First publ. in: Rivers of Europe / Klement Tockner u.a. - London: Acad. Pr., 2009, pp. 199-245 - ISBN 978-0-12-369449-2

The Rhine River Basin

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6.1. INTRODUCTION

Nine countries are in part or entirely situated within the Rhine catchment, namely Austria, Belgium, France, Germany, Italy (only 51 km^2), Liechtenstein, Luxemburg, The Netherlands and Switzerland. With a total length of about 1250 km, a drainage area of 185 260 km^2 and an average discharge of about ~2300 m^3/s, the Rhine ranks 9th among Eurasian rivers. The Rhine is the primary artery of one of the most important economic regions of Europe (annual gross domestic product of ~1750 billion US$). The human population of the basin equals ~58 million, many of them crowded in large urban areas extending along the river between Rotterdam and Basel. The Rhine provides services for transportation, power generation, industrial production, urban sanitation, drinking water for 25 million people, agriculture and tourism, and is a classic example of a 'multipurpose' waterway (Cioc 2002). The Rhine has greatly influenced the history, culture, and economy of Europe over the last 2000 years. On the other hand, its ecological integrity and biodiversity have been severely affected by human activities, particularly in the last 200 years (Friedrich & Müller 1984).

In this chapter, we first give a general overview of the Rhine basin and subsequently portray different aspects of the six morphologically distinct river sections (Figure 6.1a, b, Table 6.1) (Lauterborn 1916) that developed during the genesis of the river. These are: (1) The Alpine Rhine (Alpenrhein) and its tributaries, that is, the reach between the Rhine source (Lake Toma) and Lake Constance, (2) the High Rhine (Hochrhein) that flows from lower Lake Constance to Basel, there merging with the Aare, a paramount tributary of the Rhine with respect to discharge, (3) the Upper Rhine (Oberrhein), flowing through the rift valley of the Rhine Graben that extends from Basel to Bingen with the Neckar and Main Rivers as major tributaries, (4) the Middle Rhine (Mittelrhein), flowing through a narrow valley deeply incised in the Rhenish Slate Mountains and picking up waters of the Mosel River at Koblenz, (5) the Lower Rhine (Niederrhein), extending from Bonn to Lobith with Ruhr, Emscher and Lippe Rivers as major tributaries and (6) the Delta Rhine, where the discharge is divided in three major branches called Nederrijn–Lek, Waal and IJssel.

6.1.1. Historical Perspective

Early evidence of human presence in the Rhine catchment comprises the jaw bone of *Homo heidelbergensis* (400 000–700 000 years BP) and bones of *Homo neanderthalensis* (42 000 years BP). About 35 000 years ago, modern man (*Homo sapiens*) spread out across Europe. The tracks left by hunters in the last Ice Age and early postglacial include tools, hunting gear and prey leftovers, which have been found at numerous sites within the Rhine basin. As a consequence of postglacial warming, tundra that originally extended between the ice shields of Scandinavia and the Alps was invaded by trees; about 7000 BP vast forest covered Europe between the Atlantic coast and western Russia (Küster 1999). The loss of hunting grounds limited the size of the human population, except for the Neolithic culture that adopted agriculture from the Middle East to central and western Europe (6000–7000 years BP).

After 800 BC, western and central Europe and the Alps were settled by the Celts, presumably originating from late Bronze Age cultures. Their heritage includes numerous archaeological artefacts such as weapons, fineries, tombs, fortresses, and the names of streams and rivers. The name of the Rhine is of Celtic origin (Renos), which means flowing water. The Rhine becomes part of written human history with the arrival of the Romans. Caesar crossed and bridged the Rhine in 55 and 53 BC, and also gave a first description of the Rhine in his commentaries on the Gallic War 'The Rhine rises in the land of the Lepontii, who inhabit the Alps. In a long swift course, it flows through the territories of Nantuates, Helvetii, Sequani, Mediomatrices, Triboci and Treveri'. On its approach to the Ocean it divides into several streams, forming many large islands, and then through many mouths it flows into the Ocean (cited in Cioc 2002). Plinius wrote about the dwelling places in the delta as 'There throws the Ocean itself, two times a day, daily and nightly, in a tremendous stream over a wide country, so one is in doubt if the ground belongs to the land or to the sea. There is living a miserable people on the highest known level of the tide and at these they built their huts, living like sailors when the water covers their environment and like shipwrecked when the water has gone' (Huisman et al. 1998).

With the conquest of Gaul, the Rhine between the sea and Neuwied (Middle Rhine) became part of the northern frontier of the Roman Empire (12–9 BC). The Romans fortified the border (Limes) from Neuwied in a southeast direction to the Danube at Regensburg, thereby extending the empire across the right bank. The Roman legacy includes many cities along the Rhine such as Chur (Curia) on the Alpine Rhine, Basel (Basilea), Mainz (Mogontiacum), Koblenz (Castellum apud Confluentes), Cologne (Claudia Ara Agrippinensium) and Nijmegen (Ulpia Noviomagus Batavorum). In the 3rd century AD, Germanic tribes increasingly ~~invaded~~ the area on the left bank, which was finally abandoned about 260 AD, and the Rhine then became the empire border between Lake Constance and the North Sea. Roman rule in the Rhine basin ended about 400 AD with the invasion of Germanic tribes.

After 500 AD, the Rhine was part of the Kingdom of the Franks and with the coronation of Charlemagne (800 AD) it became the central axis of the Holy Roman Empire. In the following centuries, the empire became increasingly fragmented into numerous duchies, ecclesiastical and knightly states, each pursuing their own policy with growing success. In 1581, the seven northern provinces of The Netherlands declared independence from Spain. At the end of the Thirty Years' War (1618–1648), The Netherlands and the Swiss Confederation, territories that included the Delta Rhine and Rhine headwaters, left the Holy Roman Empire. The expansion policy of Louis XIV, king of France, ended with the annexation of Alsace (1681) by which the Upper Rhine became the border river between the Kingdom of France and the Holy Roman Empire.

During the French Revolution and subsequent Napoleonic wars, the Rhine came completely under the influence of France. In 1806, the Holy Roman Empire was dissolved and the number of independent territorial units drastically reduced. The remaining duchies, principalities, and kingdoms joined together as the Confederation of the Rhine (except for Austria, Prussia, Holstein and Pomerania). France annexed the west bank of the Rhine, which became the northeast border of France between Basel and the Napoleonic Kingdom of The Netherlands, which was annexed by France in 1810. Although the Congress of Vienna (1815) redrew the political map of Europe, changes within the area right of the Rhine were small except for Prussia gaining major territories along the Lower and Middle Rhine that included Rhineland and Westfalia. After the Franco-German War (1870–1871), the unified German Empire annexed Alsace and Lorraine and the Rhine became entirely German between Basel and Lobith. At the end of World War I (1918), both territories returned to France. The administration of Alsace and Lorraine by the Government in Berlin during World War II was a short episode. Today, all countries in the Rhine basin are members of the European Community except for Switzerland and Principality of Liechtenstein.

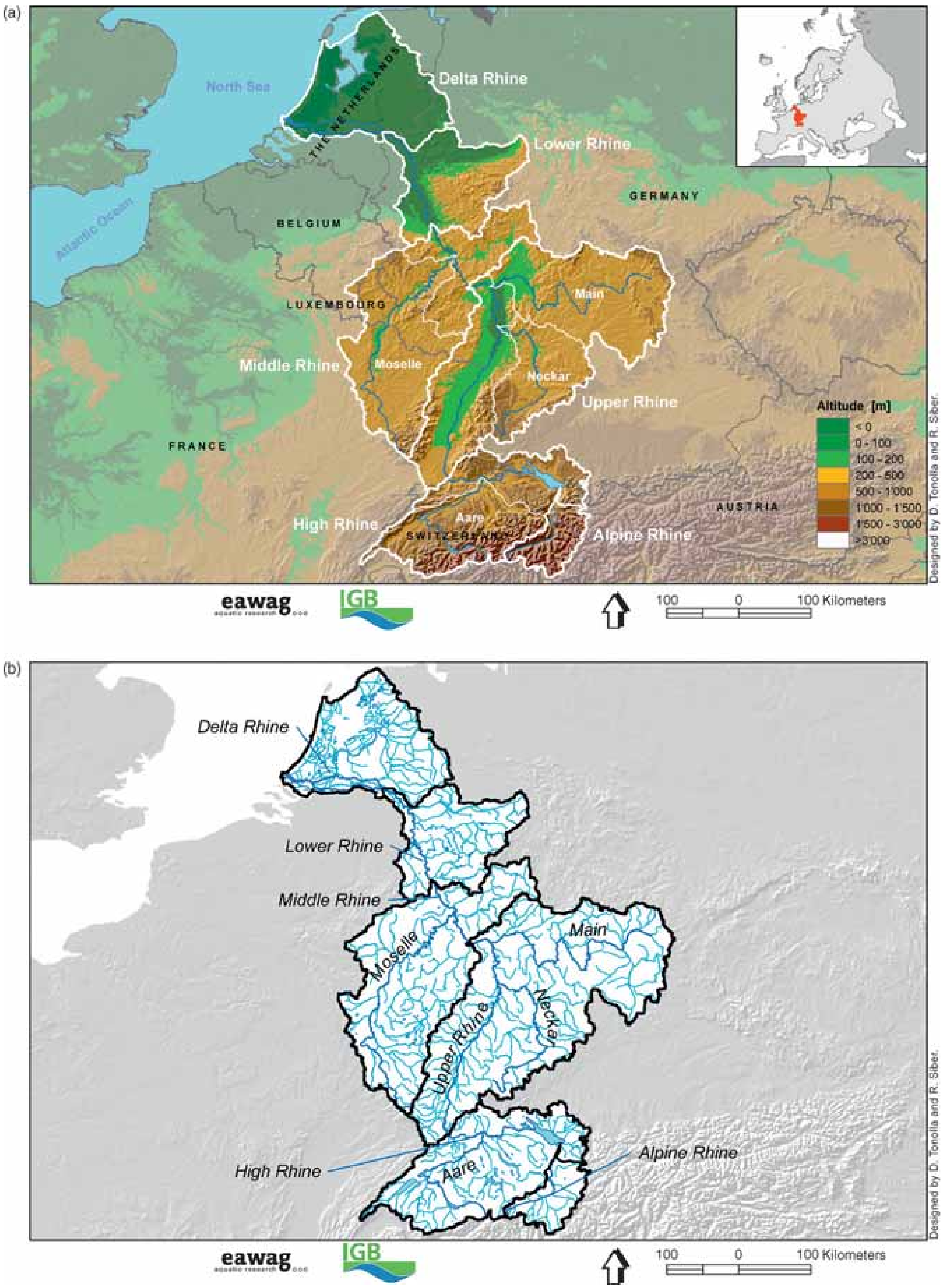

FIGURE 6.1 Digital elevation model (upper panel) and drainage network (lower panel) of the Rhine River Basin.

TABLE 6.1 General characterization of the Rhine River Basin

	Alpine Rhine	High Rhine	Upper Rhine	Middle Rhine	Lower Rhine	Delta Rhine	Aare (High Rhine)	Neckar (Upper Rhine)	Main (Upper Rhine)	Moselle (Middle Rhine)
Mean catchment elevation (m)	1764	902	348	336	202	12	1067	432	345	342
Catchment area (km^2)	6155	30 148	62 967	41 810	18 836	25 347	17 606	13 950	27 251	28 133
Mean annual discharge (km^3)	7.3[a]	33.4[a]	50.1[a]	64.4[a]	72.4[a]	>72.4	17.6[a]	4.7[b]	7.1[c]	10.3[d]
Mean annual precipitation (cm)	192.6	134.9	73.5	81.1	79.7	76.4	148.9	75.7	65.5	84.1
Mean air temperature (°C)	2.7	6.8	8.6	9.0	9.0	9.2	6.1	8.6	8.2	9.1
Number of ecological regions (see Chapter 1)	2	2	1	2	2	1	2	1	1	1
Dominant (≥25%) ecological regions	2	2; 70	70	70	6; 70	6	2; 70	70	70	70
Land use (% of catchment)										
Urban	0.4	0.9	2.1	1.1	9.0	3.9	0.7	2.1	1.8	1.0
Grassland	6.8	1.6	0.0	0.0	0.2	0.1	2.7	0.0	0.0	0.0
Cropland	19.8	55.0	74.1	83.5	79.4	89.7	50.5	74.6	80.2	84.6
Shrub	17.9	3.1	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0
Forest	52.4	32.4	23.7	15.1	10.9	1.9	32.3	23.3	18.0	14.1
Barren	1.3	1.7	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0
Wetland	1.4	0.2	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
Open water	0.0	5.2	0.2	0.3	0.6	4.4	5.4	0.0	0.0	0.3
Protected area (% of catchment)	0.0	0.4	0.2	0.3	1.0	0.9	0.4	0.0	0.0	0.5
Water stress (1–3)										
1995	2.0	1.9	2.0	2.0	2.0	2.1	1.9	2.0	2.0	2.0
2070	2.1	2.0	2.1	2.0	2.0	2.2	1.9	2.1	2.1	2.0
Fragmentation (1–3)	3	3	3	2	2	1[e]	3	3	3	3
Number of large dams (>15 m)[f]	0	0	0	0	0	0	3	0	0	0
Native fish species[g]	17	31	39	30	33	35				
Non-native fish species[g]	2	5	17	11	4	11				
Large cities (>100 000)	0	3	15	5	14	13	2	3	4	3
Human population density (people/km^2)	57	229	299	172	668	492	192	380	242	150
Annual gross domestic product ($ per person)	46 469	56 429	28 296	23 819	25 639	25 185	65 169	30 780	28 047	23 915

Catchment boundaries see Figure 6.1a.

[a] *Mean 1931–2003.*

[b] *MUV BW (2005).*

[c] *BSUFV 2004.*

[d] *IKSMS (2005).*

[e] *Of the three Delta Rhine distributaries only the connection Waal-Nieuwe Waterweg is not impeded by weirs or dams.*

[f] *No large dams along the main stems of the Rhine an the major Rhine tributaries except from the Aare (3 dams in the uppermost 9 km of the headwater reach*

[g] *IKSR (2002b).*

For data sources and detailed exlanation see Chapter 1.

Up to the early 19th century, the economy in the Rhine catchment was primarily based on agriculture and relatively small-scale manufacturing, including mining and metallurgy in mountainous areas. The impacts of theses activities were mostly local. This changed dramatically with development of the coal and iron industry, particularly in Rhineland–Westphalia. The chemical industry along the Rhine from Rhineland–Westphalia to Basel and the tributaries Wupper, Main and Neckar, and rapid urbanization that manifested in the Frankfurt–Wiesbaden, Ludwigshafen–Mannheim and Basel further increased human impacts in the catchment. In the German part of the Rhine catchment, the population increased between 1819 and 1970 from 5.4 to 32 million (Kalweit 1976). As a consequence, the Rhine became increasingly affected by domestic and industrial sewage. The first sewage treatment facility was established in 1887 in Frankfurt and more cities followed, but these efforts did not keep pace with the growing wastewater production. Moreover, authorities were hesitating in imposing restrictions believed to impede industrial growth (Cioc 2002).

Until the early 20th century, the impact of pollution was locally limited in the High, Upper and Middle Rhine reaches. The entire Lower Rhine suffered from heavy pollution, primarily from sewage outfall from the industrial centres in the Ruhr district. Water quality continued to deteriorate until the mid 1970s, although a short recovery period after World War II resulted from the destruction of industrial and urban sanitary facilities. It also became increasingly difficult to withdraw drinking water from Rhine because of high salinity resulting from the Alsatian potash mines dumping wastes into the river. The need to handle general pollution issues lead in 1950 to the establishment of the International Commission for the Protection of the Rhine (ICPR) in which all riparian states were represented. The Bern Convention of 1963 became the legal foundation of the ICPR, to which the European Community became affiliated in 1976. The Convention on the Protection of the Rhine against Pollution (Bern 1999), replacing the conventions of 1963 and 1976 (Convention on the Protection of the Rhine against chemical pollution), also dealt with ecological issues and flood risk management. In 2001, the Conference of Rhine Ministers in Strasbourg adopted a program for sustainable development of the Rhine ('Rhine 2020'). This program aimed to combine ecology with flood prevention, surface and groundwater protection, and comparably considers ecological, economic and social aspects. The International Commission for the Hydrology of the Rhine basin (CHR/IKHR) was founded in 1970 and aimed to expand knowledge on the hydrology in the Rhine basin, contribute to the solution of cross-border problems, and develop joint hydrological measures for sustainable development of the Rhine basin. Member states of the CHR are Austria, France, Germany, Luxembourg, The Netherlands, and Switzerland.

On 1 November 1986 during a warehouse fire of the Sandoz company in Schweizerhalle near Basel, about 20 tons of pesticides, dyes, solvents, raw and intermediate chemicals were flushed into the Rhine and, over a distance of 400 km, killed all fish and other organisms, and prompted a drinking water alert from the Swiss border to The Netherlands. This disaster led the ICPR to set up the Rhine action program with ambitious water goals such as reducing the discharge of noxious substances and restoring the rivers original flora and fauna. Many of these goals have been met. Noxious substances were cut by 70–100% and heavy metals were significantly reduced. Still problematic are nitrogen, pharmaceuticals, and hormone active substances, but within a period of $\sim$30 years the water quality of the Rhine experienced a significant improvement (see Section 6.5.3). Between 1970 and 1990, $\sim$40 billion Euros were spent for installation of new and efficient sewage treatment facilities.

In the 19th and 20th centuries, river engineering driven by flood protection, agricultural land reclamation, and navigation transformed the Rhine from a morphological near-natural state to a confined channelized river. This affected the Alpine Rhine (e.g., Photo 6.1) as well as Upper, Lower and Delta Rhine. Before the 19th century, the impact of flood protection on river morphology was usually local, except for the Lower Rhine and Delta Rhine (Table 6.2). Land use in floodplains already resulted in the Middle Ages to the loss of floodplain forests along the Lower Rhine (Tittizer & Krebs 1996). Before the late 18th century, humans were highly effective in modifying vegetation, but lacked the technical and socio-economic resources necessary for the realization of large river training projects (Vischer 2003).

The Rhine was used for the transport of goods in prehistoric times, but during the Roman period it became an important trade route (Böcking 1980). Initially, it was the Roman fleet operating on the Rhine during the wars against Germanic tribes. Later, ports and quays to unload goods from barges and rafts were established in prosperous towns along the Rhine. With the beginning of invasions by Germanic tribes, trade and navigation on the Rhine started to decline and presumably ended before it resumed during the Carolingian period. Until the 19th century, rapids and shifting gravel or sand bars imposed major physical restrictions on navigation. In addition, the patchwork of independent territories along the river severely hampered navigation through numerous and often arbitrary restrictions, duties and privileges. Imposing tolls and taxes on ships and cargo was a common practice along the entire river since the Romans. Several castles along the Middle Rhine are a testimony of the medieval toll-collecting practices.

Navigation was dominated by downriver transport by rafts, barges and sailing boats. For upstream transport, barges had to be towed by horse- or manpower, which required the maintenance of towing paths along the river banks. In 1815, the principle of freedom of navigation on international waterways was established in the Final Act of the Congress of Vienna. To enforce common rules and communication between the riparian states (Prussia, Hesse, Nassau, Baden, Bavaria, The Netherlands and France), the Central Commission for the Navigation of the Rhine (CCNR) was constituted

(a)
(b)

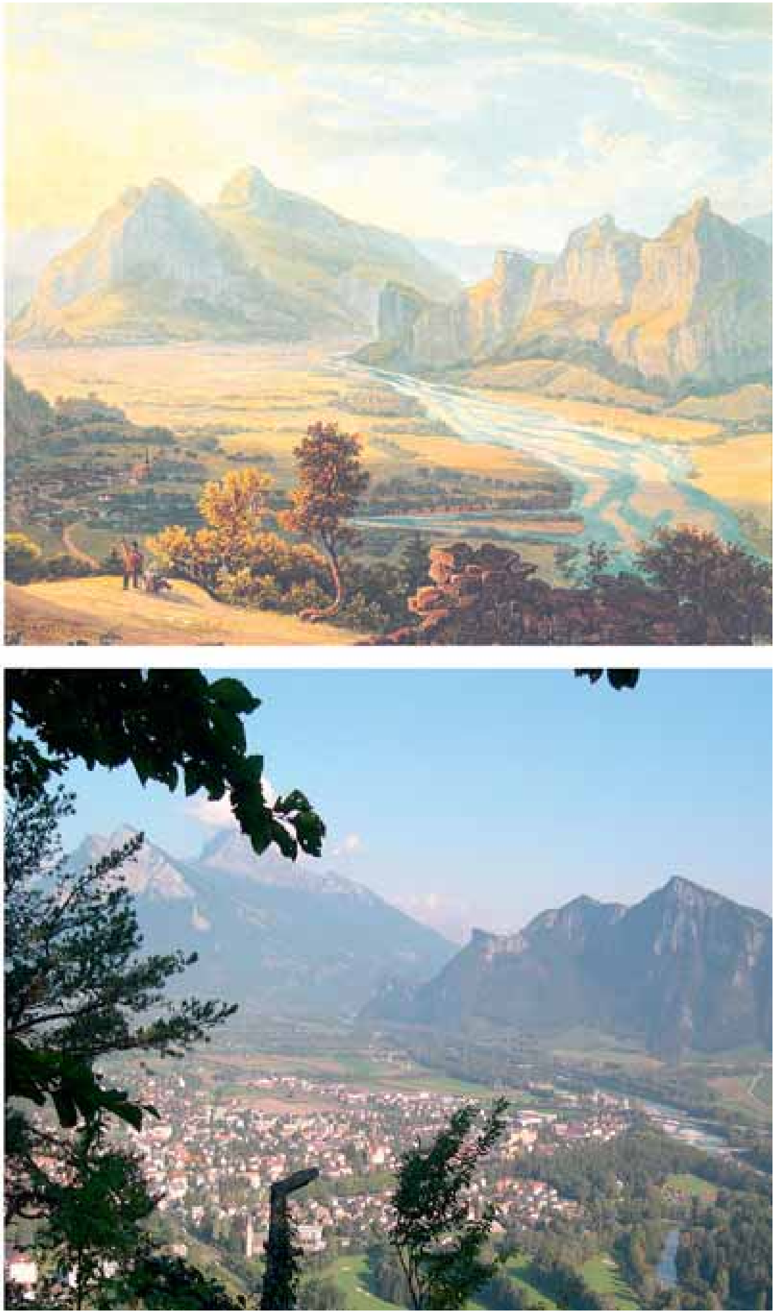

PHOTO 6.1 Alpine Rhine (Alpenrhein) near Bad Ragaz (about 100 km from the source) in 1826 (detail of an aquatinta by J. Schmidt, upper panel) and in 2005 (photo U. Uehlinger, lower panel).

(1816). However, the prospect of an open Rhine was not generally appreciated because some players faced to lose their private privileges and transfer rights. After a partial solution to these conflicts (Mainz Acts 1831), the remaining issues were finally resolved in 1868 (Mannheim Acts) and free navigation on the Rhine became a reality. As part of the Versailles treaty of 1919, the CNNR was moved from Mannheim to Strasbourg, and Belgium, Italy and Switzerland became Committee members along with The Netherlands, Germany and France, which was excluded between 1871 (end of the Franco-German War) and 1918.

Modern Rhine navigation began with the appearance of self-propelled ships. The first steamboat 'Prince of Orange' arrived from Rotterdam in Cologne in 1816, and the first steamboats reached Strassbourg in 1825 and Basel in 1832. Steam-powered tugs already towed barges around 1840. Diesel-powered freighters appearing in the 1920s displaced the tug-barge systems into the 1950s when the first push-tow units started to navigate on the river (Böcking 1980). Today the Rhine is navigable between the sea (Rkm 1033[1]) and Rheinfelden (Rkm 147). All major natural obstacles impeding navigation have been

1. The kilometration (mileage) of the Rhine begins in Constance at the outflow of upper Lake Constance at Rkm 0.0 and ends in Hoek van Holland at Rkm 1032.8.

