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The rivers Rhine and Meuse in The Netherlands: present state and signs of ecological recovery

W. Admiraal[1], G. van der Velde[2], H. Smit[3] & W.G. Cazemier[4]
[1]*National Institute of Public Health and Environmental Protection, P.O. Box 1, 3720 BA Bilthoven, The Netherlands;* [2]*Laboratory of Aquatic Ecology, Catholic University of Nijmegen, Toernooiveld, 6525 ED Nijmegen, The Netherlands;* [3]*Institute for Inland Water Management and Waste Water Treatment, P.O. Box 17, 8200 AA Lelystad, The Netherlands;* [4]*Netherlands Institute for Fisheries Research, P.O. Box 68, 1970 AB IJmuiden, The Netherlands*

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Abstract

The ecosystems of the rivers Rhine and Meuse have suffered drastic environmental changes, for example because of the regulation of the stream bed and the construction of weirs and dams. Furthermore, discharges of industrial and municipal waste water have caused the water quality of these rivers to deteriorate; this problem became acute in the sixties and seventies. Recently some chemical parameters of water quality have improved in the Rhine, and as a consequence some aquatic communities are showing signs of recovery after decades of severe degradation. This paper describes the present state of the aquatic communities in the Dutch part of the rivers Rhine and Meuse, using published observations on plankton, macrophytes, invertebrates, and fish. The sparse information on the food chain in these rivers is summarized. The main channels of the Rhine and Meuse are characterized by a dense plankton that develops rapidly in the nutrient-rich river waters. The stream beds, now dominated by wave-exposed sand and gravel, have a sparse fauna and flora. The river banks, mostly consolidated by blocks of stone, offer a substratum for numerous benthic organisms, particularly now that the water quality has improved. The floodplain waters and old river channels harbour a flora and fauna rich in species. The degree of water exchange with the river is crucial for the ecological development of the river and its backwaters. Today the freshwater tidal reaches of the rivers occupy a very restricted area, and only remnants of the previously abundant vegetation of rushes are found.

Losses in the numbers of animal and plant species, notably those specific to rivers, are evident, but over the last 15 years several species have returned. Allochthonous species (exotics), including crustaceans and molluscs, have also settled in the Rhine and Meuse. Fish species characteristic of these rivers, such as river lamprey, sea trout, barbel, and flounder, have recently been observed in appreciable numbers.

The Rhine Action Programme provides a framework for the large-scale rehabilitation of the Rhine. Experiments on re-stocking the Rhine with Atlantic salmon and on the ecological rehabilitation of floodplains are being carried out on the assumption that there will be a further reduction of the pollution load. A similar programme is required for the Meuse.

Introduction

The rivers Rhine and Meuse play a vital role in the hydrology of The Netherlands (TNO, 1986). The ecosystems of these two major rivers with their extensive floodplains and delta regions once encompassed a considerable part of The Netherlands, but since the Middle Ages, when the inhabitants started to build dikes, they have been subjected to human interference and have altered greatly. For centuries the rivers have been intensively exploited for various purposes; inevitably, conflicts of interests arose. By the end of the 19th century the Rhine was being intensively fished, and in 1885 problems with the exploitation of salmon stocks led to the 'salmon treaty' between the Rhine states (Smit & de Jong, 1989). Hydrographic changes, such as the damming of Rhine tributaries in Germany, contributed to the decline of migratory fish species. The construction of sewer systems in this century and the subsequent massive discharge of organically polluted water into the Rhine and Meuse caused the oxygen conditions of the rivers to deteriorate. Post-war industrial development added a massive load of toxic materials, culminating in an overall degradation of biological conditions in the Rhine over the period 1960–1970 (Wolff, 1978). Since then, the organic load has been effectively reduced in the Rhine, but concentrations of nitrogen and phosphorus in the water of the two rivers are still very high. The input of toxic materials into the Rhine, notably of some of the heavy metals, has also been considerably reduced, under the pressure of international agreements made by the Rhine states. Sanitation measures enabled the biological communities to recover partially in the early eighties (Friedrich & Müller, 1984; Van Urk, 1984b). Today the Rhine and Meuse are highly eutrophic rivers with a strongly modified morphology, carrying a reduced but persisting load of many toxic compounds.

A growing public awareness of the widespread detrimental effects of river water on the North Sea and Wadden Sea and on the quality of drinking water paved the way for the next phase in the rehabilitation of the river. After the Sandoz accident in Basle November 1986 the states bordering the river Rhine agreed on the Rhine Action Programme (IKSR, 1987), which has three main aims: to create conditions which would enable the return of higher organisms (such as the salmon); to safeguard the use of Rhine water for the preparation of drinking water; and to abate the contamination of sediments with toxic compounds. Recently a fourth objective has been added: to fulfil the requirements of the North Sea Action Plan. The Rhine Action Programme was the first pollution abatement programme for the Rhine to include ecological objectives (Smit & van Urk, 1987). So far, a 'Meuse Action Programme' has not been adopted, despite the similarities between the environmental problems in the rivers Rhine and Meuse.

Since ca. 1970 the hydrobiology of several of the Dutch wetlands has been intensively studied and some have been subjected to systems analysis (cf. Nienhuis *et al.*, de Jonge *et al.*, de Haan *et al.*, 1993). The Rhine and Meuse, however, which had deteriorated so much, attracted little interest. However, since the seventies, when these rivers began to show signs of recovery, the research has been intensified, particularly after the project 'Ecological Rehabilitation of the Rhine' started in 1988. This review describes the ecosystems of the rivers Rhine and Meuse in their present state and analyses the trends in their rehabilitation.

Morphology and hydrology

The Rhine and Meuse catchment areas have been described extensively by Friedrich & Müller (1984), Van Urk (1984b), and Descy & Empain (1984). An essential difference between these two rivers is their water source: the Rhine is fed by meltwater from the Alps and by rainwater from its catchment, whereas the Meuse is fed by rainwater only. Hence, the Rhine has a more stable discharge over the seasons, while the Meuse usually shows a distinct summer minimum in its flow.

The water systems of the Rhine and Meuse in The Netherlands can be divided into truly riverine reaches that include the distributaries of the Rhine: the R. Waal, the R. Nederrijn/Lek, and the R. IJssel as well as the slow-flowing delta waters: the former main estuary of the Rhine and Meuse, the Hollands Diep/Haringvliet, and the Rotterdam Waterway (Fig. 1). Each of these waterways is strongly affected by engineering works.

River regulation has strongly modified the river beds in the course of the centuries (Van Urk & Smit, 1989). Figure 2 shows the changes over the last 200 years in a short stretch of the R. Waal resulting from the construction of groynes. The narrowing of the main bed, the 'summer bed', together with the straightening of river bends has increased the scour that deepened the shipping route, resulting in a facilitated water transport and a lowered water level. In the German section of the lower Rhine the water level has fallen by 1 or 2 m in the course of this century (Fig. 3). There is an increased incidence of inundation of the floodplains during discharge peaks in summer

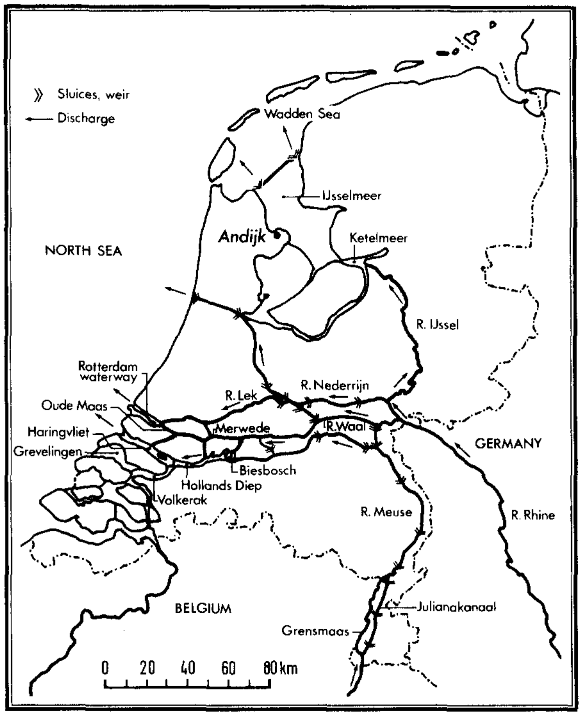

Fig. 1. The lower course of the R. Rhine and Meuse in the Netherlands. The location of the main engineering works is indicated. After TNO (1986).

(Brock *et al.*, 1987), probably because of accelerated water transport from the catchment.

The weirs in the River Nederrijn/Lek (Fig. 1) were primarily constructed to ensure a minimum river flow in the R. IJssel. They are closed at low water discharge. The weirs in the R. Meuse and a lateral canal (the Julianakanaal) were primarily constructed to allow shipping to pass during low summer discharge (Fig. 1).

Until very recently all these works were executed without regard to their ecological consequences. In 1970, for instance, the former main estuary of the Rhine, the Haringvliet, was dammed and a large intertidal marsh, the Biesbosch, lost its unique character (cf. Van Urk, 1984). The tidal amplitude in another freshwater tidal area, the Oude Maas, was reduced from ca. 1.9 m to ca. 1.1 m after the Haringvliet was closed. As a result the only freshwater tidal marsh is now restricted to the banks of the Oude Maas (south of Rotterdam) and the western stretch of the R. Lek (Fig. 4).

The freshwater basin of the Hollands Diep/Haringvliet receives about 35% of the Rhine water; the discharge of the Haringvliet sluices depends on the discharge of the Rhine and on the water flow in the Rotterdam Waterway needed to limit the intrusion of salt water. Hence the residence time of Rhine water in the Hollands Diep/Haringvliet is very variable. It averages between 1 and 2 weeks.

The R. IJssel discharges about 15% of the Rhine water into the IJsselmeer via the Ketelmeer. These basins were created by the closure of the Zuiderzee in 1932 and the construction of polders. The Rhine water in the lake has a residence time of 0.5 year and affects the quality of the water in the western Wadden Sea (cf. de Jonge *et al.*, 1993), and in shallow lakes in the northern part of the Netherlands (cf. de Haan *et al.*, 1993), as well as the drinking water inlet at the village of Andijk (Province of North Holland).The rivers have numerous backwaters in the 'winter bed'. The backwaters situated in the river forelands are normally flooded by river water when water levels are high in winter or spring, and occasionally also in summer. Smits (1989) made an inventory

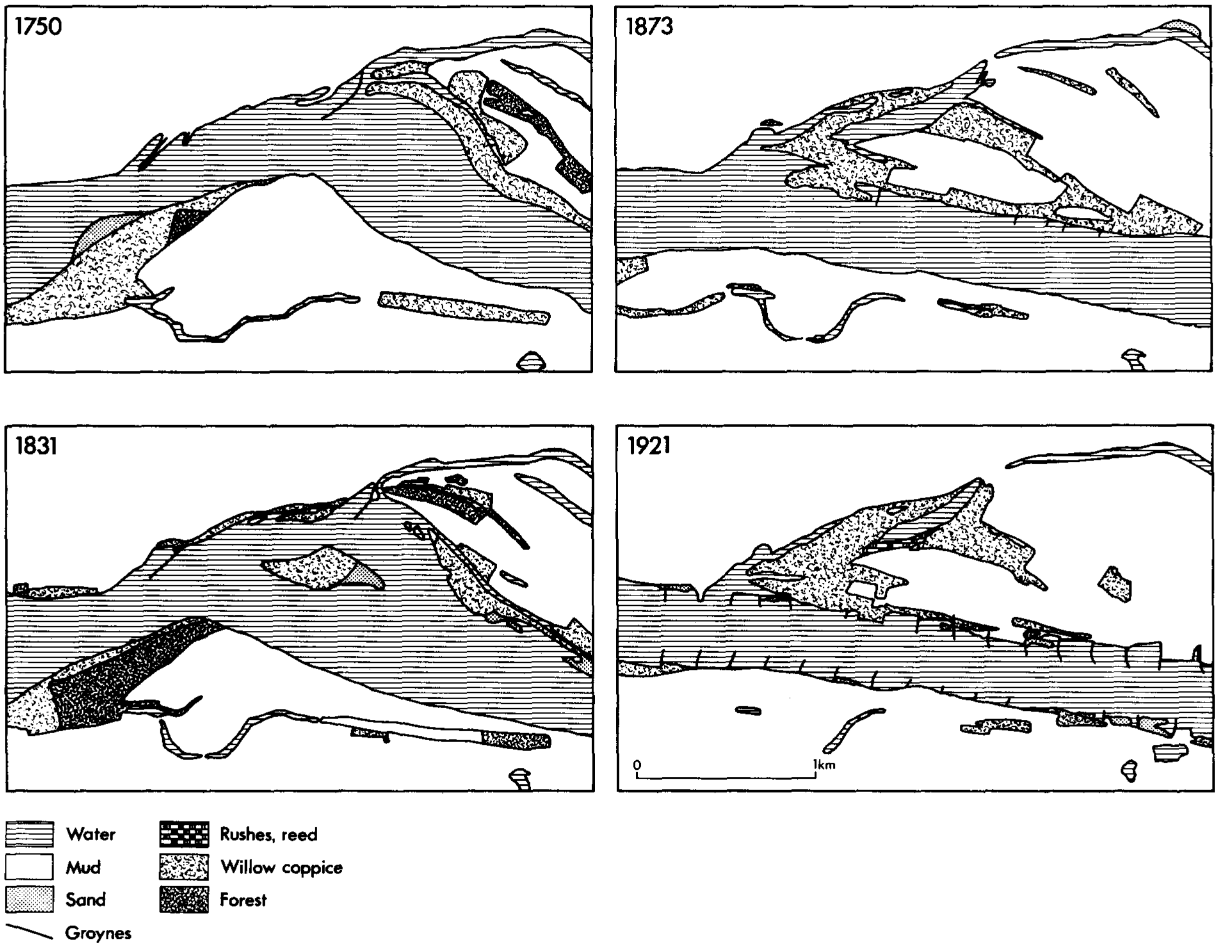

Fig. 2. Development of the morphology of a short stretch of the R. Waal (river km 899–901) since 1750. After Van Urk & Smit (1989).

