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Long-term developments in ecological rehabilitation of the main distributaries in the Rhine delta: fish and macroinvertebrates

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Abstract

Significant anthropogenic pressure in the Dutch part of the River Rhine is present from the 12th century. River engineering and water pollution were the main stress factors for flora and fauna. From the middle of the 20th century measures were taken to reduce water pollution. Recently, from 1987 onwards, these activities were put into a wider context of ecological river rehabilitation. Effects of improvements on fish and macroinvertebrates in the main distributaries in the Rhine delta are reviewed. The conclusions are that (a) most of the alterations in the Rhine delta are irreversible due to hard socio-economic boundary conditions (e.g. safety, navigation); (b) chances for the development of riverine biotopes have therefore to be found in the forelands and not in the main channels of the Rhine delta; (c) further reduction of pollutants, especially thermal pollution, is needed to help original species to colonise the Rhine delta again; (d) non-indigenous species clearly leave a mark on recolonisation possibilities of original species.

Introduction

The Rhine valley, including the Rhine–Meuse delta, has been densely populated for many centuries. From the point of view of water management the river has different functions now, varying from discharge of water and waste to transport route for raw materials and products (Anonymous, 2001; Bij de Vaate, 2003). Anthropogenic influence evolved in the 12th century with the construction of levees along the main channel for the purpose of protecting inhabitants against flooding (Middelkoop, 1997). Later on, shipping asked for the adjustment of the main channel to allow larger freighters sailing. These activities led to irreversible changes, not only in the occurrence of riverine habitats caused by disruption of the natural sequence of backwaters, but also in the disappearance of aquatic-terrestrial transition zones (e.g. Gore & Shields, 1995; Sparks, 1995; Galat et al., 1998; Nienhuis & Leuven, 2001). In the Rhine delta (The Netherlands) the smaller distributaries were dammed, and the remaining larger ones (called IJssel, Nederrijn/Lek and Waal; Fig. 1) changed from meandering streams with extensive floodplains, into shipping canals surrounded by relatively low, so-called summer dikes, on the banks and major dikes at a greater distance (Fig. 2; Middelkoop, 1997; Van Urk & Smit, 1989). Moreover, from the 19th century the summer beds in the distributaries were fixed with groynes of basalt stones to promote channel bottom erosion (Van Urk, 1984; Kalweit, 1993), a measure to deepen the channel in a 'natural' way for shipping.

Effects of domestic and industrial waste water discharges into the whole catchment area

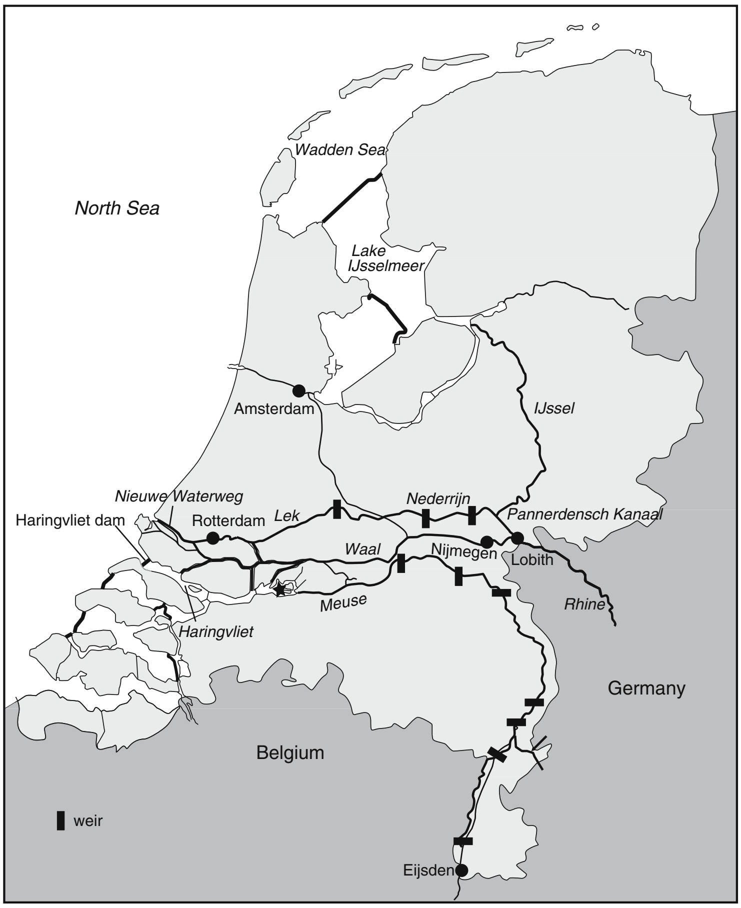

Figure 1. The main distributaries in the Rhine delta.

surfaced in the second part of the 19th and first part of the 20th century and resulted in a strong reduction of population sizes and large scale extinction of many riverine organisms (Klink, 1989; Lelek, 1989; Van den Brink et al., 1990). However, from the 1960s measures have been taken to improve water quality (Cals et al., 1996). The first signs of water quality improvement became visible in macroinvertebrate and fish communities from the second half of the 1970s (Lelek, 1989; Van Urk & Bij de Vaate, 1990; Admiraal et al., 1993).

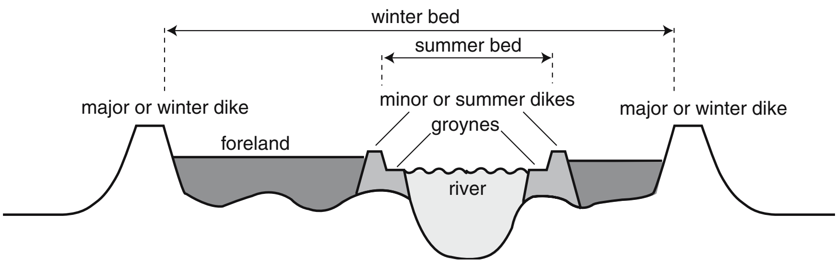

Figure 2. Cross section of the large rivers in the Netherlands. (winter bed, major or winter dike, forelands, minor or summer dike, groynes, summer bed).

An international ecological rehabilitation programme for the river Rhine was initiated in 1987 after the so-called Sandoz-accident in November 1986, an environmental disaster caused by extinguishing water used for a fire control in the Sandoz chemical concern in the vicinity of the Swiss town of Basel (Van Dijk et al., 1995). In addition to further water quality improvement, ecological rehabilitation of the river Rhine in the Netherlands has been focused from that time on the river forelands, the remaining part of the floodplain between the summer and major dikes on both sides of the river channel (Fig. 2; Schropp & Bakker, 1998). The reason for exclusion of the main channel in river rehabilitation is its function as a transport route and the need for unhampered discharge of water, ice and suspended matter.

Floodplain rehabilitation and nature development in the Dutch part of the river Rhine has been based on insights formulated by De Bruin et al. (1987) and WWF (1992). The aim is to give the river back, as much as possible, its natural dynamics in the forelands with regard to its imposed functions (Cals et al., 1996). Effects of biotope alterations on fish and macroinvertebrates in the Rhine delta are the topic of this paper. After an overview of river engineering activities and water quality developments their influence on fish and macroinvertebrate communities are discussed in view of results of investigations mainly performed from the 1980s providing water managers and decision makers a better insight into the functioning of a river ecosystem still influenced by severe anthropogenic stress.