TABLE 6.2 Major human interventions in the Rhine Delta since the Middle Ages (Lenders 2003; Ten Brinke 2005)

Period AD	Intervention
1150–1450	Construction of primary dikes
1570–1600	Creation of connections between rivers Meuse and Waal
1595–1680	Construction of groines at Rhine bifurcation points
1639–1655	Meander cut-off in river Waal
1600–1900	Construction of summer dikes
1700	Engineering work on Rhine branches Waal and IJssel
1707	Opening of Pannerdensch Kanaal
1727–1734	Closing of Waal–Meuse connection at Heerwaarden and Voorn
1775–1782	Meander cut-off in Waal, new bifurcation of Pannerdensch Kanaal into Nederrijn and IJssel and modification of bifurcation at Pannerdensche Kop
1850–1870	Digging of the Nieuwe Merwede and opening Nieuwe Waterweg (Rotterdam)
1850–1885	First river training at Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn, Lek and IJssel
1869–1885	Modification of the IJssel river mouth
1874–1906	Meander cut-off and correction of river bends in Nederrijn
1888–1890	Second river training at Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn, Lek and IJssel
1912–1934	Third river training at Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn, Lek and IJssel
1927	Digging of Meuse–Waal canal (Nijmegen)
1952–1953	Construction of Amsterdam–Rijn Kanaal and modification of Pannerdensch Kanaal
1954–1967	Construction of three weirs in the rivers Nederrijn–Lek
1954–1969	Meander cut-off in the river IJssel
1961–1997	Delta project with closure of former estuary Haringvliet and the storm-surge barriers in the Oosterschelde and Nieuwe Waterweg
1900–2006	Large-scale sand and gravel excavations

removed, and the only temporary constraints on navigation are flow extremes.

The wish to expand navigation routes across catchment boundaries led to the construction of navigation canals that connected the Rhine with the rivers Scheldt (1832), ~~Rhone~~ (1833), Seine (1853), Elbe (1938) and Danube (1843 and 1992). The first attempt (793 AD) to overcome the divide between the Main River and the Danube failed (Fossa Carolina). In 1843, Bavaria finally completed a canal connecting the Main River with the upper Danube, but water shortage and numerous locks impeded navigation from the beginning. From 1960 to 1992, the connection of the Main and Danube was upgraded to a modern waterway. The 55-m wide and 4-m deep Main–Donau–Kanal is suitable for navigation with push-tow units. These navigation canals also opened immigration routes for aquatic organisms from different zoo-geographic provinces (Bij de Vaate et al. 2002; Leuven et al. 2009).

6.2. BIOGEOGRAPHIC SETTING

The Rhine basin contains parts of three biogeographic regions – Alpine, Continental and Atlantic – and four ecoregions – conifer and mixed forests of the Alps, western European broadleaf forests, and the northern and southern temperate Atlantic region. The range of latitude extends from Atlantic climatic conditions in the Rhine delta to a moderate continental influence in the southeast Alpine forelands. It spans a fairly wide altitudinal range from sea level to the cryosphere of the high Alpine mountain range. At altitudes above ~2000 m asl, alpine vegetation (grasslands) prevails. In the transition zone from alpine grasslands to timberline, vegetation is characterized by dwarf shrubs. Subalpine forests dominated by fir (*Picea abies*) extend between 1200 and 2000 m asl. Common trees in the forests of the Alps, Black forest, Jura and Vosges (600–1600) include spruce (*Picea abies*), fir (*Abies alba*), beech (*Fagus silvatica*), sycamore (*Acer pseudoplatnus*) and ash (*Fraxinus excelsior*). Different types of beech forests and mixed beech forests prevail at lower elevations. Floodplain vegetation includes willow (*Salix* spp.) and poplar (*Populus nigra*, *P. alba*) forests in frequently inundated areas. In areas less influenced by inundation, floodplain forests include oak (*Quercus robur*), ash and elm (*Ulmus* spp.) (Schnitzler 1994).

6.3. PALAEOGEOGRAPHY

The Rhine is the only large Alpine river flowing north to the sea, which resulted from a complex geological history. Over large parts, the river follows the European Cenozoic Rift System, which crosses different tectonic domains between the Mediterranean and North Sea (Preusser 2005). Crust movement (uplift, rift formation, large-scale tilting) and glaciation modified the Rhine course since the early Neogene (Figure 6.2). The uplift of the Black Forest and Vosges during early phases of the Alpine orogeny and subsequent rift valley formation (Upper Rhine Graben) founded the present Rhine system. The area that later became the Rhenish Mountains, rivers developed that drained north and south. As a consequence of rift formation and uplift, a precursor of

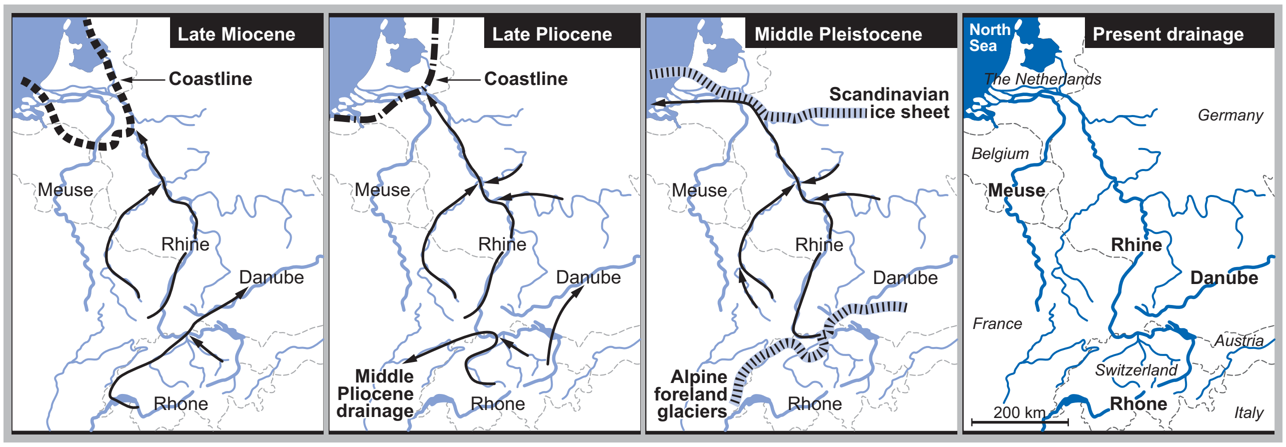

FIGURE 6.2 The Cenozoic evolution of the Rhine drainage after Preusser (2005) and Quitzow (1976).

the Rhine started to flow across the Rhenish Mountains, thereby directing the Moselle and Lahn Rivers to the north. With subsidence of the Upper Rhine Graben, Rhine headwaters moved east. In the late Pliocene, the Aare River, which was a Danube tributary, started to flow west along the depression between the Jura Mountains and Black Forest. The Main and Neckar Rivers increased their watershed size by capturing tributaries of the upper Danube.

The loss of the upper ~~Rhone~~ catchment, which was part of the Aare drainage, presumably occurred during the Pleistocene. The period between the late Pliocene and late Pleistocene is characterized by 15 major glacial advances from the Alps into the northern forelands (Schlüchter 2004). The advancing Alpine glaciers of the Mindel Ice Age crossed the Rhine/Danube and directed meltwaters to the west. Subsequent eastward regressive erosion of the High Rhine and its tributaries finally tapped the Alpine Rhine, which earlier drained to the Danube. During the Riss Ice Age, a branch of the Meuse River originating in the Vosges was directed to the north and became the upper Moselle River. The capture of the most southern headwater river of the Danube by a High Rhine tributary (Wutach River) occurred after the maximum of the Würm glacial stage (~20 000 years BP). Glacio-fluvial erosion also opened the top of a large karstic system near the Danube/Rhine, and today ~65% of the water of the upper Danube flows through a karstic drainage towards the Rhine.

During the Pleistocene, ~600 000–10 000 years BP, six major Ice Ages occurred in northwestern Europe (e.g., Berendsen & Stouthamer 2001). The sea level dropped 120 m and much of the continental margins became exposed. In the early Pleistocene, the Rhine followed a course to the northwest, through the present North Sea. During the so-called Elsterien glaciation (~420 000 years BP), the northern part of the present North Sea was blocked by ice and a large lake developed that overflowed towards the English Channel. There is evidence that two catastrophic floods (with an estimated discharge of 0.2×10^6–1×10^6 m^3/s and the largest on Earth) in 425 000 and 200 000 BP breached the Weald-Artois Anticline, which separated the North Sea from the English Channel, and finally reorganized the paleo-drainages of northwest Europe (Gupta et al. 2007). The last flood re-routed the Rhine–Thames river system through the English Channel, thereby forming the Channel River, one of Europe's largest paleo-drainages during the quaternary low sea-level stands. The mouth of the Channel River, which included waters of the Seine River, was located near Brest (France).

During interglacials, when sea level rose to approximately the present level, the Rhine developed a delta in what is now known as The Netherlands. During the last Ice Age (~70 000–10 000 years BP), at the end of the Pleistocene, the lower Rhine flowed roughly west through The Netherlands, then southwest through the English Channel, and finally to the Atlantic Ocean (Berendsen & Stouthamer 2001). The English and Irish Channels, the Baltic Sea and the North Sea were still dry land, mainly because the sea level was ~120 m lower than today. At about 5000 BC, flooding and erosion began to open the English Channel. Most of the Delta Rhine was not under ice during the last Ice Age. Tundra with Ice Age flora and fauna stretched across middle Europe from Asia to the Atlantic Ocean. Such was the case during the Last Glacial Maximum, ~22 000–14 000 years BP, when ice covered Scandinavia and the Baltics, Britain and the Alps, but left the space between as open tundra. Loess, or wind-blown dust, over that tundra settled throughout the Rhine valley, contributing to its current agricultural value. Meltwater to the ocean and land subsidence caused inundation of the former coast of Europe. Today, the sea level is still rising at a rate of ~1–3 mm per year.

6.4. PHYSIOGRAPHY, CLIMATE AND LAND USE

6.4.1. Geological Structure and Relief

The Rhine basin (average elevation 426 m asl), sloping from south to north, spans parts of three physiographic regions: (1) European highlands with the Alps, including their foothills and foreland, (2) the central upland and plateau regions, which includes the northeast Jura range, the Vosges, Black Forest, Rhenish mountains and South German Scarplands and (3) the northern lowland with the coastal plain. The Alps, including their northern foothills, contribute about 16 400 km^2 (8%) to the Rhine catchment. The geologically young mountain range of the Alps is characterized by a rugged topography, steep slopes, and deeply incised valleys. Mountains exceeding 3000 m asl typically have snow or ice covered summits. The highest peak of the Rhine catchment is the Finsteraarhorn at 4274 m asl.

Granitoids prevail in the headwaters of the Rhine and Aare, and limestone of the helvetic nappes in the northern front range. The adjacent northern Alpine foreland, a sedimentary basin simultaneously formed with the uplift of the Alps and filled with debris of the rising mountain range, extends to the southern fringes of the Swiss Jura and Suebian Alb. This area, shaped by several Pleistocene glacial cycles, is covered by moraines, gravels, sands and silt; Tertiary sediments still outcrop at several sites. The landscape is characterized by hills, wide valleys and lakes, the largest is Lake Constance. The South German Scarp land is made up of Triassic and Jurassic sediments slightly dipping east, with denudation surfaces, cuestas, escarpments, basins and valleys (Koster 2005a). Elevations range from 200 to 1000 m asl. Karstic features such as dry valleys, sinkholes or karst springs occur where limestone prevails.

The Central European Uplands within the Rhine catchment include the rift and valley ranges of the Vosges, Black Forest, Odenwald, Rhenish Slate Mountains, and Nahe-Saar Uplands. Relief is characterized by planation surfaces, cuestas, hogbacks, basin and deeply incised valleys. Black Forest and Vosges consists of highly metamorphic and granitic rocks partly covered by Permian and Triassic sediments. At elevations over 1400 m asl, Vosges and Black Forest became partly glacierized during the Pleistocene. The Upper Rhine Graben is a 310-km long and 35-km wide spectacular subsidence zone within the European Cenozoic Rift system (Illies 1972). The rift valley is fringed on the right side by the Black Forest, Odenwald and on the left side by the Vosges and Palatinate uplands. The base of the Tertiary valley fill ranges from 2000 to 3000 m and Quaternary deposits reach up to 200 m. Landforms include Pleistocene river terraces and alluvial fans extending from the rift flanks.

The Rhenanian Slate mountains are the remnants of the Hercynian Mountains, with predominantly Devonian and Carboniferous slates, greywackes and limestones (Koster 2005a). The folded and metamorphosed Paleozoic rocks form an extensive mountainous plateau deeply dissected by the Rhine and its tributaries. The Lower Rhine and Delta Rhine are part of the northern European Lowlands. The Lower Rhine embayment is currently one of the most active sectors of the European Cenozoic rift system (Schäfer et al. 2005). Fault zones fragmenting tertiary sediments in horst and graben extend from southeast to northwest. Quaternary glacial and fluvial deposits cover tertiary sediments and respective landforms include river terraces (particularly in the southern part) and moraines. The area is relatively flat with a relief typically of a few ten meters.

6.4.2. Climate

General climate of the Rhine basin is determined by its location in a temperate climate zone characterized by frequent weather changes. Precipitation occurs at any time of the year. From the sea to the east and southeast of the catchment, the climate gradually changes from maritime to more continental. General weather patterns during winter are primarily influenced by weather dynamics in the northern and eastern Atlantic, and in the North Sea. The Eurasian land mass also favours the formation of relatively persistent cold anticyclones over northeast Europe and western Russia, which temporarily reduce the influx of relatively warm humid air from the Atlanic.

Temperature and precipitation vary considerably with altitude and local topography. The mean annual temperature of the Rhine basin is 8.3 °C, 11.2 °C in the thermally favoured valley of the Upper Rhine, and <0 °C at elevations >3000 m asl. Precipitation in the basin averages 945 mm/year. The orographic effect of mountain ranges or uplands results in heterogeneous precipitation patterns at different spatial scales. In the upper (higher) basin (High Rhine and Alpine Rhine), yearly precipitation is ~1500 mm. Precipitation is high on the west slopes of mountain ranges such as the Vosges (1500–2200 mm/year) and Black Forest (1860–1960 mm/year) and peaks at the northern front range of the Alps at 2000–3500 mm (Hendl 1995; Schwarb et al. 2001). In contrast, the area in the rain shadow of the Vosges only receives 515–615 mm/year. In the Alpine parts of the basin about 30% of the annual precipitation falls during summer (June-August); seasonal differences are slightly less pronounced in the lower basin.

6.4.3. Land Use

About ~~74~~% of the Rhine basin area (185 263 km^2) consists of agricultural area, followed by forests ~~(20~~%), urban areas (~~2.6~~%) including 50 cities with >100 000 people, ~~open water (1.6%), shrubland (1.1%), barren areas (0.3%) and wetlands (0.1%)~~ (Table 6.1). Forest cover is maximum in the ~~Alpine Rhine~~ sub-basin ~~(52%~~) and minimum in the Delta Rhine (~~1.9%~~). Agricultural areas range from ~~20~~% in the basin of the Alpine Rhine to ~~about~~ ~~90~~% in the Delta Rhine. The urban area is maximum in the Lower Rhine basin with ~~9%~~.

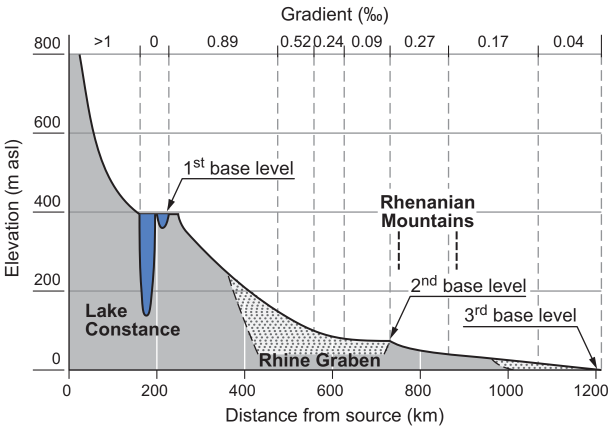

FIGURE 6.3 Longitudinal profile of the Rhine. Modified from Mangelsdorf et al. (1990).

6.5. GEOMORPHOLOGY, HYDROLOGY AND BIOGEOCHEMISTRY

6.5.1. Geomorphology of the Main Corridor

The longitudinal profile of the Rhine is characterized by two additional base levels of erosion apart from the sea (Mangelsdorf et al. 1990). The first level is Lake Constance, where the Alpine Rhine deposits its sediment load, and the second is the quartzite reef at the beginning of the Middle Rhine section near the town of Bingen (Figure 6.3). Upstream of each base level, the river attempts to establish a concave equilibrium curve. Valley side-slopes confine major parts of Alpine headwaters, the High Rhine, and Middle Rhine. Before major river engineering works, the river was braiding or meandering in naturally unconfined reaches of the Alpine, Upper, Lower and Delta Rhine.

The catchment area of the Alpine Rhine has an area of ~~6516~~ km^2 with elevations ranging from 395 m (Lake Constance) to 3614 m asl (Tödi). About 1.4% of the catchment is covered by glaciers, most of which are rapidly receding. The two major headwaters of the Rhine, Vorderrhein and Hinterrhein, lie on an old Oligocene relief (Keller 2006). The catchment of the Vorderrhein consists of granite, granodiorite and gneiss of the Gotthard massif, limestone, sandstone and marl of the Helvetic nappes that forms the northern boundary of the main valley, and gneiss, schist, quarzite and sandstone of the Penninic nappes in the northeastern part of the valley. Granite, gneiss, granodiorite, schists and triassic-dolomite of the Penninic and East-Alpine nappes characterize the geology of the Hinterrhein catchment.

The formation of the Alpine Rhine valley began at the end of the Miocene when a shear fault zone opened a new valley to the north (Handke 2006). With the retreat of the Rhine Glacier at the end of the last Ice Age (~16 000 BP), Lake Constance extended about 80 km into the valley of the Alpine Rhine. The Rhine and its tributaries rapidly filled this lake with sediments. In Roman times, the lake-shore was only 1–2 km south of the present shore line (Keller 2006). The geology of the Alpine Rhine catchment is characterized by limestone, sandstone and marl of the Helvetic nappes, and granite, gneiss, granodiorite, schists and triassic-dolomite of the Penninic and East-Alpine nappes. Near Lake Constance, Tertiary molasse sediments (conglomerates, sandstone) prevail.

The source of the 71.5 km long Vorderrhein is Lake Toma, a small lake at 2343 m asl on the east slope of the Gotthard massif in the central Swiss Alps, from where it flows east to the confluence with the Hinterrhein near Reichenau (583 m asl). Lake Toma is considered to be the source of the Rhine. After an initial steep descent, the Vorderhein flows through a relatively wide valley bordered by mountains with elevations >3000 m asl. Side-slopes and sediment deposition of tributaries naturally confine the river at many sites, but where the valley is wider the river braids. Between Illanz and Reichenau, the river has carved deep into the debris of a huge rockslide occurring 9487 years BP and mobilized 12 km^3 of Jurassic calcareous rock matter (Photo 6.2) (Schneider et al. 2004; Wassmer et al. 2004). At many sites the Vorderrhein has been channelized to gain and protect land for housing, transportation and agriculture (pasture). This reduced the length of the original braided reaches from 23 to 6 km.

The 57-km long Hinterrhein begins at the terminus of the Paradis Glacier (~2400 m asl) of the Rheinwald massif (maximum elevation 3402 m asl) and flows east for about 30 km before turning north. Two steep gorges (Roffla and Via Mala) divide the river corridor in three sections with one or more channels. For the same reasons as in the Vorderrhein, major parts of braided reaches were lost (thalweg reduction from 28 to 11 km). Between Via Mala and the confluence, where the valley is relatively wide, river engineering in the 19th century forced the Hinterrhein into a straight narrow channel. Only the last 4.5 km, characterized by a widely natural morphology, are listed today in the Swiss inventory of floodplains of national importance.

Near the town of Reichenau (582 m asl), Vorderrhein and Hinterrhein merge to become the Alpine Rhine, which flows into Lake Constance (396 m asl). In the upper 9 km of the 93 km long Alpine Rhine valley, the channel is deeply incised in the 1.5 km wide, valley floor (slope 3 m/km). The channel is about 60 m wide with coarse substrate prevailing (d_{90} = 20 cm). Between Reichenau and Lake Constance, the mean diameter of bed sediment particles decreases from about 10 to 2 cm. In the adjacent 71-km long reach, the Alpine Rhine was originally a braided river; at some locations the active channel width presumably exceeded 500 m. The tributaries Plessur (mean annual discharge (Q_{mean}) 8 m^3/s), Landquart (Q_{mean} 25 m^3/s^1) and Ill (Q_{mean} 66 m^3/s) supply large amounts of sediments. The valley floor with slopes ranging from 1 to 3 m/km varies between 3 and 4 km. In the last reach before Lake Constance, the valley floor becomes up to 15 km wide and slope decreases to 0.6 m/km.

Before regulation of this reach, channel patterns reflected the transition from a braided to a meandering river with

PHOTO 6.2 The Vorderrhein at Versam. The river is incised in the debris of prehistoric rockslide. (Photo U. Uehlinger).

channel widths originally ranging from 120 to 400 m. Today, channel morphology and plan view of the Alpine Rhine primarily reflects the comprehensive river engineering works of the 19–20th century aimed to provide flood protection for agricultural land and human settlements (Vischer 2003). The channel has a trapezoidal profile (width at the base 100 m) with a boulder riprap protecting the base of flood embankments between the confluences Rhine–Landquart (20 km downstream of Reichenau) and Rhine/Ill River (66 km downstream of Reichenau). Alternating gravel bars with backwaters are a typical morphological feature of this reach (Photo 6.3). The only remnant of the original braided reach is the 2.5-km long Mastrilser Rheinaue. Downstream of the Ill confluence, the shape of the channel cross-section becomes a double-trapezoid. The width of the main channel decreases downstream from 80 to 40 m; distances between the flood embankments vary between 200 and 400 m. Alternating bars are lacking because of the reduction in slope, sediment caliber and channel width.

The first river engineering works intended to enhance sediment transport but the channel aggraded, and as a consequence, increased the flood risk. Therefore, the channel was narrowed and gravel extracted. However, enhanced transport capacity and excessive gravel exploitation, in

PHOTO 6.3 Middle section of the Alpine Rhine with alternating gravel bars. (Photo U. Uehlinger).

PHOTO 6.4 High Rhine reach at Rkm 38 upstream of Schaffhausen. (Photo U. Uehlinger).

particular, (sediment transport was overestimated because the decrease in sediment caliber by abrasion proved to be smaller than assumed) resulted in channel erosion locally by several meters (Zarn et al. 1995). Efforts to stabilize the riverbed included the construction of boulder ramps and local channel-widening, in addition to a major reduction in gravel extraction. Today, the delta of the Alpine Rhine annually grows by 23 m into Lake Constance primarily due to the deposition of fine sediments since coarse sediments (gravel) are extracted near the river mouth. The separation of the Rhine by dikes from its former floodplain required the construction of side channels as recipients of side tributaries and groundwater. These channels drain parallel to the channelized river before they discharge into the Rhine or directly into Lake Constance.

Between the delta of the Alpine Rhine and the beginning of the High Rhine, the continuum of the Rhine main stem is interrupted for about 60 km by Lake Constance. This large naturally formed lake consists of two basins, the upper and lower Lake Constance, connected by a short (4.4 km) Rhine reach called 'Seerhein'. The respective volumes and surface areas of both lakes are 47.6 and 0.8 km^3 and 472 and 62 km^2, respectively. The High Rhine begins near the town Stein am Rhein as the outflow of lower Lake Constance and drains a catchment of 29 787 km^2 that includes the Aare catchment and the catchments draining into Lake Constance (without the Alpine Rhine). Elevations range from 246 m asl in Basel to 4274 m asl in the Aare catchment. The 142 km long High Rhine flows west from the lake (390 m asl, Rkm 22.9) to Basel (Rkm 165). The river is naturally confined by river terraces and the side-slopes of the Black Forest and Jura Mountains. Floodplains are lacking or restricted to narrow strips (Photo 6.4); the only significant floodplains originally existed at the Rhine–Thur and Rhine–Aare confluences.