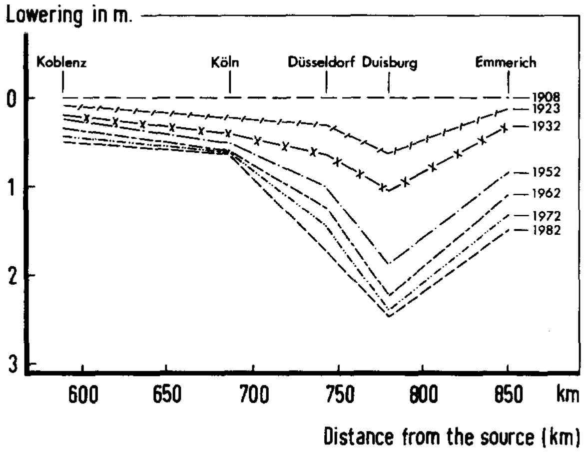

Fig. 3. Lowering of the mean water level in the Middle and Lower Rhine since 1908. The large decrease near Duisburg is partly due to mining. After Smit & de Jong (1989).

of the backwaters in the river forelands of the Rhine and Meuse. He found 170 abandoned meanders, 76 of which are connected with the river. He also described 47 breakthrough ponds (15 still connected with the river), 50 small rivers and brooks, 84 clay pits (12 still connected with the river), 163 sand and gravel pits (81 connected with the river), 101 harbours and 41 ditches and canals. There are also thousands of small areas of water (marshes, shallow ponds, etc.), most of which are temporary.

Shipping on the rivers is intensive (266×10^9 tons in 1986) and is a physical threat to biological communities on the banks. The wave action churns up the river sediments so that coarse-grained 'beaches' prevail between the groynes, as

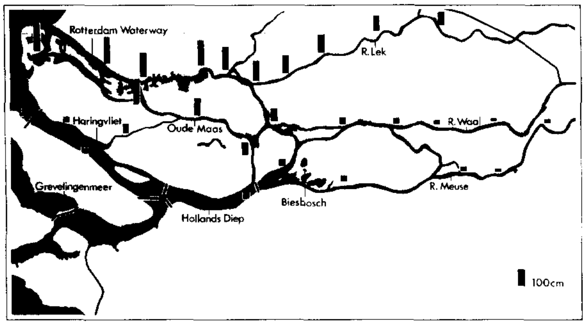

Fig. 4. Tidal amplitude (in m) in the Rhine-Meuse delta after closure of the Haringvliet. After H. Coops, unpublished.

on the R. Waal; in other places rubble is dumped to protect the banks from erosion.

The temporary occurrence of an ice cover on rivers is probably a powerful factor enforcing morphological changes in natural rivers. These effects are probably limited in the Rhine and Meuse because of the thermal pollution. The temperature of the Rhine water is raised by about 2 °C above its natural value. The Meuse waters are also warmed up by several degrees (Descy & Empain, 1984). Klink (1989) has argued that the numbers of days with an ice cover on the Rhine have declined significantly during this century.

Transport and fate of materials

Rivers are typically 'open' systems; the flow of water and the dissolved or particulate substances therein is essentially unidirectional. This is also true for the relatively short pre-estuarine reach of the lower Rhine and Meuse in The Netherlands. It is only in the estuarine reaches of the rivers that materials may accumulate or be transported upstream.

The Rhine carries an average of 3.4 10^9 kg yr^{-1} of suspended matter (Van Urk & Smit, 1989). The concentrations in the Rhine are generally somewhat higher than in the Meuse, but there is a typical difference in the behaviour of silt in the two rivers. The bed load transport in the Rhine may be limited (cf. Van Urk & Smit, 1989), but the compartments of the Meuse between the weirs tend to accumulate silt by sedimentation in the relatively slow-flowing waters. This material may be resuspended during peak discharge and transported downstream. It has been suggested that the transport of suspended matter in the Rhine has decreased, due to the changed morphology, from 4.2 to 3.4 10^9 kg yr^{-1} over the period of 1880–1980 (Van Urk & Smit, 1989).

In the past the suspended matter of the Rhine and Meuse supplemented the estuarine cycle of this material (de Jonge *et al.*, 1993; Nienhuis *et al.*, 1993), but now most of the riverine particulate matter is deposited in the Hollands Diep, the Rotterdam Harbours, the Ketelmeer, and in the IJsselmeer. The disproportional dimensions of water volume and water discharge in the Hollands Diep/Haringvliet has led to a typical accretion pattern, with materials from different periods tending to accumulate in different parts of the basin (Fig. 5).

The load of various substances in the Rhine and Meuse (*e.g.* cadmium or phosphate) dominates the budgets of these substances for The Netherlands; a significant fraction of the material is retained by the settling river sediment (De Kruijf *et al.*, 1988). Heavy metals and refractive organic pollutants have been accumulating in the sediment for decades, and large deposits are now present (Van Broekhoven, 1987). It is not known whether these toxic materials have been effectively immobilized or whether they are available

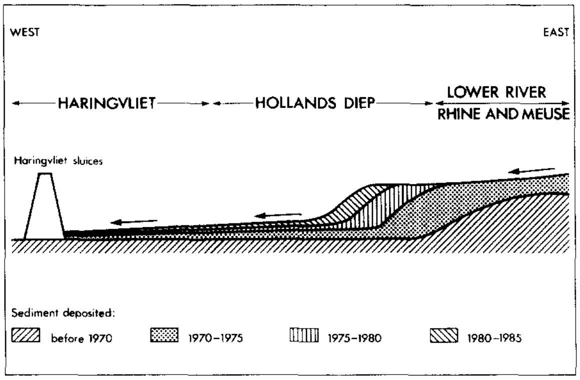

Fig. 5. Schematic representation of the sedimentation of riverine silt in the Hollands Diep and Haringvliet, recent sediments tending to be deposited further downstream. After Rijkswaterstaat (1987).

to organisms when they are re-exposed by scouring.

The concentrations of most heavy metals in the Rhine water fell appreciably over the period 1975–1985 (Van Broekhoven, 1987; Fig. 6), but the values are still much higher than the background levels (Salomons & Förstner, 1984). The concentrations of metals in the Meuse water do not show the consistent decrease found in the Rhine water. Concentrations of copper (Fig. 6) have fallen to levels similar to those in the Rhine, but concentrations of chromium and cadmium (especially the latter) have recently begun to rise. The annual load of cadmium carried by the Meuse now exceeds that of the much larger Rhine (Van Vuuren, 1989).

Oxygen concentrations in the Rhine and Meuse are shown in Fig. 7. In recent years the average oxygen concentrations in the Rhine and Meuse have been equivalent to a saturation level of slightly over 80%. The Rhine has recovered from periods with low oxygen levels in the sixties and

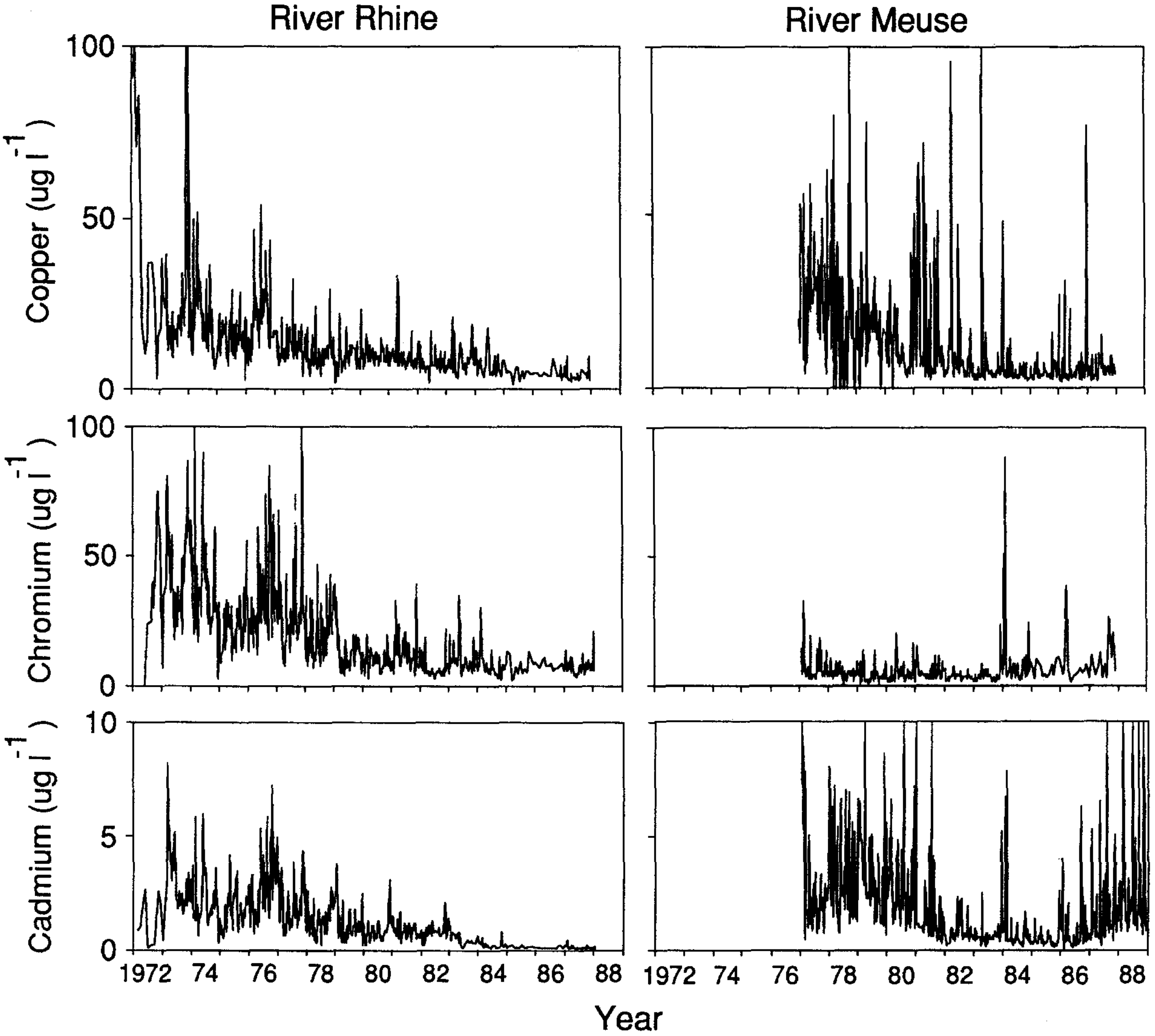

Fig. 6. Concentrations of total copper, total chromium, and total cadmium in the water of the Rhine and Meuse in 1972–1988. Data from Cooperating Drinking Water Companies (RIWA).

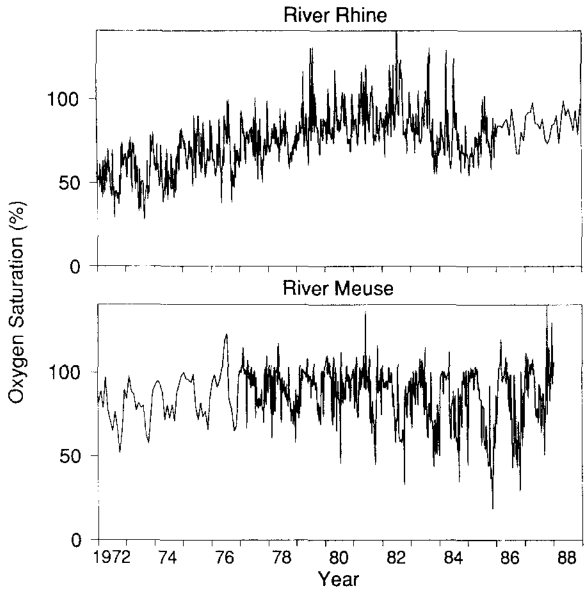

Fig. 7. As Fig. 6 for oxygen saturation.

seventies. The Meuse shows considerable summer depressions in oxygen concentration.

At present the concentrations of nitrogen compounds in the Rhine are higher than in the Meuse, but the opposite is true for the phosphate concentrations (Fig. 8). In the Rhine, phosphate concentrations have fallen consistently over the last decade, probably as a result of measures reducing the production and emission of phosphates. No such consistent trend is seen in the Meuse.

Chloride concentrations in the two rivers are different (Fig. 9): the continuously high levels in the Rhine are due to the ongoing discharges from the French potassium mines, together with the increasing discharge of salt drainage water from coal mining in Germany. In autumn, chloride concentrations in both rivers are relatively high because of the low water discharge.

Concentrations of organic micropollutants in the Rhine and Meuse differ as well. In recent years, cholinesterase-inhibiting compounds have amounted to 0.5–3 $\mu g\,l^{-1}$ in the Meuse and to 0.2–2 $\mu g\,l^{-1}$ in the Rhine, whereas the levels of absorbable organic halogen compounds in the Rhine are twice those in the Meuse (40–50 $\mu g\,l^{-1}$ versus 10–20 μg l – 1; data from the Cooperating Drinking Water Companies, RIWA). There is a similar difference between the rivers in the extractable and volatile fractions of halogen compounds.

The concentrations shown in Figs 6–8 were measured at the Dutch/German and Dutch/Belgian borders. Some of the values may decrease in the Dutch reaches of the rivers, due to adsorption, evaporation, or degradation. In the Dutch reach of the Meuse the long residence time of the water may allow water quality to improve despite the local discharges. De Zwart & Folkerts (1990) indicated that the toxicity of the concentrated organic fraction in Rhine water decreased during transport in the Netherlands. However, the concentrations of a few substances such as cadmium rise in the Rotterdam Waterway, as a consequence of discharges in the Rotterdam harbour.