River engineering

River regulation and damming are considered to have the most important destructive impact on biota due to terrestrialisation and fragmentation of the river floodplain system (Schiemer, 1999). Alterations in the catchment area changed runoff patterns. Its originally large water storage capacity had reduced strongly with the result that the relatively slow release of water during wet periods had disappeared. The consequence was an increase in water level fluctuations, which in turn resulted in alterations in sediment transport. The forelands between the summer and winter dikes (Fig. 2) became a trap for fine-grained sediment and in the course of time the natural relief was levelled down by the deposition of clay and by actions of farmers and river managers (Nienhuis & Leuven, 2001). Geo-morphological processes decreased drastically, and were captured in straight jackets by dikes, groynes and weirs. During and after the process of river normalisation the lateral connectivity between the main channel and the water bodies in the forelands gradually disappeared. Incision of the river bed in the remaining single channel was the main effect; loss of shallow lotic habitats the main result.

After embankments in the 12th–14th century the former floodplain was regularly exposed to flooding as the result of dike breaches, particularly in the 18th and in the first part of the 19th century. These breaches were the result of a combination of the poor discharge capacity of the river channels and the relatively poor condition of the river dikes (Middelkoop, 1997). Ice jams in spring were an important cause of the breaches (Driessen, 1994). River engineering activities in the main channel of the Rhine distributaries initially focused on the improvement of the discharge of water and ice, and thereafter on the improvement of navigation. Adjustments of the discharge distribution at the bifurcations in the Rhine delta contributed to those improvements. The first adjustment occurred in the 17th century. Main interventions in the past three centuries are listed in Table 1 (Van der Ven, 1996; Middelkoop, 1997, 1998).

Water quality development

Klink (1989) distinguished four types of river pollution covering more or less successive phases in pollution history. Pollution started with the discharge of organic substances in domestic waste waters, causing an increase of COD (chemical oxygen demand) and BOD (biological oxygen demand), resulting in a decrease of the dissolved oxygen concentration. This was followed by the pollution from heavy metals, being the combined result of mining and industrial activity. The third type is formed by pollution with organic compounds (e.g. PCBs, PAHs), and the lasting the contamination by pesticides. Pollution in both the latter types is caused by organic micropollutants, which have been produced by the chemical industry

Table 1. Main interventions in the Rhine delta in the past three centuries (Van der Ven, 1996; Middelkoop, 1997, 1998) (for geographic names see Fig. 1)

Period/year	Intervention
1707	Opening of the Pannerdensch Kanaal, constructed for the improvement of the northern distributary at the first bifurcation in the Rhine delta. Later on this bifurcation was adjusted several times
1727–1734	Damming of the connections between the rivers Meuse and Waal at Heerewaarden and Voorn. Both connections served as an overflow for the River Waal in periods with high Rhine discharge
1775	Reconstruction of the second bifurcation where the Pannerdensch Kanaal splits into the rivers Nederrijn and IJssel
1850–1870	Digging of the Nieuwe Merwede
1850–1885	Normalisation of the river IJssel
1868	Opening of the Nieuwe Waterweg. Construction of this canal was needed to improve the entrance to the harbours of Rotterdam for sea-going vessels. It forms an artificial outlet in the Rhine delta
1875–1916	Normalisation of the river Waal
1932	Completion of the Zuiderzee damming (De Jong & Bij de Vaate 1989)
1954–1967	Construction of three weirs in the Nederrijn/Lek
1970	Completion of the Haringvliet damming, the joint estuary of the rivers Rhine and Meuse
1989-present	Lowering of forelands and construction of secondary channels along the distributaries (Cals et al., 1996; Schropp & Bakker, 1998)

in the river valleys (point sources of pollution), are everywhere used, causing diffuse pollution.

Discharge of industrial waste water became a serious problem during the process of industrialisation of the river valleys in the 19th century. However, water quality data from the river Rhine are very scarce from the period before 1965. Analysis of dated sediment layers in the forelands have shown to be a helpful tool in reconstructing pollution history with heavy metals and organic micropollutants (Klink, 1989; Beurskens et al., 1993).

The implementation of national laws against pollution and protection of the environment, and the establishment (in 1950) of the International Commission for Protection of the Rhine (ICPR), which got its internationally recognised juridical basis after signing the Treaty of Bern in 1963, were important impulses for the development and realisation of chemical monitoring programmes (Dieperink, 1997). Permanent monitoring stations were erected at several sites along the distributaries. The station in the vicinity of Lobith, at the German–Dutch border, became the primary Dutch reference station for water quality developments in the river Rhine (recently this station was integrated into the two km downstream situated German monitoring station at Bimmen on the south bank).

The Rhine Action Programme, launched in 1987, initially focused on water quality improvement. The countries in the Rhine basin, united in the ICPR, agreed upon a target reduction of at least 50% of the pollution caused by priority compounds by the year 1995 (compared with the situation in 1985). Furthermore, water quality targets for the river Rhine were set for about 50 priority compounds (reduction of 70–90%), not only based on requirements for drinking water production and the protection of aquatic life, but also on human tolerance levels for fish consumption (Van Dijk et al., 1995).

Although calamities in the river Rhine caused a political reveille needed for the rehabilitation of the river Rhine (Dieperink, 1997; *viz*. the endosulphan and the so-called Sandoz calamity in 1969 and 1986, respectively), calamitous pollution accidents still occur (Institute for Inland Water Management and Waste Water Treatment, unpublished data). Long and short term impacts on the river fauna of these short lasting accidents are unknown due to the lack of suitable monitoring programmes. Furthermore, it is difficult to assign effects of specific pollutants on colonisation, growth and reproduction of autochthonous aquatic species in an environment of continuous changing water quality variables in the case of long term effects (e.g. Hellawell, 1989).

Main pollutants

Around the turn of the 19th and 20th centuries, the river was already seriously polluted with domestic and industrial waste water (Tittizer & Krebs, 1996). Phenols in the river made the commercially interesting fish species, such as Atlantic Salmon (*Salmo salar*) and Eel (*Anguilla anguilla*), unfit for consumption (Lobrecht & Van Os, 1977; Van Drimmelen, 1987). Rock bottom of the river pollution was reached in the first part of the 1970s. At that time the river water was acute toxic for water flies and trout embryos, and caused malformation and other effects in fish and insect larvae (Alink et al., 1980; Poels et al., 1980; Slooff, 1982, 1983a, b; Slooff et al., 1983; Van Urk & Kerkum, 1986, 1987; Van der Gaag, 1987). From the second half of the 1970s water quality improved considerably because of:

a. the implementation of environmental protection laws;
b. the construction of waste water treatment plants;
c. international agreements;
d. foundation of policy with monitoring results;
e. development of cleaner production methods;
f. reduction of spills (e.g. caused by calamities);
g. increased public awareness.

