculture (Table 8.3). For many rivers, these forms of river regulation started already centuries ago. For the river Po, the impact of humans became already important during the roman age. In this period, the dramatic increase in agricultural development and deforestation strongly increased the sediment load of the river and caused an extension of the Po delta along the Adriatic coastline. Deforestration also had a strong influence on the hydromorphology of other rivers (e.g. Ebro). Additionally, in all case studies large parts of (formerly active) floodplains were embanked, both for flood protection and agricultural use of the land. These results are in line with many other rivers in northern temperate regions. For North-America and Europe, it has been estimated that approximately 90% of the original floodplain of rivers has been permanently cut off from river flooding by the construction of embankments (Tockner & Stanford 2002). This has resulted in a huge loss of low-dynamic habitats in floodplains, such as wetlands and hardwood forest.

Navigation is also an important driver for regulation of large rivers. For many rivers at around 1800 (before the major impacts of river regulation due to navigation), this has resulted in a river landscape in which the floodplain area was strongly reduced, but with the possibility for the main channel to migrate freely in the remaining active floodplain, resulting in a dynamic landscape with regular rejuvenation.

Especially from the start of the industrial revolution (at about 1850), there was a strong need to improve conditions for navigation. Channelization of rivers for shipping activities has a negative impact on the occurrence of highly dynamic habitats as a result of the stabilisation of the river bed (by groynes, bank protection) and by deepening of the main channel. From this moment onwards, the position of the main channel became fixed and the area of shallow water in the main channel declined strongly. Navigation plays an important role in many rivers in Europe, and accordingly, also for the case studies in this report. Of our case studies, only the river Vistula in Poland has not been regulated anymore for navigation purposes, and – hence – large parts of the main channel of the river have not been channelised.

In the decades after the Second World War, many dams were constructed in the rivers. These dams were used for the generation of hydropower, as well as for water supply and irrigation. This has resulted in a decreased longitudinal connectivity, thereby impeding conditions for migratory fish and other species. Additionally, the construction of the dams resulted in altered hydrological regimes in rivers and reduced the sediment supply to downstream sections, as well to river deltas. Of the case studies, especially the rivers

Trent, Po, Ebro and Lower Danube have been severely impacted by the construction of dams.

Table 8.2 Overview of drivers and pressures for hydromorphology in different case studies

Drivers								Case studies					
Agriculture	Flood protection	Drinking water	Hydropower	Industries	Navigation	Urbanisation	Pressures	Trent	Delta Rhine	Po	Ebro	Vistula	Lower Danube & Danube Delta
x							Irrigation	1		1	1		
x							Removal riparian forest	1	1	1	1		
x	x						Water level management	1	1	1	1		
x	x						Accelarated discharge	1	1	1	1		1
x	x				x		Maintenance (intensive)				1		
x		x		x			Water abstraction	1		1		1	
			x				Hydropeaking						1
				x			Cooling water	1	1	1			
	x		x				Dams	1		1	1		1
x	x					x	Reduction natural inundation zone/active floodplain	1	1	1	1	1	1
x	x					x	Embankment	1	1	1	1	1	1
x	x						Intern basin water transfer	1	1				
				x			Land acquisition						1
					x		Water bed protection	1					
	x				x		Channelisation	1	1	1	1		1
					x	x	Bank protection	1	1	1	1	1	1
					x		Groynes	?	1	1		1	
					x		Deepening	1	1	1	1	1	1
					x		Weirs, sluices: passable/not passable	1	1	1			
					x		Sediment trap						
						x	Culvert etc.	1		1	1		

Table 8.3 Timing of most dominant pressures for hydromorphology in the catchments of the rivers Trent, Po, Ebro, Delta Rhine, Vistula and Danube Delta. When no information is given, then this pressure is not considered as an important pressure

River	Deforestation of catchment	Construction of embankments	Channelisation, bank protection, dredging	Large dams	Water dams
Trent	Middle Age?	19th - today	19th - today	19th - today	
Delta Rhine	Middle Age	14th - today	19th - today		
Po	Roman time	20th	19th - today	20th	19th - today
Ebro	Middle Age - 1950	> 1950	> 1950	> 1950	> 1950
Vistula	Middle Age?	1850 - today	14th - 18th		
Lower Danube & Danube Delta	Middle Age?	1960 - today	1880 - 1990	> 1950	

Pressure effects on hydromorphological processes and ecology

For the majority of the case studies, only limited information was available regarding the effects of pressures on hydromorphology and ecology. In the REFORM-project, a review of pressure effects on hydromorphological variables and ecologically relevant processes have been described by García de Jálon et al. (2013). Over time, the most important drivers (and associated pressures) for hydromorphology and ecology of rivers have been: agriculture (deforestation and embankments), flood protection (embankments, dams), and navigation (channelisation, bank protection, dams). It seems that these drivers (and associated) have initiated major transition points for ecological processes and biota along large rivers. Below, the main results are discussed in respect to the time line of occurrence of these drivers and pressures.