The river forelands of the Rhine and Meuse are polluted by heavy metals and organic micropollutants such as PCB's. The deposition of contaminated silt after flooding adversely affects soil quality: the most frequently flooded soils have the highest concentrations of zinc, cadmium, copper, lead, cobalt, nickel and chromium in their top layers (Demon & Van Broekhoven, 1989), whereas erosive sediments show lower values. The Rhine Action Programme aims at halving the concentrations of pollutants in river water, including suspended materials, by 1995, the reference year being 1985. In most cases the contaminated soil in the river forelands is covered by or mixed with less contaminated silt, but this process of 'dilution' takes many decades, especially if the summer dikes remain intact. In forelands with summer dikes the sedimentation rate is estimated at 3 mm per year, based on measurements after floods in 1987 and 1988. After removal of the summer dikes this rate is estimated to increase to at least 10 mm per year.

Plankton

Peelen (1975) and Friedrich & Müller (1984) analysed trends in plankton development in the Rhine and Meuse on the basis of older, mostly qualitative observations. Peelen (1975) concluded

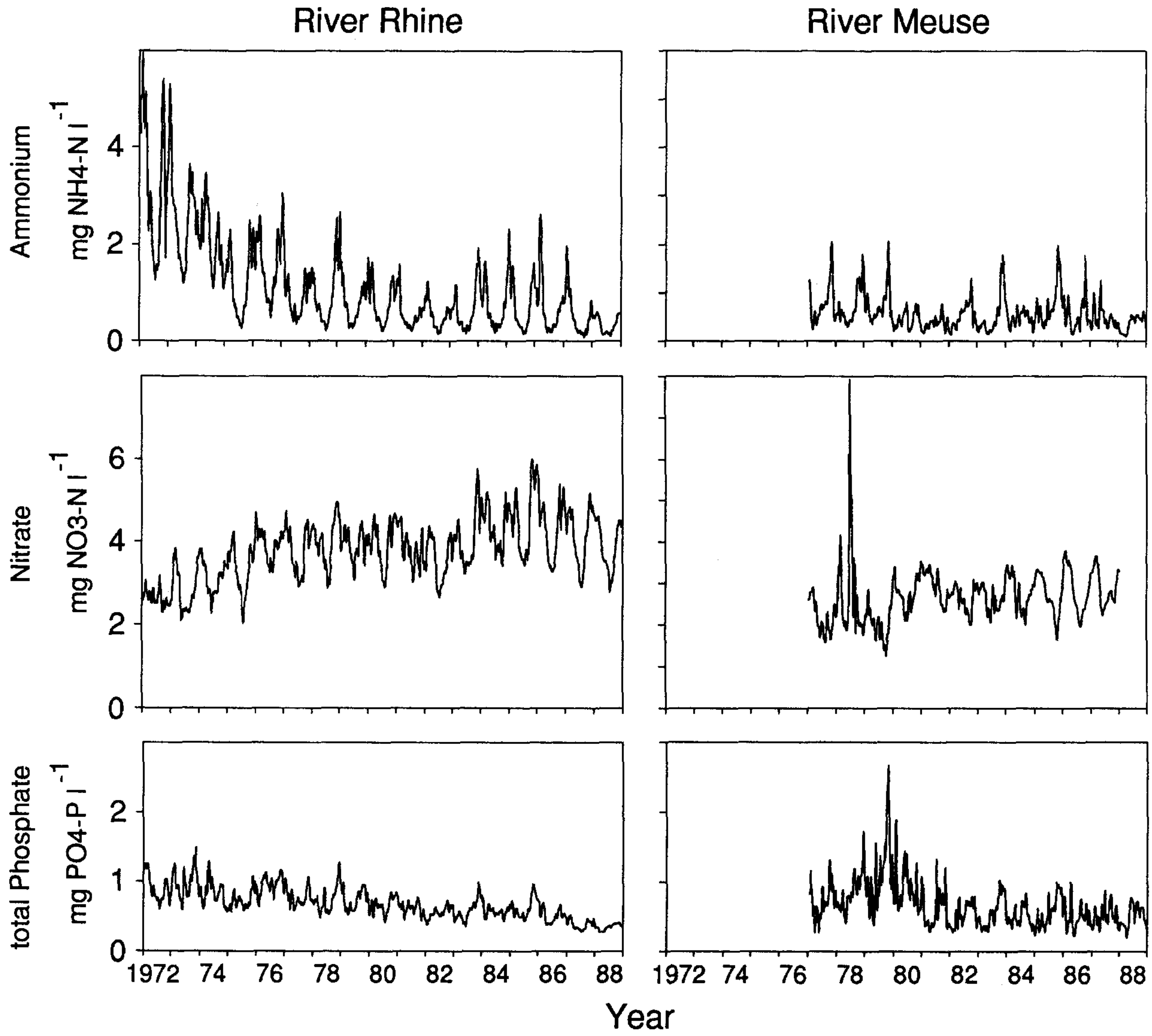

Fig. 8. As Fig. 6 for nitrogen compounds and total phosphate.

that between 1916 and 1972 the saprobic index of the phyto- and zooplankton did not shift significantly. However, it was clear that the plankton of both rivers was more sparse when it was investigated by De Lint (1916, in the Rhine, quoted in Peelen, 1975) and Romijn (1918, in the Meuse, quoted in Peelen, 1975) than in the period 1966–1972 (Peelen, 1975). According to Lauterborn (1939, in Peelen, 1975) plankton numbers in the Rhine increased rapidly after about 1890 (cf. Friedrich & Müller, 1984; Friedrich, 1990). In 1918 the Meuse was still free flowing. After the weirs were constructed in The Netherlands (from the twenties onwards) the residence time of the water increased; this, in addition to the increasing nutrient load, will have stimulated plankton development. Similar conditions may have stimulated the plankton input to the Rhine from tributaries. Increased development of plankton has also been reported for the regulated Rivers Ruhr (Nusch, 1978) and Neckar (Backhaus & Kemball, 1978).

The massive occurrence of planktonic microalgae, notably diatoms, in recent years has become

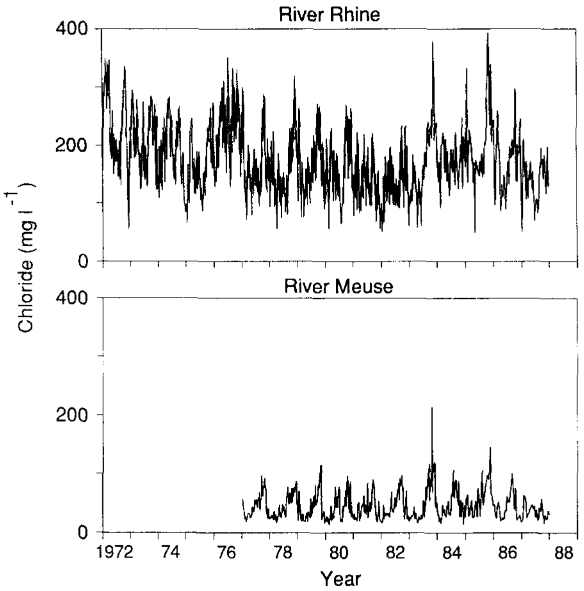

Fig. 9. As Fig. 6 for chloride.

clear in a palaeolimnological study of sediment cores from the Rhine area (A. Klink, unpublished), which showed that sediment-inhabiting pennate diatoms dominate the spectrum of diatom frustules in the sediments deposited in the 19th century, whereas planktonic centric species are numerically dominant in sediment layers deposited in the course of the 20th century.

A few ubiquitous species nowadays dominate the phytoplankton of the Rhine and Meuse. They include *Stephanodiscus hantzschii* Grün., *Melosira granulata* Ehr., and *Cyclotella meneghiniana* Kütz. (Friedrich & Müller, 1984; Descy, 1987). These species are also very common in other eutrophic rivers (*e.g* the R. Thames, Lack, 1971). Friedrich & Müller (1984) suggested that, in addition to eutrophication, the input of salt into the Rhine has contributed to the abundance of indifferent algal species.

In 1977 the *Daphnia* toxicity test showed that Rhine water in The Netherlands was acutely toxic (Slooff, 1983; Slooff *et al.*, 1985). Therefore, it seems likely that the zooplankton development in the river must also have suffered. Phytoplankton development in the Rhine between the Ruhr area and the German/Dutch border was interrupted in 1983 by the local input of toxic materials (Friedrich & Viehweg, 1984). Recently, Tubbing & Admiraal (1991) and Tubbing *et al.* (1992) have indicated that the present pollution of the Rhine is still affecting the growth of bacterioplankton and the photosynthesis of the phytoplankton.

Nowadays, the Rhine and the Meuse have similar densities of phytoplankton and zooplankton (De Ruyter van Steveninck *et al.*, 1990b). However, in the Dutch reaches of the Rhine the zooplankton is in an early stage of development (Admiraal *et al.*, 1990a; De Ruyter van Steveninck *et al.*, 1990a, b), whereas in the Meuse at the Belgian/Dutch border a fully developed zooplankton with numerous rotifers and crustaceans may be present (Fig. 10).

The phytoplankton, dominated by diatoms and green algae (Friedrich & Müller, 1984; Peelen, 1975), develops in the middle reach of the river, probably by selective development of inocula from tributaries and backwaters. Friedrich & Viehweg (1984) have demonstrated the growth of phytoplankton in the Rhine upstream of The Netherlands (cf. Franz, 1990), but the chlorophyll concentrations in the Netherlands tend to be more or less stable in the pre-estuarine river sections (Van

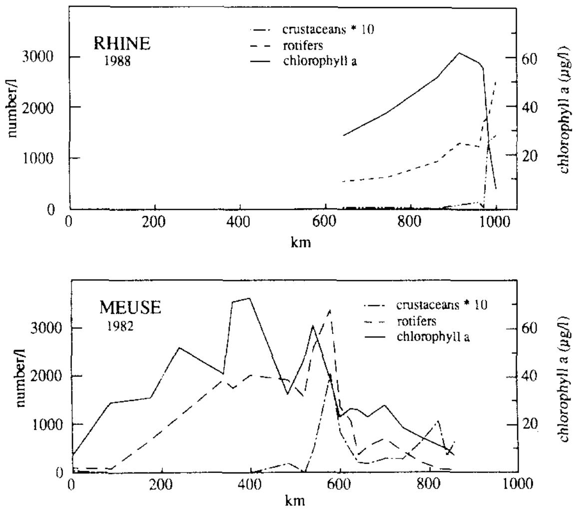

Fig. 10. Development of the plankton during transport of water in the R. Rhine (in May 1988) and Meuse (in Sept 1982). Density of phytoplankton measured as chlorophyll-*a*; density of zooplankton as numbers per l. Horizontal scale: km from the source. From De Ruyter van Steveninck *et al.* (1990b).

Urk, 1984a) or decrease in the sedimentation areas. However, trends in the dissolved silicate concentrations measured at various stations in the Rhine and Meuse indicate rapid growth of phytoplankton (certainly of diatoms) during transport in The Netherlands (Admiraal *et al.*, 1990b; De Ruyter van Steveninck *et al.*, 1990b).

The development of zooplankton (Fig. 11) follows that of the phytoplankton through the seasons. In addition to the true zooplankton, large numbers of the planktonic larvae of the zebra mussel *Dreissena polymorpha* (Pallas) have been found in the Rhine (De Ruyter van Steveninck *et al.*, 1990a; Borcherding & de Ruyter van Steveninck, 1992) and in the Meuse (RIWA, 1988).

Zooplankton develops in higher numbers and densities in standing waters than in the river.

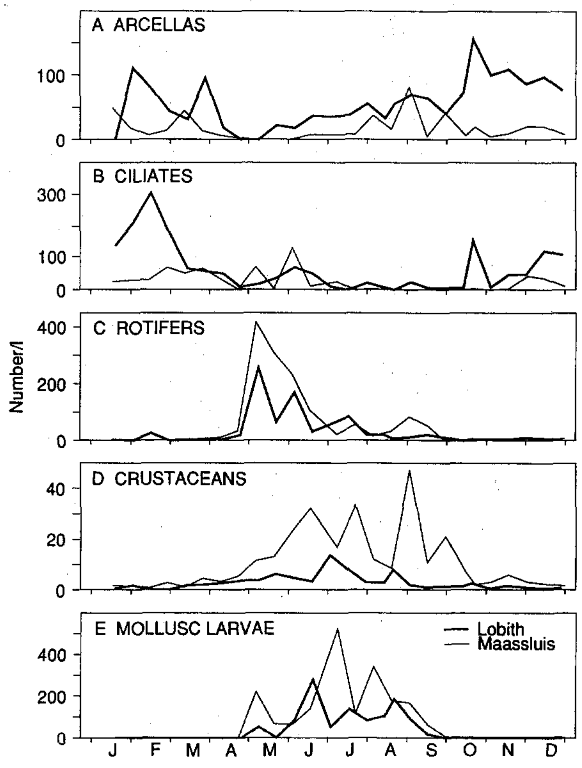

Fig. 11. Seasonal changes in zooplankton densities at two stations on the Dutch part of the R. Rhine. Data 1987. Station Lobith is at the German-Dutch border; Station Maassluis is downstream of Rotterdam (De Ruyter van Steveninck *et al.*, 1990a).

Wibaut-Isebree Moens (1965) found that gravel pits along the Meuse contain higher biomasses of zooplankton, mainly *Cyclops* sp., than the river. There are probably also typical differences between the phytoplankton of the river and the backwaters. Thus Leentvaar (1966) found *Ceratium hirundinella* (O.F. Müller) Schrank in the breakthrough ponds; this dinoflagellate dominates where there is a deep thermocline.