Firstly, focussing on priority substances, the organic load and the amount of polluting substances such as heavy metals and organic micropollutants in discharges of domestic and industrial waste water decreased dramatically within a period of approximately 10 years (De Kruijf, 1982; Van der Weijden & Middelburg, 1989; Heymen & Van der Weijden, 1991; Van der Klei et al., 1991). A significant decrease of the organic load resulted in better oxygen conditions for the river fauna (Table 2; Fig. 3). Between 1952 and 1972 the oxygen concentration, measured at the German–Dutch border, had significantly decreased. However, from 1973 onwards, a significant improvement was observed (Table 2). Of relevance here is the fact that the yearly observed

Table 2. One-way ANOVA of trends in water quality parameters measured in the river Rhine at the German–Dutch border

Parameter	Unit	Period	N^a	Slope[b]	R^2	F	p
O_2	mg l^{-1}	1952–1972	21	−0.019	0.560	26	< 0.001
O_2	mg l^{-1}	1973–2003	31	0.018	0.810	124	< 0.001
COD	mg l^{-1}	1968–1996	23	−0.043	0.846	122	< 0.001
Chlorophyll a	μg l^{-1}	1977–2003	26	−0.063	0.582	36	< 0.001
Cl^-	mg l^{-1}	1971–2003	33	−0.021	0.600	42	< 0.001
Cl^-	mg l^{-1}	1990–2003	14	−0.068	0.810	51	< 0.001
Cd_{total}	μg.l^{-1}	1975–2003	29	−0.149	0.761	90	< 0.001
Cu_{total}	μg l^{-1}	1970–2003	34	−0.066	0.819	145	< 0.001
Hg_{total}	μg l^{-1}	1971–2003	33	−0.035	0.916	350	< 0.001
Pb_{total}	μg l^{-1}	1971–2003	33	−0.077	0.737	85	< 0.001
Zn_{total}	μg l^{-1}	1971–2003	33	−0.091	0.908	318	< 0.001
Mineral oil [g]	mg kg^{-1}	1972–1987	16	−0.270	0.888	111	< 0.001
$PCB_{sum}^{c,g}$	μg kg^{-1}	1988–2003	16	−0.031	0.244	5.8	< 0.05
PAHs[d]	μg l^{-1}	1979–1988	10	−0.239	0.891	66	< 0.001
γ-HCH[e]	μg l^{-1}	1973–2003	30	−0.139	0.907	285	< 0.001
ACEI[f]	μg l^{-1}	1973–2003	31	−0.111	0.734	84	< 0.001

[a]number of yearly averages (number of observations ≥6 per year); [b]based on ln transformed averages; [c]sum of the 28, 52, 101, 118, 138, 153 and 180 PCB congeners; [d]six of Borneff; [e]linden; [f]acetyl-choline esterase inhibitors; [g]in dry suspended matter.

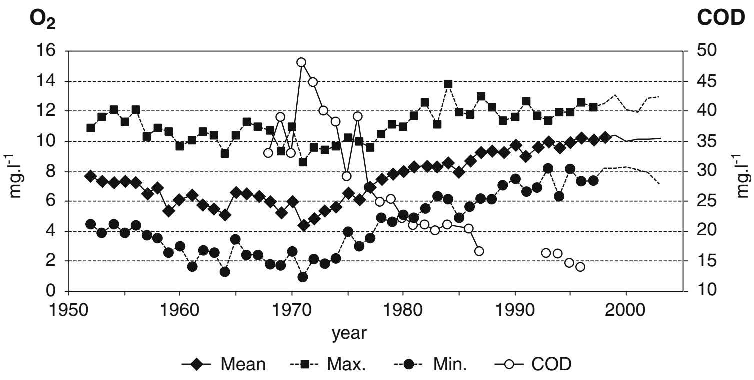

Figure 3. Yearly average, minimum and maximum observed dissolved oxygen concentrations, and yearly average of the COD in the river Rhine measured at the German–Dutch border.

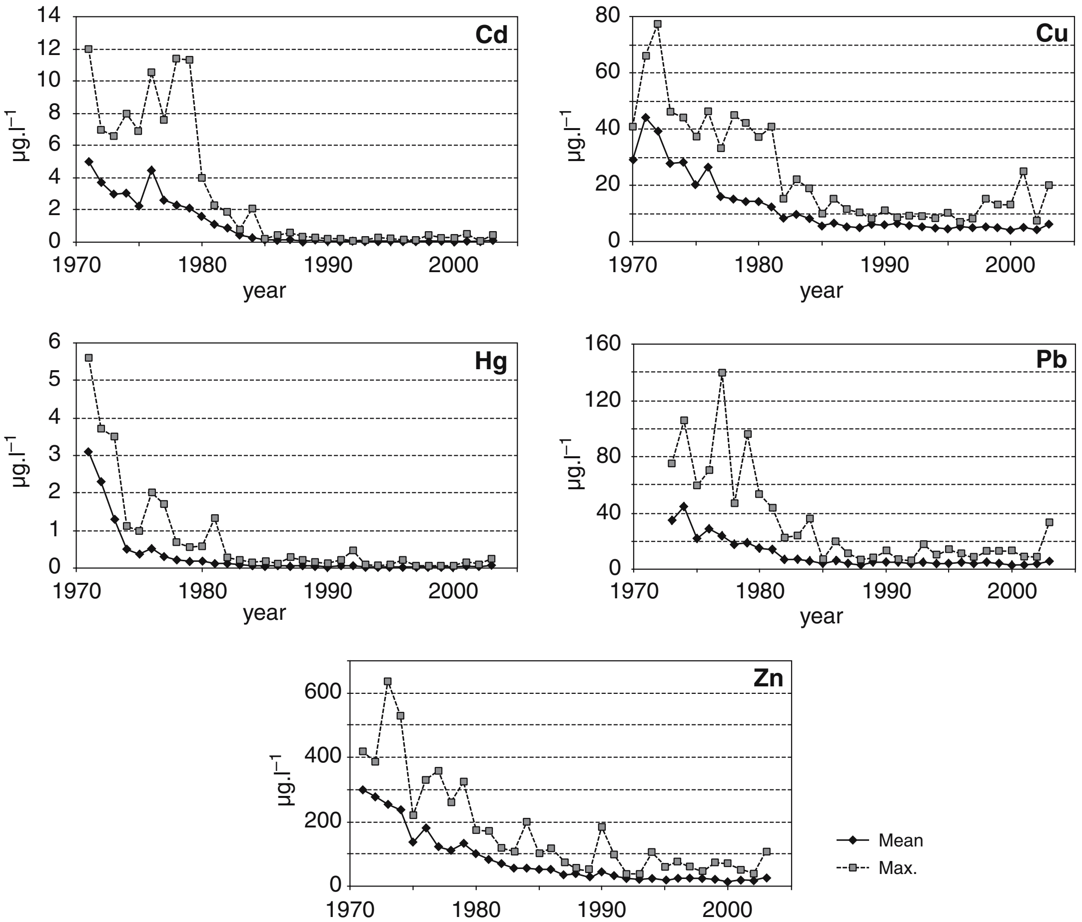

Figure 4. Yearly average and maximum observed total concentrations of Cd, Cu, Hg, Pb and Zn in the river Rhine measured at the German–Dutch border.