Effects of deforestation

Many catchments of rivers have been strongly affected by deforestation. This has already started many centuries ago, and occurred during the Roman age (river Po) to medieval times (for many other rivers). As a result of deforestation, there was a strong increase in runoff of sediments into the river, which has a strong impact on the hydromorphological processes and - hence – on river style. Although this must have had a large impact on river systems, there is a large lack of knowledge on the effects on hydromorphological processes, as well on ecological processes and species composition. Moreover, gradual changes in climate (e.g. increased precipitation) may have caused similar changes to river systems, by changing vegetation composition and runoff patterns of river catchments.

Effects of embankments

The construction of embankments has resulted in a strong reduction of the active floodplains along rivers. Along the Delta Rhine, the river was already complete embanked at about 1400, but for other case studies this started from the 19th century (Table 8.3). Almost all rivers in Europe are embanked, and – hence there are only a few examples left of extensive, intact floodplains. The case study of the Danube Delta may serve as an example for such systems. In extensive floodplains, there are clear gradients in hydrologic residence time i.e. water age and hydraulic resistance, resulting in gradients of sedimentation and nutrients along the lateral dimension of floodplains. Along embanked rivers, however, such gradients are strongly shortened, because of the reduced width of the active floodplain.

Effects of pressures related to navigation

In Europe, large parts of river floodplains were already embanked and floodplains were partly used for agricultural purposes. However, the main channel river was still able to change its course, resulting in a more or less continuous formation of new habitats, such as island, point bars and abandoned channels. The main channel was still shallow, and in the river-bed there was a gradient from coarse sands in the erosive zones to silt in the depositional areas. Thus, although these rivers did not represent pristine conditions, they were still dynamic with extensive land use that was largely adapted to the natural morphological patterns and processes (Middelkoop et al, 2005). Paleolimnological research along the Delta Rhine indicates that parts of the river banks may have been covered by macrophytes, while dead trees provide snag habitats which were important for a large number of macro-evertebrate species (e.g. Simulidae; Klink, 1989).

For many rivers, there have already been minor adjustments to the river bed to facilitate navigation. From the start of the Industrial Revolution however, there was a strong need to improve conditions for navigation. Consequently, groynes were constructed, river banks of the main channel were protected with rip-rap and the main channel was deepened. Additionally, dead wood (snag habitat) was removed. As a result, the rejuvenation of the landscape stopped due to the fixed position of the main channel. This has had strong impact on hydromorphological processes and species composition. Because of the fixed main channel, the continuous formation of new river habitats ceased while succession continues, and thus the overall landscape age increases. This has resulted in a dramatic change in landscape composition in favour of species typical for less dynamic habitats, as was shown and discussed in several studies (Petts and Amoros, 1996, Johnson, 1997, Hughes, 2001, Marston et al., 1995, Tockner and Stanford, 2002). It takes quite some time for such effects to become visible in the landscape. An observed high biodiversity is often a relict of former conditions that will develop towards a lower diversity and a shift in landscape position (Geerling, 2008; Bravard et al., 1986, Tockner and Stanford, 2002). In such a setting, floodplain age distribution can develop as shown in Figure 8.1. In addition to rejuvenation, succession will also cease in landuse in the floodplains is (partially) changed towards agriculture, as is the case along many regulated rivers. Some ecotopes are converted to pastures or fields, while other will remain in a more natural state. The latter will become relic ecotopes that stay in ecological succession, e.g. relic disconnected side channels. Such a landscape has 'gaps' in its age distribution; it is a temporal discontinuous landscape (Geerling, 2008; Figure 8.2). These relic ecotopes move toward older succession stages, similar to developments in figure 8.1.

Although data is scarce, it can be assumed that this has resulted in a strong decline of many riverine species. Nowadays, a large number of riverine species characteristic for young, dynamic habitats are extinct or have strongly declined in number.