Vegetation

The vegetation along the rivers and in the backwaters has changed since 1950 (Maenen, 1989, Van den Brink *et al.*, 1991a). Most of the man-made banks of the Rhine and Meuse are now totally unsuitable for macrophytes (Leemans & Reiling, 1986; Leemans, 1989). The numbers of species of aquatic macrophytes and helophytes in the floodplain waters have declined dramatically, probably because summer floods are more common and the average water level is lower and hence the floodplain drier (Van Urk & Smit, 1989). Janse (1986) and Van den Brink *et al.* (1991a) classified the backwaters according to inundation frequency. Preliminary results (Fig. 12) indicate that the more frequent the flooding, the fewer the taxa in the vegetation (as well as in the macroinvertebrate fauna). This agrees with earlier findings by Van der Voo & Westhoff (1961), Van Donselaar (1961), Van de Steeg (1984), Brock *et al.* (1987), and Van der Sman *et al.* (1988). Species predominating in situations of infrequent inundation, such as *Stratiotes aloides* L., *Ranunculus lingua* L. and *Sparganium erectum* L. have declined.

The increased salinity of the river water has also contributed to the decline of formerly common species (cf. Table 1). Higher salinities together with the increased fluctuations in water-level and the increased turbulence of the water (shipping), may have contributed to the decline of the pondweed *Potamogeton nodosus* Poiret. This species was known from several localities in the River Waal, but has now disappeared. It is still present at some localities in the River Meuse,

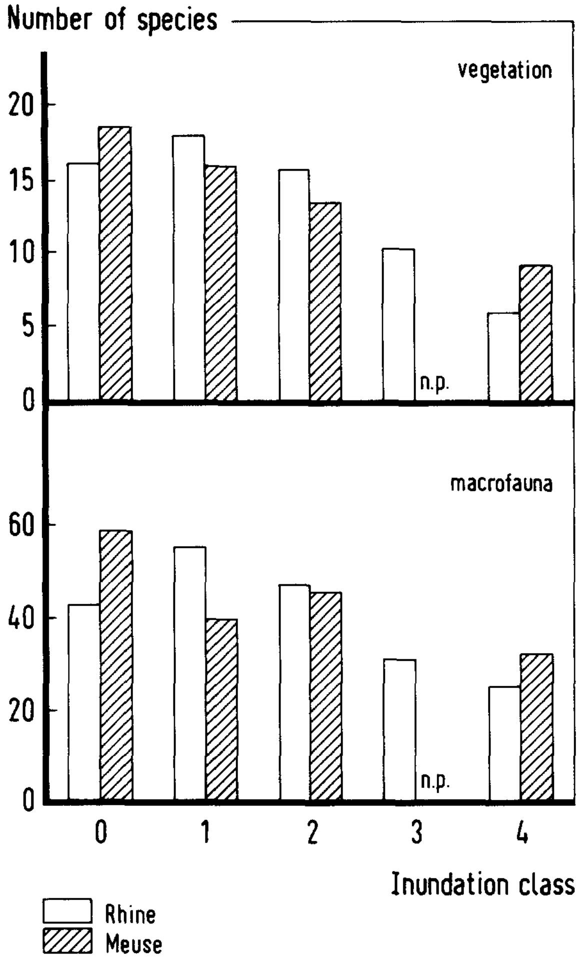

Fig. 12. Mean numbers of aquatic and helophyte plant species and macroinvertebrate species in riverine backwaters subjected to different regimes of inundation. Class 0: not inundated; class 1: <2 inundations per year; class 2: 2–20 inundations per year; class 3: 21–40 inundations per year; class 4: >40 inundations per year. n.p.: not present. Source: Van den Brink & van der Velde (1989).

near Kampen in the mouth of the River IJssel (Maenen, 1989) and in the Biesbosch (Smit & Coops, 1988). In contrast, *Potamogeton pectinatus* L., a species tolerant of high salinities, organic pollution and turbulence, has expanded in a number of areas in the Meuse and lower Rhine.

The distribution of nymphaeid and other macrophytes in abandoned meanders was studied 30 years ago by Van der Voo & Westhoff (1961); they frequently found species such as *Nuphar lutea* (L.) Sm. and *Nymphoides peltata* (Gmelin) O. Kuntze. The increased frequency of summer inundations has negatively affected the abundance of these plant species, and in particular that of *Nymphoides* (Brock *et al.*, 1987).

In the tidal part of the lower River Rhine there are vestiges of marsh vegetation on the banks of the River Oude Maas (Fig. 13; WOM, 1977); most of this vegetation disappeared from the delta after the Haringvliet was dammed in 1970. The richness of this vegetation is well known from the former intertidal marshes of the Biesbosch (Zonneveld, 1960; Van Urk,1984b). The rush species *Scirpus triqueter* L. still occurs in a few small localities along the R. Oude Maas. This species may be considered as an endangered component of the Rhine ecosystem. Bulrush (*Scirpus lacustris* L.) and sea clubrush (*Scirpus maritimus* L.) may grow higher up on the banks; the former in silty to sandy sites and the latter in exposed sandy sites (Coops & Smit, 1988). Two subspecies of the bulrush can be found, the freshwater bulrush (*S. l.* spp. *lacustris* L.) and the brackish water bulrush, *S. l.* spp. *tabernaemontani* (Gmelin) Syme. *S.* × *carinatus* Smith, a hybrid between *S. lacustris* and *S. triqueter*, occurs together with *S. lacustris*.

People have long exploited this vegetation zone, cultivating bulrush (*Scirpus lacustris*). In 1988 0.19 km^2 was still being cultivated by two growers, compared with about 2 km^2 in the sixties. In their stands *S. lacustris* spp. *lacustris, S. lacustris ssp tabernaemontani*, and *S.* × *carinatus* co-exist with *Callitriche stagnalis* Scop. and *Polygonum hydropiper* L. (Anonymous, 1977). The dried stems are used to weave chair seats and as a material to stopper whiskey vats. This extensive 'wetland farming' is a good example of a sustainable exploitation of the natural resources in the Rhine (Smit & Coops, 1991).

The characteristic mixed community of reed (*Phragmites australis* (Cav.)) Trin ex Steudel and *Caltha palustris* L. occurs higher up on the banks. This vegetation is limited to areas were the reed is commercially cut, which is still done in several areas, although the economic prospects are bleak. *Caltha palustris* is well adapted to the intertidal environment. In contrast to the normal form, the variety growing along the R. Oude Maas pro-

Table 1. Classification of macrophyte species according to their occurrence in gradients of salinity and inundation in the R. Rhine and Meuse. After Maenen (1989).

Highest fluctuation in water level in m.

Highest salinity in meq · l^{-1}	4.00 – 7.52	7.52 – 8.75	8.75 – 9.41
12.2 – 15.9	*Alisma plantago-aquatica* *Callitriche obtusangula* *Callitriche stagnalis* *Carex disticha* *Glyceria fluitans* *Juncus articulatus* *Potamogeton lucens* *Potamogeton nodosus* *Potamogeton perfoliatus* *Sium latifolia*	*Callitriche platycarpa* *Nymphoides peltata* *Typha angustifolia* *Typha latifolia*	*Eleocharis acicularis* *Scirpus maritimus*
15.9 – 17.9	*Carex acutiformis* *Nasturtium officinale* *Potamogeton trichoides* *Sagittaria sagittifolia* *Sparganium erectum* *Spirodela polyrhiza*	*Acorus calamus* *Alisma lanceolatum* *Caltha palustris* *Epilobium hirsu-stum* *Glyceria maxima* *Lysimachia vulgaris* *Myosotis laxa* *Nuphar lutea* *Phragmites australis* *Potamogeton crispus* *Potamogeton pusillus* *Rumex conglomeratus* *Rumex hydrolapathum* *Scirpus lacustris* *Scirpus sylvaticus* *Senecio paludosus* *Sparganium emersum* *Veronica anagallis-aquatica* *Veronica beccabunga*	*Butomus umbellatus* *Eleocharis palustris* *Galium palustre* *Iris pseudacorus* *Juncus bufonius* *Lycopus europaeus* *Mentha aquatica* *Thalictrum flavum*
17.9 – 19.2		*Ceratophyllum demersum* *Elodea nuttallii* *Myriophyllum spicatum* *Oenanthe aquatica* *Scutellaria galericulata* *Senecio congestus* *Zannichellia palustris*	*Carex acuta* *Lemna minor* *Lythrum salicaria* *Myosotis palustris* *Phalaris arundinacea* *Polygonum amphibium* *Potamogeton pectinatus* *Rorippa amphibia* *Veronica catenata*

duces additional roots at the internodes and is called *C. p.* var. *araneosa* van Steenis, because these extra roots resemble a spider. The rooted nodes promote vegetative reproduction. Many marsh plants can be found in places where the reed is not cut: *Angelica archangelica* L., *Leucojum*

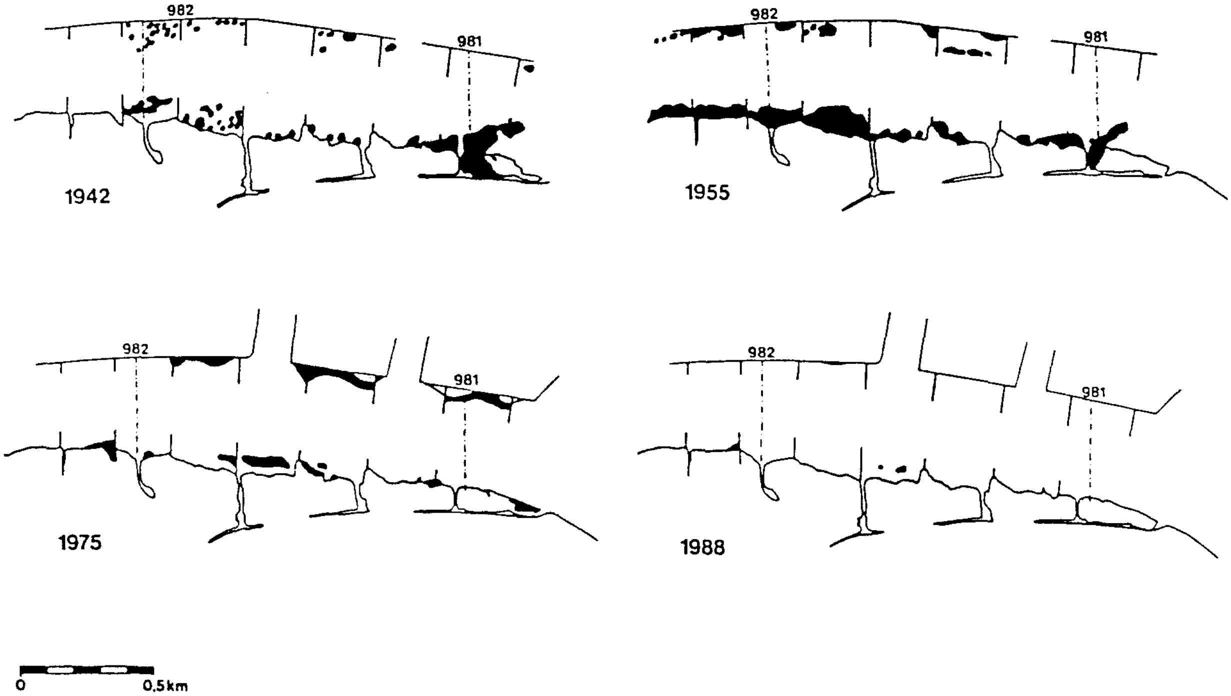

Fig. 13. Development of bulrush vegetation (black) on the banks of the R. Oude Maas (Rhine km 981–982) in the period 1942–1988. From Smit & Coops (1990).

aestivum L. and *Senecio fluviatilis* Wallr. are typical. A well developed willow zone is found higher up on the banks, with *Salix alba* L., *S. viminalis* L., *S. dasyclados* Wimmer and *S. fragilis* L. as the most important species. Willow shoots used to be a useful crop, but its importance has greatly declined because of the hard labour involved and low prices obtained for this material.

Macro-invertebrates

The large Dutch rivers have lost most of their characteristic macroinvertebrate species, although a relatively rich fauna was present until 1940 (Redeke, 1948). Figure 14 shows that even before 1940 the numbers of insect species in the Rhine had decreased strongly; this can be attributed to canalization, regulation, increased shipping and input of organic wastewater. Representatives of the Trichoptera, Ephemeroptera, and Plecoptera, which can be regarded as typical elements of the fauna in large European rivers, have almost completely disappeared from the Rhine and Meuse (Smit, 1985; Van den Brink *et al.*, 1989). Burrowing filter-feeding animals like the mayfly larva *Palingenia longicauda* (Ol.) have vanished (Van Urk & Smit, 1989). Many rheophilous species of insects have disappeared because suitable sites for larval development and oviposition have become scarce. The river pearl mussel *Margaritifera auricularia* (Spengler), a species of deep sandy rivers, used to live in the Rhine and Meuse until about a century ago, but it too has become extinct (Kuijper, 1988).