Left-hand tributaries drain the south slopes of the Black Forest and parts of the southwestern spurs of the Swabian Alb. Right-hand tributaries include the two major High Rhine tributaries, Aare (Q_{mean} 559 m^3/s) and Thur Rivers (Q_{mean} 48 m^3/s), and smaller rivers draining the northeast Swiss Plateau and parts of the Jura Mountains. Downstream of the town of Schaffhausen (Rkm 45), the river is incised in glacial river terraces. The channel form is typically straight except for a double meander partly incised into the bedrock at Rheinau (Rkm 56). Channel slopes range from 0.03% in the upper 21-km long lake outlet reach to 0.8–1.3% in downstream reaches. Channel width varies between 120 and 150 m upstream of the Rhine–Aare confluence and averages 200 m downstream. Near-natural channel morphology, and hydraulic conditions prevail in most parts of the free-flowing reaches. Substrate is dominated by gravel; bedrock outcrops (Jurassic limestone or Black Forest granite) at a few sites, resulting in the formation of the 21-m high Rhine Falls near Schaffhausen and rapids such as upstream of Waldshut at Rkm 98 and in Laufenburg at Rkm 122. The Laufenburg rapids once hosted a spectacular salmon run that was lost because of dam construction.

The relatively steep and narrow High Rhine valley offers favourable conditions for the production of hydropower. The first run-of-river power plant was completed in 1866 in Schaffhausen. The energy produced was transmitted by steel cables (mechanical transmission) to factories that lined the river before the facility was upgraded with electric generators in 1898. Between 1898 and 1966, 10 additional hydroelectrical power plants were installed (the plant Albruck/Dogern has a 3.5-km long diversion canal) producing today 4400 × 10^6 kWh per year. The once swift flowing river is now a chain of impoundments (Photo 6.5) with only three major free-flowing reaches that include the outlet of lower

PHOTO 6.5 High Rhine (Rkm 106) near the nuclear power plant of Leibstadt. The river is impounded by the dam of the Albruck–Dogern hydropower plant. (Photo U. Uehlinger).

Lake Constance (12 km), a reach downstream of the power plant of Rheinau (5 km long), and a reach upstream of the Rhine–Aare confluence (11 km long). The sediment load of the High Rhine is naturally low because of the large lakes fringing the Alps retain sediments of the Rhine and its major tributary Aare. Bedload transport is influenced by the minor sediment supply and the reduced transport capacity due to the impounded reaches upstream of the 11 power plants.

At Basel, the Rhine enters the Rhine Graben rift valley and flows now as the Upper Rhine north for ∼300 km. Downstream of Mainz, it turns west and after 33 km reaches the southern fringe of the Rhenanin Mountains at Bingen (Rkm 528.5). The area of the Upper Rhine catchment is 62 967 km^2, including the catchments of the Neckar and Main Rivers. Elevations range from 1493 m asl (Black Forest) to 88 m asl (Bingen). The Rhein Graben rift valley is fringed on the right by the mountain ranges of the Black Forest and Odenwald and on the left by the Vosges Mountains and Palatinate plateau. From Basel to Mainz, the width of the rift valley ranges from 30 to 40 km (Figure 6.1a). Between Basel and Strassbourg (Rkm 294), the Rhine was originally a braided river within a 2–4 km wide floodplain (slope ∼0.1%) and 220-km long thalweg. The reduction in valley slope downstream of Strassbourg turned the river into a meandering system. The meandering reach extended from Karlsruhe (Rkm 362) to Mainz (Rkm 498) and included numerous island sandbars and oxbow lakes. The width of meanders ranged from 2 to 7 km and the valley slope averages 0.025%. Downstream of Mainz, where the valley is naturally confined by spurs of the Palatinate upland and Taunus range, the floodplain is only about 1 km wide and the straight channel includes islands and sand bars.

River engineering works of the 19th and 20th centuries completely changed the morphology of the Upper Rhine. Over several centuries, the growing population in the floodplain took protective measures against the river, which constantly changed its course. Artificial meander cuts date since the 14th century, but the effect of such actions did not affect natural river dynamics. Settlements often had to be abandoned and rebuilt at safer locations (Musall 1982). Some of these problems disappeared with regulation of the Upper Rhine beginning in 1817 under the direction of the Badenese engineer Johann Gottfried Tulla (1770–1828) and continuing under his successors until the end of the 19th century. The primary goal of the project was floodplain reclamation, fixation of the international border between France and the Duchy of Baden, and improved flood protection of settlements. Channelization by cuts, excavations and embankments reduced the thalweg between Basel and Worms (Rkm 443) by 81 km (23% of the original length). More than 2000 islands disappeared and an area of about 100 km^2 was reclaimed. The shortening of the river and narrowing of the channel to a width of 200–250 m enhanced vertical erosion.

In the former braided reach, the river deeply cut into its bed, in the upper 30 km up to 7 m. At Istein (Rkm 178), it reached the bedrock of a cliff, thereby forming rapids and impeding navigation between Mannheim and Basel. With incision of the riverbed, the water table decreased and turned former wetlands in to arable land, which now require irrigation for agricultural productivity. The construction of the Grand Canal d'Alsace (1928–1959), a concrete canal parallel to the left bank of the Rhine (international border), was aimed to produce hydropower and improve navigation (Photo 6.6). The 130 m wide and 9 m deep canal extends from the Swiss border to Breisach (Rkm 226) and encompasses four hydropower plants. During baseflow, only 15–20 m^3/s

PHOTO 6.6 Upper Rhine: The Grand Canal d'Alsace (Rkm 216) near Breisach. (Photo U. Uehlinger).

remain in the old Rhine (IKHR 1993), which accelerated the lowering of the water table. In the 61-km long reach downstream of the Grand Canal, four additional power plants were completed between 1963 and 1970. The loop diversion design of these plants, which leaves the water in the riverbed for most of the reach, was intended to mitigate the rapid loss in the water table. Continuing erosion problems resulted in the construction of two additional power plants (run-of-river plants without loop diversion) at Rkm 209 and 335. Downstream of the last power plant (Iffezheim), ~180 000 m^3 gravel must be added annually to the river to prevent further channel degradation (IKSR 1993).

After 180 years of river engineering, the Upper Rhine is primarily a straight single-thread river with uniform cross-sections, protected banks and dikes (Photo 6.7). All the islands except for a few large ones disappeared. Near power plants, dikes top over the adjacent former floodplain by >10 m. Bed sediments include gravel in the upper reaches, and fine gravel and sand in the former meandering reach. Channel widths range from 130 to 300 m between Basel and the last power plant, 250–300 between Karlsruhe and Mainz, and from 350 to 500 m between Mainz and Bingen. The width of the uniformly deep navigation channel within the channel varies between 100 and 450 m.

PHOTO 6.7 Upper Rhine near Rastatt at Rkm 340. (Photo U. Uehlinger).

PHOTO 6.8 Middle Rhine at St. Goar (Rkm 556). (Photo Klaus Wendling, Mainz).

The catchment of the Middle Rhine covers an area of 41 810 km^2 with elevations ranging from 43 m asl near Bonn to 880 m asl in the Taunus Mountains. It includes the Rhenanian Slate Mountains, remnants of the Hercynian Mountains, with predominantly Devonian and Carboniferous slates, greywackes and limestones (Koster 2005a). Parts of the uplands are covered by volcanic deposits originating from Tertiary and Quaternary volcanic activity. The most recent eruption dated 11 000 years BP (Schmincke et al. 1999). The Rhenanian massif is dissected by the Rhine from south to north, the River Moselle from southwest to northeast, and River Lahn from northeast to southwest.

The Middle Rhine begins at Bingen (Rkm 529), where the Rhine turns north and enters a canyon-like reach characterized by a relatively steep gradient (0.04%) and narrow channel (200–300 m) (Photo 6.8). From continuous upland uplift and subsidence of marginal areas, the Rhine deepened its valley by ~200 m. The riverbed mainly consists of bedrock (Devonic schist and quartzite), forming reefs and some islands apart from gravel bars (Photo 6.9; gravel is added by the Nahe River merging with the Rhine at Bingen). Only some of the bed sediments transported at Mainz (Rkm 498) reach the Middle Rhine (IKSR 2005). Mid and point bars occur where the gradient is low. About 30 000 m^3 sediment must be annually removed from the river to keep the navigation channel open. Sediment supply from the tributaries Moselle and Lahn stopped with the regulation of both rivers.

Downstream of Koblenz (Rkm 591.5), the Rhine flows unconstrained for about 22 km through the Neuwied basin, a relatively small tectonic depression. From Andernach (Rkm 613), the Rhine continues in a straight channel to Bonn (Rkm 655), thereby cutting through the volcanic field of the East Eifel. About 12 900 years BP, a disastrous Plininan eruption of the Lacher See Volcano (~7 km west of the Rhine) deposited large amounts of fallout tephra that congested the outlet of the Neuwied basin and formed a lake of ~140 km^2. The collapse of the tephra dam during the late stage of the eruption caused a catastrophic flood; respective deposits can be found as far as 50 km downstream (Park & Schmincke 1997).

In contrast to the Alpine Rhine, Upper, Lower and Delta Rhine, the plan view of the Middle Rhine course was little affected by humans. River engineering in the 19th and 20th centuries aimed to improve navigation by primarily modifying channel cross-sections by removing cliffs (IKSR 1993). Up to the 1980s, the width of the navigation channel has been excavated or blasted to a depth of 2.1 m at baseflow (Q_{345}) and widened to 120–140 m. This included the quartzite reef at Bingen, once the most infamous navigation obstacle on the river. In some reaches, groynes including lateral ones were used to maintain baseflow depths. Railroad tracks and roads isolate the river from adjacent uplands by walls, particularly along confined reaches.

The Lower Rhine flows from Bonn (Rkm 655) to the Dutch–German border (Rkm 858). It drains a catchment of 18 836 km^2, including parts of the Münster Embayment in the northeast and the Rhenanian massif in the south and southeast. On the right of the Rhine between the Münster Embayment and the Rhenanian massif is the Ruhr basin with up to 3000 m thick Upper Carboniferous coal bearing sediments extending into the southern North Sea (Henningsen & Katzung 2002). The coal contained in >200 seams fuelled

PHOTO 6.9 Middle Rhine. Stabilzied gravel island at Rkm 534 (Clemensgrund). (Photo K.M. Wantzen).

the development of the Ruhr area from a rural area in the early 19th century to the largest heavy-industry landscape in western Europe in the first half of the 20th century. The Lower Rhine basin, a marginal marine rift basin extends into the northern spurs of the Rhenish Massif forming an embayment. The sediment fill of the basin contains siliclastic sediments with intercalated lignite (brown coal) originating from peat bogs formed during the lower and middle Miocene when the sea-level was high (Schäfer et al. 2004). Today, the up to 100 m thick lignite deposits are extracted by opencast mining 20–40 km west of Cologne.

The Lower Rhine, which drains parallel to the main tectonic basin faults, is fringed on both sides by river terraces. The complex terrace system is the result of several Pleistocene glaciations. In the hinging area between the uplifting area in Germany and the subsiding North Sea basin, that is at the border of the Lower Rhine and Delta Rhine, terraces have been little preserved (Bridgeland 2000). The valley slope decreases from 0.023% at the beginning of the reach to 0.008% near the Dutch–German border. Between Bonn and Leverkusen (Rkm 700), the river channel is relatively straight with widths varying between 250 and 500 m. The prevailing substrate is gravel, sand occurs locally. Downstream of Leverkusen, the Rhine originally turned into single channel meandering river for ~75 km. Further downstream, the meandering channel also included side channels and many islands. Dominant substrate was fine gravel and sand.

Flood protection and improvement for navigation have been an issue along the Lower Rhine since the late Middle Age (Von Looz-Corswarem 1996). Efforts included attempts to fix the channel location with groynes, local bank stabilization, dyke construction, and cutting of meanders. River engineering in the late 18th century was aimed to standardize plan view and cross-sections that also included a major loss of islands. Under the direction of a Central Rhine River Administration (Zentrale Rheinstromverwaltung) constituted in 1851 under the Prussian government, the Lower Rhine was finally transformed to a waterway of uniform depth and width (Photo 6.10). Artificial meander cutting in the 18–19th centuries shortened the length of the thalweg by ~23 km (IKSR 1993). The increased sediment transport capacity resulted in vertical erosion (locally up to 2 m), which was aggravated by gravel extraction, reduced sediment supply by tributaries, subsidence of the riverbed following mining, and scouring by ship propeller wash (IKSR 1993). In the 20th century, coal and salt mining below the river lead to depressions of the riverbed, particularly between Duisburg (Rkm 775) and Xanten (Rkm 824). These areas of human-induced subsidence, trap sediments and enhance erosion in downstream areas despite additions of mining debris. Downstream of the subsidence area, vertical erosion rates reach up to 3 cm/y (IKSR 2005). Today, the river is between 300 and 600 m wide, with riprap protected banks and numerous groynes fixing the uniform navigation channel (depth at low flow 2.5–2.8 m) (Photo 6.11). About 640 km^2 of the original floodplain area of 900 km^2 are now protected by dikes.

The Holocene development of the Rhine delta has been reconstructed by Berendsen & Stouthamer 2000, using a large number of lithological borehole descriptions, ^{14}C dates, archaeological artefacts and gradients of palaeochannels (cited by Koster 2005b). During this period, avulsion was an important process, resulting in frequent shifts of areas

PHOTO 6.10 Lower Rhine near Krefeld Uerdingen (Rkm 760). (Photo Marcel Sowade, Moers, Germany).

of clastic sedimentation. Palaeogeographic evolution of the Rhine delta is mainly governed by complex interactions among several factors such as (1) location and shape of the palaeo-valley, (2) sea level rise, which resulted in back-filling of the palaeo-valley, (3) peat formation, which was most extensive in the western part of the back-barrier area, especially between 4000 and 3000 years BP, that more or less fixed the river pattern at that time and resulted in few avulsions, (4) differential tectonic movements, especially from 4500 to 2800 years BP when the rate of sea level rise had decreased. After 2800 years BP, sea level rise further decreased, and tectonics still may have influenced avulsions, but from then on other factors became dominant. (5) Increased discharge, sediment load and/or within-channel sedimentation.

After 2800 years BP, river meanders of the Rhine show remarkable increases in wavelength, interpreted as a result of increased bankfull discharge and sediment load. Increased

PHOTO 6.11 The boundary Lower Rhine/Delta Rhine. The bifurcation of the Rhine in the Waal branch (right) and the Pannerdensch Kanaal (left), at the Pannerdensche kop (~~river 867.5 km~~). (Photo Rijkswaterstaat, The Netherlands).

discharge may initially have been caused by higher precipitation. Alternatively, decreasing gradients (as a result of sea level rise) may have caused increased within-channel sedimentation and channel-widening, which would also lead to increased meander wavelengths. Other factors included (6) composition of the river banks. Meandering river channels tend to adhere to the sandy margins of the palaeo-valley, and high channel sinuosity is found in areas where river banks consisted of sand, (7) marine ingressions, for example, the 1421 AD St. Elizabeth's flood caused large-scale erosion and created a wide estuary in the southwestern part of the fluvial deltaic plain of the Rhine and Meuse, and (8) human influence dominating the palaeogeographic evolution since about 1100 AD. There is evidence that since the last Ice Age humans locally cleared the forested floodplains in the Rhine basin and put them to use for agricultural purposes (Bos & Urz 2003). The first settlers in the 'lowlands' of the Rhine delta found themselves in a poorly drained flat delta and floodplains intersected by streams, tidal inlets and small and large river channels (Havinga & Smits 2000). In the Rhine delta, human occupation of high ridges and river dunes along the water course already existed 6500 years ago (Groenman-van Waateringe 1978). People lived by hunting and fishing, and small dikes and flumes were built to create appropriate conditions for agriculture activities locally. The Romans undertook the first large-scale river interventions. Generals Corbulo and Drusus connected the Rhine River with the Meuse and IJssel Rivers (Huisman et al. 1998). After 2000 years BP, both discharge and sediment load in the Rhine delta have increased as a result of human influence (Berendsen & Stouthamer 2000).

From the Roman period onwards, many other river management measures in the Rhine delta have followed, resulting in a riverine landscape which is now completely different from the time when the Romans entered the Rhine basin (Table 6.2) (Huisman et al. 1998; Havinga & Smits 2000; Middelkoop et al. 2005; Ten Brinke 2005). In the Rhine delta, the gradual construction of high water-free dwelling zones and dikes along the various river branches resulted in a closed dike system by 1450 AD (Ten Brinke 2005). This restricted fluvial dynamics to narrow parts of the alluvial system between the dikes, leaving a 0.5–1.0 km wide zone of active floodplain along the river where erosion and sedimentation processes continued (Middelkoop et al. 2005). The decreased dynamics in the floodplain and but increased dynamics within the river channel had a devastating effect on biodiversity in river-floodplain ecosystems.

During the 17–19th centuries, meanders were artificially cut-off, side channels were closed and the discharge distribution over the various Rhine branches was adapted (Middelkoop et al. 2005; Ten Brinke 2005). Physical normalisation of the Rhine branches in The Netherlands in the18–20th centuries, mainly aimed at increasing safety against flooding and opportunities for shipping, further diminished fluvial dynamics (Havinga & Smits 2000; Ten Brinke 2005). River bank reinforcements, groynes and longitudinal dikes along the riverbed were built to prevent erosion of the banks and to catch sediment to create farmland in the floodplain. These measures were intended to increase flow velocities in the main channel, thus preventing the formation of sandbanks. In winter, these shallows were prone to develop ice dams, which formed a serious threat to the dikes as the flowing water pushed them up. Later it was found that these measures also benefited navigation because they had deepened the main channel. In order to optimise navigation, several weirs (sluice-dams) were constructed and so-called 'width normalisations' were carried out since 1870. Width normalisation means that the low water bed is limited to one main channel with a constant (normal) width. Groynes were constructed at regular intervals, which confined the low water bed into a narrower channel and kept the water flow away from the erodible bank. In the 19th and 20th centuries, after many uncoordinated regulations, two large-scale width normalisations were carried out in the main Dutch Rhine branches. Moreover, discharge distribution over the various channels is today strictly controlled. Apart from agricultural land use, sand and gravel extractions in the 20th century also had massive impacts on the structural diversity of river floodplain ecosystems.

Middelkoop & Van Haselen (1999) and Ten Brinke (2005) give detailed descriptions of the present situation of the Rhine delta. At the Dutch–German border, the so-called Bovenrijn is a single river channel. About 10 km downstream, the river changes to a system of Rhine branches. At the Pannerdensche Kop, the river bifurcates into the River Waal and Pannerdensche Kanaal (Photo 6.11). Around 10 km further downstream, the Pannerdensche Kanaal bifurcates into the Rivers Nederrijn and IJssel. Further downstream, the name of the Nederrijn changes to Lek, and the Lek and Waal merge through a number of water courses around the city of Rotterdam. This area is known as the northern part of the Rhine–Meuse estuary. In the south, this estuary is connected with the River Scheldt estuary. The IJssel flows into Lake Ketelmeer, which is in turn connected to Lake IJsselmeer.

The weir at Driel divides the river water between the Nederrijn and IJssel and ensures that a sufficient proportion flows into the IJssel during low flow periods. The Waal is the largest of all Rhine branches and is a broad free-flowing river (Photo 6.12). The river's main channels are bounded by dikes (relatively low embankments), protecting agricultural areas in the floodplain from summer flooding. Primary river dikes prevent the floodplain from flooding during high flows. In total, the surface area of the Rhine channels in The Netherlands is ∼36 700 ha, including some 28 000 ha of floodplains. In addition, the northern Rhine–Meuse estuary covers some 60 000 ha of river and floodplains. Land use of the embanked floodplains along the Rhine branches varies remarkably (Table 6.3).

The history of the Rhine–Meuse–Scheldt estuary in southwest Netherlands is marked by a continuous struggle between man and the sea. Since the year 1000, humans reclaimed salt-marsh areas and transformed them into

PHOTO 6.12 Delta Rhine. Meander of the river Waal west of Zaltbommel in the Netherlands (~~river 933.5–938 km~~). The secondary channel (foreground) constructed in the forelands mitigates the effects of river engineering. (Photo B. Boekhoven, Rijkswaterstaat, The Netherlands).

agricultural land (Smits et al. 2006). But periodic storm-floods destroyed the seawalls and recaptured parts of the reclaimed land. Between 1900 and 1950, an area of ~10 000 km^2 had a large number of islands and peninsulas, deep and shallow tidal channels, extensive intertidal sand- and mudflats reaching up to 20 km from the coast, vegetated coastal plains, and salt and brackish marshes above mean high water. The most landward parts of the estuaries, where the Rivers Rhine, Meuse and Scheldt enter the delta, were characterized by freshwater tidal marshes and willow coppice.

The need for continuous coastal construction has intensified over the years as a result of population growth, land subsidence and rising sea level. The potential threat of storm surges from the North Sea led to the closure of Brielse Meer in 1950. After a large storm flood in 1953, the so-called Delta project was conceived as an answer to the continuous risk of flooding. The core of this project was to maintain a safe coastline, and called for the closure of main tidal estuaries and inlets in the SW Netherlands, except for Westerschelde and Nieuwe Waterweg. The former (semi-)estuaries Veersche Gat and Grevelingen were isolated from the North Sea by high sea-walls in 1961 and 1971, respectively, and converted into non-tidal lakes or lagoons filled with brackish or saline water. The Haringvliet was closed in 1970 by the construction of large sluices, meant to function as an outlet for the Rhine and Meuse. Construction of primary sea-walls in the mouths of estuaries included the need to reduce tidal-current velocities in the estuaries by constructing secondary compartmental barriers (Zankreekdam, Grevelingendam and Volkerakdam).

In 1986, after much debate about the ecological impacts of dams in the Rhine–Meuse estuary, a storm-surge barrier across the mouth of the Oosterschelde estuary was installed

TABLE 6.3 Land use (%) of embanked floodplains of Dutch Rhine branches (Middelkoop & Van Haselen 1999)

	Bovenrijn–Waal	Pannerdensch Canal–Nederrijn–Lek	IJssel
Floodplain forest (nature)	4	1	1
Brush/marsh	5	2	1
Grassland	1	5	3
Water	19	11	11
Production forest	0	1	1
Arable land	4	4	8
Grass production	61	69	72
Buit-up area	5	5	3
Other land use	1	1	1
Nature	29	20	16
Non-nature	71	80	84

PHOTO 6.13 Delta Rhine. Outflow of the Nieuwe Waterweg in the North Sea (top) with the heavily industrialized Maasvlakte and in the south (foreground) the large disposal site 'Slufter' for controlled storage of polluted river sediments. (Photo B. Boekhoven, Rijkswaterstaat, The Netherlands).

as a compromise (Nienhuis & Smaal 1994). On one hand, this barrier allows low tides to enter the estuary freely, thus safeguarding the ecology of the tidal ecosystem. On the other hand, the barrier guarantees safety for the human population and their properties when large storm floods threaten the area. Along the Westerschelde, the existing dikes have been raised to maintain international shipping access to Antwerp. In the Nieuwe Waterweg (Photo 6.13), the shipping route to the mainport of Rotterdam, the Maesland kering, a moving barrier protecting Rotterdam from storm surges, was finished in 1997. This enterprise was considered to be the final phase of the Delta project.

6.5.2. Hydrology and Temperature

From headwaters to the sea, monthly discharge patterns of the Rhine exhibit a remarkable shift that reflects changes in the contribution of runoff from hydrologically different areas. The hydrology of the Rhine shows the influence of the Alps and the low mountain ranges, hills and plains of the remaining catchment. Alpine Rhine and Aare provide on average 34% of the annual discharge at the Dutch–German border; during summer this percentage exceeds 50% (Viviroli & Weingartner 2004). The annual flow pulse from the Alps, primarily fed by the melting of snow and ice, arrives downstream when the water balance of low elevation catchments is negative. Therefore, the Lower Rhine and Delta Rhine exhibit moderate seasonal variation in the long-term mean monthly discharge (Figure 6.4). With distance from the Alps, monthly hydrographs exhibit increasingly stochastic variation that reflects the influence of the Oceanic climate and a less predictable rain-dominated precipitation (Figure 6.5). Specific discharge declines from ~40 L/s/km^2 in the Alpine catchments of the Rhine and Aare, to 17 L/s/km^2 in the Upper Rhine catchment and 15 L/s/km^2 in the Lower Rhine catchment.