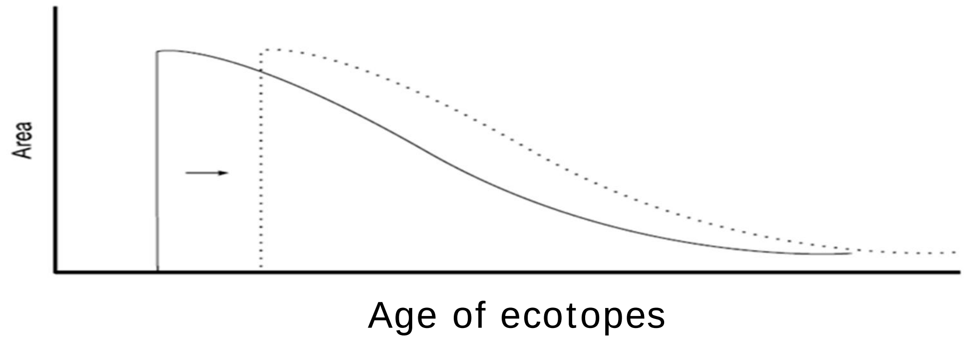

Figure 8.1 Conceptual graph of a hypothetical area versus age of natural ecotopes of river with habitat rejuvenation (solid line) versus a regulated river without rejuvenation (dotted line). Along regulated rivers, existing ecotopes continue their succession, while pionier sites are disappearing (after Geerling, 2008).

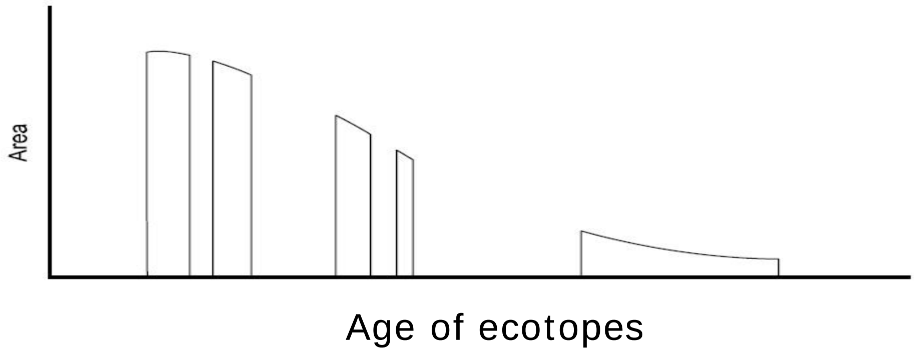

Figure 8.2 Conceptual graph of a hypothetical area versus age of natural ecotopes in regulated river floodplains without rejuvenation and with landuse changes to agriculture (after Geerling, 2008).

Construction of dams

In many rivers, large dams have been constructed, especially after the Second World War. There are many comprehensive reviews of the hydromorphological effects and ecological impacts downstream of dams (e.g. García de Jálon et al. 2013 and references in this report). Overal, the ecological impact of dams often result in three types of environmental alterations (Rood, 2005), viz.: (1) changes in the released flow regime (quantity and quality); (2) reduced passage of alluvial materals, in particular suspended solids, and (3) fragmentation of the river corridor, resulting in interruptions in downstream and upstream passage of biota (e.g. diadromous fish species).

From pressures to measures

Between the case studies, there are some striking differences in the measures that are taken (Table 8.4). Along low gradient lowland rivers, such as the Lower Danube and the Delta Rhine, measures focus on the restoration of the lateral connectivity gradient in floodplains. Along this river section, large parts of the floodplains have been embanked over the past century, and have subsequently been used for agriculture or aquaculture (fish ponds). Along the Lower Danube, large areas of the (formerly active floodplains) may be reconnected to the river by opening of the embankments. Also along the Delta Rhine in The Netherlands, the connectivity between the river and floodplains is partly restored by relocating of embankments, removal of minor embankments and lowering of aggraded floodplains. The surface area of these measures is however, much smaller compared to the Lower Danube.

Because of constraints related to navigation, only a limited number of measures are taken that improve conditions for rejuvenation of the river landscape. Along the river Trent and Po (and to some extent, the Delta Rhine), measures are taken that increase variation in width and depth of the main channel, which is an important variable for the occurrence of several hydromorphological processes in rivers. Restoring conditions for island and shoal formation will only be carried out along the river Vistula, for which navigation is not an important driver.

Do the measures eliminate or mitigate the pressures?

Between the case studies, there are large differences in the occurrence of pressures, and the measures that are taken to eliminate or mitigate them. Relative intact river stretches, such as the case studies of the Vistula and Danube delta, have a low number of pressures, and – hence – a relative small amount of measures can be taken to improve ecological conditions. Highly regulated rivers such as the river Trent and Delta Rhine, have a high number of pressures, and – consequently – a large number of measures are taken. By contrast, the Mediterranean Rivers Ebro and Po are also highly regulated, but along these rivers only a small number of measures are planned so far.

Recommendations

The river training works have drastically decreased the morphodynamic nature of the Delta Rhine, and have considerably levelled out the natural variation in hydro-morphodynamics. Island formation cannot occur in any reach of the Delta Rhine because of the artificial reduction of the Width/depth ratio. The Waal is the only reach where alternating banks still may develop. In addition, dredging practices for maintenance of the fairway channels prevents the formation of sand bars and islands. Ecotopes associated with channel migration, such as backwaters or residual channels no longer develop, because the channel banks have been fixed.