Discharge of industrial waste and organic pollution have caused low oxygen concentrations and high levels of toxic substances (Figs 6 and 7). Thick layers of contaminated silt have been deposited on the river bed in the lower reaches of the Rhine and Meuse, leading to a further decline of characteristic zoobenthos species. At present most rheophilous species occur on the stones of the groynes. The effects of contaminants on the

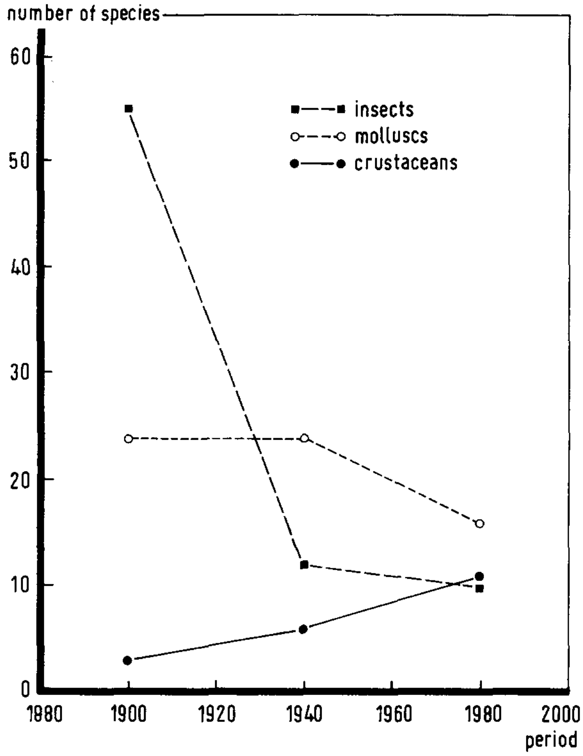

Fig. 14. Changes in the numbers of macroinvertebrate species in the Dutch section of the R. Rhine in the course of this century. Number of insect species excluding chironomids. Based on Van den Brink *et al.* (1990).

invertebrate communities in the sedimentation areas have recently been demonstrated. Van Urk & bij de Vaate (1990) investigated chironomids in a pollution gradient from the polluted Ketelmeer to an adjacent less polluted area. Mean densities and individual weight increased and the incidence of malformations in the larvae decreased along this gradient. A distinct increase in head capsule malformations of chironomid larvae has occurred during this century (Klink, 1986a). Heavy metals and pesticides are considered to be responsible for the severe head capsule malformations, especially in the sedimentation areas (Van Urk & Kerkum, 1986, 1987).

Van Urk & Smit (1989) found very low densities of macrofauna in the sediments of the river Waal and Van Urk *et al.* (1990) found very low densities of chironomids in the R. IJssel. From the presence of exuviae of chironomids, Wilson & Wilson (1985a) concluded that the lower Rhine and the Waal have low proportions of sediment-dwellers, suggesting that the sediments are unable to support a normal chironomid fauna. Accordingly, Klink (1986a) found appreciable numbers of Simuliidae deposited in sediments of the river Rhine dating from the 18th century (numbers of Simuliidae amounting to 0.3 of those of the Chironomidae), whereas at present Simuliidae are virtually absent in the Rhine.

The bed of the River Meuse harbours more macro-invertebrate species than the beds of the Rhine branches. In the Meuse, especially in the section called the Grensmaas, there are more characteristic riverine species than in the Rhine because shipping is less intensive and the morphology is less disturbed (i.e. more of the natural habitats have been preserved: Klink & Moller Pillot, 1982; Smit, 1982; Peeters, 1988). Smit & Gardeniers (1986) found 17 species of macro-invertebrates on the deep bed of the River Meuse, of which 7 were restricted to this habitat.

Although the fauna inhabiting the sandy bottom of the rivers Rhine and Meuse is very poor, new species are occasionally discovered. The chironomid *Lipiniella arenicola* Shilova established itself on sandy flats after the Haringvliet was dammed (Smit *et al.*, 1991), and *Paratendipes intermedius* Mg. was discovered in sandy river sediment of the Rhine in 1989 (H.P.J.J. Cuppen, pers. comm.). Two new fluviatile immigrant mussel species living on sandy and sandy-clayey sediments (*Corbicula* spec.) have recently been discovered in the R. Lek, the Hollands Diep (Bij de Vaate & Greijdanus-Klaas, 1990), and in the R. Waal and Rhine near the German/Dutch border (Bij de Vaate, 1991). A clear indication of the improvement of the circumstances for the sand inhabiting fauna is the recolonization by the mayfly *Ephoron virgo* (Olivier) after almost 50 years of absence. Settlement started in the German part of the R.Rhine and in 1991 it reached the Netherlands section of the river (Van den Brink *et al.*, 1991c).

Although the fauna typical of detrital and clayey deposits has suffered less from pollution than that of sandy sediments, it too has declined. Large mussels (*Anodonta* and *Unio*) were important in this community. In the seventies no large mussels were observed in the river Rhine (Peeters & Wolff, 1973), but since then oxygen conditions have improved and they have been found again. At the very low water levels in 1989 six-year-old specimens of *Anodonta anatina* (L.) and *Unio pictorum* (L.) were found to be abundant in the R. Waal near Nijmegen, and there were smaller numbers of *U. tumidus* (Philipsson). In 1990 the fluviatile species *Pseudanodonta complanata* (Rosm.) has been found in the R. IJssel and the R. Merwede (J.N. de Vries, F.W.B. van den Brink, pers. comm.).

Numerous chironomid species nowadays inhabit the stony substrates in the Rhine (Moller-Pillot & Krebs, 1981; Klink 1982, 1983; Wilson & Wilson, 1985a, b). The caddis flies *Hydropsyche contubernalis* McLachlan and *Ecnomus tenellus* (Ramb.) returned in 1978 and 1980 respectively, after an absence of many years (Fig. 15, Van Urk *et al.*, 1990). The stony embankments of the rivers are also very suitable for some immigrant species such as the zebra mussel *Dreissena polymorpha* from the Ponto-Caspian area, the snail *Potamopyrgus antipodarum* (Gray) from New Zealand, *Physella acuta* (Drap.) from Southern Europe and North Africa, and the North American planarian *Dugesia tigrina* (Girard). These species coexist

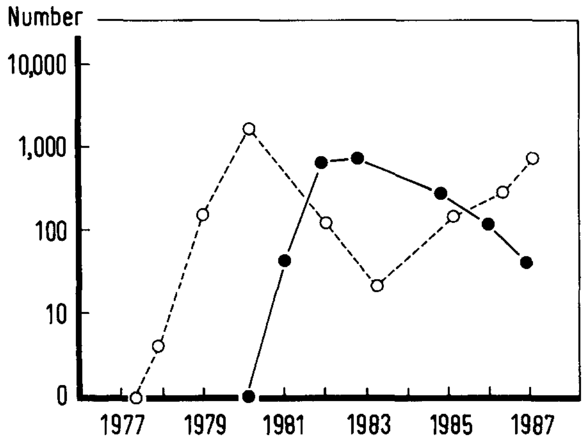

Fig. 15. Recolonization of the R. IJssel by caddis flies. Numbers of larvae of *Hydropsyche contubernalis* (open symbols) and *Ecnomus tenellus* (closed symbols) on 40 stones collected from groynes in the period 1977–1987. Source: Van Urk *et al.* (1990) (quoted in De Wit *et al.*, 1989).

with ubiquitous species like the snails *Radix peregra f. ovata* (O.F. Müller) and *Bithynia tentaculata* (L.) and the river limpet *Ancylus fluviatilis* (O.F. Müller). In 1987 Van den Brink *et al.* (1989) found an immigrant amphipod species, *Corophium curvispinum* Sars, from the Ponto-Caspian area. This species appeared to be very successful and nowadays very high densities of more than 100,000 specimens per m^2 of stone surface occur. Its success is due to a combination of factors, viz. the increased salinity, higher temperatures and the increased food supply. *C. curvispinum* is a filter feeder stimulated by the dense phytoplankton development, caused by eutrophication. The muddy tubes build by this animal species covers the entire surface of solid substrates, thereby diminishing the populations of other animal species occupying this habitat (Van den Brink *et al.*, 1991b, c). *Corophium curvispinum* is still expanding its area in the Netherlands and in 1991 it has already been found in the IJsselmeer, Markermeer and a number of canals (S. Pinkster, pers. comm.).

Klink (1989) indicated that the rise in water temperature due to discharge of cooling water benefits some chironomid species, *e.g. Rheocricotopus chalybeatus* (Edw.), *Nanocladius rectinervis* (K.) and the *Rheotanytarsus* species, all of which are now very abundant. These higher temperatures are also favourable for other invertebrate species, such as the shrimps *Atyaephyra desmaresti* (Millet) and *Palaemon longirostris* H. Milne Edwards (Van den Brink & Van der Velde, 1986a, b), the planarians *Dugesia polychroa* (Schmidt) and *D. tigrina*, the snails *Physella acuta* and *Ferrissia wautieri* (Mirolli), etc. Further research on the distribution of these thermophilous species is necessary in order to predict future changes that might result from a climate-induced temperature rise.

Salt concentrations in Rhine water often exceed 200 mg l^{-1} (Fig. 9) and this explains why mobile macro-invertebrate species formerly restricted to the brackish or tidal parts of the river have been observed as far upstream as the German-Dutch border. When the filtering screens of the cooling-water intakes of some power plants along the rivers were sampled recently it was found that the mudcrab *Rhithropanopeus harrisi* (Gould), an early immigrant from North-America, as well as the white prawn (*Palaemon longirostris*) and the brackish water amphipod *Gammarus zaddachi* Sexton had all extended their range eastwards (Den Hartog *et al.*, 1989). However, another brackish water amphipod *Gammarus tigrinus* Sexton, originating from North America, is able to breed in the river and has caused the numbers of the freshwater amphipod *Gammarus pulex* (L.) to decline. Van den Brink & van der Velde (1986a) and Van der Velde *et al.* (1990) proved that the typical migrating brackish water crustacean species showed a pattern of occurrence similar to that of *G. zaddachi*, with low numbers in summer and high numbers in spring and autumn, whereas river-dwelling species like the North-American crayfish *Orconectes limosus* (Rafinesque), the amphipod *Gammarus pulex*, the isopod *Asellus aquaticus* (L.) and the freshwater shrimp *Atyaephyra desmaresti* showed peaks in numbers in summer as a result of reproduction (see also Van den Brink *et al.*, 1988). Van den Brink & van der Velde and their colleagues did not find the estuarine species as small juveniles or as adults carrying eggs. Furthermore, these species showed very skewed sex ratios in the freshwater section of the river, in contrast to the river-dwelling species.

Both *Palaemon longirostris* and *Atyaephyra desmaresti* have an Atlantic-Mediterranean distribution and are at the northern limit of their range in the Netherlands. The annual records on both species show a negative correlation with the number of frosty days; mild winters favour these species (Van den Brink & van der Velde, 1986a, b).

Fish

Fish populations in the rivers Rhine and Meuse have changed dramatically during the last century. Table 2 shows that about ten indigenous species of fish have become extinct or very rare. Characteristic migrating species such as sturgeon (*Acipenser sturio* L.), houting (*Coregonus oxyrinchus* (L.)), and salmon (*Salmo salar* L.) have died out, and populations of allis shad (*Alosa alosa* (L.)), twaite shad (*Alosa fallax* (Lac.)), sea lamprey (*Petromyzon marinus* L.), and river lamprey (*Lampetra fluviatilis* (L.)) have declined drastically. Other characteristic species, like barbel (*Barbus barbus* (L.)), dace (*Leuciscus leuciscus* (L.)), minnow (*Phoxinus phoxinus* (L.)), and burbot (*Lota lota* (L.)) have also suffered seriously.

For centuries the anadromous species that were caught during their spawning run were fished in the Rhine and Meuse. The highly flourishing fisheries for sturgeon, salmon, sea trout, allis shad, twaite shad and houting largely disappeared in the first half of this century, as has been described by numerous authors (Boddeke, 1974; Bürger, 1926; Cazemier, 1988, Deelder & van Drimmelen, 1959; Denzer, 1966; Van Drimmelen, 1981 and 1987; De Groot 1988, 1989a, b, c, d, 1990a, b; Hoek, 1916; De Jong *et al.*, 1988; Kuhn, 1976; Leentvaar, 1963; Lobregt & van Os, 1977; Lelek & Köhler, 1989; Van Lonkhuyzen & Vonk, 1920; Philippart, 1985, 1988a, b; Redeke, 1941; Van Ruremonde, 1988; Verhey, 1961; Wolff, 1978). In Fig. 16 catches of sturgeon, allis shad, salmon and twaite shad are plotted to demonstrate the decline of the stocks. Despite rescue operations

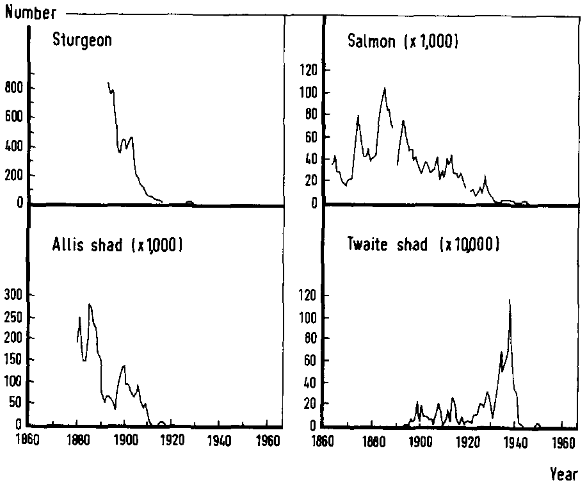

Fig. 16. Landings of four anadromous fish species in the Netherlands in the period 1880–1950. For scientific names see Table 2. Source: fisheries statistics summarized by W.G. Cazemier.