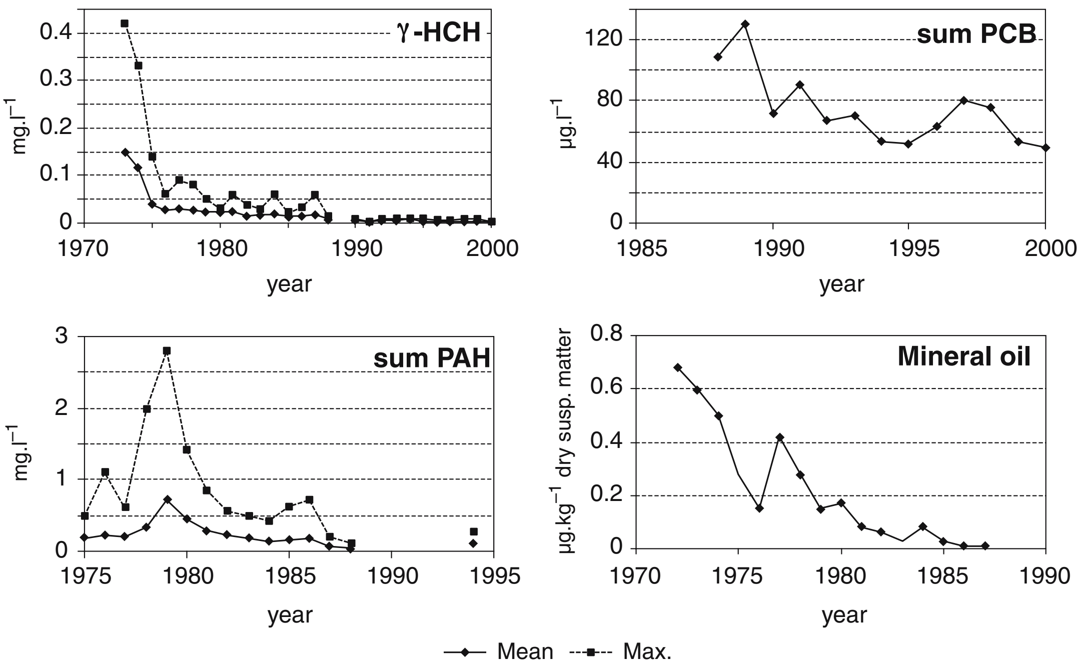

Figure 5. Yearly average concentrations of γ-HCH, sum PCB, sum PAH and mineral oil in the river Rhine measured at the German–Dutch border, including maximum observed concentrations of γ-HCH and sum PAH.

minimum concentration in the latter period increased from 2 to 8 mg l^{-1}.

Concentrations of toxic substances in the river water such as heavy metals, organic micropollutants (e.g. PAHs, γ-HCH), as well as mineral oil, significantly reduced with at least a factor 10 in the period 1970–1990 (Fig. 4 and 5; Heymen & Van der Weijden, 1991; Van der Velde et al., 1991; Admiraal et al., 1993; Van Urk et al., 1993). As a result of this decrease, the differences, in general, between the yearly average and the maximum observed concentrations were also strongly reduced (Fig. 4 and 5).

Although water quality improvement of the river Rhine became a success story, toxicity of the Rhine water did not disappear completely because of the sum-toxicity of thousands of chemical compounds present in the water, most of them in concentrations below detection level (Hendriks et al., 1994; Leuven et al., 1998; Van der Velde & Leuven, 1999). In 1993, for example, Nolan et al.

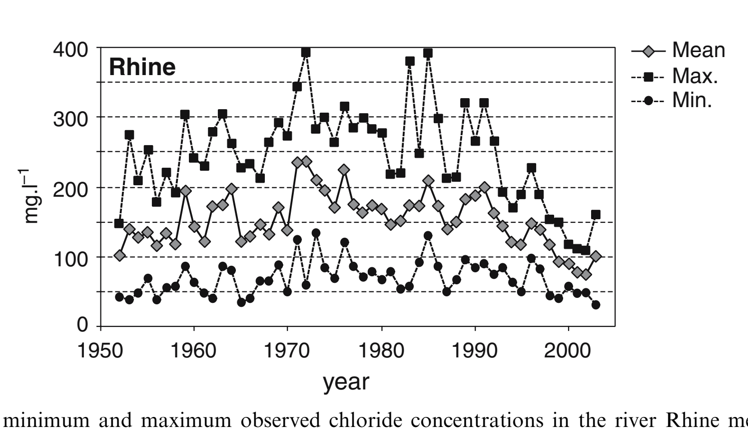

Figure 6. Yearly average, minimum and maximum observed chloride concentrations in the river Rhine measured at the German–Dutch border.

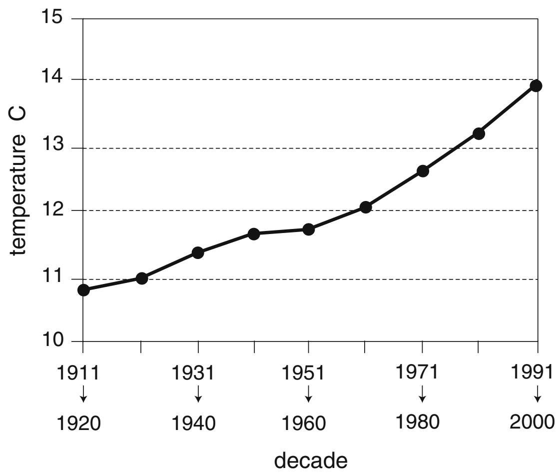

Figure 7. Decade averages of the water temperature of the river Rhine.

(1998; 2000) observed toxic effects on the skin and in the immune system of sea trout smolts (*Salmo trutta*). Other important water quality related habitat components for the river fauna, such as chloride concentration and water temperature, did not improve to the same extent (chloride, Fig. 6) or, quite the contrary, even deteriorated (water temperature, Fig. 7). Main sources of chloride enrichment are potassium mines in the Alsace (France) and brown coal mines in Germany. In the period 1960–2000 the yearly average chloride concentration varied between 90 and 240 mg l^{-1} (Fig. 6) with minimum and maximum concentrations measuring 35 and 420 mg l^{-1}, respectively (this maximum value was reported in the annual reports of the Combined Rhine and Meuse Waterworks, RIWA, Amsterdam). To put these values into the right context, it should be noted that the natural chloride concentration assessed was 12 mg l^{-1} on average (Molt, 1961). Reduction of the chloride discharge of the potassium mines was an important issue in international discussions on water quality improvement in the period 1960–1990. A final agreement with France was reached in 1991 consisting of a salt discharge reduction of 60 kg s^{-1} and temporary salt storage during periods in which the chloride concentration in the river Rhine exceeds 200 mg l^{-1} at the German–Dutch border (Dieperink, 1997). Results of all negotiations were visible in a significant decline of the average chloride concentration from 1971, noticeably after 1990 (Table 2).

Thermal pollution has been mainly caused by discharge of heated cooling water of electric power plants and industries. Recently part of the water temperature increase could also be attributed to climate changes probably due to global warming. Compared with the situation around 1900, the average water temperature had increased by 3 °C till around 1980 (Wessels, 1984), and has increased with 0.5 °C per 10 years from 1952 (Fig. 7).

Effects on the fauna

Before the initiation of the National Biological Monitoring Programme in the river Rhine in 1992, data on macroinvertebrates and fish were not collected systematically with a long-term horizon, but only in relatively short-term research projects. In 1973 Van Urk (1981, 1984) started to study changes in the epilithic littoral macroinvertebrate fauna in the river IJssel, one of the three main distributaries of the river Rhine. This study has been continued until today and has resulted in the longest macroinvertebrate time series known in larger rivers in the Netherlands. From the 1960s till 1992 fisheries independent fish stock monitoring was mainly focussed on commercially interesting species (Klinge et al., 1998).