The discharge (Q_{mean}) of Vorderrhein and Hinterrhein is 56 and 61 m^3/s, respectively, at their confluence near Reichenau. From Reichenau to Lake Constance, Q_{mean} increases from 117 to 242 m^3/s. Flow regimes of the Alpine Rhine and its tributaries and headwaters range from glacial to nivo-pluival (Weingartner & Aschwanden 1986). The glacial influence is small because only 86 km^2 (1.4%) of the catchment are glacierized. Only 450 km^2 of the entire Rhine

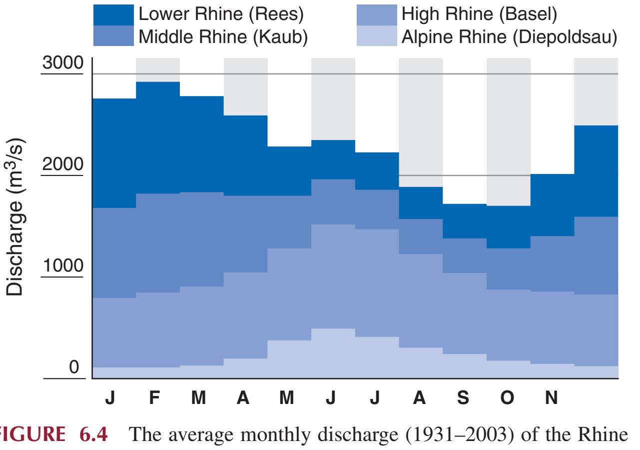

FIGURE 6.4 The average monthly discharge (1931–2003) of the Rhine between Diepoldsau (Alpine Rhine) and Rees (20 km upstream of the Dutch–German border). The gauging station of Kaub is 45 km upstream of the Rhine–Moselle River confluence.

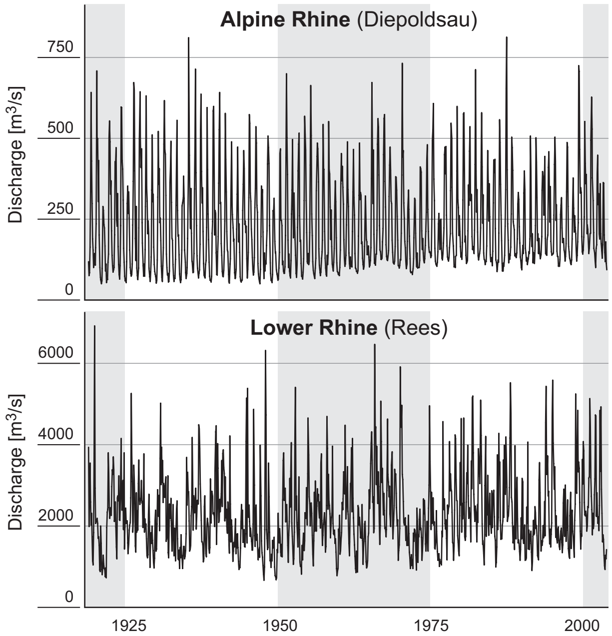

FIGURE 6.5 Monthly discharge in the Alpine Rhine (Diepoldsau) and Lower Rhine (Rees).
Sources: Federal Office for the Environment, Berne, Switzerland, and Global Runoff Data Centre (GRDC), Koblenz, Germany.

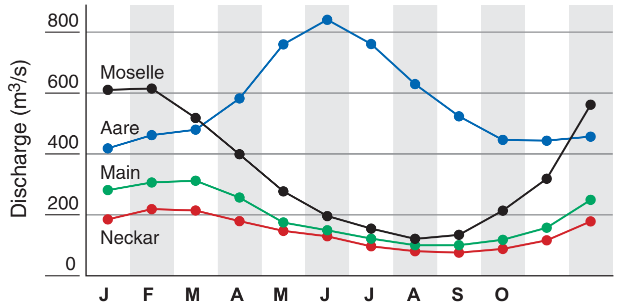

FIGURE 6.6 Average monthly discharge of the Rhine tributaries Aare, Neckar, Main, and Moselle (1964–2003).

catchment are covered by glaciers, most of which are in the catchment of the Aare (80%). Snowmelt is the primary water source of the Alpine Rhine. Depending on altitude, snowmelt peaks between April and June. Major parts of the catchment are relatively high in altitude (55% > 2000 m asl). As a consequence, mean monthly discharge peaks in June at ~460 m^3/s and the minimum typically occurs in January at 128 m^3/s. Rainfall induced flow peaks often are superimposed on the seasonal flow pulse, primarily between March and November. Observed minimum and maximum discharge was 49 m^3/s (December 1985) and 2665 m^3/s (July 1987).

The hydrology of the Alpine Rhine and its tributaries has been seriously affected by the operation of hydroelectric power facilities such as storage and pumped storage power stations constructed from 1950 to 1980s. The water of the Rhine is already diverted for hydropower production <2 km downstream of Lake Toma. Water is abstracted at numerous sites, primarily in smaller tributaries but also in the main stems of the Vorderrhein and Hinterrhein. Most of this water is transiently stored in reservoirs and used on demand for power production. The results are substantial flow reductions between withdrawal and return sites, and hydropeaking downstream of return sites. Today, flow reductions of >60% affect 30% of the Hinterrhein and 70% of the Vorderrhein, and smaller tributaries fall temporarily dry downstream of withdrawal sites. The lower Vorderrhein and Hinterrhein and the entire Alpine Rhine are strongly affected by hydropeaking. About 13 km upstream of Lake Constance, daily flow variation still is ~100 m^3/s; this corresponds to stage variations in the range of 0.6 m during winter low flow.

The combined maximum storage volume of reservoirs in the Alpine Rhine catchment is 773×10^6 m^3, which approximates 10% of the average annual Alpine Rhine discharge. The operation of storage power plants has damped the annual flow pulse and augmented winter low flow (Figure 6.5). Between 1939 and 2003, the average monthly summer discharge decreased by 60 m^3/s and the average monthly winter discharge increased by 50 m^3/s. The only run-of-river power plant at Domat-Ems (3 km downstream of the confluence of the Vorderrhein and Hinterrhein) has no influence on the flow regime because the impounded reach is relatively short (~3 km).

The catchment draining into Lake Constance excluding the Alpine Rhine comprises an area of 4960 km^2 and provides ~140 m^3/s to the annual discharge of the High Rhine. The lake loses on average 12 m^3/s by evaporation (Baumgartner et al. 1983) and about 5.5 m^3/s are withdrawn for drinking water. Annual discharge increases between the outlet of Lake Constance and the Aare–Rhine confluence from 368 to 442 m^3/s, and reaches 1059 m^3/s in Basel. Monthly flow of the upper High Rhine reach shows a similar annual pattern like the Alpine Rhine, but Lake Constance delays the annual maximum by ~3 weeks (Naef 1989). Except for the Aare River, flow regimes of tributaries are flashy with maximum monthly flow in March/April and minimum in September/October. In the Thur River, unpredictable spates with peak flows >350 m^3/s occur on average 3.7 times per year (Uehlinger 2006).

The Aare is the paramount Alpine river of the entire Rhine basin with a flow regime similar to that of the Rhine (Figure 6.6). At the confluence, the annual discharge of the Aare exceeds (at 559 m^3/s) that of the Rhine by 23%. Relatively large lakes with volumes ranging from 1.2 to 11.8 km^3 moderate short-term flow variations of the Aare as well as its two major Alpine tributaries, Reuss River and Limmat River. The Alpine influence in the form of meltwater is still evident in the annual flow pulse along the entire High Rhine, but with distance from Lake Constance, particularly downstream of the Thur River confluence, the hydrograph has increasingly irregular flow peaks. Flow extremes were 104 m^3/s (1909) and 1180 m^3/s (1999) in the upper reach (outlet of Lake Constance), 120 m^3/s (1910) and 2250 m^3/s (1910) upstream of the Rhine–Aare confluence, and 357 m^3/s (1921) and

5090 m^3/s (1999) in Basel. From Basel to the end of the Upper Rhine reach, mean annual discharge increases from 1059 to 1588 m^3/s with the two tributaries Neckar and Main contributing 149 and 225 m^3/s.

Smaller tributaries from the right bank are the Rivers Wiese (Q_{mean} 11.4 m^3/s), Kinzig (Q_{mean} 23 m^3/s) and Murg (Q_{mean} 17 m^3/s), and from the left bank the River Ill (Q_{mean} 60 m^3/s). The signature of the Alpine flow pulse in the hydrograph disappears at the end of the Upper Rhine, reflecting the growing influence of tributaries with pluvial–nival regimes (monthly flow maximum between February and April depending on altitude, and minimum monthly flow between August and October). Minimum and maximum flows recorded at Mainz were 460 m^3/s (1947) and 7000 m^3/s (1882), respectively. Along the Middle Rhine, annual discharge increases from 1588 to 2043 m^3/s, primarily due to the contribution of the Moselle River (Q_{mean} 328 m^3/s). Two smaller tributaries provide 31 m^3/s (Nahe) and 51 m^3/s (Lahn). At the end of this reach, the monthly flow is maximal in February and minimal in October; a seasonal pattern prevailing to the Delta Rhine (Figure 6.4). Major tributaries of the Lower Rhine are the Ruhr (Q_{mean} 70 m^3/s) and Lippe River (Q_{mean} 67 m^3/s). Upstream of the channel splitting of the Delta Rhine, annual discharge averaged 2297 m^3/s, and maximum and minimum discharges recorded were 12 600 and 574 m^3/s. During the dry and hot summer of 2003, discharge was <800 m^3/s. The average annual ratio of maximum to minimum discharge is about 15 (Ten Brinke 2005). Of the three Delta Rhine branches, the Waal, Neederijn–Lek, and IJssel receive on average 65, 23 and 12%, respectively, of the discharge of the Bovenrijn (Rhine main stem).

Most global circulation models suggest higher winter and lower summer rainfall for the Rhine basin. Hydrological simulations predict a progressive shift of the Rhine from a rain-fed/meltwater-fed river into a mainly rain-fed river (Pfister et al. 2004). From the Middle Rhine to the sea, the difference between present-day high average discharge in winter and the low average discharge in autumn should increase in all scenarios. This trend is assumed to be largest in the Alpine part of the basin. According to Lenderink et al. (2007), mean annual discharge is expected to decline in summer by 40% and increase in winter by 30%. Flows with a return period of 100 years (today) are assumed to increase between 10% and 30%.

Temperature regimes along the Rhine main stem are characterized by minimum temperatures in January and maximum temperatures in July and early August. Annual mean water temperatures range from <1 °C at the terminus of Paradise Glacier (Hinterrhein) to almost 15 °C in the northern part of the Upper Rhine. The respective seasonal amplitude ranges from a few degrees to about 20 °C. In the Vorderhein at Illanz (693 m asl), monthly water temperatures vary between 1.8 (January) and 10.9 °C (July), and daily mean temperatures between 0.2 and 13.8 °C. At Diepoldsau (410 m asl) near the lower end of the Alpine Rhine,

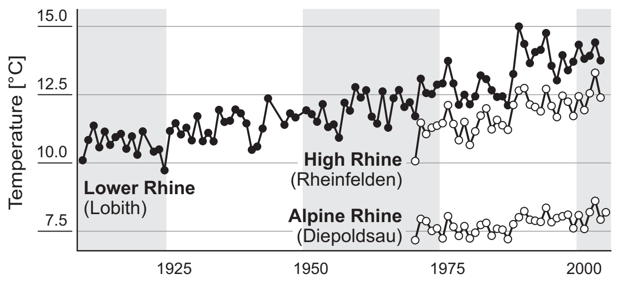

FIGURE 6.7 Mean annual temperature at three stations along the Rhine. *Sources*: Data from the Dutch Ministry for Traffic and Public Works (Lobith) and the Swiss Federal Office for the Environment (Diepoldsau, Rheinfelden).

corresponding monthly means are 3.3 and 13.5 °C and daily means are 1.1 and 17.6 °C. Power plant operations in the Alpine reaches affect the diel temperature regimes; for example, up to 2 °C during winter low flow at Illanz.

Lake Constance causes a major thermal discontinuity within the main stem of the Rhine. Between the mouth of the Alpine Rhine and the upper High Rhine, mean annual temperature increases by ~4 °C. From the outflow of Lake Constance to Basel, temperatures slightly increase: mean annual temperatures from 12.0 to 12.7 °C, minimum monthly means from 3.7 to 4.9 °C, and maximum monthly means from 20.9 to 21.3 °C. At Reckingen (Rkm 90.5), maximum daily temperatures varied from 23 (2002) to 26.1 °C (2003). Daily temperatures of the Aare River at the confluence are almost identical with those of the Rhine. From Basel to Mainz, annual temperatures of the Upper Rhine increase from 12.7 to 14.8 °C. At Mainz, water temperatures average 6.3 °C in January and 24.1 °C in July, and maximum daily temperatures recorded from 2002 to 2006 ranged from 24.5 to 28.7 °C. High temperatures of the Upper Rhine reflect the warm climate of the Rhine Graben rift valley and thermal pollution from the discharge of cooling water from numerous power plants and industrial facilities. From Mainz to the end of the Lower Rhine, annual mean water temperatures decline by 0.7 °C and the average temperatures in January and July by 1 and 1.5 °C, respectively.

From 1971 to 2003, annual temperatures increased by 0.5 °C in the Alpine Rhine (Diepoldsau) and by 1.0 °C along the High Rhine (Figure 6.7). Much of this warming abruptly occurred in 1987–1988 (Hari et al. 2006). Upstream of the Rhine–Aare confluence, the effect of thermal pollution can be neglected. The Aare is the recipient of cooling water of three nuclear power plants of which two are ~7.5 km upstream of the confluence with the Rhine. Thermal dumps are maximal in the north Upper Rhine where cooling water discharges equal 14 700 MW (45% of permitted cooling water discharges of the entire Rhine catchment). At Lobith (Lower Rhine), annual mean water temperatures increased between 1908 and 1986 from 10.8 to 12.6 °C, primarily reflecting the growing thermal pollution. The increase of 1.4 °C between 1988 and 2004 may be attributed mostly to global warming (Figure 6.7).

6.5.3. Biogeochemistry

Water chemistry along the Rhine reflects the changing influence of watershed characteristics, runoff patters, atmospheric inputs and anthropogenic sources such as agricultural runoff and effluent discharges from urban and industrial areas. The Rhine is a hardwater river (Golterman & Meyer 1985). Rhine water is neutral to slightly alkaline and the buffering capacity is high. Areas where siliceous crystalline rocks (granite, gneiss) prevail include minor parts of the Rhine drainage such as the headwaters in the Aare and Gotthard massif or Vosges and Black Forest, and parts of the Odenwald along the Upper Rhine. Calcareous mesozoic sediments dominate the northern front range of the Alps, and the Jura Mountains and south German Scarplands. Paleozoic and prepaleozoic sediments occur in the Rhenish massif. Large areas are covered by quaternary sediments such as the northern forelands of the Alps, Rhinegraben rift valley, lower Rhine Embayment and Rhine delta.

Chemical composition of the Rhine reflects to some extent this geochemical background. Conductivity and concentrations of major cations (except from Mg^{2+}) and anions distinctly increase between the Alps and Rhine delta (Table 6.4). Mean annual pH (1995–2004) varies between 7.9 and 8.3, and decreases from the Alps to the delta by about 0.3. Seasonal pH amplitudes range from 0.7 to 0.9. The meso-oligotrophic Lake Constance has a relatively minor influence on average concentrations of most biogeochemical parameters, but affects seasonal patterns in the upper High Rhine.

The input of industrial and domestic sewage beginning in the 19th century increasingly impaired water quality, particularly in navigable Rhine sections (see Section 6.1). A number of parameters showed that pollution levels peaked between 1970 and 1975 (Figure 6.8). In the Lower Rhine, annual concentrations of dissolved oxygen decreased to ~4 mg/L, and ammonia concentrations reached 2.7 mg/L. Since then, the water quality has significantly improved because of joint efforts of the riparian states that resulted in the upgrading and construction of new sewage treatment plants.

Available water quality data for Alpine headwaters of the Rhine are scarce, but anthropogenic influences on water quality are local and small because of low population density; an assumption supported by diatom indices (IKGB 2004). Data from nine water quality monitoring stations show distinct gradients in nitrogen and phosphorus along the Rhine main stem (Table 6.4). In the Alpine Rhine, an average phosphate concentration of 0.003 mg P/L contrasts with total P concentrations of 0.108 mg P/L that are dominated by the particulate inorganic fraction originating from glacial and snowmelt fed tributaries. Most of the particulate P-load is retained in Lake Constance. Phosphate concentrations increase from 0.007 mg P/L in the outlet of Lake Constance to 0.077 mg P/L at Koblenz, and remain relatively constant along the entire Lower Rhine.

Nitrate and total nitrogen concentrations showed similar longitudinal trends, but in contrast to phosphate, nitrate reached high values of 0.59 mg N/L and total nitrogen 0.68 mg N/L already in the Alpine Rhine. In the Alpine catchments, atmospheric nitrogen deposits range from 10 to 15 kg N/ha/year, which is about five times above baseline deposition in minimally impacted systems (Rihm 1996) and results in high NO_3–N concentrations in otherwise little affected high Alpine headwaters (Robinson et al. 2001; Tockner et al. 2002). From Lake Constance to the Upper Rhine at Basel, average nitrate concentration increase from 0.76 to 1.46 mg N/L and finally to ~3 mg N/L at the Dutch–German border.

The annual input (1996/1997) of total phosphorus and nitrogen into streams and rivers of the Rhine catchment equalled 26 175 tons P and 419 854 tons N. About 70% of the nitrogen and 54% of the phosphorus originated from diffuse sources (IKSR 2005). Improved phosphate elimination and substitution of phosphate in detergents resulted in a significant decrease of phosphate and total phosphorus concentrations at all stations between Lake Constance and the Rhine Delta, primarily after 1975 (Figure 6.8), but concentrations remained relatively constant after 1995. Nitrate concentrations peaked around 1985 and have declined since, reflecting construction and improved performance of sewage treatment facilities. Ammonium concentrations are presently <0.3 mg NH_4–N/L. The transition from saturation to limitation of phosphate has been reported to be 0.006–0.015 mg P/L (Bothwell 1989; Newbold 1992), a threshold that is exceeded downsteam of the Rhine–Aare confluence.

Concentrations of dissolved oxygen in the Rhine main stem are relatively high today. The 10%-percentile varies between 5.9 mg O_2/L in Mainz to 9.2 mg O_2/L in the outlet of Lake Constance (DKR 2001). Chloride concentrations increase from 3 mg/L in the Alpine Rhine to 106 mg/L at the Dutch–German border. Sources of chloride include domestic sewage, road salt (during winter), industrial effluents and mining. Exploitation of the Alsatian potash mines ended in 2003, but runoff from tailings still results in a major increase in chloride concentrations in the Upper Rhine. Chloride from potash mines in Lorraine enter the Rhine via the Moselle River. Drainage waters from active and abandoned coal mines substantially contribute to the high chloride concentrations in the Lower Rhine, including effluents of chemical plants (LUA NWR 2002).

Concentrations of dissolved organic carbon (DOC), which today range from 1.2 mg C/L in the Alpine Rhine to 2.8 mg C/L at the Dutch–German border (Table 6.4), decreased from 1976 at 13–15 mg C/L in the Middle and Lower Rhine to 3–4 g C/L in 1985. In the Alpine Rhine, DOC showed no significant trend since 1977, and between Lake Constance and Karlsruhe, where concentrations were <3 mg C/L, the decrease was moderate. More than 10 000 organic compounds synthesized in relatively large amounts, many with toxic or mutagenic properties, enter the Rhine in low concentrations. Today, about 150 compounds are

TABLE 6.4 **Biogeochemical parameters at different stations along the main stem of the Rhine**

Station	River section	D.f.s. km	Cond. (μS/cm)	NO_3–N (mg/L)	PO_4–P mg/L	TP (mg/L)	Cl^- (mg/L)	H_2SiO_4 mg/L	SO_4^{2-} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	DOC (mg/L)	TSS (mg/L)
Diepoldsau	AR	**150**	**299**	**0.58**	**0.005**	**0.091**	**3.0**	**5.5**	**46.1**	**3.1**	**1.0**	**44.0**	**9.1**	**1.2**	**134.4**
			52	*0.15*	*0.004*	*0.129*	*1.4*	*0.6*	*11.8*	*1.2*	*0.2*	*6.3*	*1.9*	*0.5*	*189.7*
Stein am Rh.	HR	**225**	**306**	**0.76**	**0.007**	**0.020***	**5.9**	**3.3**	**32.0**	**4.8**	**1.5**	**45.6**	**8.1**	**1.6**	**n.d.**
			13	*0.10*	*0.003*		*0.4*	*0.5*	*1.2*	*0.3*	*0.1*	*1.0*	*0.2*	*0.1*	
Reckingen	HR	**293**	**340**	**1.27**	**0.014**	**0.040**	**7.8**	**4.4**	**29.7**	**6.4**	**1.7**	**50.0**	**10.2**	**2.2**	**16.1**
			32	*0.36*	*0.007*	*0.023*	*1.6*	*1.2*	*2.5*	*1.1*	*0.2*	*5.0*	*1.0*	*0.5*	*23.5*
Weil	HR/UR	**373**	**355**	**1.46**	**0.018**	**0.047**	**10.3**	**4.7**	**26.7**	**8.7**	**1.9**	**52.5**	**8.2**	**2.3**	**13.5**
			34	*0.36*	*0.008*	*0.020*	*2.5*	*1.3*	*2.5*	*2.1*	*0.3*	*5.1*	*0.8*	*0.5*	*16.4*
Karlsruhe	UR	**564**	**498**	**1.62**	**0.036**	**0.061**	**52.9**	**6.2**	**29.3**	**35.8**	**3.5**	**54.6**	**7.4**	**2.0**	**16.3**
			85	*0.12*	*0.007*	*0.012*	*23.4*	*0.3*	*2.1*	*15.3*	*1.0*	*3.3*	*0.3*	*0.2*	*8.2*
Mainz	UR	**701**	**505**	**2.54**	**0.057**	**0.092**	**53.6**	**n.d.**	**50.3**	**35.6**	**4.3**	**63.1**	**9.8**	**2.6**	**21.4**
			53	*0.23*	*0.007*	*0.010*	*17.1*		*6.0*	*11.5*	*0.8*	*3.4*	*0.6*	*0.1*	*7.9*
Koblenz	MR	**794**	**524**	**2.54**	**0.077**	**0.179**	**n.d.**	**6.8**	**53.6**	**43.5**	**4.7**	**65.7**	**11.1**	**2.4**	**23.3**
Bad Honnef	LR/MR	**841**	**533**	**2.67**	**0.071**	**0.154**	**62.5**	**8.4**	**49.3**	**39.5**	**5.0**	**66.4**	**11.1**	**2.7**	**28.0**
			54	*0.25*	*0.011*	*0.022*	*16.4*	*1.1*	*5.1*	*10.5*	*1.7*	*3.1*	*0.7*	*0.3*	*11.7*
Kleve Bimmen	LR	**1067**	**634**	**2.92**	**0.076**	**0.150**	**105.5**	**8.2**	**59.0**	**56.9**	**5.7**	**78.6**	**11.7**	**2.8**	**29.4**
			74	*0.33*	*0.017*	*0.012*	*23.1*	*0.9*	*6.2*	*12.0*	*1.8*	*4.2*	*0.7*	*0.3*	*9.7*

Average (bold) and standard deviation (italics) (1995–2004). River sections: AR = Alpine Rhine, HR = High Rhine, UR = Upper Rhine, MR = Middle Rhine, LR = Lower Rhine. D.f.s. = distance from source. Data sources: International Commission for the Protection of the Rhine (ICPR), Deutsche Kommission zur Reinhaltung des Rheins (DKR) and NADUF (National Long-term Surveillance of Swiss Rivers).

* *Average of 2004.*

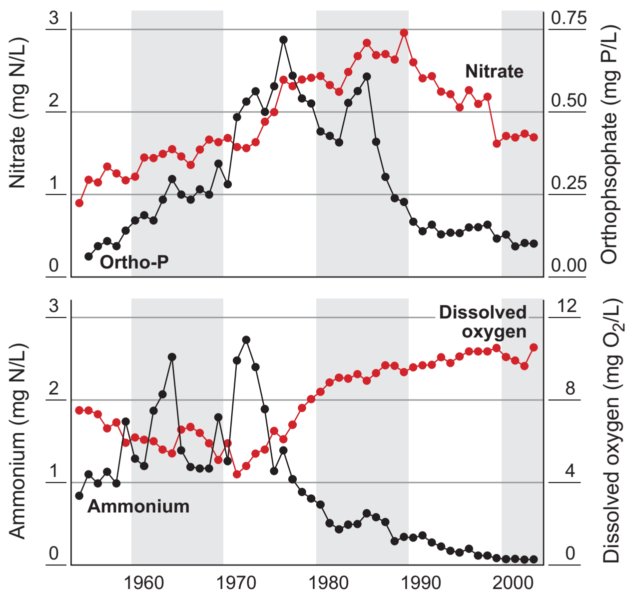

FIGURE 6.8 Annual average concentration of nitrate, orthophosphate, ammonia and dissolved oxygen at Kleve-Bimmen (river 865 km).

routinely analyzed. These organic micropollutants include anilines, chlorinated benzenes, herbicides and pesticides, phosphoric acid ester, and volatile and non-volatile organic compounds. Weak and moderate polar organic pollutants adsorb onto suspended solids and sediments that result in relatively high concentrations in sediments of impounded reaches (e.g., chlorinated–benzene up to 3 mg/kg). Bulk heavy metals are associated with suspended solids and fine sediments. Concentrations of dissolved heavy metals are often below detection limits (e.g., mercury and cadmium). Natural background concentrations in suspended solids are low, values for mercury, cadmium, copper and zinc are 0.2 mg Hg/kg, 0.3 mg Cd/kg, 20 mg Cu/kg and <200 mg Zn/kg. Actual concentrations usually exceed these background values about 2–4 times (DKR 2001). Concentrations of lead, cadmium, chromium, copper mercury and zinc, primarily originating from human activities, increase downstream (LUA NWR 2002).