Conclusions

In many case studies, emphasize is given to the rehabilitation of highly dynamic habitats (and processes) which are situated close to main channel. Far less attention is given to the importance of low-dynamic, rarely flooded habitats, as well as to vertical connectivity and the importance of time (succession: long term *versus* fluctuations short-term).

Table 8.4 Measures for river rehabilitation along the rivers Trent, Po, Vistula, Ebro, Delta Rhine and Danube delta

Restoration or mitigation measure	Trent	Delta Rhine	Po	Ebro	Vistula	Lower Danube & Danube delta
Quantity and dynamics water flow						
Natural water level fluctuations				1		
Weir/sluice/hydropower management						
Reduce water abstraction						
Restoring continuity/fish migration						
Restoring connectivity to tributaries		1				
Fish passage	1	1	1	1		
Downstream fish guidance systems						
Morphology: variation in width/depth						
Main channel widening					1	
Remeandering	1					
Increase lateral migration of channel	1		1			
Addition of sediment	1		1?			
Restoring conditions for island/shoal formation					1	
Structure of riparian zone						
Side channel	1	1	1			
Downstream connected side arm		1				
Connecting man-made water bodies	1	1				1
Longitudinal dams		1				
Natural riparian zones	1	1	1		1	1
Groyne adjustment		1			1	
Increase/restore wetlands	1	1				1
Increase/restore meadows		1			1	
Flow disrupter						
Large woody debris in stream	1	1				
Reactivating floodplains						
Opening embankments		1				1
Relocating embankments		1				
Lowering aggraded floodplains		1				
Ongoing pressures						
Construction of weirs					1	

8.1 ***References***

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Appendix I. Information asked to different partners for case studies

To all contributors of the case studies, the following information was asked to include in the reviews:

Introduction and Characterisation:

- Locale of the river stretch, country, climate, geology.
- Maps / aerial photographs
- Name
- General characteristics of the large river stretch (length, catchment size, low, mean and flood discharge, slope, width). Short physical description.
- Use Gurnell et al. (2014) to characterise the river systematically on the various spatial scales. The lowest scale is the scale of your case study area/river.
- If present in "rivers of Europe" give a reference.
- Images of present situation

Historical situation or reference situation:

- Describe the historical state (preferably prior to major regulations; indicative 100 – 200 years ago). When applicable, use terms of Gurnell et al. (2014).
- If known and used, give a reference river.
- Use pictures, maps of historical states, and/or images of the reference situation.

Drivers: socio economic functions:

- List and short description of the socio economic functions / drivers (those who instigated the pressures, see below). "Where is the river used for?"
- If possible, and drivers have changed through time; give a timeline of the occurrence of drivers.
- Images of functions or uses are welcome.

Pressures and effects on processes:

- What are the present pressures and constraints to improve ecological status, the list of pressures as formulated on www.wiki.reformrivers.eu was used, add to it when needed. Differentiate:
  - in general the upper catchment, only in case of downstream effects,
  - in more detail the case study site,
  - indicate when the pressures were applied on a timeline (years as max detail).
- Use García de Jálo et al. (2013) (deliverable 1.2 REFORM) to describe the effects on processes and major state variables.

Effects on ecology of pressures:

- Use the systematic description of previous paragraphs together with any known studies to estimate or describe the effects on hydromorphological and ecological processes and ecology (species).
- Minimally describe effects on fish, macro-invertebrates, aquatic flora.
- Other biota only if specific for the case study at hand or when typical for the case study
- Qualitatively on historical time scale (what has been lost since historical reference)
- End with present ecological state
- If possible quantitatively based on available studies

Rehabilitation and mitigation measures:

- Use the list in they wiki.reformrivers.eu to show what measures are being carried out. Add to the list if necessary.
- Planned measures (referring to 1st RBMP – programme of measures and Natura 2000)
- Quantify the amount of measures per type, or show on a map, or table.
- If possible show a timeline (years as max detail) the implementation (historical, planned if possible)

Ecological effects of measures:

- Indicate which measures have been evaluated in the case study, and which measures have not been evaluated.
- Give a summary of results for the evaluations if possible based on reports or literature specific for the case study (not general literature that is outside the scope of the case study). Preferably quantitative if available.
- Use graphs if available.
- Minimally describe effects on fish, macro-invertebrates, aquatic flora.
- Other biota only if specific for the case study at hand or when typical for the case study

General remarks or conclusions

Reference list

García de Jálo D; Alonso C, Gonzalez del Tango M, Martinez V, Gurnell A, Lozrenz S, Wolter C, Rinaldi M, Belletti B, Mosselman E, Hendriks D, Geerling G (2013) Review on pressure effects on hydromorphological variables and ecologically relevant processes. Deliverable D1.2 “Effects of pressures on hydromorphology” REFORM.

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