Macroinvertebrates

As indicated above, the macroinvertebrate community on riprap in the littoral zone of the river IJssel has been monitored from 1973 on a yearly basis (Van Urk, 1984; Van Urk & Bij de Vaate, 1990; Bij de Vaate, 1994). Apart from an incidental survey made by Lauterborn in the beginning of the 20th century (Lauterborn, 1918), the IJssel dataset is the only source for data older than 15 years. To fill this gap, results of palaeolimnological investigations are used (Klink, 1989) to reconstruct macroinvertebrate communities for e.g. target and reference descriptions. However, only the remains of insects can be found in sediment layers. On the other hand, insect larvae constitute the main part of the species richness in a healthy river. Van den Brink et al. (1990) combined different sources to reconstruct macroinvertebrate development in the Rhine delta from the beginning of the 20th century. They concluded that around 1985 the number of rheophilic species had declined, while the number of euryoecious species had increased. As a result of the increased chloride concentration (Fig. 6) a number of brackish water crustaceans were found approximately 100 km upstream from their original limits of distribution (Den Hartog et al., 1989).

From recolonisation patterns of autochthonous species in the Rhine delta, two phases in water quality recovery could be distinguished. Between 1975 and 1980 some pollution stress tolerant insects (in this initial period mainly chironomid and a few caddis fly species) and molluscs began to recolonise the river. Density increase of these macroinvertebrates in the years after that period correlated well with a decrease of chemical pollutants in the river water (Van Urk, 1981; Van Urk & Bij de Vaate, 1990; Van Urk et al., 1993).

Recolonisation of the lower Rhine by the burrowing mayfly *Ephoron virgo* in 1991 (Bij de Vaate et al., 1992) and its mass development in the following years marked the start of the second phase in water quality rehabilitation of the river. Concentrations of toxicants had strongly decreased in

Table 3. Dominant (••) and subdominant (•) macroinvertebrate species in two habitats in the free flowing distributaries in the Rhine delta in the period 1975–2000 (R = riprap in the littoral zone; B = channel bottom)

Taxon	1975		1980		1990		1995		2000	
	R	B	R	B	R	B	R	B	R	B
River Waal										
Corbicula fluminalis								•		
Corbicula fluminea						•		••		••
Dreissena polymorpha							•			
Potamopyrgus antipodarum						•				
Propappus volcki								••		
Chelicorophium curvispinum					••	••	••		••	
Jaera istri									••	
Dikerogammarus villosus									••	
Gammarus tigrinus					•			••		•
Cricotopus bicinctus									•	
Kloosia pusilla								•		
Neozavriella species									•	
River IJssel										
Corbicula fluminea										•
Dreissena polymorpha	•				•					
Ancylus fluviatilis									•	
Potamopyrgus antipodarum								•		
Hypania invalida										••
Asellus aquaticus	••									
Jaera istri									••	
Chelicorophium curvispinum					••		••	••	••	••
Dikerogammarus villosus									•	••
Gammarus tigrinus					•		•	••		
Hydropsyche contubernalis			•							
Dicrotendipes nervosus			•							
Cricotopus intersectus							•			
Cricotopus species			••							

Species were considered to be dominant or subdominant if their density contributed to > 20% of the total macroinvertebrate density or >20% of the macroinvertebrate density minus the dominant species respectively. If no dominant species were present, those contributing to 10–20% of the total macroinvertebrate density were considered to be subdominant. Non-indigenous species underlined.

the past two decades, and oxygen concentration had reached a level that no longer seemed to be the limiting factor for the colonisation of many macroinvertebrate species with a higher demand for oxygen. Another example is the dragonfly *Gomphus flavipes* that recolonised the Rhine delta from 1996 (Habraken & Crombaghs, 1997; Goudsmits, 1998). Although potentially several other sensitive autochthonous macroinvertebrate species could also extend their territory in the Rhine distributaries due to water quality improvement, other factors such as the absence of physical habitat and the increased water temperature most probably prevent successful colonisation of these species.

Macroinvertebrate communities are currently (since 1985) dominated by non-indigenous species (Table 3), mainly species from the Ponto-Caspian area. The colonisation of the River Rhine by Ponto-Caspian species was accelerated by the opening of the Main-Danube Canal in September 1992 (Bij de Vaate et al., 2002; Van der Velde et al., 2002). Some Ponto-Caspian species (e.g. *Chelicorophium curvispinum* and *Dikerogammarus villosus*) have had a relatively strong negative impact on densities of other macroinvertebrates (Van den Brink et al., 1991, 1993; Van der Velde et al., 1994, 2002; Rajagopal et al., 1999; Dick & Platvoet, 2000).

Fishes

Van den Brink et al. (1990) gave a brief overview of developments in the fish fauna in the Rhine delta from the start of the 20th century till 1985. In general, densities of most species were relatively low in the period 1960–1980. The groups of the rheophilic and anadromous species suffered the most from the combination of water quality deterioration, river engineering, damming, and the closure of river outlets (e.g. Lelek, 1989). On the other hand, the fish fauna took most advantage of the ecological rehabilitation programmes that were introduced after the Sandoz-accident in 1986, especially Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*) which have been reintroduced on a large scale in the main tributaries. In 2000, species richness was higher than the previous century (Fig. 8), being the result of colonisation of the Rhine delta by introduced species. Nature development in the river forelands has been important from the point of view of fish stocks as well. The construction of secondary channels positively contributed to fish stocks in the main channel of the distributaries (Grift, 2001).

Rehabilitation perspectives

Rivers restoration has become an important issue from the end of the 1980s (Boon et al., 1992; Sparks, 1995; Nienhuis & Leuven, 1998; Pedroli & Postma, 1998; Nienhuis et al., 2002; Buijse et al., 2005). Important general aspects are (a) improvement of the lateral and (b) longitudinal connectivity and (c) connectivity with the groundwater. Dutch policy aim for river restoration is also to reduce habitat fragmentation since river valleys are considered to be important corridors for migration and dispersal of aquatic and terrestrial ani-

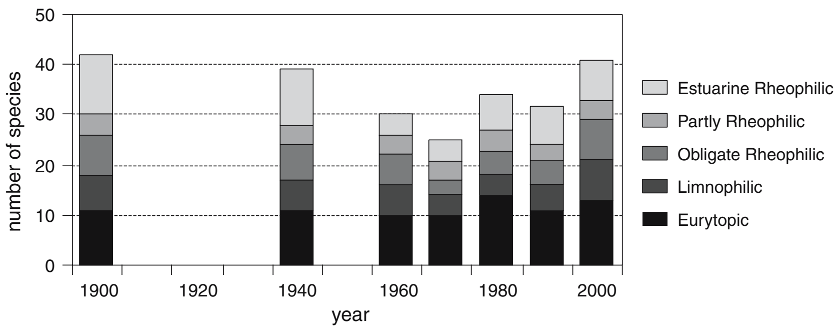

Figure 8. Number of fish species per guild in the Rhine distributaries (1900–2000). Sources: Lelek (1989), Oosterbroek (1990), Van den Brink et al. (1990), De Nie (1997), and unpublished results of the National Biological Monitoring Programme 1992–2000.