Sediments in rivers, canals and harbours in the Rhine–Meuse delta are moderately to heavily contaminated due to (trans)national and local water pollution. In the past nautic dredging sludge was deposited off shore. However, environmental laws and policy called for isolated and fully controlled storage of dredging sludge. Therfore, in 1986–1987 a large-scale storage facility for contaminated dredging sludge was constructed on the Maasvlakte, a part of the Port of Rotterdam located south of the Nieuwe Waterweg (Photo 6.13). The total surface area of the Slufter depot is 260 ha and the storage capacity is circa 150 million/m^3. While 15 years ago about 50% of the dredging sludge was still so contaminated, it needed to be stored at the special Slufter depot, nowadays only 10% qualifies for storage.

Due to continuous industrial, communal and agricultural discharges of pollutants and recurrent flooding, large amounts of particulate-bound toxic substances are deposited in floodplains along the Delta Rhine (Middelkoop 2002). A major problem that remains to be solved is the pollution that has been accumulated over the last century in river sediments and floodplain deposits. Floodplain soils keep the heritage and risks of earlier river pollution. Respectively, 65, 45 and 35% of soil samples from floodplains along the rivers Waal, Nederrijn and IJssel exceed environmental quality standards for one or more contaminants (mainly metals), resulting in high remediation costs and impediment of physical reconstruction and ecological rehabilitation projects (Leuven et al. 2005). Persistent organic substances and (heavy) metals are continuously redistributed and mixed or covered by cleaner sediments (Middelkoop 2002; Wijnhoven et al. 2006). Both natural processes (e.g., flooding) and human influences (e.g., excavation, agriculture, and construction of embankments) have been and are still resulting in large environmental heterogeneity. Soil concentrations can vary greatly, even over small distances. These potentially toxic substances can enter food chains via uptake in vegetation and soil-dwelling invertebrates. For instance, for Cd, Cu, Pb and Zn, significant relations were found between concentrations in soil and arthropods (Schipper et al. 2008). For several vulnerable vertebrate species foraging in floodplains, such as the common shrew (*Sorex araneus*), the badger (*Meles meles*) and the little owl (*Athene noctua*), this might lead to toxicological risks resulting from exposure to contaminated food (e.g., Kooistra et al. 2001; Leuven & Poudevigne 2002).

6.6. AQUATIC AND RIPARIAN BIODIVERSITY

6.6.1. Habitat Structure and Riparian Zone

The natural riparian vegetation of the Rhine has been largely modified, for example, along the Upper and Middle Rhine the prevailing tree today is poplar (*Populus x canadensis*). The fertile floodplain was reclaimed quite early, and many cities along the Rhine contributed to further floodplain deforestation. Traditionally, the left bank was kept free of vegetation for towing boats. In the Middle Ages, dense forests (so-called ‘Gehecke’) were planted to protect settlements in the north Middle Rhine. Rings of willow trees were planted upstream of settlements to protect the settlements from ice scouring during winter floods, and produce raw material for wattles. After water table lowering in the southern Upper Rhine valley, the former floodplain was colonized by species of *terra firme* plants (not adapted to inundation).

The upper Rhine headwaters are steep with boulders or bedrock substrate, and patches of finer sediments. During early summer, snowmelt and spates exert hydraulic stress on benthic communities. During low water, water abstraction results in low residual flow (loss of habitats with high current velocity) and flow intermittency. Bank protection (walls or stone riprap) and uniform cross-sections also resulted in habitat loss. In the relatively few reaches not affected by river engineering, habitat diversity is relatively high, for example, the 18-km long gorge of the Vorderrhein and the braided floodplain of the Hinterrhein near the confluence. However, both reaches are strongly affected by hydropeaking. Upstream of the Ill confluence, alternating point bars with backwaters provide some habitat heterogeneity but more downstream these bars are missing. In addition to a poorly structured channel, the entire Alpine Rhine is subject to hydropeaking. Clear and macrophyte rich groundwater-fed side-canals provide a contrasting habitat but, apart from a few rehabilitated reaches, the morphology of these man-made streams is quite uniform.

Riparian vegetation above treeline is characterized by alpine grassland vegetation. At lower elevations (~1500 m asl), willow (*Salix appendiculata*) and green alder (*Alnus viridis*) occur, and on coarse substrate on banks grow macrophytes such as common butterbur (*Petasites hybridus*), *Rumex alpinus*, *Epilobium angustifolium* and *Cirsium olearaceum* (Roullier 2005). More downstream (1200 m asl), tree vegetation is dominated by grey alder (*Alnus incana*) and willow shrub (*Salix daphnoides*, *Salix elaeagnos*). On stable floodplain terraces fir (*P. abies*) and grey alder occur. In the Alpine Rhine, the riparian zone is characterized by boulder riprap, except for a short reach near Mastrils, and relatively narrow strips of grassland. The scattered remnants of former floodplain forests are isolated from the river by high artificial embankments.

Between the delta of the Alpine Rhine and the upper High Rhine, lentic habitat conditions prevail for ~60 km, except for the short riverine passage (Seerhein) between upper and lower Lake Constance. The load of suspended solids is deposited near the deltaic river mouth and along the lacustrine subsurface flowpath of the Alpine Rhine. Erosional banks along the surf zone of Lake Constance provide appropriate conditions for some lotic invertebrates (Scheifhacken et al. 2007). The annually flooded littoral zone of the lake provides habitat for communities adapted to large stage variations (Wantzen & Rothaupt 2008). In the Seerhein (outlet of upper Lake Constance), conditions are favourable for filter-feeders, especially zebra mussel (*Dreissena polymorpha*) (Werner et al. 2005). In lower Lake Constance, extensive shallow areas are habitats for aquatic macrophytes. Large reed belts occur in lower Lake Constance.

Unregulated reaches of the High Rhine are characterized by relatively high habitat diversity with respect to depth and current velocity. In the upper High Rhine, coarse gravel forms few point bars along the naturally confined channel. Lake plankton supports a typical lake outlet community. Local scour holes in the riverbed are important spawning and wintering habitats for grayling (*Thymallus thymallus*). In shallow runs, the gravel sediments are covered by *D. polymorpha* or macrophytes, both creating specific habitats for invertebrates. Counter currents below point bars, few snags (snags are usually removed) and pillars of bridges provide habitats for resting fish. Particularly downstream of the Rhine Fall, river banks in the relatively steep valley are narrow and floodplains are marginal. The riparian zone typically changes within a few meters from gravel banks or rock outcrops to upland forests. Today, rapids only occur in two short (<1.5 km long) reaches. Stone ripraps and concrete walls are not only typical along developed areas such as villages or towns but also are widely found outside of such areas.

Downstream of Rhine Fall, substrate in fast-flowing stretches between the power plants is dominated by gravel, and bedrock occurs at few sites. Channel morphology is relatively uniform in impounded reaches and the lower High Rhine, which is open to navigation (Rkm 146.5–165). Deposition of fine sediments occurs in slow flowing areas upstream of power plants. Tree vegetation in a narrow zone subject to inundation primarily includes black alder (*Alnus glutinosa*) and various willows. The largest remnant floodplain (4.3 km^2) is at the Thur–Rhine confluence, but bank stabilization stopped natural river dynamics. Stands of ash (*Fraxinocenetum excelsioris*) dominate the floodplain forest (Roullier 2005). Existing riparian forests along the High Rhine are managed, with beech and oak (*Q. robur*) prevailing.

In the southern section of the Upper Rhine, habitat diversity is extremely low in the Grand Canal d'Alsace with its concrete walls (Rkm 170–226) and relatively high in the old Rhine (Restrhein) that parallels the Grand Canal. Sediments in this near-natural river channel are subject to siltation or become locally anoxic at base flow (10–15 m^3/s) (Becker 1994). The remaining floodplain channels have largely lost their hydro-geomorphic dynamics, but still persist because of episodic floods. Only 6% of the floodplain area between Basel and Iffezheim (Rkm 335), which existed in1800, escaped channelization and regulation (Hügin 1981). The few remnants of the original floodplain are today natural preserves such as Taubergiessen (near Rhinau at Rkm 256). Because of reduced fluvial dynamics, the diversity of newly formed habitats such as gravel bars or slumped banks are limited. Existing meanders, oxbow lakes and other functional floodplain features are static and subject to siltation.

Nevertheless, the diversity of aquatic habitats is still impressive. A particular floodplain habitat is clear groundwater-fed streams (so-called Giessen) that exist because of regionally coarse and porous aquifers. Between Breisach and Strasbourg (Rkm 294), the old Rhine channel is paralleled by monotonous loop diversion canals from four power plants. Habitat conditions are similar to those described for the Restrhein and Grand Canal, but the old Rhine receives far more water. Below Strasbourg, where the river is one single channel, physical habitat is limited to the river channel and the few floodplain relicts are small, except for the cut-off meander Kühkopf (near Riedstadt at Rkm 468–474). Bed sediments consist of gravel (in the fast-flowing section between Karlsruhe and Mannheim) and coarse sand below Mannheim (Becker 1994). Rock outcrops are rare, for example, near Nackenheim (Rkm 488).

In the sections where sand prevails, dynamic underwater dunes develop (Carling et al. 2000). Apart from sheet-pile walls along harbours, almost all banks are stabilized with riprap. The few islands occurring in the Upper Rhine are partly protected against erosion. Seven oblong islands between Eltville (Rkm 509) and Bingen (Rkm 528) are longitudinally connected by riprap dikes forming shallow waters between the islands. In this area, a 566 ha zone has been designated as a Ramsar Site (no. 88), serving as a resting and wintering area for waterfowl. The present floodplain forest is a mixture of remaining original vegetation, planted trees, and *terra firme* species invading rarely flooded areas.

In remnants of the Alsacian floodplains, Carbiener (1974) identified the following phytosociological units on a floodplain of a regularly flooded island (Rhinau): (a) young (20 years) initial stages of pioneer vegetation (*Salicetum eleagni*, *Salici albae–Populetum nigrae*) on disturbed soils, (b) mature softwood floodplain forest (*Salici–Populetum*) of 50 years and older, (c) mixed softwood/hardwood floodplain forest with poplar, ash and elm trees (*Fraxino–Populetum albae*) developing from the pre-rectification period and (d) old hardwood forest (*Querco–Ulmetum*) as a climax stage of the floodplain forest with several gradient-specific subclasses. Recent studies have analyzed the successional status of the alluvial hardwood forests, and the influences of management and nutrient inputs on their vegetation structure. Under natural conditions, pioneer softwoods are generally replaced by hardwoods in $<$100 years, and the high diversity of the Upper Rhine alluvial forests is a result of regular flooding (Schnitzler 1994; Schnitzler et al. 2005). Floodplain forests seem to be more diverse than the surrounding *terra firme* forests, and the drying of former floodplain forests has led to a decrease in litter production, leaf N and P concentrations (Tremolières et al. 1998).

In the Middle Rhine between Bingen and Koblenz, high current velocities (6–7 km/h) keep fine sediments suspended. Poorly rounded bed sediments become visibly smaller in the upper Middle Rhine and bedrock outcrops occur at many sites. In coarser sediments, colonization of the hyporheic zone by epibenthic invertebrates may go as deep as 70 cm, for example, by larvae of the mayfly *Ephoron virgo* (Wantzen 1992). Dense beds of *D. polymorpha* and mud tubes of *Chelicorophium curvispinum* reduce bed porosity and the oxygen availability in interstices (Rajagopal et al. 1999). Hyporheic fauna in tributaries from the mid-Rhenanian Mountains and Rhine often mix, for example, stygal gammarids (genus *Niphargus*) frequently occurs in the hyporheic zone of the Rhine below tributary confluences (Wantzen 1992).

Below thalweg crossings, central bars occur. Some of these bars recently became sparsely vegetated islands ('Gründe') because their banks have been protected (Photo 6.9). Alternating wet and dry conditions provide a special habitat for some biota (Wantzen 1992). Older islands are covered by dense woody vegetation typical of the lower end of the floodplain gradient. Groynes provide special habitats somewhat comparable to natural floodplains. Between groynes, large amounts of fine inorganic and organic particles can accumulate when protected by islands against the impact of waves from ship traffic. These accumulations provide habitats for mud-dwellers similar to slack water areas below islands. Woody vegetation in this section is generally restricted to islands. The gravel islands are irregularly flooded and have scarce vegetation from resprouting logs and branches of *Populus* and *Salix*. *Salix* is especially adapted to breakage of branches during hydraulic stress that drift downriver and serve as propagules for recolonization of pioneer habitats. Older islands with alluvial soils show a mixture of *Populus x canadensis* and native softwood forest species (*P. nigra*, *Salix alba*, *S. viminalis*, *S. fragilis*, *Sambucus nigra*, *Corylus avellana*, *Rhamnus frangula*, *Viburnum lantana*, *Crataegus monogyna*) that are often covered with lianas (*Clematis vitalba*). Some islands host vinyards or are used for horticulture because of high soil fertility.

In the Lower Rhine below the widening of the Rhine valley near the cities of Brohl and Bonn (Rkm 620–656), gravel sediments locally disappear and sand dunes develop. Downstream of Düsseldorf, vertical erosion into the Tertiary and Devonian clay deposits regionally results in an impermeable river bottom. Outside of large cities, the river banks are almost completely stabilized by riprap. Lateral sand bars occur occasionally. Flooding is restricted to the mostly managed zone between the dikes and river, which are generally used as meadows for cattle ranching. Several artificial lakes (sand pits) are directly or indirectly connected to the main channel and provide habitats that partially fulfill functions of former floodplain waterbodies. Groyn fields characterize the three Rhine branches in the Delta. Forelands occur between the summer and winter dikes. Waterbodies in the forelands have lost the lateral connectivity with the main channel, which is deeply incised. Shallow lotic habitats are widely lacking (Bij de Vaate et al. 2006). Groyns and training walls along the river provide habitats for lithophilous species (Raat 2001).

6.6.2. Benthic Algae

Friedrich & Müller (1984) mentioned the lack of a comprehensive account of benthic algae along the Rhine. Early studies include that of Lauterborn (1910) on the Upper Rhine and in a section of the High Rhine (Rkm 20–74). The study of Jaag (1938), who carefully studied different habitats of the Rhine Falls, mentioned 338 algal species. In a more recent study, Zimmerli (1991) focused on benthic and suspended algae at 37 stations along the Rhine main stem from the Rhine source (Lake Toma) to Basel and in 19 tributaries. He identified 552 species of which 455 occurred in the Rhine. He found that local (reach) species richness increased from 40 in the Alpine headwaters to about 80 in Basel. The algal community was dominated by Bacillariophyceae (194 species), Chlorophyceae (72 species), Cyanobacteria (72 species), and Conjugatophyceae (46 species). An investigation of benthic diatoms in the High Rhine between Lake Constance and Basel by Swiss and German authorities recorded 226 taxa (BUWAL 1993). A periphyton census neglecting diatoms of the same High Rhine section in 1995 (LFU BW 1996) showed that crust-forming algae typical of lowland lake outlets such as *Phormidium incrustatum* and *Homeothrix crustacea* were abundant.

6.6.3. Macrophytes and Bryophytes

Early studies on hydrophytes date back to Lauterborn (1910, 1916, 1917, 1921). The major part of the Rhine (Lake Constance to Cologne) was recently studied and the literature revised by Vanderpoorten & Klein (1999). They found five species clusters for both macrophytes and bryophytes, with the highest overlap of clusters in the southern Upper Rhine. Thermal and trophic conditions of floodplain waterbodies differ strongly between the southern Upper Rhine (stenothermic, oligotrophic groundwater-fed 'Giessen') and the northern Upper Rhine (eurythermic, eutrophic oxbow lakes), resulting in distinctly different macrophyte vegetation. In the main channel of the Rhine, growth of aquatic phanerogams is hindered by coarse and mobile substrates, whereas bank habitats exhibit a rich bryophyte diversity.

Macrophytes are mostly found in floodplain habitats and slow-flowing habitats of the main channel. River regulation has strongly influenced the hydrophytes. Rheophilic bryophytes that formerly only occurred in the upper, high-gradient section of the river were favoured by the occurrence of solid substrates, and several species are found today in the Lower Rhine. Characean algae that were formerly found as pioneer vegetation on mobile coarse sands in dynamic floodplain channels have been reduced, but now colonize the gravel-pit lakes, especially in the Upper Rhine. Phanerogamic macrophytes show a less distinct longitudinal pattern than bryophytes because of homogenous habitat structure resulting from river engineering. However, remnant floodplain habitats ranging from exclusively groundwater-fed (at low discharge) to Rhine-water fed (at high discharge) waterbodies result in a distinct lateral gradient in aquatic plant communities (Vanderpoorten & Klein 1999).

In the Alpine Rhine and its headwaters, unstable sediments and turbidity impede the growth of macrophytes, but mosses such as *Philonotis seriata* and *Hygrohypnum smithi* are adapted to these conditions (Vanderpoorten & Klein 1999). Water plants show a luxurious growth in lower Lake Constance and upper High Rhine, where nutrient supply, light conditions (low turbidity) and moderate current velocities provide ideal environmental conditions. The diverse aquatic flora comprises *Myriophyllum spicatum*, *Zannichelia palustris*, *Elodea canadensis*, *Ranunculus fluitans*, *Potamogeton perfoliatus* and *P. crispus*. During the oligotrophication period of the lake (1978–1993), the diversity of the plant community increased (Schmieder & Lehmann 2004). Today, several macrophytes, for example, *Potamogeton* associations, are increasingly replaced by various *Chara* species, presumably because of ongoing oligotrophication. The macrophyte community is also influenced by aquatic herbivorous invertebrates (Gross et al. 2001) or seasonally by birds (Schmieder & Lehmann 2004).

The High Rhine is habitat for many rheophilic plants, for example, bryophytes such as *Cratoneuron filicinum* and *Fissidens crassipes*, as well as macrophytes like *Potamogeton friesii, Groenlandia densa*, *Berula erecta* and *Callitriche obtusangula* (Vanderpoorten & Klein 1999). In the Upper Rhine, macrophyte colonization is largely limited to the Restrhein and remnant floodplain waterbodies. In the Taubergiessen area, undisturbed groundwater-fed ponds are characterized by a specific flora, for example, the red algae *Batrachospermum* sp. and *Hildenbrandia rivularis*, and in the lower sections, thick carpets of *C. obtusangula*. Robach et al. (1997) compared the macrophyte vegetation structure in several eutrophic channels of the former Alsacian floodplain that were either directly connected to the Rhine (conductivity 350–800 μS cm^{-1}) and the Ill River, a more acidic and less ion-loaded tributary descending from the Vosges Mountains (conductivity 150–750 μS cm^{-1}). The Rhine-connected habitats had higher species richness (43 versus 25 species), greater biomass, and a more complex structure (4–5 versus $<$3 strata) than the Ill-connected channels. According to Braun-Blanquet (1964), the prevailing macrophyte communites in the Rhine-connected habitats were *Lemnetum gibbae*, *Ceratophylletum demersi*, *Potamogenetum perfoliati*, *Ranunculetum fluitantis* and *Callitrichetum obtusangulae*.

In the Middle Rhine, fast currents limit macrophyte growth. However, the reduction in nutrients and turbidity enhanced the growth of vascular aquatic macrophytes in all hydrologically suitable habitats (e.g., the area between groynes and in small stillwater interstices within riprap). In the last 5–10 years, meso-eutrophic species such as *Butomus umbellatus*, *Ceratophyllum demersum* and *M. spicatum* are increasingly spreading. In the Lower Rhine and Delta Rhine high salinity and turbidity influence the occurrence of several macrophytes. Mesocosm experiments by (Van den Brink & Van der Velde 1993) demonstrated a high sensitivity of *Potamogeton lucens*, *P. perfoliatus* and *P. nodosus* to increased salinity.

6.6.4. Plankton

6.6.4.1 Phytoplankton

Early studies of the Rhine phytoplankton included investigations by Lauterborn (1905) and Kolkwitz (1912). Lakes fringing the Alps and standing waterbodies connected with the main stem such as oxbow lakes provided planktonic alge in low numbers. In the early 20th century, cell densities were generally low and it was debated whether autochtonous river plankton existed (Friedrich 1990). Most common plankton in the early 20th century were diatoms such as *Cyclotella bodanica*, *Cyclotella* spp., *Asterionalla formosa*, *Fragilaria crotonenis*, *Diatoma elongatum*, and different forms of *Synedra acus*, besides Chrysophycea such as *Dinobryon sertularia* and *Spaerocystis schroederi* and a few Cryptomonads. Seeler (1936) studied phytoplankton in 1933 between Strasbourg and Rotterdam. He found a coincidence of phytoplankton minima with the discharge of waste-water (phytoplankton cell numbers ranged from 240 to 6900 m/L). The occurrence of Cyanobacteria, *Planktothrix rubescens*, in Rhine samples reflect the increasing eutrophication of lakes in Alpine forelands (Czernin-Chudenitz 1958). In the 1970s, cell densities reached $>10 \times 10^6$/L, and Tubbing et al. (1994) reported a maximum of $>50 \times 10^6$/L, corresponding to ~140 mg chlorophyll *a*, at the Dutch–German border.

Recent observations of phytoplankton, mainly within the 'Rhine Action Programme', covered the entire stretch between Lake Constance and the sea (IKSR 2002c; Tubbing et al. 1994) or parts of it (Admiraal et al. 1994; De Ruyter van Steveninck et al. 1992; Ibelings et al. 1998). Annual concentrations of suspended chlorophyll a ranged in 2000 from 2.9 to 3.4 μg/L from the High Rhine to the beginning of the Lower Rhine, and reached 8.3 mg/L at the Dutch–German border (Rkm 863), and decreased to 3.8 μg/L in Massluis (Rkm 1019) (IKSR 2002c). Chlorophyll a concentrations peaked in April/early May, with maximum values of 43 μg/L at the Dutch–German border and 46 μg/L in Kampen (Ijssel, Rkm 995). The chlorophyll a record at Lobith (Rkm 863) showed a decline in average chlorophyll a concentrations from 26 5 μg/L (average 1977–1981) to 11 4 μg/L (average 2001–2005), which may be attributed to improved water quality. The decline in the Delta reach may be attributed to grazing and sedimentation loss by plankton and dense populations of sessile filter-feeders (Ibelings et al. 1998). Chlorophyll a concentrations typically peak in spring and usually to a minor extent in July/August (Tubbing et al. 1994).

The study of De Ruyter van Steveninck et al. (1992) showed increasing bacterial numbers from the Upper Rhine to Maassluis (9×10^9 to about 13×10^9 cells/L) during the spring phytoplankton bloom in 1990. The census of 2000 (IKSR 2002c) showed that Cyanobacteria were maximum during winter and diatoms prevailed in spring and summer. More frequent during summer also were Chlorophyceae, Chrysophyceae, and Dynophyceae. The influence of Lake Constance is evident until the Upper Rhine (dominance of *Planktothrix agardhii*/*rubescens*). Further downstream the plankton composition is influenced by the export of alge from the major tributaries Neckar, Main and Moselle. Cryptomonads and diatoms were dominant in the High Rhine, where Cyanobacteria peaked in autumn. Frequent species in the southern Upper Rhine were *Planktothrix agardhii*/*rubescens*, *Rhodomonas minuta*, and tychoplanktonic taxa such as *Diatoma vulgaris* and *Cocconeis* sp. More downstream, the abundance of *Planktothrix agardhii*/*rubescens* declined and centric diatoms became more important. In the Middle Rhine, *Planktothrix* spp. dominated in winter and early spring and afterwards centric diatoms; cryptomonads and *Rhodomonas minuta* var. *nannoplanctica* became more important during summer. Near the Dutch–German border, the *Cyclotella*–*Stephanodiscus*–*Cyclostephanos*–*Thalassiosira* complex dominated; *Planktothrix agardhii*/*rubescens* reached high numbers in winter. The community in Maasluis was similar but *Spermatozopsis* sp., *Rhodomonas* spp., and unicellular chlorophytes reached high abundances in summer.