Table 2. Occurrence of fish species in the R. Rhine and R. Meuse in the period 1987–1988. Data for The Netherlands from Cazemier & Heermans (1988); data for Germany from Berg *et al.* (1989), Borchard *et al.* (1986), Hessisches Ministerium (1987), and Lelek (1989); data on the Belgian part of the Meuse according to Philippart *et al.* (1988 a, b)

		A	B	C	D	E	F	G	H	I	J
Petromyzon marinus L.	Sea lamprey	+	+	–	3	3	+	2	–	+	
Lampetra fluviatilis (L.)	River lamprey	+	+	–	4	4	+	2	–	+	
Lampetra planeri (Bloch)	Brook lamprey	+	–	–	1	1	+	1	–	–	
Acipenser sturio L.	Sturgeon	+	+	–	0	0	–	0	–	–	
Anguilla anguilla (L.)	Eel	+	–	+	5	5	+	5	+	+	
Alosa alosa (L.)	Allis shad	+	+	–	2	1	+	1	–	–	
Alosa fallax (Lac.)	Twaite shad	+	+	–	3	2	+	1	–	+	
Salmo salar L.	Atlantic salmon	+	+	–	2	2	?	0	–	–	
Oncorhynchus mykiss (Walbaum)	Rainbouw trout	–	–	–	2	2	+	1	+	–	
Salmo trutta trutta L.	Sea trout	+	+	–	4	4	+	4	+	+	
Salmo trutta trutta morpha fario L.	Brown trout	+	–	–	1	1	+	3	+	–	
Oncorhynchus kisutch (Walbaum)	Coho salmon	–	+	–	2	1	+	1	–	–	a
Salvelinus fontinalis (Mitchill)	American brook trout	–	–	–	1	1	+	2	+	–	
Coregonus albula (L.)	Vendace	+	–	–	0	0	–	0	–	–	
Coregonus lavaretus (L.)	Powan	+	–	–	3	3	+	3	–	–	
Coregonus oxyrinchus (L.)	Houting	+	+	–	0	0	–	–	–	–	
Thymallus thymallus (L.)	Grayling	+	–	–	1	1	+	2	+	–	
Osmerus eperlanus (L.)	Smelt	+	+	–	3	5	+	4	–	+	b
Esox lucius L.	Pike	+	–	–	4	4	+	4	+	–	
Umbra pygmaea (De Kay)	Mud minnow	–	–	–	1	1	–	3	+	–	
Cyprinus carpio (L.)	Carp	–	–	–	4	4	+	4	+	–	
Abramis brama (L.)	Bream	+	–	–	5	5	+	5	+	–	
Abramis bjoerkna (L.)	White Bream	+	–	–	5	4	+	5	+	–	
Alburnoides bipunctatus (Bl.)	Stream bleak (Spirlin)	+	–	–	0	0	+	0	+	–	
Alburnus alburnus (L.)	Bleak	+	–	–	5	5	+	5	+	–	
Aspius aspius (L.)	Asp	–	–	–	1	1	+	2	–	–	
Barbus barbus (L.)	Barbel	+	–	–	3	1	+	3	+	–	
Carassius carassius (L.)	Crucian carp	+	–	–	3	2	+	3	+	–	
Carassius auratus (L.)	Goldfish	–	–	–	1	1	+	1	+	–	
Carassius auratus gibelio (Bloch)	Gibel carp	–	–	–	3	2	+	4	+	–	
Chondrostoma nasus (L.)	Hotu or nase	+	–	–	2	1	+	1	+	–	
Ctenopharyngodon idella (Val.)	Grass carp	–	–	–	2	2	+	2	–	–	
Gobio gobio (L.)	Gudgeon	+	–	–	4	3	+	4	+	–	
Hypophtalmichthys molitrix (Val.)	Silver carp	–	–	–	1	1	+	2	–	–	
Hypophtalmichthys nobilis (Richardson)	Big head	–	–	–	2	2	–	2	–	–	
Leucaspius delineatus (Heckel)	Rain bleak	+	–	–	1	1	+	1	+	–	
Leuciscus leuciscus (L.)	Dace	+	–	–	3	2	+	4	+	–	
Leuciscus idus (L.)	Ide	+	–	–	4	4	+	4	+	–	
Leuciscus cephalus (L.)	Chub	+	–	–	2	1	+	4	+	–	
Phoxinus phoxinus (L.)	Minnow	+	–	–	1	1	+	1	+	–	
Rhodeus sericeus amarus (Bloch)	Bitterling	+	–	–	1	2	+	2	+	–	
Rutilus rutilus (L.)	Roach	+	–	–	5	5	+	5	+	–	
Rutilus erythrophthalmus (L.)	Rudd	+	–	–	4	4	+	4	+	–	

Table 2. (Continued)

		A	B	C	D	E	F	G	H	I	J
Tinca tinca (L.)	Tench	+	–	–	4	3	+	4	+	–	
Vimba vimba (L.)	Vimba	–	–	–	2	1	+	1	–	–	c
Cobitis taenia L.	Spiny loach	+	–	–	3	2	+	3	–	–	
Misgurnus fossilis (L.)	Weather loach	+	–	–	3	3	+	1	+	–	
Noemacheilus barbatulus (L.)	Stone loach	+	–	–	3	1	+	3	+	–	
Silurus glanis L.	Sheatfish	+	–	–	2	2	+	2	+	–	
Ictalurus melas (Raf.)	Black bullhead	–	–	–	1	1	+	2	+	–	
Ictalurus nebulosus (Le S.)	Brown bullhead	–	–	–	2	1	+	2	+	–	
Lota lota (L.)	Burbot	+	–	–	3	1	+	2	+	–	
Gasterosteus aculeatus L.	Three-spined stickleback	+	+	–	4	4	+	4	+	+	
Pungitius pungitius (L.)	Ten-spined stickleback	+	–	–	2	1	+	2	–	–	
Lebistes reticulatus (Peters)	Guppy	–	–	–	1	1	–	1	–	–	
Lepomis gibbosus (L.)	Pumpkinseed	–	–	–	1	2	+	1	+	–	
Perca fluviatilis L.	Perch	+	–	–	5	5	+	5	+	–	
Gymnocephalus cernuus (L.)	Ruffe	+	–	–	5	5	+	5	+	–	
Stizostedion lucioperca (L.)	Pikeperch	–	–	–	5	5	+	5	+	–	
Cottus gobio L.	Bullhead	+	–	–	4	4	+	4	+	–	
Platichthys flesus (L.)	Flounder	+	–	+	4	5	+	4	+	+	

A: Indigenous in The Netherlands
B: Anadromous
C: Catadromous
D: Present frequency in the lower Rhine in The Netherlands (0: extinct: 1: no recent records; 2: occasionally; 3: fairly rare; 4: (locally) common; 5: abundant).
E: Present frequency of occurrence in the IJselmeer and Ketelmeer (classes as under D).
F: Presence in the German part of the river Rhine. –: no records; +: presence established; ?: identification dubious.
G: Presence in the Dutch part of the Meuse classes as under D.
H: Presence in the Belgian part of the Meuse.
I: Presence in Dutch coastal waters.
J: a: record from the tidal zone only; b: mainly as land-locked populations; c: first and only specimen, captured in the R. Nederrijn in 1989 (Cazemier & Heesen, 1989).

by means of fishery regulations and mass releases of hatchery-reared salmon, houting and allis shad, the decline of the migratory fish stocks has continued (De Groot, 1985). The fisheries exploiting the anadromous fish species smelt (*Osmerus eperlanus* (L.)) and twaite shad in the Haringvliet were brought to an end by the closure of the Haringvliet in 1970 (Steinmetz, 1975; Wiegerinck & Heesen, 1987).

In the 19th century the fisheries for eel (*Anguilla anguilla* (L.)), pike (*Esox lucius* L.), barbel (*Barbus barbus* (L.)), chub (*Leuciscus cephalus* (L.)), bream (*Abramis brama* (L.)), roach (*Rutilus rutilus* (L.)), and perch (*Perca fluviatilis* (L.)) were of minor importance in the Dutch rivers. But after the anadromous species had disappeared, the fishermen who remained in the trade concentrated on eel and resident fish, of which pikeperch (*Stizostedion lucioperca* (L.)) became more and more important (De Boer & te Brinke, 1984; Lobregt & van Os, 1977). These fisheries however, have also declined: Table 3 shows the decreasing number of eel fisheries in the Dutch part of the Rhine.

The collapse of fish stocks and fisheries was most probably caused by the reconstruction of the river system plus the deterioration of the water quality. There is ample evidence that river engineering works have had deleterious effects on the

Table 3. Numbers of eel fisheries in the Dutch branches of the R. Rhine. After Cazemier (1988).

Year	Number	Reference
1913	193	Lobregt & van Os, 1977
1949	100	Deelder & van Drimmelen, 1959
1952	76	Lobregt & van Os, 1977
1957	35	Leentvaar, 1963
1957	26	Deelder & van Drimmelen, 1959
1963	16	Leentvaar, 1963

species numbers and abundance (Hoek, 1916; Alabaster, 1985; Klein, 1989; Lelek, 1989; Lelek & Köhler, 1989). The construction of fish passes in combination with almost every weir in the main stream seems to have been insufficient to prevent the decline of migrating fish populations. The water works in general led to the disappearance of specific spawning grounds, feeding biotopes and nursery areas and to the obstruction of migration routes.

The low oxygen concentration in the rivers and the massive discharge of toxic materials in the period of 1960 to 1970 were the most likely causes of the nadir in the number of fish species (Van den Brink *et al.*, 1990; Van der Velde *et al.*, 1990). Slooff (1983) and Slooff *et al.* (1985) demonstrated the abundance of deformations in bream in the Rhine.

Since the water quality of the Rhine began to improve in the mid-seventies, the fish community has been recovering (Willemsen, 1983; Cazemier, 1984; Cazemier, 1988; Lelek, 1989). The present oxygen content of the Rhine water even at low river discharge is suitable for salmonids. The severe pollution of the R. Meuse in the sixties is also decreasing (Philippart *et al.*, 1988a). Despite the continuing problems with *e.g.* high levels of polychlorinated biphenyls (PCB) and mercury in fish (Van der Valk *et al.*, 1989), water quality as a whole has substantially improved and as a consequence the concentrations of several pollutants in fish have fallen (Fig. 17). Some of the characteristic fish species are showing signs of recovery (Hadderingh *et al.*, 1983; Cazemier, 1984; Cazemier & Heermans, 1988; Cazemier, 1989; Heesen, 1989; P.J.M. Bergers, pers. comm., 1989).

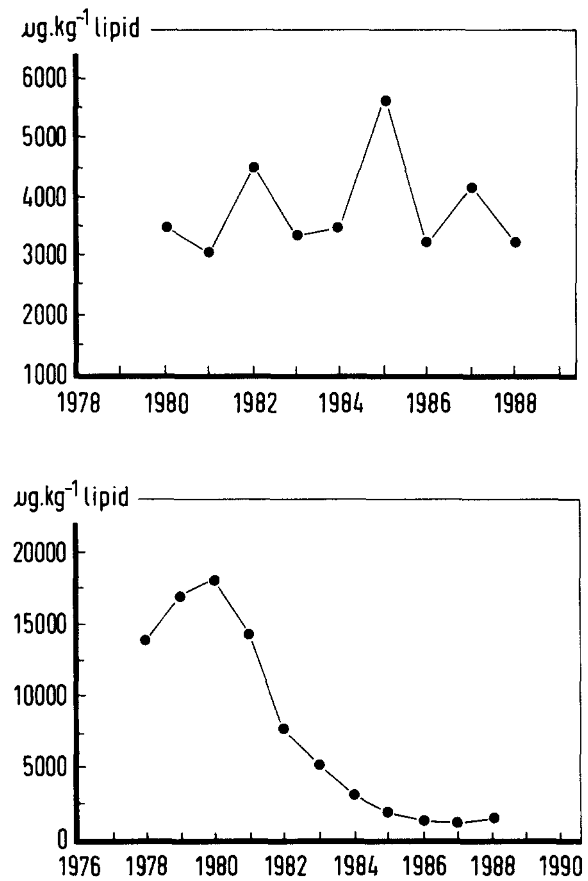

Fig. 17. Development of the concentrations of PCB-153 (upper plot) and HCB (lower plot) in the fat of yellow eel (*Anguilla anguilla*) in the period 1978–1988. Source: Van der Valk *et al.* (1989).

During the sixties and early seventies a number of species, such as river lamprey, sea trout (*Salmo trutta trutta* L.), whitefish (*C. lavaretus* L.), bleak (*Alburnus alburnus* (L.)), barbel, ide (*Leuciscus idus* (L.)), burbot, bullhead (*C. gobio* L.), and flounder (*Platichthys flesus* (L.)) were extremely scarce in the rivers. Now these species are caught regularly at different sites, some in appreciable numbers (Table 4).

In Table 2 a few indigenous species are qualified as 'extinct', 'no recent records', or 'occasionally occurring' in the rivers Rhine and Meuse. The prospects of re-establishing these species in the Dutch parts of the rivers Rhine and Meuse were recently discussed by De Groot (1989a, b, c, d). A natural comeback of sturgeon seems very un-

Table 4. Numbers of some characteristic fish species caught by eight professional fishermen during 1987 and 1988 in different river reaches. Common commercial fish species were not recorded. Numbers have indicative value only, because of different fishing techniques and fishing effort. After Cazemier & Heermans (1988) and Heesen (1989).