mal species, and for biodiversity conservation (Anonymous, 1998; 2001). As the consequence of this policy, structure and functioning of ecological networks need to be improved in order to create viable populations of target species (ICPR, 1998; Foppen & Reijnen, 1998; Chardon et al., 2000). However, restoration of geo-morphological processes to improve connectivity in the Rhine distributaries is only possible in a very limited way because of the functions assigned. Unhampered discharge of water and ice and the economy related functions remain more important than their ecological functions due to safety and socio-economic reasons, respectively (Anonymous, 2001). In practice, possibilities for restoration of large rivers in the Netherlands are thus mainly possible in aquatic/terrestrial transition zones in the Rhine delta (Van Dijk et al., 1995; Heiler et al., 1995; Simons et al., 2001; Buijse et al., 2002, 2005). Several large ecologically important reaches (1000–6000 ha each), with smaller areas in between, were identified along the Rhine distributaries, of which totally about 7500 ha of floodplain area have an important ecological function (Van Dijk et al., 1995). Improvement of longitudinal connectivity within the river channel was realised in 2004 by the construction of fish ladders at the weirs in the Nederrijn/Lek distributary. Further improvement will be realised by optimalisation of the discharge regime of the sluices in the barrier dams separating the Wadden Sea and Lake IJsselmeer in the northern, and the North Sea and lake Haringvliet in the south western part of the Netherlands (Fig. 1). Measures will focus on improvement of fish migration through both dams and on the creation of a brackish zone on both sides of the Haringvliet dam (Smit et al., 1997).

Conclusions

The Rhine delta had become an area with a strong anthropogenic pressure on the environment. This will not change in the future due to the resulting unacceptable social and economical impacts. Therefore the conclusions from this review are that (a) most of the alterations in the Rhine delta are irreversible; (b) chances for the development of riverine biotopes have therefore to be found in the relatively narrow forelands and not in the main channels of the Rhine delta or in the original floodplain; (c) further reduction of pollutants, especially thermal pollution is needed to help original species to colonise the Rhine delta again; (d) the ongoing process of invasions by non-indigenous species clearly leaves a mark on the existing communities and on recolonisation possibilities of original species. This is CWE publication no. 425.

References

Admiraal, W., G. van der Velde, H. Smit & W. G. Cazemier, 1993. The rivers Rhine and Meuse in The Netherlands: present state and signs of ecological recovery. Hydrobiologia 265: 97–128.

Alink, G. M., E. M. H. Frederix-Wolters, M. A. van der Gaag, J. F. J. van der Kerkhoff & C. L. M. Poels, 1980. Induction of sister-chromatid exchanges in fish exposed to Rhine water. Mutation Research 78: 369–374.

Anonymous, 1998. Vierde nota waterhuishouding. Regeringsbeslissing. Ministerie van Verkeer en Waterstaat, 's Gravenhage (in Dutch).

Anonymous, 2001. Beheersplan voor de Rijkswateren. Programma voor het beheer in de periode 2001–2004. Report Ministerie voor Verkeer & Waterstaat, 's Gravenhage (in Dutch).

Beurskens, J. E. M., G. A. J. Mol, H. L. Barreveld, B. van Munster & H. J. Winkels, 1993. Geochronology of priority pollutants in a sedimentation area of the Rhine River. Environmental Toxicology and Chemistry 12: 1549–1566.

Bij de Vaate, A., 1994. Long-term changes in the macroinvertebrate fauna of the River IJssel, The Netherlands. Verhandlungen der Internationale Vereinigung für theoretische und angewandte Limnologie 25: 1563–1567.

Bij de Vaate, A., 2003. Degradation and recovery of the freshwater fauna in the lower sections of the rivers Rhine and Meuse. Ph.D. thesis Wageningen University, Wageningen.

Bij de Vaate, A., A. Klink & F. Oosterbroek, 1992. The mayfly, *Ephoron virgo* (Olivier), back in the Dutch parts of the rivers Rhine and Meuse. Hydrobiological Bulletin 25: 237–240.

Bij de Vaate, A., K. Jazdzewski, H. Ketelaars, S. Gollasch & G. van der Velde, 2002. Geographical patterns in range extension of macroinvertebrate Ponto-Caspian species in Europe. Canadian Journal of Fisheries and Aquatic Sciences 59: 1159–1174.

Boon, P. J., P. Calow & G. E. Petts, 1992. River Conservation and Management. John Wiley, Chichester.

Buijse, A. D., H. Coops, M. Staras, L. H. Jans, G. J. van Geest, R. E. Grift, B. W. Ibelings, W. Oosterberg & F. C. J. M. Roozen, 2002. Restoration strategies for river-floodplains along large lowland rivers in Europe. Freshwater Biology 47: 889–907.

Buijse, A. D., F. Klijn, R. S. E. W. Leuven, H. Middelkoop, F. Schiermer, J. Thorp & H. Wolfert, 2005. Rehabilitation of large rivers: references, achievements and integration into river management. Archiv für Hydrobiologie, Supplement 155, Large Rivers 15: 715–738.

Cals, M. J. R., R. Postma & E. C. L. Marteijn, 1996. Ecological river restoration in The Netherlands: state of the art and strategies for the future. Aquatic Conservation: Marine and Freshwater Ecosystems 8: 61–70.

Chardon, J. P., R. P. B. Foppen & N. Geilen, 2000. LACRH-RIVER: a method to assess the functioning of rivers as ecological networks. European Water Management 3: 35–43.

De Bruin, D., D. Hamhuis, L. van Nieuwenhuijze, W. Overmars, D. Sijmons & F. Vera, 1987. Ooievaar : de toekomst van het rivierengebied. Report Stichting Gelderse Milieufederatie, Arnhem (in Dutch).

De Jong, J. & A. bij de Vaate, 1989. Dams and the environment. The Zuiderzee damming. Bulletin International Commission on Large Dams 66: 1–85.

De Kruijf, H. A. M., 1982. Progress in the application of the convention against the chemical pollution of the River Rhine. Toxicological and Environmental Chemistry 6: 41–63.

De Nie, H., 1997. Atlas van de Nederlandse zoetwatervissen. Media Publishing, Doetinchem (in Dutch).

Den Hartog, C., F. B. W. van den Brink & G. van der Velde, 1989. Brackish-water invaders in the River Rhine. A bioindication for increased salinity level over the years. Naturwissenschaften 76: 80–81.

Dick, J. T. A. & D. Platvoet, 2000. Invading predatory crustacean *Dikerogammarus villosus* eliminates both native and exotic species. Proceedings of the Royal Society of London B Biology 267: 977–983.

Dieperink, C., 1997. Tussen zout en zalm. Lessen uit de ontwikkeling van het regime inzake de Rijnvervuiling. Ph.D. thesis, University Utrecht, Utrecht (in Dutch).

Driessen, A. M. A. J., 1994. Watersnood tussen Maas en Waal. Overstromingsrampen in het rivierengebied tussen 1780 en 1810. Walburg Pers, Zutphen (in Dutch).

Foppen, R. P. B. & R. Reijnen, 1998. Ecological networks in riparian systems: Examples for Dutch floodplain rivers. In Nienhuis, P. H., R. S. E. W. Leuven & A. M. J. Ragas (eds), New Concepts for Sustainable Management of River Basins. Backhuys Publishers, Leiden, 85–93.