6.6.4.2 Zooplankton

Investigations of zooplankton are less comprehensive and typically restricted to selected reaches or stations along the Rhine main stem. Low abundance and species richness characterized the zooplankton in 1933 (Seeler 1936). A study performed in 1986/87 on the Lower Rhine showed zooplankton maxima in spring (Friedrich 1990). Common species included the genera *Brachionus*, *Keratella* and *Polyarthra*. Rotifers reached maximum densities of ~160 individuals/L, and crustaceans were scarce ≤1 individuals/L. Higher densities were reported by Tubbing et al. (1994). During spring, rotifers, mainly *Brachionus calyciflorus*, *Kreatella cochlearis* and *K. quadrata*, reached up to 100 individuals/L at Koblenz, >1000 individuals/L at the Dutch–German border and 500 individuals/L in Maassluis. Crustaceans (mainly nauplii) increased along the same stretch from 1 to 10 individuals/L, and up to 178 individuals/L in Maasluis. Cladocerans (*Bosmina* spp. and *Daphnia* spp.) were rare in the upper section (1–3 individuals/L), but increased downstream to 25 individuals/L. According to the IKSR census of 2000 (IKSR 2002c), the reported decrease in zooplankton density in this stretch since 1990 has continued, presumably due to the decline in phytoplankton biomass.

6.6.5. Benthic Invertebrates

Macrozoobenthic communities of the Rhine originally exhibited a distinct longitudinal zonation that reflected recent ecological conditions and paleogeographic settings, particularly in the southern Upper Rhine once belonging to the Danube and ~~Rhone~~ drainage (Kinzelbach 1990). River engineering in the last two centuries and pollution are considered to be the main causes eliminating faunistic boundaries. Macrozoobenthic communities are increasingly affected by non-natives migrating into the Rhine catchment through the north German and eastern European system of waterways connecting the ~~Dniepr~~ and Bug with the Rhine, the French waterway system (Mediterranean species), and the Main–Danube–Canal (Bij de Vaate et al. 2002; BUWAL 2005; Leuven et al. 2009; Tittizer et al. 1994). The number of non-native species in the Delta Rhine increased

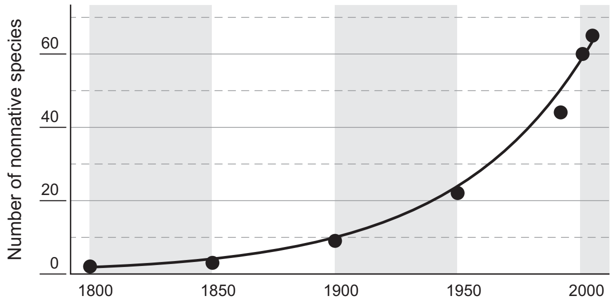

FIGURE 6.9 Cummulative number of non-native species in the Rhine Delta since 1800. Modified from Leuven et al. (2009).

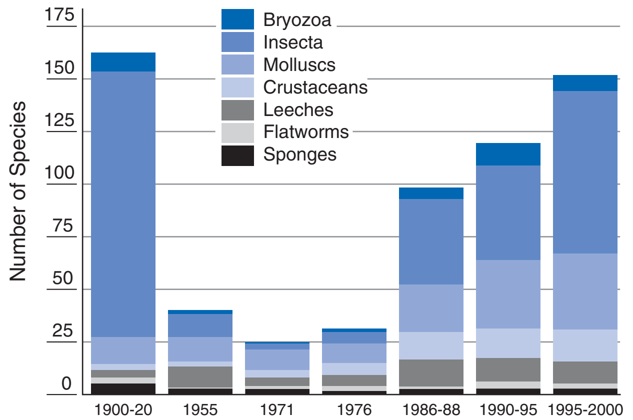

FIGURE 6.10 Taxa richness of benthic macroinvertebrates between Basel (river 152 km) and the Dutch–German border (river 870 km) during the 20th century. Taxa levels adjusted to allow comparison between different periods. Modified from Tittizer et al. (1994) and IKSR (2002a).

exponentially during the last 200 years (Figure 6.9) (Leuven et al. 2009). An important gateway for non-natives is the port of Rotterdam, which is the terminus of Rhine navigation and Europe's largest seaport (yearly discharge of 5 billion tons of ballast water harbouring many non-native species). Ongoing warming will affect a higher percentage of indigenous species than non-natives (Leuven et al. 2007). Compared to the Ponto-Caspian province, the benthic invertebrate richness of the fauna north of the Alps is reduced because the Alps form a barrier that impeded the accessibility of southern refuges during Pleistocene glaciations, which enhanced species extinction and impeded or delayed re-colonization from these refuges after the last glaciation.

Benthic invertebrates of the Rhine have been studied since the early 20th century (e.g., Lauterborn 1916, 1917, 1918) when the river was already affected by pollution and river engineering. During peak pollution in the 1970s, the number of taxa in the navigable Rhine sections was minimal but subsequently increased parallel to the increase in water quality (Figure 6.10). The Sandoz-disaster of 1986 gave rise to detailed assessments of the recovery of the biota. Results from this monitoring program indicated that the Rhine has basically re-gained the number of taxa reported by Lauterborn (LFU BW 2004; Marten 2001) but the community, once characterized by insects, is now dominated by crustaceans and molluscs. This shift in community structure reflects the loss of natural habitat diversity, the widespread occurrence of artificial substrates such as stone riprap or concrete walls, and the invasion of non-natives. Non-natives now contribute $\sim$18% to the taxa inventory and dominate in abundance and biomass by >90% (IKSR 2002a; Nehring 2003).

The invasion of Ponto-Caspian species dramatically increased with the opening of the Main–Danube–Canal in 1992. The polychaete *Hypania invalida* arrived in the Rhine already in 1996 (IKSR 2002a). Amphipods such as *Dikerogammarus villosus*, *D. haemobaphes* and *Echinogammarus berilloni* successfully immigrated through the Main–Danube–Canal. *D. villosus* colonized the Rhine between Lake Constance and the sea within 10 years, thereby strongly reducing the abundances of most other benthic species (Haas et al. 2002; Van Riel et al. 2006). *Chelicorophium curvispinum*, another Ponto-Caspian amphipod, reached the Lower Rhine through the North German waterway system in the 1980s and spread out at an amazing speed along the Rhine and its major tributaries Moselle, Main, and Neckar before the 'Danube' population arrived through the Main–Danube Canal. It out-competes the native fauna by building extensive networks of mud-tubes on firm substrate, including mussel shells, leading to the decay of *Dreissena* populations. Since 2001, numbers of *C. curvispinum* have declined due increasing predation and parasite impacts (Van Riel et al. 2006). Asian clams *Corbicula fluminea* and *C. fluminalis* colonized the Rhine from the sea. Both species presumably arrived from North America with ballast water of ships (Rajagopal et al. 2000). The clams reach high densities (60 000–100 000 individuals/m^2), but occasionally die back during low water periods in summer (IKSR 2002a). Recently, the Ponto-Caspian Quagga mussel (*Dreissena rostriformis bugensis*) was recorded in the Rhine basin (Van der Velde & Platvoet 2007). This species has expanded it geographical distribution in Europe at a slower rate than the zebra mussel. The Chinese mitten crab (*Eriocheir sinensis*), a large grapsid, migrated from the sea to Lake Constance. This large benthic omnivore affects the invertebrate community at different levels and can damage dikes by its burrowing activities.

The most recent census (IKSR 2002a) reported 479 taxa along the Rhine main stem between Lake Constance and the sea with dipterans contributing 105 taxa, trichopterans 79, ephemeropterans 49, oligochaets (37), gastropods 33, large crustaceans 23, and lamellibranchiats 22. Plecopterans included 11 taxa typically occurring in low abundances. Only 26% of today's taxa have been found by Lauterborn and others. The number of taxa declines from the non-navigable upper High Rhine reach to the Rhine Delta (Figure 6.11), reflecting changes in water quality and habitat structure. About 20% of the benthic invertebrates in the examined Rhine sections are considered to be endangered (IKSR 2002a).

Lauterborn (1916) described the benthic communities of the Vorderrhein and Hinterrhein before the impact of hydropower plants but when most river engineering works had

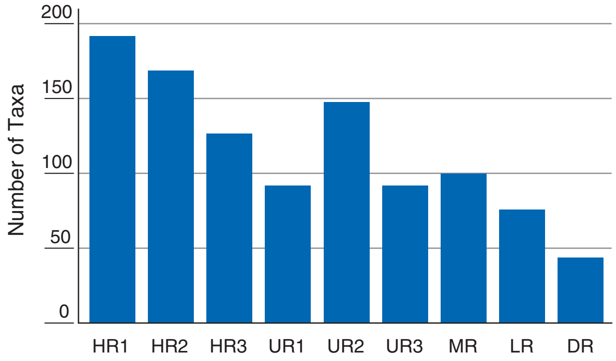

FIGURE 6.11 Taxa richness of macroinvertebrates along the Rhine between the lower Lake Constance and the sea. The same taxonomic level has been applied for all Rhine sections. HR1 = High Rhine between Lake Constance and Aare confluence. HR2 = High Rhine between Aare confluence and beginning of the navigable reach. HR3 = High Rhine navigable reach. UR1 = southern Upper Rhine: Grand Canal. UR2 = southern Upper Rhine: Restrhein. UR3 = northern Upper Rhine. MR = Middle Rhine. LR = Lower Rhine. DR = Delta Rhine. Modified from BUWAL (2002).

been completed. Information on today's benthic invertebrates is widely lacking. Environmental conditions in the Alpine Rhine are impaired by hydropeaking, which encompasses fast and major stage variations, high turbidity, and bedload transport during the daily peak flow. Invertebrate sampling performed in autumn and late winter showed low abundances and biomass (Moritz & Pfister 2001). The number of taxa increases along the studied 55-km long reach from 35 to 50. The invertebrate community is dominated by chironomids, mainly Orthocladinae, *Diamesa* sp. and *Eukiefferella* sp. Most frequent species or taxa are *Baetis alpinus* and *B. rhodani* among the mayflies, *Leuctra* sp., *Capnia* sp. and *Rhabdiopterix* sp.among the stoneflies, and *Allogamus* sp. and *Rhyacophila* sp. among the caddisflies. Dominant among the blackflies were *Simulium* sp. Hydropeaking enhances the clogging of bed sediments, which negatively affects interstitial fauna. Small interstitial animals such as the chironomids *Heleniall*a sp. or *Parakiefferella* sp. cannot use sand-clogged interstices. *Allogamus auricollis* flushed away during peak flows accumulates in low-current areas, where they reach high densities. The combined effects of hydropeaking and channel rectification shift the structure of the benthic community towards that of a torrential mountain river (Moritz & Pfister 2001).

The benthic fauna of Lake Constance is well documented; historical records include studies by Lauterborn (1921) and Muckle (1942). The native fauna is highly habitat-specific and includes oligochaete and chironomid communities in deep sediments, wave-adapted species at erosional banks (Scheifhacken et al. 2007), and a segregation between the lower, the upper and uppermost section of the littoral zone that falls dry from autumn to spring (Mörtl 2004). Macrophyte-covered habitats of the lower Lake Constance harbour a specific fauna that includes several herbivorous species (e.g., the pyralid moth *Acentria ephemerella*, Gross & Kornijow 2002). Only recently, the invertebrate fauna of the limnetic-depositional and erosional habitats of the lake has been changed by non-natives. The most abundant gammarid species, *Gammarus roeseli* (probably an invader that replaced the native *G. lacustris* in large parts of the lake during the eutropication phase in the 1960–1970s) is currently being severely threatened by the invasive *D. villosus* (Hesselschwerdt et al., in press). The decapod fauna, once including large specimens of the crayfish *Astacus astacus*, has been replaced almost completely by non-native *Astacus leptodactylus* and *Orconectes limosus*. When writing this chapter, the Ponto-Caspian freshwater shrimp *Limnomysis benedeni* arrived in Lake Constance, where it started to form large swarms (Fritz et al. 2006).

The invasion by *D. polymorpha* in 1965 had a major ecological impact (Siessegger 1969). Mass populations caused the clogging of water intakes of drinking water facilities and changed the sediment structure by masses of shells and byssus threads. The large native mussels *Anodonta anatina* and *A. cygnea* suffered from competition and physical stress because *Dreissena* colonized their shells (Bauer 2002). *Dreissena* also lead to an increase of waterfowl wintering on Lake Constance (Werner et al. 2005). In the Seerhein, which connects the upper and lower Lake Constance, >90% of the standing crop (9.9 kg fresh weight/m^2 corresponding to 60 000 animals/m^2) was consumed by wintering waterfowl, mainly tufted ducks (*Aythya fuligula*) and pochards (*Aythya farina*) (Cleven & Frenzel 1993). Currently, the Asian clam *C. fluminea* is spreading in shallow zones of the lake. Because of its hard shell, it may probably be less integrated in the food web than *Dreissena* and change the structure of soft substrate habitats.

The benthic community of the upper 26-km long High Rhine is typical for lake outlets with high densities of filter-feeders (*D. polymorpha*, Hydropsychidae, Simuliidae) (Caspers 1980). Low turbidity (plankton concentrations in the meso-oligotrophic Lake Constance are relatively small) and moderate nutrient contents favours benthic algal growth on stable gravel substrate, supporting benthic grazers such as the neretid snail *Theodoxus fluviatilis*. Rhithral taxa include *Dugesia gonocephala*, *Gammarus fossarum*, the mayflies *Potamanthus luteus*, *Habroleptoides confusa*, *Rhithrogena semicolorata*, *Ecdyonurus* sp., *Baetis* spp., stoneflies *Perlodes* sp., *Leuctra sp*., *Nemoura* sp., *Amphinemura* sp. and caddisflies *Sericostoma*, *Glossosoma* and *Silo* (IKSR 2002a). Tubificids and other pelophilic species reach high densities in impounded reaches upstream of power plants, where muddy sediments prevail. In free-flowing reaches between power plants, the composition of benthic invertebrates is similar to that in the lake outlet but with fewer filter-feeders. *D. polymorpha* occurs in the entire High Rhine. Densities decline with distance from Lake Constance. The navigable High Rhine stretch is characterized by high densities of non-natives (up to 95%) such as *Chelicorophium curvispinum*, *D. villosus*, *H. invalida*, *Corbicula* sp. and *Jaera istri*.

In the southern Upper Rhine (Rkm 172–355), taxa richness is distinctly lower in the uniform Grand Canal d'Alsace and loop diversion channels of the run-of-river power plants than in the stretches with residual flow such as Restrhein and the old Rhine bed that parallel the four loop diversions (Figure 6.11). On the concrete walls of the Grand Canal, only a few species are abundant, e.g., *Psychomya pusilla*, that can cope with the green algae covering the concrete surface. The walls are nearly void of invertebrates during winter (IKSR 2002a). The occurrence of the mayfly *P. luteus* or caddisfly *Cheumatopsyche lepida* reflects the influence of the High Rhine fauna on community composition in residual stretches. In the nearly stagnant waters of residual stretches, limnetic species such as *Lymnaea stagnalis* and *Caenis horaria* can be found.

In the northern ~~High~~ Rhine (Rkm 355–530), the number of taxa excluding Oligochaeta and Chiromomidae is 95 (IKSR 2002a). The crustaceans *D. villosus*, *Echinogammarus ischnus* and *Corophium curvispinum* reach high densities, as well as *D. polymorpha* and the snail *Bithynia tenticulata*. In oxbow lakes connected to the main stem and sections where islands reduce the ship-induced wave action, native mussels such as *Unio pictorum*, *U. tumidus*, *A. anatina*, *A. cygnea* and the non-native shrimp *Athyaephyra desmaresti* colonize mud and sand substrates (IKSR 2002a). The occurrence of species such as *Baetis muticus*, *Heptagenia flava*, *Ephemera vulgata*, *Limnius perrisi* and *Macronychus quadrituberculatus* indicate the improved water quality since 1995 (LFU BW 2004). However, many species, especially stoneflies, mayflies and caddisflies, found by early investigators are still missing (Marten 2001). Like in the northern Upper Rhine, invertebrate communities of the Middle Rhine and northern Lower Rhine are dominated by species common and frequent in large rivers with low demands regarding habitat conditions (IKSR 2002a). In the Middle Rhine, areas protected from waves provide habitat for epipotamal species like *C. lepida* and *P. luteus* but also for the Ponto-Caspian freshwater shrimps *L. benedeni* and *Hemimysis anomala*.

Mayflies and caddisflies of the Lower Rhine include species characteristic of potamal reaches of large rivers such as *Heptagenia sulfurea*, *E. virgo*, *Hydropsyche contubernalis*, *H. bulgaromanorum* and *P. pusilla*. The dominant species with respect to biomass and abundance are non-natives such as *J. istri*, *D. villosus* and *Corophium curvispinum*. The large mussels *Pseudoanodonta complanata* and *Unio crassus* were found in small numbers within groyne fields. More frequent are *U. pictorum*, *A. cygnea* and the non-native *C. fluminea*. Sessile filter-feeders, mostly bryozoans (*Fredericiella sultana*, *Paludicella articulata*, *Plumatella emarginata*, *Plumatella repens*) and freshwater sponges (*Spongilla*), are important for the self-cleansing potential of the river (IKSR 2002a).

Native species, which disappeared during the peak pollution period, re-colonized the river but only a few species have reached pre-pollution biomasses, for example, *E. virgo* (Marten 2001; IKSR 2002a). Larvae of this polymitarcid mayfly live in U-shaped burrows and in hyporheic sediments (Wantzen 1992; Kureck & Fontes 1996). In July 1991, a spectacular mass emergence of *E. virgo* caused car accidents and traffic jams on Rhine bridges illuminated by streetlamps. Recently re-found native species also include larvae of the gomphid dragonflies *Gomphus vulgatissimus* and *G. flavipes* in groyne fields. The change from gravel to sand coincides with the occurrence of species able to cope with the moving sand dunes such as the chironomids *Kloosia pusilla* and *Robackia demeijeri*, and the oligochaete *Propappus volki* (IKSR 2002a; Schöll & Haybach 2004).

Invertebrates of the Delta Rhine, where sandy substrate prevails, is characterized by a diverse chironomid and Oligochaete fauna (IKSR 2002a). Like in the Lower Rhine, *K. pusilla* und *R. demeijeri* reach high densities in habitats with fast flow. Oligochaets (Enchytraeidae, *P. volki*) are dwellers of the navigation channel, where flow is high and sediments are moving. Tubificidae are frequent in low current areas. Sand also provides habitat for small mussels such as *Pisidium henslowanum*, *Pisidium moitessierianum* and *Pisidium nitidum*. *Corophium curvispinum* and the chironomid *Dicrotendipes nervosus* are frequent on solid substrates (groynes and bank riprap). The brackish water zone of the lower Delta Rhine hosts only a few euryhaline species like *Corophium multisetosum*, *C. volutator*, the crab *Rhithropanopeus harrisii* and the shrimp *Palaemon longirostris*, both migrating upstream up to 150 km from the sea (IKSR 2002a).

6.6.6. Fish

Ausonius, a latin poet of the 4th century, provided a culinary and aesthetic description of the fishes of the Moselle River and later Leonhard Baldner, a Strasbourg fisherman, wrote in 1666 AD the faunal study ‘Das Fisch-, Vogel- und Thierbuch’ that included much information on large and commercially interesting fish (Geus 1964; Lelek 1989). A first description of the distribution of fishes between Lake Toma and the sea was given in Lauterborn’s Rhine monograph (Lauterborn, 1916, 1917, 1918). The fish fauna of the Rhine have a heterogeneous longitudinal distribution, which is unusual compared to other European rivers and reflects the historical development of the Rhine drainage, including the Pleistocene glaciations (Kinzelbach 1990; Lelek & Buhse 1992). At the end of the ice ages, fishes north of the Alps almost became extinct. As a consequence, the diversity of today’s fauna is relatively low. Recolonization by fishes occurred from refuges located southwest and southeast of the Alps and Carpathians (Lelek & Buhse 1992).

The indigenous fish fauna between Lake Constance and the Lower Rhine comprised about 44 species until 1880 (Lelek 1989). In the High, Upper and Middle Rhine, 19 species disappeared by 1950, and 3 species later. In the Lower Rhine, 42 species were lost by 1880, another 14 species by 1950, and 4 species later. Many of the remaining species also decreased in abundance. The decrease in diversity and abundance coincided with increasing pollution,

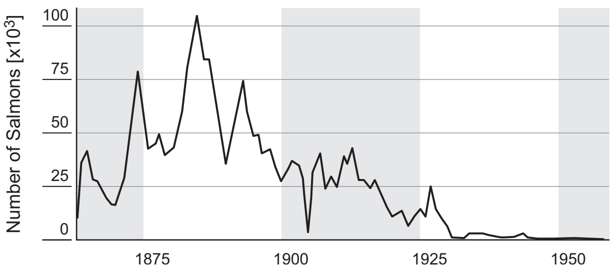

FIGURE 6.12 Salmon catches in the Dutch part of the Rhine (1863–1953). Modified from De Groot (2002).

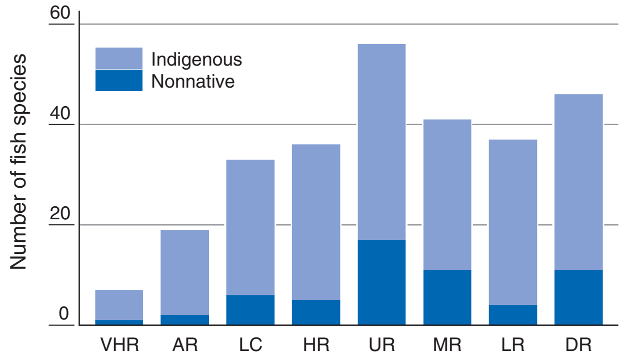

FIGURE 6.13 Species richness of fish in the Rhine between the Alps and the sea. VHR = Vorderrhein and Hinterhein, AR = Alpine Rhine, LC = Lake Constance, HR = High Rhine, UR = Upper Rhine, MR = Middle Rhine, LR = Lower Rhine and DR = Delta Rhine.

habitat loss by river engineering, and construction of powerplants. The closure of Afsluitdijk (1935), which separated the Zuiderzee from the sea, and Haringvliet sluices (1970) limited migratory fishes from moving from the sea to freshwater spawning areas. The remaining open channel, the Nieuwe Waterweg, flows through a highly industrialized area with many harbours and intense ship traffic (Brenner et al. 2003).

Populations of long-distance migrating fish such as Atlantic salmon (*Salmo salar*), allis shad (*Alosa alosa*), twait shad (*Alosa fallax*), Atlantic sturgeon (*Acipenser sturio*), sea trout (*Salmo trutta trutta*), sea lamprey (*Petromyzon marinus*) and eel (*Anguilla anguilla*) declined or became extinct (Lelek 1989; De Groot 2002). The Rhine was the European river with the largest salmon population. Salmon once migrated >1000 km to their spawning sites in the Aare and Upper Rhine tributaries before overfishing, chemical pollution, and migration barriers drove the population to extinction in the 1950s (Figure 6.12). The most recent census of IKSR indicate a substantial regeneration of fish communities: 43 of the original 44 indigenous species were present in the river, including an additional 20 non-native species (IKSR 2002b). Only the Atlantic sturgeon was not reported. The recurrence of Atlantic salmon in the Rhine reflects an improved water quality, restoration of spawning and nursery areas in tributaries and massive stocking (fingerlings of Irish, French, Scottish and Scandinavian populations) but today, the number of salmon is still small compared to their abundance in 19th century. About 1000 individuals reached the Upper Rhine north of Strasbourg because of new fish passes at Iffezheim (Rkm 334) and Gambsheim (Rkm 309). Video records of the Iffezheim fish pass showed the passage of Atlantic salmon, sea lamprey, shad, sea trout and eel. Eight powerplants still obstruct the upstream migration to the Swiss border. The Rhine Minister Conference in 2007 adopted the masterplan ‘Migratory Fish’ that concerns an improvement of upstream migration of migratory fish by modifying the floodgates at Haringvliet and constructing a fish passage at Strasbourg by 2015 (IKSR 2007).