Species	River reaches			
	Rijn, IJssel, Nederrijn	Ketelmeer	Maas, Amer	Hollands Diep
Petromyzon marinus	12	5	1	25
Lampetra fluviatilis	15	140	20	50
Salmo trutta trutta	300	650	50	120
Coregonus lavaretus	20	190	50	0
Osmerus eperlanus	0	> 23,000	> 3,900	70
Alburnus alburnus	2,600	> 7,500	> 10,000	> 1,700
Barbus barbus	100	0	15	0
Gobio gobio	4,000	10	500	0
Leuciscus leuciscus	0	1	250	0
Leuciscus idus	500	1,300	2,800	2
Leuciscus cephalus	7	0	700	4
Siluris glanis	15	10	4	0
Lota lota	600	20	1	0
Cottus gobio	6,000	0	500	20
Platichthys flesus	130	5,500	280	17,000

likely even if the water quality improves. There is no evidence that spawning and nursery grounds are available in the lower Rhine or Meuse. Furthermore, the nearest population of sturgeon is a very small one in the R. Garonne (France). A spontaneous revival of a natural population of shad and salmon also seems unlikely, for more or less the same reasons as those mentioned for sturgeon. Even improvement of the water quality and the opening up of the spawning areas for the salmon in the tributaries, the rivers would have to be re-stocked with eggs, parr or smolts. De Groot (1989a, 1990a) has discussed the problems associated with such a reintroduction. The return of the salmon in the Rhine is one of the objectives of the 'Rhine Action Programme'. Therefore, much of the fishery research focuses on this fish. In the Belgian state of Wallonia a programme called Saumon 2000 has also been started for the reintroduction of the salmon in the Meuse drainage basin (Philippart *et al.*, 1988b). The rearing of smolts of salmon and the closely related sea trout started some years ago in Nordrhein-Westfalen (Germany) and in Wallonia, and small numbers have already been introduced into tributaries. Three marked smolts of salmon and eight marked sea trout smolts, stocked in the R. Sieg, have already been captured in Dutch parts of the Rhine. Since the mid-seventies juvenile and adult sea trout have been observed in increasing numbers in the Dutch parts of the Rhine and Meuse, and since 1984 adults of this species have appeared every year in the lower reaches of some Rhine tributaries: the R. Dhünn (Borchard *et al.*, 1986), the R. Sieg (Steinberg, pers. comm.) and the R. Lahn (Brenner, pers. comm.; Klein, 1989). Adult sea trout is also regularly caught in the Belgian part of the Meuse (Philippart, 1985). These phenomena indicate that the water quality of the main rivers may no longer be an obstacle to the migration of juvenile and adult anadromous salmonids. However, Van Brummelen (1989) indicated that the current concentrations of some pollutants in the Rhine may still interfere with the homing behaviour of salmon. Nevertheless in the period 1957–1991 ten adult salmon have been reported from Dutch inland waters and one from the German part of the R. Rhine. Three of these were tagged in Scandinavia; the origin of the other ones is not known. The frequency of the salmon catches tends to increase: seven individuals were caught in 1990 and 1991 together.

Food chains

The trophic relations between organisms are generally decisive factors determining the structure of plant and animal communities. Regrettably, the food chains of the Dutch rivers have only marginally been investigated. The available information on plant/herbivore interaction (Gregory, 1983) and on predator/prey relations in streams (Allan, 1983) mostly pertains to streams smaller than the lower reaches of the Rhine and Meuse. These review papers prompted us to consider the basic structure of the food chains in the large rivers in The Netherlands. Allochthonous material (detritus) is introduced into the lower Rhine and Meuse by the transport of particulates in river water and hardly by direct terrestrial input. Autochthonous production of benthic macrophytes and microphytes, directly exploited by stream herbivores, is restricted to shallow waters near the banks and to floodplain waters with abundant macrophyte growth. As in the smaller streams referred to by Allan (1983), grazing on microphytes, i.e. diatoms or filamentous green algae, is probably essential for the local fauna. A well-developed microphytobenthos is present in the floodplain waters (van der Velde, pers. obs.), in the shallow parts of the Haringvliet (Bijkerk, pers. comm.; De Jong *et al.*, 1989) and on hard substrates on the river banks (Admiraal, pers. obs.). Chironomid communities in shallow parts of the Haringvliet probably feed mainly on benthic microalgae that are stimulated by the light penetrating deeply into the relatively clear water. Well-developed and productive microalgal mats of diatoms, or occasionally desmids, have been found on the shallows of the 'Ventjagersplaat' (Bijkerk, pers. comm.; De Jong *et al.*, 1989). Locally, dense populations of herbivorous nematodes have been found (Bongers & van de Haar, 1990). Despite the local importance of benthic algal production in the Rhine and Meuse, planktonic production at present plays a dominant role. A typical difference between the food chains of small streams (cf. Allan, 1983) and those of the Rhine/Meuse is the occurrence of a dense and productive plankton.

In the early seventies Wolff (1978) observed an incomplete exploitation of the phytoplankton and detritus input by the sparse zooplankton and filter-feeding invertebrates. In that period the deposit-feeding oligochaetes (*e.g. Tubifex tubifex* (Müller)) were the only benthic animals of quantitative importance. This food source was most probably exploited by several fish species (*e.g.* roach, *Rutilus rutilus* (L.)) and diving ducks (Wolff, 1978). Recent research has cast light on other aspects of the food chains. This is discussed below.

Carbon budget

The quantitative basis of the food chains in the main channel has been analysed via a tentative carbon budget of the lower Rhine (Fig. 18; Admiraal & van Zanten, 1988). The *in situ* productivity of phytoplankton and the mineralization rate in water and sediment are high compared to the import of detrital particles (POC). In other words: the turnover of organic material is high (Admiraal & van Zanten, 1988). A significant part of the import and production of organic carbon is deposited in the sedimentation areas (Van Eck, 1982; Admiraal & van Zanten, 1988), where it offers an ample food source to benthic fauna. However, the conditions in the deposits, *e.g.* the superficial oxygen penetration and the liberation of high concentrations of ammonium ions in the sediment (de Jong *et al.*, 1989) may be a selection factor for the nematode fauna (Bongers & van de Haar, 1990). The density of the macro-invertebrates does not reflect the very high input rate of organic material (cf. Fortuin, 1985). Admiraal & Botermans (1989) suggested that the coarse river sediments with their effective water exchange offer favourable conditions for nitrification, which is responsible for the oxidation of the large quantities of ammonium ions discharged by the Rhine.

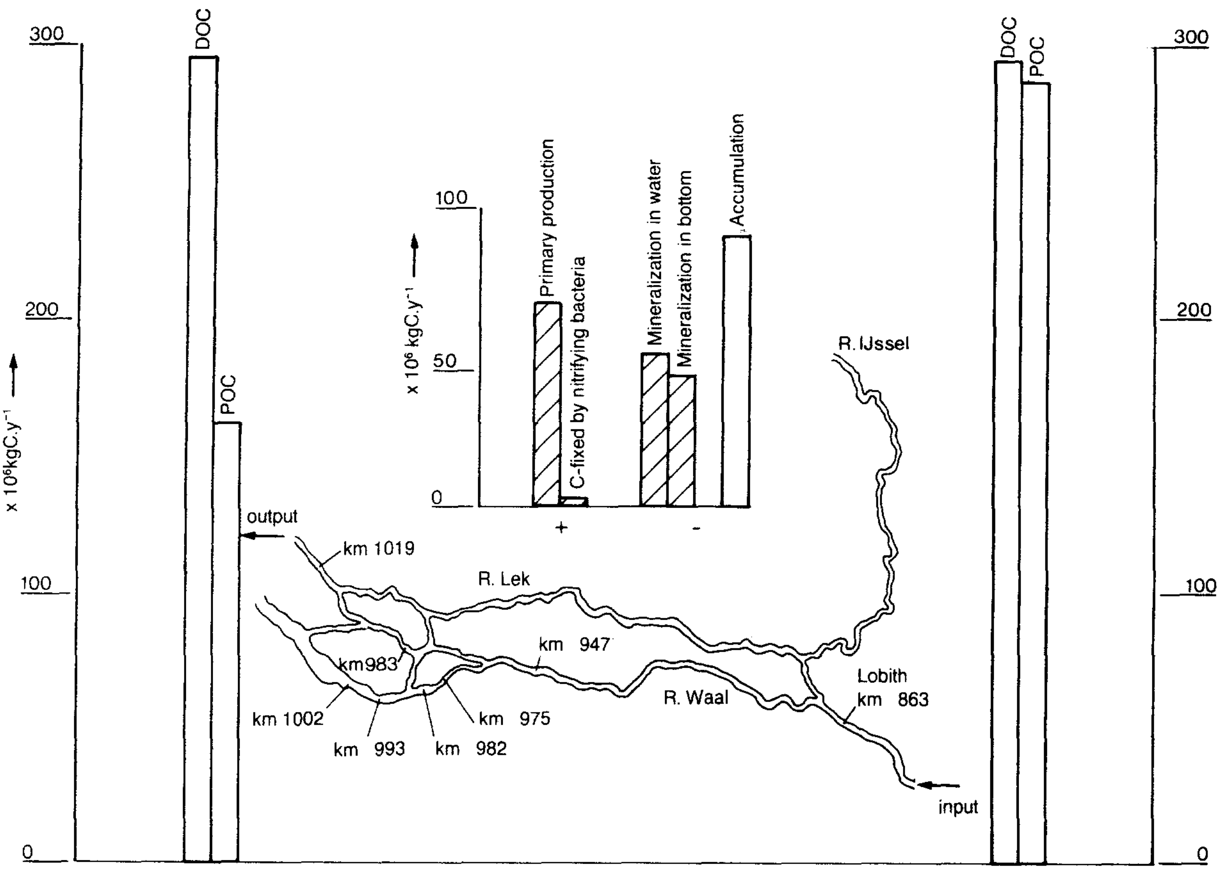

Fig. 18. Summary of input, output, production, mineralization and accumulation of organic carbon in the Dutch section of the lower R. Rhine. POC: particulate organic carbon. DOC: dissolved organic carbon. Source: Admiraal *et al.* (1990).

However, the quantity of organic carbon fixed by nitrifying bacteria is small.

Planktonic food chain

Since the Rhine and Meuse delta forms an important sedimentation basin, we expect that at least part of the phytoplankton losses are caused by settling algae. However, another part of the phytoplankton losses may be attributed to grazing. The depression in numbers of phytoplankton, arcellas, and ciliates in the R. Rhine during the summer is probably caused by the activities of rotifers, crustaceans, and possibly mollusc veliger larvae (De Ruyter van Steveninck *et al.*, 1990a). This is in agreement with the observation that the seasonal increase in zooplankton biomass follows the spring peak in phytoplankton biomass in the German R. Ruhr (a tributary of the Rhine; cf. Nusch, 1978). No quantitative analysis like that established for stagnant waters (cf. de Haan *et al.*, 1993) has been done for the food relations in the river plankton. Yet phytoplankton density is an important variable explaining the nitrogen, carbon, and phosphorus content of suspended matter in the Rhine (Van Eck, 1982; Admiraal *et al.*, 1991). Therefore it seems likely that the prevailing phytoplankton concentrations offer a rich food source for filter-feeding organisms. Smit (unpublished) made preliminary calculations of the production of phytoplankton in the Hollands Diep/Haringvliet and its consumption by the main herbivores, the zooplankton and the abundant zebra mussel (*Dreissena polymorpha* (Pallas)), and indicated that grazing by planktonic and benthic filter feeders matched the strong decreases in phytoplankton density in the river water during its transport in that area. The amphipod *Corophium curvispinum* is nowadays an important filter feeder in the R. Rhine and is likely a significant consumer of phytoplankton (Van den Brink *et al.*, 1991b).

Food of the macrofauna and fish

The food for the macro-invertebrates can be classified into different categories. Cummins (1973) distinguished four functional types among the benthic macrofauna: shredders (chewers and miners), collectors (filter or suspension feeders and sediment or deposit feeders), scrapers (feeding on mineral or organic surfaces), and predators (swallowers and piercers). The diagram in Fig. 19 (after Barnes and Mann, 1980), shows the relationships between these categories, adapted for the Dutch rivers.

Van der Velde *et al.* (1989) analyzed the contents of fish stomachs and found that in the R. Waal perch (*Perca fluviatilis*) had a preference for gammarids, whereas the ruffe (*Gymnocephalus cernuus* (L.)) had a preference for *Hydropsyche* larvae. Pikeperch (*Stizostedion lucioperca*) shifts its diet during its growth in the river (Bergers, pers. comm.). Specimens of perch caught in the backwaters of the Rhine had hardly any gammarids in their stomachs, but specimens caught in the main channel close to the groynes did. The immigrant amphipod species *C. curvispinum* is very numerous and must be considered as a new important food item for fish; it has already been found in the stomachs of ruffe, perch, pikeperch, bullhead and eel.

Although complicated, the food chains involving fish must be worked out, so that the fish populations of the river Rhine can successfully be re-established within the framework of the Rhine Action Programme.

Birds

The backwaters of the Rhine and Meuse are of great ornithological value. Of the 76 bird species observed there, 36 have been found to breed near these waters. Furthermore, 33 species of waders have been observed (De Soet, 1976).

The rush vegetation and the bare mudflats in the tidal reaches of the Rhine/Meuse are attractive habitats for ducks and geese. During winter the banks remain ice-free longer than other waters, because of the tidal movement. Five to ten per cent of the total numbers of teal (*Anas crecca* L.) occurring in the river delta have been found on the muddy banks of the R. Oude Maas.

The sandy stream bed of the R. Oude Maas contains variable amounts of oligochaetes, chironomids and molluscs. Large numbers of tufted ducks (*Aythya fuligula* L.) have been recorded during the last five winters; many of these diving ducks probably forage on the zebra mussel, *Dreissena polymorpha* (M. van Wouwe, pers. comm.).