Galat, D. L., L. H. Fredrickson, D. D. Humburg, K. J. Bataille, J. R. Bodie, J. Dohrenwend, G. T. Gelwicks, J. E. Havel, D. L. Helmers, J. B. Hooker, J. R. Jones, M. F. Knowlton, J. Kubisiak, J. Mazourek, A. C. McColpin, R. B. Renken & R. D. Semlitsch, 1998. Flooding to restore connectivity of regulated, large-river wetlands. BioScience 48: 721–733.

Gore, J. A. & F. D. Shields Jr., 1995. Can large rivers be restored? BioScience 45: 142–152.

Goudsmits, K., 1998. De rivierrombout (*Gomphus flavipes*) terug in Nederland. Nieuwsbrief Nederlandse Vereniging voor Libellenstudie 2(3): 2 (in Dutch).

Grift, R. E., 2001. How fish benefit from floodplain restoration along the lower River Rhine. Ph.D. thesis Wageningen University, Wageningen.

Habraken, J. M. P. M. & B. H. J. M. Crombaghs, 1997. Een vondst van de rivierrombout (*Gomphus flavipes* (Carpentier)) langs de Waal. Brachytron 1(1): 3–5 (in Dutch).

Heiler, G., T. Hein, F. Schiemer & G. Bornette, 1995. Hydrological connectivity and flood pulses as the central aspects for the integrity of a river-floodplain system. Regulated Rivers: Research & Management 11: 351–361.

Hellawell, J. M., 1989. Biological Indicators of Freshwater Pollution and Environmental Management. Elsevier, London.

Hendriks, A. J., J. L. Maas-Diepeveen, A. Noordsij & M. A. van der Gaag, 1994. Monitoring response of XAD-concentrated water in the Rhine delta: a major part of the toxic compounds remains unidentified. Water Research 28: 581–598.

Heymen, R. & M. van der Weijden, 1991. Resultaten van waterkwaliteitsonderzoek in de Rijn in Nederland. Report 91.047, Institute for Inland Water Management & Waste Water Treatment, Lelystad (in Dutch).

ICPR, 1998. Bestandsaufnahme der ökologisch wertvollen Gebiete am Rhein und erste Schritte auf dem Weg zum Biotopverbund. Report International Commission for Protection of the Rhine against Pollution (ICPR), Koblenz (in German).

Kalweit, H. (eds), 1993. Der Rhein unter der Einwirkung des Menschen: Ausbau Schiffahrt, Wasserwirtschaft. International Commission for Hydrology of the River Rhine, Lelystad (in German).

Klinge, M., A. D. Buijse, W. G. Cazemier, E. H. R. R. Lammens & K. H. Prins, 1998. Biologische monitoring zoete rijkswateren: vis in de zoete rijkswateren, 1992–1996. Report 98.017. Institute for Inland Water Management & Waste Water Treatment, Lelystad (in Dutch).

Klink, A., 1989. The Lower Rhine: palaeoecological analysis. In Petts G. E. (ed.), Historical Change of Large Alluvial Rivers: Western Europe. John Wiley, Chichester, 183–201.

Lauterborn, R., 1918. Die geographische und biologische Gliederung des Rheinstroms III. Sitzungsberichte der Heidelberger Akademie der Wissenschaften. Mathematisch-Naturwissenschaftliche Klasse 9: 1–87.

Lelek, A., 1989. The Rhine River and some of its tributaries under human impact in the last two centuries. In Dodge, D.P. (ed.), Proc. Intern. Large River Symposium. Canadian Special Publication of Fisheries and Aquatic Sciences 106: 469–487.

Leuven, R. S. E. W., J. L. M. Haans, A. J. Hendriks, R. A. C. Lock & S. E. Wendelaar Bonga, 1998. Assessing cumulative impacts of multiple stressors on river systems. In Nienhuis, P. H., R. S. E. W. Leuven & A. M. J. Ragas (eds), New Concepts for Sustainable Management of River Basins. Backhuys Publishers, Leiden: 241–260.

Lobregt, P. & J. van Os, 1977. De laatste Riviervissers. De Walburg Pers, Zutphen (in Dutch).

Middelkoop, H., 1997. Embanked floodplains in the Netherlands: geomorphological evolution over various time scales. Nederlandse Geografische Studies 224: 1–341.

Middelkoop, H. (eds), 1998. Twee rivieren. Rijn en Maas in Nederland. Report 98.041 Institute for Inland Water Management & Waste Water Treatment, Arnhem (in Dutch).

Molt, E .L., 1961. Pollution of the River Rhine water. In Anonymous, The River Rhine. Report Technical University Delft, Delft (in Dutch).

Nienhuis, P. H., A. D Buijse, R. S. E. W. Leuven, A. J. M. Smits, R. J. W. de Nooij & E. M. Samborska, 2002. Ecological rehabilitation of the lowland basin of the River Rhine (NW Europe). Hydrobiologia 478: 241–260.

Nienhuis, P. H. & R. S. E. W. Leuven, 1998. Ecological concepts for the sustainable management of lowland river basins: a review. In Nienhuis P. H., R. S. E. W. Leuven & A. M. J. Ragas (eds), New Concepts for Sustainable Management of River Basins. Backhuys Publishers, Leiden: 7–33.

Nienhuis, P. H. & R. S. E. W. Leuven, 2001. River restoration and flood protection: controversy or synergism? Hydrobiologia 444: 85–99.

Nolan, D. T., R. H. Hadderingh, F. A. T. Spanings, H. A. Jenner & S. E. Wendelaar Bonga, 2000. Acute temperature elevation in tap and Rhine water affects skin and gill epithelia, hydromineral balance, and gill Na^{+}/K^{+}-ATPase activity of brown trout (*Salmo trutta*) smolts. Canadian Journal of Fisheries and Aquatic Sciences 57: 708–718.

Nolan, D. T., R. H. Hadderingh, H. A. Jenner & S. E. Wendelaar Bonga, 1998. The effects of exposure to Rhine water on sea trout smolt (*Salmo trutta trutta* L.): an ultrastructural and physiological study. In Nienhuis, P. H., R. S. E. W. Leuven & A. M. J. Ragas (eds), New Concepts for Sustainable Management of River Basins. Backhuys Publishers, Leiden: 261–271.

Oosterbroek, F. M. J., 1990. Drie jaar monitoring van de visstand in de Waal bij de EPON-centrale te Nijmegen. Report 287, Catholic University, Nijmegen, Department of Aquatic Ecology & Biogeology (in Dutch).

Pedroli, G. B. M. & R. Postma, 1998. Nature rehabilitation in European river ecosystems: three cases. In Nienhuis, P.H., R.S.E.W. Leuven & A.M.J. Ragas (eds), New Concepts for Sustainable Management of River Basins. Backhuys Publishers, Leiden: 67–84.

Poels, C. L. M., M. A. van der Gaag & J. F. J. van de Kerkhoff, 1980. An investigation into the long-term effects of Rhine water on rainbow trout. Water Research 14: 1029–1035.