Along the main stem of the Rhine, the number of species changes substantially (Figure 6.13). Investigations of the fish fauna in the Rhine headwaters are scarce. According to Lauterborn (1916), the fish of Vorderrhein and Hinterrhein included brown trout (*Salmo trutta* f. *fario*), migrating lake trout (*Salmo trutta* f. *lacustris*) that spawned in the Vorderrhein up to an elevation of ~900 m asl, minnow (*Phoxinus phoxinus*) and bullhead (*Cottus gobio*). Today, the fish fauna of the Vorderrhein and Hinterrhein includes brown trout, lake trout, bullhead, grayling (*T. thymallus*), and sporadic brook trout (*Salvelinus fontinalis*) and rainbow trout (*Oncorhynchus mykiss*). Minnows form a small population in the lower Hinterrhein and stone loach (*Barbatula barbatula*) was recently found in the lower Vorderrhein.

Before regulation, the Alpine Rhine provided habitat for about 30 fish species (Schmutz & Eberstaller 1993). Channelization of the river resulted in a major loss of stagnophile species. Besides low habitat diversity, the impact of hydropeaking (high flow variation and turbidity, poor food resources) results in small populations (<50 individuals ha^{-1} and 10 kg ha^{-1}). Today the fish population comprises 19 species, including introduced rainbow trout The non-native rainbow trout introduced in the late 19th century and stocked in Lake Constance and Binnenkanälen successfully compete with brown trout and to a minor extent lake trout. Of the fishes still present in the Alpine Rhine, 12 species are considered threatened. Lake trout spawn in fast-flowing tributaries of Lake Constance, including the Alpine Rhine, Vorderrhein and Hinterrhein, Ill and Bregenzerach. Hydropeaking, migration barriers such as the powerplant of Domat/Ems (constructed 1959–62), and isolation of tributaries and side-canals, severely affected the lake trout population (Ruhlé et al. 2005). In 2000, the powerplant had a vertical-slot fish pass installed. The side-canals provide habitat for 13 species most of which also occur in the Alpine Rhine. The more suitable habitat conditions (clear water and constant flow) in side-canals results in relatively high fish standing stocks. The highest species richness, 28 taxa including the non-native rainbow trout and zander (*Sander lucioperca*), was observed in the Alter Rhein (Old Rhine), reflecting the connectivity of this former main channel with Lake Constance (Schmutz & Eberstaller 1993).

Lake Constance is inhabited by 33 fish species, about the same number as in the beginning of the 20th century (Fischer & Eckmann 1997; Eckmann & Rösch 1998). Present species include introduced fishes such as pike perch (*S. lucioperca*), three-spined stickleback (*Gasterosteus aculeatus*), rainbow trout, sunfish (*Lepomis gibbosus*) and ruffe (*Gymnocephalus cernuus*). Ruffe, first recorded in 1987, became the dominant fish in shallow waters, feeding on benthic organisms but switching to whitefish eggs during the whitefish spawning period. Ruffe are a concern for fishery management since perch (*Perca fluviatilis*), which also feeds on benthic organisms, and whitefish are the most important catch by professional fishermen. Whitefish (*Coregonus lavaretus*, *Coregonus macrophtalmus*), lake trout, and charr (*Salvelinus alpinus*) are important pelagic species. In the littoral zone, chub (*Leuciscus cephalus*), dace (*Leuciscus leuciscus*), bream (*Abramis brama*) and percids (*Gymnocephalus cernuus*, *P. fluviatilis*) dominate during summer, whereas burbot (*Lota lota*) and stone loach (*Barbatulus barbatulus*) occur throughout the year (Fischer & Eckmann 1997). A declining fish catch, mainly perch and to a minor extent also whitefish, parallel the changing trophic state of the lake, a phenomenon observed in many lakes of the Alpine foreland under oligotrophication.

The High Rhine provides habitat for about ~~35~~ species, including five introduced fishes. Construction of powerplants between Basel and the Rhine Falls imposed major obstacles for migrating fish. After completion of the powerplant Augst-Wyhlen (Rkm 155) in 1912, catches of Atlantic salmon decreased to zero upstream of the plant. Allis shad, a less potent swimmer, once migrating up to the rapids of Laufenburg (Rkm 121) became extinct, presumably due to increased current velocities in the Upper Rhine. In reaches impounded by powerplants, rheophilic species such as brown trout, grayling, rissle minnow (*Alburnoides bipunctatus*), varione (*Leuciscus souffia agassizi*) and nase (*Chondrostoma nasus*) disappeared and stagnophile species such as bream, pike (*Esosx lucius*) and roach (*Rutilus rutilus*) became abundant. The nase, once a highly abundant fish – during the spawning period, the plentiful catches were used as pork food or fertilizer – rarely occurs today (Gerster 1991). Clogging of gravel substrate with fine sediments in impounded sections decreases spawning habitats of lithophil fish such as brown trout and grayling (Zeh & Dönni 1994). Relatively large grayling populations in the 10-km long free-flowing stretch downstream of lower Lake Constance and between the powerplant of Rheinau (Rkm 55) and the Thur River confluence (Rkm 65) are remnant populations once dominating the High Rhine. Channelization and powerplants are the most severe menaces to grayling populations. A new threat to fishes is global warming, for example, only 3% of the population between Lake Constance and the Rhine Falls survived the hot summer of 2003 (Walter 2006).

The fish fauna of the Upper Rhine at 56 species is the most diverse of all Rhine sections. The 2000 census reports the highest species richness in the 'Restrhein' (southern Upper Rhine) side channels, at tributary confluences, and oxbow lakes with a surface connection to the river. Most common species are chub (*L. cephalus*), perch and eel. Pike and barbel (*Barbus barbus*) reach high abundances in stagnant and slow-flowing water. Common fishes in the northern Upper Rhine are roach, eel, perch, white bream (*Blicca bjoerkna*), asp (*Aspius aspius*), chub and bleak (*Alburnus alburnus*). The reach below the Main–Rhine confluence recently became inhabited by tubenose goby (*Proterorhinus marmoratus*), which immigrated through the Main–Danube canal.

The fish fauna of the Middle Rhine includes about 40 species of which 25% are non-native. Although environmental conditions of the Middle Rhine are similar to those of the High Rhine, brown trout and grayling are lacking because of relatively high temperatures during summer. In the main stem, the fish community is dominated by roach. Masses of young roach and to a minor extent perch and asp have been observed in low current areas (IKSR 2002b).

The number of fishes in the Lower Rhine is 37, of which four species are non-native. Common are roach, perch, bleak, chub, eel and bream (*A. brama*). The present fish fauna of the Delta Rhine is dominated by eurytopic cyprinids, whereas rheophilic species are decreasing (Raat 2001). The most abundant fishes in the Delta Rhine are roach and bream followed by eel, perch, pike perch, white bream (*B. bjoerkna*) and ruffe. Catches of anadromous species such river lamprey (*Lampetra fluviatilis*), sea lamprey, salmon, shad, sea trout, common whitefish (*C. lavaretus*) and houting (*Coregonus oxyrhynchus*) have increased in the last few years (IKSR 2002b).

6.6.7. Amphibia and Reptiles

Few amphibians use the main channel of the Rhine for spawning or foraging. Predation by fish and the high current make the main channel a hostile environment for amphibians. Only a few central European species are adapted to high current velocities. Larvae of the fire salamander (*Salamandra salamandra*) occur in rhithral sections of tributaries along the Upper and Middle Rhine. In Lake Constance, stagnant waters occur but predation is high from avian predators (herons, grebes, storks). Alpine newts (*Triturus alpestris*) are rarely observed in the lake. Green frogs (*Rana esculenta* complex), grass frogs (*Rana temporaria*) and toads (*Bufo bufo*) regularly oviposit in shallow, macrophyte-rich shores of Lake Constance, and along the High, Upper and Middle Rhine. Ringed snakes (*Natrix natrix*) occur in the same areas. Another water-bound snake, the dice snake (*Natrix tesselata*) is very rare and restricted to isolated areas on the Nahe and Lahn tributaries.

The highest amphibian diversity is found in the floodplain areas and small waterbodies of the Upper and Middle Rhine. In recent gravel ponds, rare species such as *Bombina variegata, Alytes obstetricans* and *Bufo calamita* occur. Densely macrophyte-rich ponds harbour diverse newts (*Triturus cristatus*, *Triturus helveticus* in the southern Upper Rhine). The latter species is replaced by *T. vulgaris* in the northern Middle Rhine. In reed belts and willows of Lake Constance and floodplains of the Upper Rhine, tree frogs (*Hyla arborea*) can be heard during summer. Early studies reported populations of the European water turtle *Emys orbicularis* in floodplain ponds of the Rhine (Mertens 1947). Rare recent sightings of this species are due to the release of aquarium specimens. Several non-native reptiles (mostly the painted turtle *Chrysemys picta* and other turtles, but even caimans and alligators) are observed for the same reason; however they rarely find suitable wintering conditions to maintian populations.

Loss of habitat due to river engineering and habitat fragmentation have led to a decline or local extinction of many amphibians and reptiles (Tittizer & Krebs 1996; Lippuner & Heusser 2005). Due to land-use changes and river regulation, many amphibian populations declined or gone extinct in floodplains along the Rhine tributaries in The Netherlands (Delta Rhine). However, several common amphibian species still occur, such as *Triturus vulgaris, B. bufo*, *R. temporaria* and *R. esculenta* complex. The frequencies of occurrence and densities are still rather low in comparison with pristine areas. *B. calamita* has higher frequencies of occurrence inside than outside floodplains. Species like *H. arborea*, *Pelobates fuscus* and *T. cristatus* are rare or even locally extinct (Bosman 1994; Creemers 1994; Dorenbosch et al. 1999).

Suitability of waterbodies in floodplains is determined by water type (oxbow lake, pond, clay pits) and a combination of other factors (vegetation, water quality, and presence of fish) that are correlated with inundation frequency (Creemers 1994). Bosman et al. (1996) report on the selection of hibernation sites of toads in floodplains. *B. bufo* hibernate in meadows, thickets and bushes on sand or clay in the higher as well as lower parts of floodplains. *B. calamita* clearly prefer sandy habitats in the higher parts of floodplains. The ringed snake snake is still frequently observed in floodplains along the Nederrijn and IJssel (Creemers 1994).

6.6.8. Avifauna

A short summary of the avifauna along the Rhine can be found in Tittizer & Krebs (1996). Results of the most recent waterbirds census have been recently published (Koffijberg et al. 2001). In Europe, the Rhine valley is one of the most important wintering areas for West-Palearctic waterbirds and many species use this area as a stop-over during autumn and spring migration. Lake Constance, IJsselmeer/Markermeer and the Randmeren[2] are important resting places for a large number of waterbirds. The Rhine floodplains provide habitats for breeding, foraging and resting areas for migrating birds. Important in this respect are the four Ramsar wetlands of lower Lake Constance, the Restrhein (southern Upper Rhine), the reach between Eltville and Bingen (northern Upper Rhine), and the reach between Bislich and the beginning of the Delta Rhine.

The loss of habitats from river engineering, elimination of floodplain forests and intense agricultural activities resulted in a loss of species, and favoured generalists and the immigration of new species. The loss of sand and gravel bars and islands, and bank stabilization by stone riprap and walls strongly affected plovers (Charadridae) and waders (Scolopacidae). Large predatory birds such as lesser spotted eagle (*Aquila pomarina*), osprey or fish eagle (*Pandion haliaetus*), short-toed eagle (*Circaetus gallicus*), hen harrier (*Circus cyaneus*), peregrine falcon (*Falco peregrinus*) disappeared around 1900 but osprey and peregrine falcon have been recently observed breeding in the Rhine valley. Populations of grey heron (*Ardea cinerea*), great crested grebe (*Podiceps cristatus*), mallard (*Anas platyrhynchos*), black kite (*Milvus migrans*), Montagu's harrier (*Circus pygargus*), black woodpecker (*Dryocopus martius*), magpie (*Pica pica*), cormorant (*Phalacrocorax carbo*) and eurasian jay (*Garrulus glandarius*) are increasing; greylag goose (*Anser anser*), gadwall (*Anas strepera*), northern shoveler (*Anas clypeata*) are increasing. Common pochard (*Aythya ferina*), tufted duck (*A. fuligula*), red-crested pochard (*Netta rufina*), and black-tailed godwit (*Limosa limosa*) are relatively new birds along the Rhine (Tittizer & Krebs 1996). The zebra mussel is an important food source of benthivorous waterbirds. Lake Constance, IJsselmeer/Markermeer and Randmeren with their high mussel standing stocks are important resting areas for tufted duck, common pochard and greater scaup (*Aythya marila*).

6.6.9. Mammals

The native mammals of the floodplains along the Rhine originally included the harvest mouse (*Micromys minutus*), root vole (*Microtus oeconomus*), garden dormouse (*Eliomys quercinus*), hazel dormouse (*Muscardinus avellanarius*), black rat (*Rattus rattus*), brown rat (*R. norvegicus*), urus (*Bos primigenius*), moose (*Alces alces*), red deer (*Cervus elaphus*), roe deer (*Capreolus capreolus*), wild boar (*Sus scrofa*), European badger (*M. meles*), wildcat (*Felis silvestris*), bats (*Nyctalus noctula*, *Leucone daubentoni*, *Leucone dascyneme*), Eurasian water shrew (*Neomys fodiens*), Miller's water shrew (*Neomys anomalus*), European water vole (*Arvicola amphibius*), European beaver (*Castor fiber*), Eurasian otter (*Lutra lutra*), brown bear (*Ursus arctos*) and gray wolf (*Canis lupus*) (Tittizer & Krebs 1996). Wolf, bear and moose already went extinct in the Middle Age. Purely aquatic mammals occasionally make their way into the Rhine, for example

2. A chain of lakes created during the embankments in the 1950s and 60s separating the polders of Zuidelijk and Oostelijk Flevoland, and Noordoost polder from the provinces of Overijssel, Glederland, Utrecht and Noord-Holland.

the Beluga whale (*Delphinapterus leucas*) in the 1960s (Gewalt 1967) or the today rare harbour porpoise (*Phocoena phocoena*), which regularly occurred in the Lower and Delta Rhine before World War II. Apart from a few locations, most semi-aquatic mammals are now extinct. The European beaver, a riparian keystone species, was hunted almost to extinction in Europe for fur and castoreum. After re-introduction in France, Switzerland and the Lower and Delta Rhine, beaver populations have expanded along the Rhine. In 1988, beavers from the Middle Elbe region were re-introduced in the natural areas Biesbosch and Gelderse Poort (Nolet & Baveco 1996).

The Eurasian otter (*L. lutra*) considered as a noxius fish predator was hunted to extinction in most parts of the Rhine. Habitat loss and pollution enhanced the decline of otter populations, even though the species became protected. Otter populations are still decreasing, mostly from habitat loss and reduced fertility induced by heavy metals, pesticides, and chlorinated biphenyls. Today, otter populations are only known in the Dutch part of the Rhine. After extinction of the otter in the Rhine Delta in 1988, measures were taken to restore otter habitat in lowland peat marshes in the north of the country, and reintroduction of otters began in 2002. The population remains vulnerable to extinction due to high mortality from traffic (Lammertsma et al. 2006).

The muskrat (*Ondatra zibethicus*) is a large, stout, semi-aquatic rodent native to North America. In 1907, this species was introduced in Bohemia (near Prague) for their thick and water-resistant fur. Some animals inevitably escaped from fur farms and others were released on purpose (Hengeveld 1989). The dispersal of muskrats varies between 1 and 25 km/year (Andow et al. 1990). In 1930, muskrats also escaped from a fur farm near Belfort (France) and invaded the Rhine~~–Rhone~~ canal, the Ill River in northwest France and western Germany. Muskrats now inhabit the entire European continent, including the Rhine catchment. Water authorities in the Rhine Delta consider the muskrat to be a pest that must be exterminated. Its burrowing causes extensive damage to dikes and banks of drainage ditches, and they are trapped and hunted to keep the population low. From 1987 to 2006, the average trapping efficiency decreased from 0.83 to 0.46 animals per hour, indicating a decrease in the muskrat population in the Rhine Delta (LCMM 2007).

Trees in the floodplain forest mainly along oxbows of the Upper Rhine provide excellent habitats for bats such as pipistell bats (*Pipistrellus pygmaeus*, *Pipistrellus nathusii*, *Pipistrellus pipsitrellus*, *Plecotus auritus*), Brandt's bat (*Myotis brandtii*), Noctule bat (*N. noctula*), Leisler's bat (*Nyctlaus leisleri*), Daubenton's bat (*Myotis daubentonii*), Natterer's bat (*Myotis nattereri*) (Fuhrmann et al. 2002). Large colonies of greater mouse-eared bat (*Myotis myotis*) using old use old buildings (churches) as roosting sites can be observed in the valley of the Middle Rhine, Moselle and Lahn River during summer.

6.7. MANAGEMENT AND CONSERVATION

6.7.1. Economic Aspects

With a population of about 58 million, the Rhine basin is an important player for the economy of Europe. The Rhine basin has developed into one of the world largest areas in the chemical industry, historically profiting from the availability of energy (coal), raw materials (coal, salt, limestone) and transport facilities (Rhine navigation) (Hopp 1990). The industry is concentrated around Basel, the Rhine-Main area between Ludwigshafen and Frankfurt, the Lower Rhine between Cologne and Düsseldorf, and most recently Rotterdam. Rotterdam has the largest oil terminal in Europe and contains a huge petrochemical industry with numerous refineries of large international oil companies. About 50% of all inland navigation within the European Community takes place on the Rhine, with about 311 million tons of goods and 700 ships daily crossing the border between The Netherlands and Germany (Zentralkommission für die Rheinschifffahrt 2003). 'Duisport' at Duisburg (Rkm 780), the largest inland port in the world, handles about 70 million tons of goods annually. The transport of containers has increased remarkably from 450 000 twenty-feet equivalent units (TEU) in 1991 to 900 000 TEUs in 1997.

Large-scale hydroelectrical power production along the Rhine started in the late 19th century. Between the Alpine Rhine and the sea, 24 run-of-river powerplants produce ~7.3 TWh/year. Within the entire Rhine basin, more than 2000 hydroelctrical powerplants produce about 15–20 TWh/year; most of these plants are in the upper tributaries. The Rhine basin also has 10 nuclear powerplants (with up to four reactors) with an installed electrical power of ~19 GW for which the Rhine, and the rivers Aare, Moselle and Neckar, provide cooling water.

The Rhine, its tributaries, and lakes, supply drinking water for around 25 million people. Under the umbrella of the International Association of Waterworks in the Rhine catchment area (IAWR), 120 waterworks annually provide ~2.73 billion m^3 of raw water (IAWR 2000). Because of the existing risk of accidental pollution, the International Commission for the Protecton of the Rhine maintains a warning alarm system. The Rhine Alarm Model has been developed to forecast concentrations of harmful substances in the river, thereby allowing waterworks to take necessary measures (Broer 1991). The system covers the Rhine from Lake Constance to the sea, including the tributaries Aare, Neckar, Main and Moselle. Seven international alarm stations are on the Rhine mainstem between Basel and Arnhem.

Fishery, once an important activity along the Rhine, is today of minor economic importance. In Lake Constance, commerical fishermen caught on average (1996–2000) 1130 tons of fish (76% whitefish, 17% perch), yielding approximately 3 million Euro. In the High Rhine, only two commercial fishermen remain (Brenner et al. 2003). Traditional fishery is practiced by 80 fishermen in the southern

Upper Rhine, and in the 640-km long stretch between Iffezheim and the Dutch–German border there are about 48 active, but part-time, fishermen. According to Raat (2001), only 10 fishermen are engaged in the fishery at the Rhine–Meuse delta. In contrast, recreational fishing is done by several hundred thousand people in the main stem of the river and adjacent floodplain waterbodies. Target species are roach, bream, ide, pikeperch and pike, and in the High Rhine also brown trout and grayling.

6.7.2. Floods and Flood Defense

Extreme runoff from the Alpine region, including the Aare drainage and the three catchments of the Neckar, Main and Moselle, determines the occurrence of catastrophic Rhine floods (Disse & Engel 2001). According to the hydrological record of the last 1000 years, catastrophic floods did not occur simultaneously in all sub-basins. Because of different meteorological conditions and the respective hydrological response of the different catchments, Rhine floods show a regional pattern (IKHR 1999). In a large river system such as the Rhine, the frequency of flow extremes (floods and droughts) show decadal variability that reflect changes in atmospheric circulation modes (Jacobeit et al. 2003; Pfister et al. 2006). Floods in the Alpine area (including the forelands) that usually occur between spring and autumn have a minor impact in the Middle and Lower Rhine. Large lakes in the Alpine forelands have important retention volumes regarding flooding; for example, in 1999 these lakes retained 950×10^6 m^3 within 5 days, corresponding to an additional discharge of 2200 m^3/s in Rheinfelden (Rkm 148). Between the northern Upper Rhine and the sea, severe floods mainly occur during winter (major rainfall often associated with snowmelt in the central European uplands).

Flood damage caused by drifting ice was frequent between the 16th and 19th century (Krabe 1997). Before the 19th century, flooding along the Rhine only affected the relatively small population living in the floodplains (Pinter et al. 2006). Since the Middle Ages, floodplain residents tried to protect settlements but these efforts were local and poorly coordinated. For example, the use of groyne-like structures in the Alpine Rhine directed flow to the opposite bank and caused enhanced erosion during floods. This and poor maintenance of flood protection structures resulted in conflicts between municipalities variously affected by floods. Even in the 19th century when the large regulatory project of the Upper Rhine was realized, concerns by Prussia and Rhine Hessen that flood hazards were shifted downstream led to discussions with the Grand Duchy of Baden (Bernhardt 1998).

The regulation and harnessing of the fluvial hydrosystem in the last century have reduced the hydromorphological resilience of the Rhine river basin. For example, river engineering of the 20th century (Grand Canal d'Alscace, the construction of 10 powerplants) in the southern Upper Rhine resulted in the loss of 130 km^2 (60%) of the existing retention areas. Today, inundation areas equal $\sim$450 km^2, which corresponds to about 30% of the inundation area at the beginning of the 19th century (IKHR 1999). The increased channel depth accelerates flood waves and the loss of retention areas steepens flood hydrographs. The flood waves of the Neckar, once preceding that of the Rhine, now coincides with those of the Rhine and increase peak flows of a 50–60 year flood by 700–800 m^3/s downstream of the confluence (Disse & Engel 2001). Because hydromorphodynamic processes can be controlled to a great extent, residents of riverine areas have lost their sense of the natural dynamics of river ecosystems. Further urbanization of areas prone to flooding took place without the potential risks of flooding being recognized, in particular in the lowlying polders in the Rhine Delta (Van Stokkom et al. 2005). Today, potential flood damage along the Rhine is estimated at 165 billion Euro, and flood magnitude and frequency have increased significantly during the 20th century (Pinter et al. 2006).

The Rhine floods in the winters of 1993 and 1995 severely affected the stretch between the Middle Rhine and the Delta. During the 1995 flood, about 250 000 people had to be evacuated in the Delta area; the economic damage reached about 1 billion US$ (Van Stokkom et al. 2005). These and similar events in several other large European rivers caused a considerable change in government policy, public awareness, and international cooperation in terms of sustainable flood protection (Smits et al. 2000). Riparian countries now aim to create more space for the river, combined with objectives from other policy areas, including improvement of spatial quality and ecological rehabilitation (IKSR 1998). Each riparian country was to select appropriate measures to restore the hydromorphological resilience of their relevant part of the river basin, from the perspective of the river basin as a whole. Up to now, riparian countries have made considerable progress in selecting and implementing the measures of the Rhine Action Plan on Flood Defense (ICPR, 1998). This plan aims to: (1) reduce risk damage by 10% by 2005 and 25% by 2010, (2) reduce peak flood stages by 30 cm by 2005 and 70 cm by 2010, (3) enhance the awareness of flood risk by the publication of risk maps and 4) improve the flood alarm system. In addition, a joint flood control program was completed within the framework of Interregional Rhine–Meuse Activities. Whenever the amount of water is reduced or retained before it reaches the main river, the peak flood level is diminished and the risk of flooding reduced. Relevant measures in the Rhine catchment are (www.irma-programme.org): (1) restoration of the natural course of tributaries and their overflow areas by restoring streams, creating and restoring of meanders, and restoring floodplain vegetation to retain water, (2) reduction of the discharge from residential and industrial areas by water infiltration and improving the porosity and absorption of soil and (3) creating retention and overflow areas.