Large numbers of various species of ducks and geese overwinter in the Haringvliet (Boudewijn & Mes, 1986). Greyleg goose (*Anser anser* (L.)) and barnacle goose (*Branta leucopsis* (Bechstein)) are mainly found on the former intertidal areas that are now managed as pastures. Wigeon (*Anas penelope* L.) and coot (*Fulica atra* L.) also forage on fields and pastures during winter and use the former estuary to rest. Tufted ducks (*Aythya fuligula*) probably forage on zebra mussels, while pochard (*A. ferina* (L.)), which mainly occur in autumn, forage at night in the nearby salt-water lagoon of Lake Grevelingen (Boudewijn & Kuijpers, 1985). Mute swan (*Cygnus olor* (Gmelin)) forages in summer on filamentous algae and aquatic plants (mainly *Potamogeton pectinatus* and *Zannichellia palustris* L.). Cormorant (*Phalacrocorax carbo* (L.)) and great crested grebe (*Podiceps cristatus* (L.)) are important piscivorous bird species. In the river area cormorants appeared to feed on eleven fish species; important on all localities are eel, bream, roach, ruffe and perch, but cyprinids form the main food (Dirksen *et al.*, 1989a). Cormorants have in-

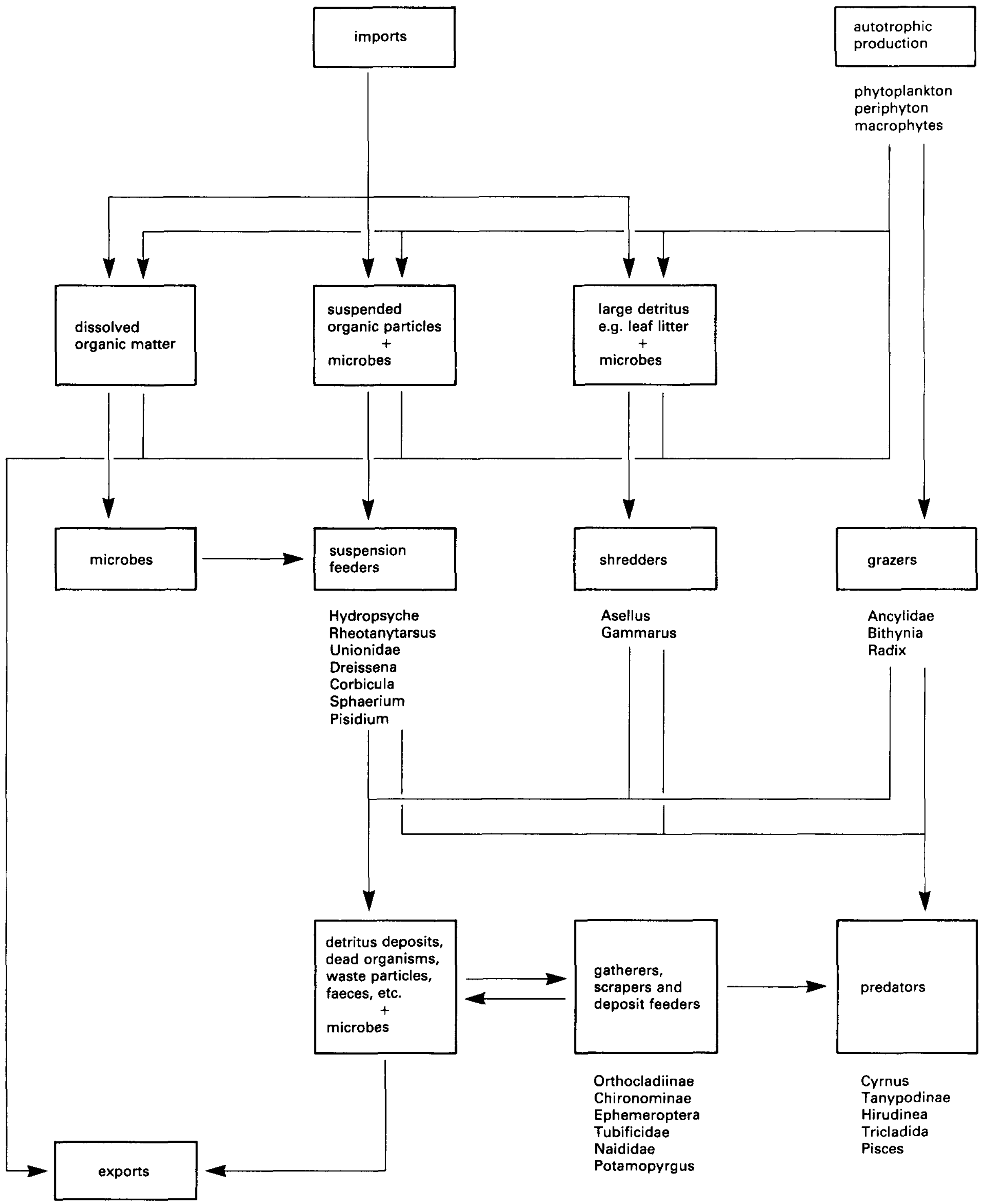

Fig. 19. Food chain of an aquatic ecosystem (after Barnes and Mann, 1980); dominant representatives for the Dutch rivers are indicated (after CUWVO, 1988).

creased in number parallel to their national population and the great crested grebe shows the same trends as in the whole delta (Boudewijn & Mes, 1986).

Recent investigations indicate that the contamination in the sedimentation areas is still interfering with the reproductive success of top carnivores. Tufted ducks (*A. fuligula*) held in captivity for three years were fed zebra mussels from the polluted Haringvliet and from the unpolluted Markermeer (in the IJsselmeer; Marquenie *et al.*, 1986). Compared with the reference group the ducks fed with mussels from the Haringvliet produced fewer and smaller eggs and sat on the nest briefly or not at all. Concentrations of polychlorinated biphenyls (PCB), pesticides and polycyclic aromatic hydrocarbons (PAH) were many times higher in the livers of the contaminated ducks. Dirksen *et al.* (1989b) compared the activities of cormorants (*P. carbo*) near the Rhine and Meuse (in the Biesbosch) and elsewhere. Only 0.55 juveniles per nest flew out in the colony near the Biesbosch, compared with 1.74 and 2.16 juveniles in the two reference colonies. The only large mammal that remained at the top of the food chain, the otter (*Lutra lutra* L.), has now disappeared completely, probably due to pollution (Janse, 1986).

Prospects for ecological recovery

Objectives of the rehabilitation plans for the Rhine and Meuse

The Rhine Action Programme includes ecological objectives (IKSR, 1987); earlier measures for restoring the river were directed mainly towards reducing chemical contamination (Rat von Sachverständigen, 1976; Santema, 1980). The rationale for including biological criteria in the international agreement of the Rhine states is probably the implicit assumption that a 'sensitive' and 'sound' river ecosystem safeguards against uncontrolled contamination of drinking water or an ongoing deposition of polluted sediment. This may be true, but undisturbed river communities no longer exist in the Rhine and Meuse. As we showed above, this is at least partly attributable to environmental conditions other than the emission of toxicants, *e.g.* morphological and hydrographical changes. The absence of pristine river communities has hampered the formulation of suitable biological criteria for rehabilitation. Slooff *et al.* (1985) emphasized the sensitive response of aquatic organisms to existing levels of pollution in the Rhine. Smit (1985) indicated the need to restore part of the morphological diversity in the river bed in addition to reducing toxicant input. In 1987 the salmon was adopted as a symbol for the restoration of the Rhine (IKSR, 1987). Research done by Smit & van Urk (1987) and Vanhemelrijk & van Broekhoven (1990) has indicated ways in which the river communities in the Rhine could develop. Following the approach of Ten Brink *et al.* (1991) they compared recent observations on the abundance of selected plant and animal species (or elements of the flora and fauna) with historical data, and presented a selection of these parameters in the form of an 'amoeba' (Fig. 20). They suggest that the environmental requirements for each of the selected organisms should be defined on the basis of autecological research and an analysis of the population dynamics. This would enable scenarios of ecological rehabilitation to be designed on the basis of a selection of biological parameters. However, there is a large discrepancy between the river communities in the past and at present (Fig. 20) and given the irreversible changes to the river, the rehabilitated communities may differ considerably from the historical ones. This means that the focus on species that characterized the communities in the past (cf. Ten Brink *et al.* (1991) may not be appropriate. Nevertheless, the species symbolic of the Rhine rehabilitation – the salmon – may have a fair chance of being re- established as a self-sustaining population.

Measures and management

It is generally assumed that the Rhine and Meuse will be ecologically rehabilitated if discharges of

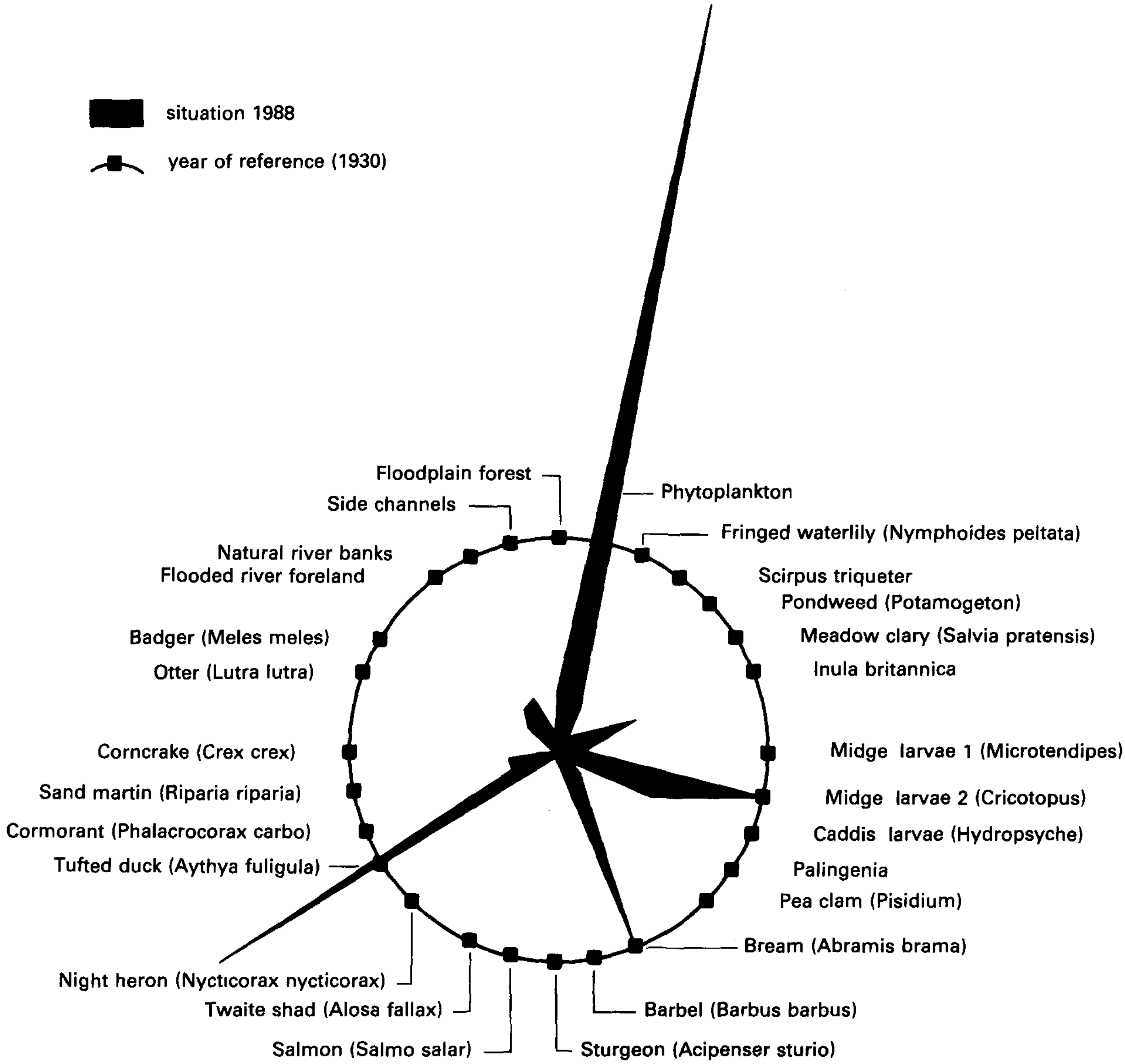

Fig. 20. Radial diagram, comparing the characteristics of the Rhine ecosystem in 1988 with that of ca. 1930. After Vanhemelrijk & Van Broekhoven (1989).

pollutants are reduced and natural habitats are restored (cf. de Wit *et al.*, 1989). So far, the reduction of emissions has been incorporated into the Rhine Action Programme: a 50% reduction in the emissions of about 30 priority substances by 1995 (as compared to 1985) has been arbitrarily chosen. Some of the input of contaminants, however, originates from diffuse sources, *e.g.* from agriculture. This means that effective control must touch on many aspects of environmental policy in the river catchment (cf. Smit & de Jong, 1989). For some of the emissions in the Rhine a 50% reduction can only be an intermediate goal, although any further reduction requires international agreement, or even measures on a river-basin level.

So far no effective remedial action has been undertaken to combat the chemical contamination and the eutrophication of the Meuse. Clearly the international and national coordination of such action is extremely complex: however, lessons can be learned from the organizational structures developed for the R. Rhine and from the international coordination by the International Rhine Commission.

Experiments on improving Rhine habitats locally are currently being discussed or are in progress; examples are presented below. An optimized bank protection policy in the tidal reaches of the river Rhine, now being developed, allocates areas for exploitable marsh vegetation, protects endangered species of flora and fauna and maintains an equilibrium between sedimentation and erosion. Experiments with the construction of breakwaters, placed at some distance from the vegetation, are now in progress; these breakwaters provide an effective shelter against intensive shipping. In the R. Waal the application of willow shoots for bank protection is presently under investigation. It has been suggested that the less artificial flow regime of the water in a morphologically unspoiled part of the Meuse (the Grensmaas) enhances the development of the flora and fauna (Klink, 1986b). The use of the Haringvliet sluices as a storm surge barrier that permits some tidal exchange between the Haringvliet and the North Sea could have far-reaching ecological consequences and is being examined. An optimization of the discharge regime of these and other sluices in favour of migrating fish is currently being tested. Furthermore, effective fish passes will be installed in 1991–1992 at the weirs in the rivers Lek and Meuse and in smaller tributaries.

The flood plains and embankments of the R. Nederrijn (at the 'Blauwe Kamer' and at 'Meinerswijk') have been 'reconstructed' in an attempt to encourage a more natural development in the flood plains. A similar project is being carried out on the R. IJssel ('Duursche Waarden'). As a result of a study on gravel and sand pits connected with the German part of the Rhine just upstream of the Netherlands, Berndt & Neumann (1985) developed recommendations to optimize these backwaters as nature reserves. These initiatives, although aiming at local improvement of the ecological conditions, may form the stepping stones for a more general ecological recovery of the rivers Rhine and Meuse, which will be possible if the policy for reducing discharges succeeds. If we are to follow the changes in water quality and communities, extensive biological monitoring programs are necessary. These are currently in progress.

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