Rajagopal, S., G. van der Velde, B. G. P. Paffen & A. bij de Vaate, 1999. Population densities, biomass, growth and production of *Corophium curvispinum* G.O. Sars (Amphipoda) in the Lower Rhine. In Schram, F. R. & J. C. von Vaupel Klein (eds), Crustaceans and the Biodiversity Crisis: Proceedings 4th international Crustacean Congress. Vol. 1, Brill, Leiden: 457–472.

Schiemer, F., 1999. Conservation of biodiversity in floodplain rivers. Archiv für Hydrobiologie Supplement 115: 423–438.

Schropp, M. H. I. & C. Bakker, 1998. Secondary channels as a basis for the ecological rehabilitation of Dutch rivers. Aquatic Conservation: Marine and Freshwater Ecosystems 8: 53–59.

Simons, H. E. J., C. Bakker, M. H. I. Schropp, L. H. Jans, F. R. Kok & R. E. Grift, 2001. Man-made secondary channels along the River Rhine (The Netherlands); results of post-project monitoring. Regulated Rivers: Research & Management 17: 473–491.

Slooff, W., 1982. Skeletal anomalies in fish from polluted surface waters. Aquatic Toxicology 2: 157–173.

Slooff, W., 1983a. Study on the use of feral fish as indicators for the presence of chemical carcinogens in Dutch surface waters. Aquatic Toxicology 3: 127–139.

Slooff, W., 1983b. Rijn-, Lek-, Waal- en IJsseluiterwaarden onder invloed van ingrepen en verontreinigingen. In Hekstra G. P. & W. Joenje (eds), Rijnwater in Nederland. Ecologische kring, Arnhem, 13–31.

Slooff, W., D. de Zwart & J. F. J. van de Kerkhoff, 1983. Monitoring the rivers Rhine and Meuse in The Netherlands for toxicity. Aquatic Toxicology 4: 189–198.

Smit, H., G. van der Velde, R. G. Smits & H. Coops, 1997. Ecosystem developments in the Rhine-Meuse delta during two decades after enclosure and steps towards estuary restoration. Estuaries 20: 504–520.

Sparks, R. E., 1995. Need for ecosystem management of large rivers and their floodplains. BioScience 45: 168–182.

Tittizer, T. & F. Krebs (eds), 1996. Ökosystemforschung: der Rhein und seine Auen, eine Bilanz. Springer Verlag, Berlin (in German).

Van den Brink, F. W. B., G. van der Velde & W. G. Cazemier, 1990. The faunistic composition of the freshwater section of the River Rhine in The Netherlands: present state and changes since 1900. In Kinzelbach, R. & G. Friedrich (eds), Biologie des Rheins. Vol. 1, Limnologie aktuell: 191–216.

Van den Brink, F. W. B., G. van der Velde & A. bij de Vaate, 1991. Amphipod invasion on the Rhine. Nature 352: 576.

Van den Brink, F. W. B., G. van der Velde & A. bij de Vaate, 1993. Ecological aspects, explosive range extension and impact of a mass invader, *Corophium curvispinum* Sars, 1895 (Crustacea: Amphipoda), in the Lower Rhine (The Netherlands). Oecologia 93: 224–232.

Van der Gaag, M. A., 1987. Tests for growth retardation and pathology in fishes exposed to complex mixtures: Experiences on polluted river water. In Vouk V. B., G. C. Butler, A. C. Upton, D. C. Parke & S. C. Asher (eds), Methods for Assessing the Effects of Mixtures of Chemicals. Wiley, Chichester: 775–796.

Van der Klei, W., R. H. Dekker, H. Kersten & J. A. W. de Wit, 1991. Water management of the River Rhine: past, present and future. Journal European Water Pollution Control Federation 1: 9–18.

Van der Velde, G., G. van Urk, F. W. B. van den Brink, F. Colijn, W. A. Bruggeman & R. S. E. W Leuven, 1991. Rein Rijnwater, een sleutelfactor in chemisch oecosysteemherstel. In Hekstra, G. P. & F. J. M. van der Linden (eds), Flora en fauna chemisch onder druk. Pudoc, Wageningen: 231–266 (in Dutch).

Van der Velde, G., F. W. B. van den Brink, B. G. P. Paffen, A. bij de Vaate & H. A. Jenner, 1994. Decline of zebra mussel populations in the Rhine: competition between two mass invaders (*Dreissena polymorpha* and *Corophium curvispinum*). Naturwissenschaften 81: 32–34.

Van der Velde, G. & R. S. E. W. Leuven, 1999. Polluted river systems: monitoring and assessment of ecotoxicological risks. Acta Hydrochimica et Hydrobiologica 27: 251–256.

Van der Velde, G., I. Nagelkerken, S. Rajagopal & A. bij de Vaate, 2002. Invasions by alien species in inland freshwater bodies in Western Europe: the Rhine delta. In Leppäkoski, E., S. Gollasch & S. Olenin (ed) Aquatic Invasive Species of Europe. Distribution, Impacts and Management. Kluwer Academic Publishers, Dordrecht: 360–372.

Van der Ven, G.P. (ed.), 1996. Man-made Lowlands. History of Water Management and land reclamation in The Netherlands. Stichting Matrijs Utrecht.

Van der Weijden, C. H. & J. J. Middelburg, 1989. Hydrogeochemistry of the River Rhine: long-term and seasonal variability, elemental budgets, base levels and pollution. Water Research 23: 1247–1266.

Van Dijk, G. M., E. C. L. Marteijn & A. Schulte-Wülwer-Leidig, 1995. Ecological rehabilitation of the River Rhine: plans, progress and perspectives. Regulated Rivers: Research & Management 11: 377–388.

Van Drimmelen, D. E., 1987. Schets van de Nederlandse rivier- en binnenvisserij tot het midden van de 20ste eeuw. Organisatie ter Verbetering van de Binnenvisserij, Nieuwegein (in Dutch).

Van Urk, G., 1981. Changes in the macroinvertebrate fauna of the River IJssel. H_2O 14: 494–499.

Van Urk, G., 1984. Lower Rhine – Meuse. In Whitton, B. A. (ed.), Ecology of European Rivers. Blackwell, Oxford: 291–315.

Van Urk, G. & F. C. M. Kerkum, 1986. Misvormingen bij muggelarven uit Nederlandse oppervlaktewateren. H_2O 19: 624–627 (in Dutch with English summary).

Van Urk, G. & F. C. M. Kerkum, 1987. Chironomid mortality after the Sandoz accident and deformities in *Chironomus* larvae due to sediment pollution in the Rhine. Aqua 4: 191–196.

Van Urk, G. & H. Smit, 1989. The Lower Rhine: geomorphological changes. In Petts, G. E. (ed.), Historical Changes of Large Alluvial Rivers: Western Europe. Wiley & Sons, Chichester: 167–182.

Van Urk, G. & A. bij de Vaate, 1990. Ecological studies in the Lower Rhine in The Netherlands. In Kinzelbach, R. & G. Friedrich (eds), Biologie des Rheins. Vol. 1, Limnologie Aktuell: 131–145.

Van Urk, G., F. Kerkum & A. bij de Vaate, 1993. Insects and insecticides in the Lower Rhine. Water Research 27: 205–213.

Wessels, H. R. A., 1984. Water temperature of the River Rhine, 1911–1984. H_2O 17(18): 396–399.

WWF., 1992. Living Rivers. World Wide Fund for Nature, Zeist.