TABLE 6.5 Flood defense projects in the Rhine basin (Van Rooy & Van Wezel 2003)

Project	Trans-national cooperation	Effect on water discharge	Effects on landscape quality	Public participation	Degree of innovation
Restoration of river confluences Kinzig and Schutter (G)	+	+	++	+	+
Restoration of Rhine meanders and floodplains along the Rhine river section Kunheim and Marckolsheim (F)	+	+	++	0	++
Infiltration of rainwater in urban area of Neuenberg am Rhein (G)	0	0*	+	++	0
Realization and management of retention areas along the Rems River (G)	+	+	+	++	+
Infiltration of rainwater in rural area of Massenbachhausen (G)	+	+	+	+	++
Dike relocation Worms-Bürgerweide (G)	++	++	++	+	+
Realization of retention areas along the Alzette River (L)	+	+	++	0	+
Floodplain rehabilitation (Klompenwaard) with construction of side channels (NL)	+	++	++	+	+
River dike relocation, creation of side channel and floodplain lowering location Bakenhof along Nederrijn River (NL)	+	+	++	+	+

F: France, G: Germany, L: Luxembourg, NL: The Netherlands.

* ~~*Requires up-scaling.*~~

Important measures in lowlands and the delta are, roughly ranked in order of decreasing efficiency (Van Stokkom et al. 2005): (1) moving dikes further inland, (2) constructing river bypasses, (3) lowering and restoring groynes, (4) dredging the riverbed in sections of the river where sedimentation occurs, (5) removing obstacles such as non-flooding areas in the floodplain, summer embankments and ferry ramps and (6) lowering floodplains, that is, by digging side channels, frequently combined with land-use changes from agriculture to habitat restoration and recreation. Moreover, polders can be created for temporary or emergency storage of river water in the floodplains. Table 6.5 gives examples of innovative flood management measures and evaluates the efficiency, transnational cooperation and public participation of some representative projects in various parts of the Rhine basin.

6.7.3. Conservation and River Rehabilitation

The socio-economic development along the Rhine has profited enormously from the Rhine regulation, because it afforded a high level of flood protection, an efficient navigation route, and high agricultural yields. On the other hand, the regulation has led to large-scale river responses such as tilting of the riverbed through erosion, deterioration of riverine habitats and loss of the natural morphological dynamics. In face of the dramatic decline of biodiversity and the lacking recovery of extinct species despite of the significantly improved water quality indicate the need to improve riverine habitat quality. The IKSR program Rhine 2020 (IKSR 2002d) focus on the biological diversity of the Rhine system. Target species within this program is not only the Atlantic salmon but also plants and animals of the riverine Rhine fauna. Measures to meet the high ecological demand of the salmon include habitat restoration, floodplain activation, removal of migration barriers and developing a habitat network. The need to establish retention areas to mitigate floods provide opportunities for local rehabilitation projects. However, the extent of human occupation and related human activities of the floodplains, navigation and hydropower production only allows a partial return natural conditions (see also EU Water Framework Directive).

The execution of the Delta project, which followed centuries of smaller interventions, triggered several (unexpected) environmental problems (Lenders 2003). It can be concluded that the long-term hydromorphological and ecological effects of the interventions in the Rhine delta were not foreseen or at least underestimated (Nienhuis & Smaal 1994; Havinga & Smits 2000; Smits et al. 2000, 2006). The building of Delta dams disconnected the hydrology and ecology along the river, both at the sea as well as between the river and floodplains (Smits et al. 2006). Ecological landscape units, especially alluvial forests, natural levee pastures, marshy floodplain pastures and side channels, have almost disappeared from the landscape (Middelkoop et al. 2005). Furthermore, water pollution and the facilitation of invasive species by connecting several large European rivers via canals have had profound impacts on the diversity of native species in the Rhine delta (Van den Brink et al. 1994, 1996; Cals et al. 1998; Grift 2001).

Recently, efforts have been made to reverse the trend in river regulation and deterioration of riverine ecosystems in the Rhine delta (Bij de Vaate 2003; Lenders 2003; Buijse et al. 2005). Efforts include improvements in water quality and rehabilitation of more natural patterns and processes akin to river-floodplain ecosystems. Rehabilitation measures include removal of summer dikes, displacement of winter dikes, (re)creation of side channels, excavation of polluted floodplain topsoils, and a management change from agricultural management to a strategy that includes the influence of river dynamics and low-density grazing by horses and cattle. These measures increase the surface area of riverine ecotopes, like natural levee pastures, river dunes and alluvial forests, which became rare. In the Rhine delta, the effects of environmental rehabilitation programs are promising but still limited by strong boundary conditions for safety and navigation (Nienhuis et al. 2002; Van der Molen & Buijse 2005; Van Stokkom et al. 2005). Although rehabilitation processes have been locally successful, the various projects did not significantly contribute yet to ecological recovery of the river at a coarser scale.

6.7.4. EU Water Framework Directive

The EU Water Framework Directive (EU WFD, http://ec.europa.eu/environment/water/water-framework/index_en.html) implemented in October 2000 sets a common framework committing member states to protect and enhance all natural surface, ground, coastal and estuarine waters and aims to achieve a good qualitative and quantitative status in 15 years with regulated waterbodies to be developed to their ecological potential. The general approach is management by river basin similar to the initiatives taken earlier for the Meuse, Scheldt or Rhine basins by respective riparian states. The implementation of the EU WFD includes several steps such as identification of river basin districts and authorities (2003), characterization of river basins such as pressures, impacts and economic analysis, establishment of monitoring networks (2004), basin management plans including programs of measures (2006), and making operational programs of measures (2008).

The implementation of the EU WFD is coordinated by a committee with representatives of the nine riparian states closely cooperating with International Commission for the Protection of the Rhine (ICPR). The report ‘Assessment of the status of the Rhine Basin’ has been submitted to the European commission in spring 2005 (http://www.iksr.org/index.php?id=102 and http://www.iksr.org/index.php?id=103). It documented the severe hydromorphological alteration of the Rhine and its tributaries. A large number of waterbodies fell in the categories artifical (e.g., channels, flooded gravel pits) or considerably modified (e.g., most of the Rhine mainstem and its major tributaries), where the probability of reaching WFD goals is low or unclear (Koordinierungskomitee 2005). The most frequent cause that waterbodies fell in the category ‘low probability reaching a good status’ was impacts affecting hydromorphological integrity. With respect to chemical status, it is expected that the WDF goals can be met upstream of Basel and in the Neckar River but more downstream these goals may not be reached. Monitoring programs for the Rhine basin have been ready since 2006; they include assessment of physico-chemical parameters and harmful chemical compounds at 20 stations along the main stem between Reichenau (Alpine Rhine) and the sea, hydromorphology, and biological quality (phytobenthos and plankton, benthic invertebrates, fish at 14 stations a long the main stem) (Koordinierungskomitee 2007).

6.8. THE MAJOR RHINE TRIBUTARIES

6.8.1. Aare

The 295-km long Aare River drains a basin of 17 606 km^2 that includes parts of the Alps, northern Alpine forelands (Swiss Plateau), and southern Jura Mountains. Elevations within the catchment range from 4274 m asl (Finsteraarhorn) to 311 m asl (confluence with the Rhine). About 2.1% (370 km^2) of the catchment is glacierized, 32% are forested and 51% used for different agricultural activities (Table 6.1). Precipitation averages 1490 mm and runoff 1003 mm. The human population is 3.4 million (192 people/km^2) and mainly concentrated in the Swiss Plateau. Industrial activities within the Aare catchment were traditionally machine and the electrical equipment manufacturing particularly in the region of the Aare-Limmat-Reuss confluence. Banking, insurance, financial services, information and communication technologies make the metropolitan area of Zurich to the economic center of Switzerland significantly contributing to the high annual gross domestic product of about 65,000 US$ per person in the Aare basin (Table 6.1).

Meltwater from the Upper (2430 m asl) and Lower Aare (1950 m asl) glaciers are the primary water source of the Aare River. The upper 20 km of the Aare valley are relatively steep (8%) and narrow. Between the relatively flat basin of Innertkrichen and the plain of Meiringen, the river cuts through a limestone ridge and forms a spectacular canyon (Aare gorge). About 40 km from the source, the Aare (Q_{mean} 35 m^3/s) flows into the turbid and oligotrophic Lake Brienz (564 m asl, volume 5.2 km^3, area 29.7 km^2), which is also the recipient of the Lütschine River, a glacial river with a Q_{mean} of 19 m^3/s. After a 5.5-km long riverine stretch, the Aare then enters the oligo/mesotrophic Lake Thun (558 m asl, volume 6.5 km^3, area 48 km^2).

The Kander River, a major alpine tributary (Q_{mean} $\sim$32 m^3/s) also flows into Lake Thun. The lowest stretch of the present Kander was the location of the first major river engineering project in Switzerland, which, however, lacked a serious evaluation of the potential consequences (Vischer 2003). The Kander originally joined the Aare downstream of Lake Thun. Sediment accumulation at the confluence resulted in frequent flooding of adjacent settlements. To mitigate this problem, the Kander was diverted through a tunnel into Lake Thun (1714 AD). The tunnel collapsed and a steep gorge was formed and the river started to build a delta. The increased discharge in Thun caused severe damage to the town at the lake outlet that required adjustments of the Aare bed downstream of Thun. From Thun, the Aare flows for $\sim$80 km northwards across the Swiss plateau towards Lake Biel (429 m asl, volume 1.24 km^3, area 39.3 km^2) at the fringe of the Jura Mountains. Here it picks up the waters of the Saane River (Q_{mean} 54 m^3/s).

Incised meanders characterize the river near the city of Bern before the powerplant of Mühleberg forms a 12-km long narrow lake. Until the first Jura Correction Project (1868–1878), the Aare did not drain into Lake Biel but meandered eastward through a relatively flat area with extended wetlands, once part of prehistoric Lake Solothurn. The Aare was redirected into Lake Biel and from there through a new canal to the old river channel ~12 km east of the Lake. Because flooding continued, a weir was installed to regulate lake levels (1939) and canal capacities were increased (1962–1973). From Lake Biel, the Aare flows in a wide valley in an east-northeast direction along the southern fringe of the Jura Mountains for about 90 km.

The Emme, a flashy prealpine river (Q_{mean} 19.2 m^3/s) is the largest tributary of this Aare reach. Rapids occur near the town of Olten where the river cuts through the most southern anticline of the Jura Mountains and in the town of Brugg where the bedrock channel narrows to ~10 m. Downstream of Brugg, about 15 km before the confluence with the Rhine, the Aare gains the waters of two major Alpine tributaries, the Rivers Reuss (Q_{mean} 140 m^3/s) and Limmat (Q_{mean} 102 m^3/s). It then turns north and crosses the Jura Mountains through a wide valley. At the confluence, mean annual discharge (1931 to 2003) is 559 m^3/s. Monthly discharge is maximum in June (826 m^3/s) and minimum in January (407 m^3/s) (Figure 6.6). A peak flow was recorded in May 1999 at 2620 m^3/s.

The Aare is strongly influenced by power production. A complex scheme of nine powerplants and seven reservoirs are found in the headwaters; the installed power equals 1062 MW. Residual flow below reservoirs and hydropeaking are typical events upstream of Lake Brienz. Reservoir storage (>190 million/m^3) influences seasonal discharge patterns, that is, low flows during summer and enhanced flows during winter. Between Lake Biel and the confluence, a chain of 12 run-of-river powerplants (installed between 1882 and 1970) impound major parts of the river, and also provide cooling water for three nuclear power plants. An eco-morphological assessment of the Aare between Lake Brienz and the border showed that only 9% of the river was judged as natural or near-natural, whereas the percentage of strongly affected stretches was 75% (GBL 2006).

Concentrations of nutrients measured before the confluence with the Reusss and Limmat were 1.72 mg NO_3–N/L and 0.014 mg PO_4–P/L. Corresponding values in the Reuss were 0.85 mg NO_3–N/L and 0.007 mg PO_4–P/L, and in the Limmat 1.19 mg NO_3–N/L and 0.013 mg PO_4–P/L. Phosphate concentrations distinctly declined since the 1980s in contrast to nitrate in which only a slight reduction was observed since the early 1990s. Concentrations of major nutrients are similar to those of the High Rhine upstream of the Aare confluence.

6.8.2. Neckar

The Neckar basin covers an area of 13 950 km^2 consisting of ~~75% cropland~~ and ~~23~~% forest (Table 6.1). Precipitation averages 757 mm and runoff 337 mm. The population is about 5.3 million, corresponding to a population density of 380 inhabitants/km^2. The 367-km long river originates as an outflow of a wetland (Schweninger Moos, 706 m asl) at the Danube–Rhine divide near the eastern fringe of the Black forest. From there it flows as a small stream northwards across the high plain of Baar. Downstream of the confluence with the Eschbach (Q_{mean} 2.5 m^3/s), the Neckar enters a narrow valley. After 20 km, the river turns northeast continuing its course between the spurs of the Black Forest and the heights of the Swabian Alb. At Plochingen (Q_{mean} 46.4 m^3/s), the river changes its direction to northwest for about 140 km. The most important tributaries, Fils (Q_{mean} 9.6 m^3/s), Jagst (Q_{mean} 17.0 m^3/s), Enz (Q_{mean} 20.9 m^3 /s) and Kocher (Q_{mean} 22.1 m^3/s) enter the Neckar here. At Eberbach, the Neckar bends westward and flows through the Odenwald range before it merges with the Rhine in Mannheim (95 m asl). Mean annual discharge at the confluence is 149 m^3/s (MUV BW 2005). Monthly flow is maximum in February and minimum in September (Figure 6.6). Flow variation is typically high; for example, the ratio of average base flow to average high flow is 1:210 at the gauging station Plochingen.

The alternation between confined and unconfined reaches characterizes the Neckar valley. Confined reaches occur were the river has eroded through calcareous Triassic sediments and include features such as incised meanders and oxbows. In areas where soft sediments (marl, clay) prevail, the valley is wide with extensive floodplains. In the 203-km long stretch between Mannheim and Plochingen, the Neckar has been regulated as a federal waterway. Regulation included the construction of separate navigation canals and numerous weirs with locks. Beginning in 1921, the work continued until completion of the last lock near Plochingen in 1968. The depth of the navigation channel is maintained at a miniumum of 2.8 m using 27 weirs with locks (26 are used for hydroelectrical power production.). In 2007, the transport of goods on the river was 7.5 million tons and 8100 cargo ships passed the locks; the transport of containers was 32 500 TEU. The inland port of Heilbronn had a cargo throughput of 4.5 million tons in 2006. The Neckar also provides cooling water for the nuclear powerplant of Neckarwestheim (2235 MW). Parts of catchment are heavily industrialized, such as areas in Stuttgart, Sindelfingen, Neckarsulm, Heilbronn and Mannheim where population density reaches up to 910 people/km^2. The manufacturing industry includes mechanical and electrical engineering, and automobile construction.

Human activities strongly affect the Neckar and its tributaries, primarily through industrial activities, navigation and agriculture. The 27 weirs in the navigable reach and an additional 18 powerplants impound the river almost along its entire course. Moreover, connectivity between the Neckar and its major tributaries is severely impeded by sills. Water quality is affected by the outfall of treated sewage from industrial and urban facilities and by diffuse inputs from agricultural areas. In 2003, concentrations of nitrate and phosphorus averaged 4.5 mg N/L and 0.17 mg PO_4–P/L at the confluence in Mannheim, exceeding by far the respective concentrations in the Rhine (see Table 6.4). Floods of the Neckar and tributaries caused severe damage in the range of 10 to >300 million Euros. The project IkoNE- 'Integrating Conception of the Catchment Area of the Neckar River' by the Water Resource Administation of the State of Baden-Würtemberg, with a budget of 200 million Euros is focused on flood mitigation but also includes measures to improve the structure and quality of the river.

6.8.3. Main

The catchment of the Main River (27 251 km^2) is in the northern part of the south-German scrapland. Land use consists of 80% agricultural land and 18% forest (Table 6.1). The population is ~6.6 million people, corresponding to an average population density of 242 individuals/km^2. Precipitation averages 655 mm and runoff 255 mm. Headwaters of the 524-km long river are the Red Main originating in the Franconian Jura with a source at 580 m asl, and the White Main. The source of the White Main (878 m asl) is in the Fichtelgebirge, a mountain range in eastern Bavaria with elevations up to 1053 m asl. The Red and White Main merge at Kulmbach, where the Main then flows west. Uplands extending from north to south divide the catchment into several sub-basins, and results in the characteristic course of the river that includes large bends with amplitudes of ~50 km.

The most important Main tributary is the River Regnitz (Q_{mean} 51 m^3/s), which merges with the Main near the town of Bamberg. Annual discharge of the Main at Bamberg is 43.4 m^3/s. Other tributaries such as Fränkische Saale (Q_{mean} 16.7 m^3/s), Tauber (Q_{mean} 8.7 m^3/s at Tauberbischofsheim) and Nidda (Q_{mean} 10.7 m^3/s) are relatively small. Monthly flow of the Main is maximum in March and minimum in September (Figure 6.6); mean annual discharge at the confluence is 225 m^3/s (BSUFV 2004). The ratio of average low flow to average high flow is relatively high at 1:20. The river is characterized by winter floods caused by rainfall and snow melt. To feed the Main–Danube canal at the Rhine–Danube divide, and to increase the base flow of the Regnitz and upper Main, ~150 million m^3 water are annually pumped (corresponds to 4.75 m^3/s) from the Altmühl (Danube catchment) to the Main drainage.

The Main has been used for cargo navigation since Roman times. From the 1880s until 1962, the river was developped to a waterway for large cargo vessels. The 388-km long stretch between the confluence and Bamberg has been transformed into a chain of impoundments encompassing 34 weirs with locks and stabilized banks. The Main–Danube canal, 55-m wide and 4-m deep, begins at Bamberg and ends after 171 km in Kehlheim at the Danube. Sixteen locks are used to overcome the 175 m altitudinal difference between Bamberg and the Rhine/Danube divide and the 68 m altitudinal change between the divide and the Danube. In 2006, the transport of goods on the Main was ~18.8 million tons and 22 316 cargo vessels passed first Main lock near the confluence. Transport of goods on the Main–Danube canal was 6.24 million tons.

Main River water quality is affected by point sources such as sewage treatment plants that release 10 591 tons total nitrogen and 729 tons total phosphorus, and diffuse agricultural inputs. Industrial discharge is substantial, particularly in the heavily industrialized lower Main but also along the Regnitz (industrialized areas of Nuremberg, Fürth and Bamberg). Most Main stretches are judged as moderately polluted. Mass development of algae with subsequent oxygen depletion can occur in slow-flowing areas of impounded reaches. Overall, water quality has improved since the beginning of monitoring programs in 1960. Phosphorus and ammonia concentrations significantly declined but nitrate still remains high. Concentrations of phosphate and nitrate (average 2003–2004) at the confluence were 0.088 mg P/L and 4.7 mg N/L; concentrations in the Rhine at the confluence were 0.058 mg P/L and 2.41 mg N/L.

6.8.4. Moselle

The Moselle River drains a catchment of 28 282 km^2 that includes major parts of the Vosges, the Plateau Lorraine, and major parts of the Rhenanian Mountains. The catchment belongs to France (54%), Germany (34%), Luxemburg (9%) and Belgium (3%). Land use is dominated by agriculture (85%), and 14% of the catchment is forested. The population is 4.21 million people, corresponding to an average population density of 150 individuals/km^2. Precipitation averages 841 mm and runoff is 365 mm. The source of the 544-km long Moselle is on the western slope of the Grand Ballon d'Alsace in the southern Vosges Mountains at an altitude of 715 m asl. From the source the river flows northeast to the town of Toul, where it flows near (12 km away) the Meuse River. This is the location where a Meuse tributary was captured by the Moselle during the Riss Ice Age to become the Upper Moselle.

About 24 km downstream of Toul, the Moselle gains water from the Meurthe River (Q_{mean} 40 m^3/s), the largest tributary of the upper Moselle. Its headwaters also originate in the Vosges Mountains. The Saare River, originating in the northern Vosges and merging with the Moselle upstream of Trier, is the largest tributary of the Moselle (Q_{mean} 80 m^3/s). The Moselle flows from Trier through a narrow valley (200–300 m wide), flanked by the Hunsrück and Eifel Mountains in a northeast direction towards the confluence with the Rhine (59 m asl). This reach has many meanders incised in

Devonian sediments. Long-term monthly discharge is maximum in January (572 m^3/s) and minimum in August (212 m^3/s) (Figure 6.6); mean annual discharge at the confluence is 328 m^3/s (IKSMS 2005). In December 1993 and January 1995, Moselle peak flows (recorded at Cochem) reached 4164 and 3350 m^3/s, respectively; these exteme flows substantially contributed to the devastating flood impact in the Lower and Delta Rhine.

The Moselle is an important international waterway. In the Moselle Treaty of 1956, France, Gemany and Luxemburg agreed to develop the river as a waterway for large cargo vessels. The agreement with Germany depended on the promise of France to abandon its plans of elongating the existing Grand Canal d'Alscace from Breisach to Strasbourg. By 1979, the river was developed to a length of 394 km, which required the construction of 28 weirs with locks. The navigation channel is 40-m wide and 3-m deep. Today, about 15–16 million tons of cargo are transported annually on the river. In the lower reach between the confluence and the French–German border, the waterway follows the main river channel. In upstream reaches, meanders are often bypassed by artifical side-canals.

Until the 1970s, industrial activities within the catchment were dominated by the coal and steel industries with centers at Thionville, Metz, and Sarbrücken, but these have subsequently declined. Economic activities shifted to the car industry (Lorraine, Sarland) and service (Luxembourg, Saarland). Wastewater from coal and ore mining (Lorraine, Saarland, Luxembourg) are a still a source of pollution, despite declining mining activities. A soda industry and salt mining are located along the lower Meurthe. Chloride concentrations in the Moselle average ~400 mg/L between Meurthe and Saar, and ~200 mg/L between Saar and Rhine. The coal and steel industry left polluted areas that are a potential hazard for surface and ground waters. Input of nitrogen and phosphorus from agricultural areas, and to a minor extent from sewage treatment plants, result in excessive algal growth and oxygen depletion in slow-flowing areas of impounded reaches. At the confluence, concentrations of nitrate and phosphate averaged (2001–2005) 3.3 mg N/L and 0.124 mg P/L. The development of the Moselle and Saar Rivers to waterways for large vessel traffic severely affected river morphology, causing uniform cross-sections, stabilized banks, and loss of gravel bars. The numerous weirs also impede fish migration.

Acknowledgements

We thank Leonie Bolwidt (Rijkswaterstaat Waterdienst, Arnhem) and Wilfried Ten Brinke (Blueland, Utrecht) for providing photos of the Delta Rhine, and the Dutch Ministerie van Verkeer and Waterstaat (Rijkswaterstaat) for permission to use temperature data. KMW received support by the Sonderforschungsbereich Bodenseelitoral (SFB 454) of the Deutsche Forschungsgemeinschaft. We thank the Global Runoff Data Centre (GRDC), Koblenz (Germany) and the Federal Office for the Environment for discharge data. The Federal Institute of Hydrology BfG in Koblenz (Dr. Fritz Kohmann), the Landesumweltamt für Nordrhein-Westfalen, and the Landesamt für Umwelt, Wasserwirtschaft und Gewerbeaufsicht Rheinland-Pfalz kindly provided water quality data. We also appreciate the helpful comments of Dr. Jörg Lange (regioWASSER, Freiburg i./Br.).

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http://www.dk-rhein.de/ Deutsche Kommission zur Reinhaltung des Rheins.

http://www.chr-khr.org/ International Commission for the Hydrology of the Rhine basin (CHR).

http://grdc.bafg.de/ Global Runoff Data Center

http://www.bafg.de Federal Institute of Hydrology (Koblenz, Germany)

http://www.rijkswaterstaat.nl/ Rijkswaterstaat - Waterdienst

http://www.watermarkt.nl/ Watermarkt: Information about the Dutch National Monitoring.

http://www.naduf.ch/ National Long-term Surveillance of Swiss Rivers' (NADUF) programme

http://www.hydrodaten.admin.ch/e/ Federal Office for the Environment. Hydrologcial foundations and data