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Ecosystem Responses in the Rhine-Meuse Delta During Two Decades After Enclosure and Steps Toward Estuary Restoration

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ABSTRACT: Changes in hydrology, and developments in morphology, water quality, and ecology of the Rhine-Meuse estuary after its enclosure in 1970 are analyzed on the basis of existing monitoring data. Annual averages of ammonium, nitrate plus nitrite, total phosphate, total lead, and chlorophyll-*a* concentrations as well as transparency of the water are presented. Abundances of some water bird species are given for the period 1970–1993, and the relative fish biomass for the period 1971–1988 is discussed. The gradual evolution led toward the dominance of bream. The area has developed toward a system with generally low natural ecological values. Ecological impacts of present sluice management are discussed and include the accumulation of contaminated sediments, disappearance of intertidal areas and nursery grounds for fish, disturbance of fish migration, and less mixing of river and seawater. Recent policy developments have brought the present management of the Haringvliet sluices back into discussion. A recent policy document has presented several management alternatives, including partial and complete reopening of the sluices to permit saltwater intrusion. Three management options are compared in terms of costs and ecological benefits. It is concluded that a complete reopening, and thus a partial restoration of the estuarine characteristics, is most beneficial for the ecosystems of the area itself, for the upstream Rhine and Meuse rivers, and for the adjacent North Sea, but costs amount to about 600 million US $.

Introduction

Estuaries link rivers to the sea. They form an essential link between marine and river ecosystems. This was true for the rivers Rhine and Meuse until November 1970, when the completion of the Haringvliet Dam created a barrier between these rivers and the North Sea (Fig. 1). The first aim of the closure was to safeguard the surrounding land against floods. The second aim was to improve control of the distribution of river water through the main outlets of the rivers (i.e., the Nieuwe Waterweg and Haringvliet). This was needed to reduce salt intrusion into the Nieuwe Waterweg. The third aim was to improve the freshwater supply to the surrounding former islands for agricultural purposes and to provide new and more suitable inlets for the production of drinking water.

The closure had a dramatic impact on the ecology of the former estuary (De Boois 1982; Ferguson and Wolff 1983), which emphasized the fact that hydrodynamics are a crucial element of this ecosystem. As a consequence of the construction of the dam, the coastline became considerably shorter (e.g., Saeijs 1982; Knoester 1983).

In the first half of the 1980s various negative long-term effects of the closure of the river mouth became apparent such as the accumulation of large amounts of contaminated sediments and the disappearance and degradation of former and remaining intertidal areas. In the same period, the Dutch Ministry of Transport and Public Works (1985), which is responsible for water management in the enclosed Rhine-Meuse Delta, adopted the principle of integrated water management, re-

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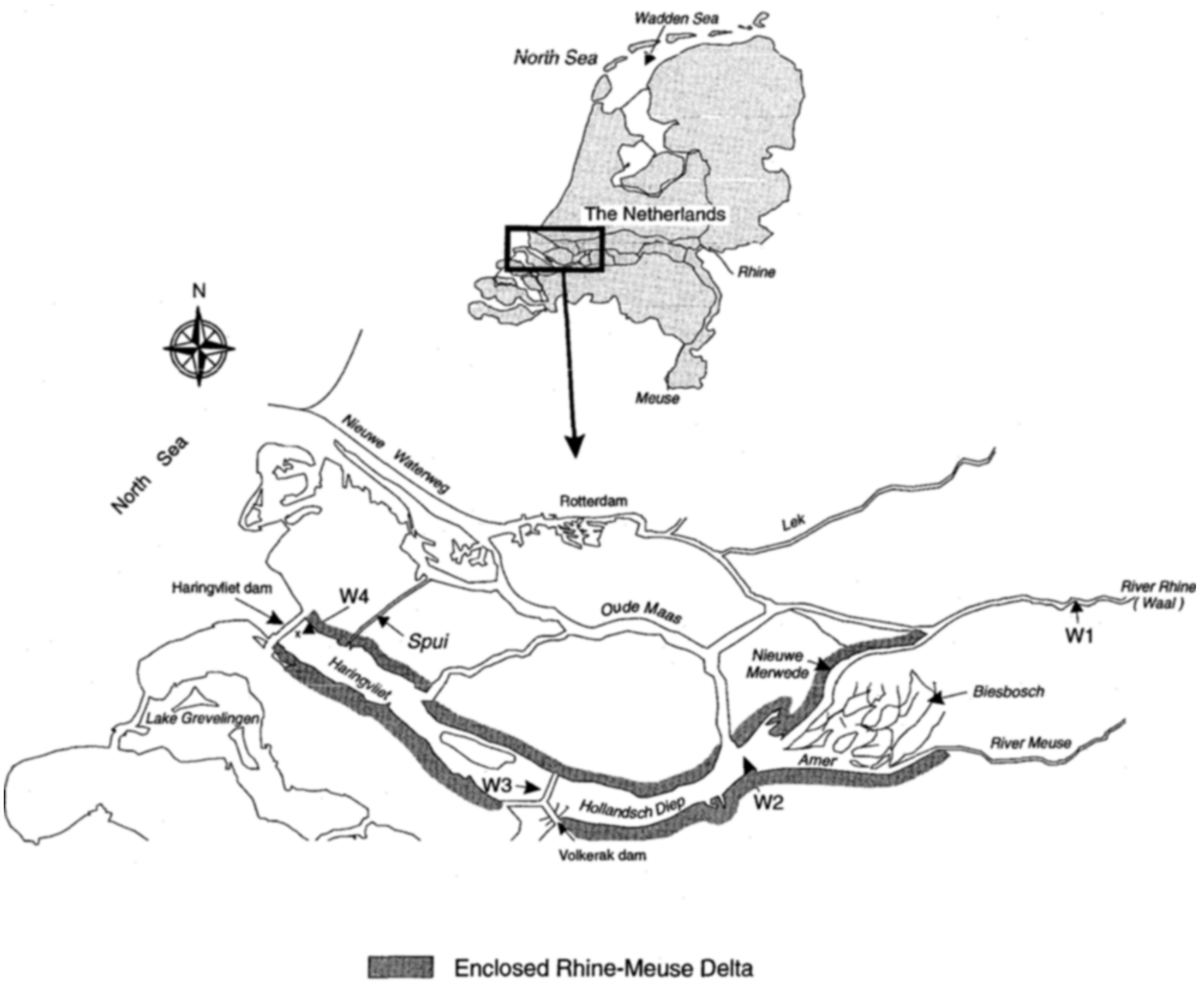

Fig. 1. Overview over the enclosed Rhine-Meuse Delta and its position in the Netherlands. W1 to W4 are water quality sampling sites.

quiring that all functions of water systems be included in their management. Simultaneously, the natural values and potentials of river ecosystems (e.g., De Bruin et al. 1987) and coastal wetlands (e.g., Ministry of Housing, Spatial Planning and the Environment 1993; Bisseling et al. 1994) were becoming increasingly recognized and appreciated in Dutch society. Most recently, sustainable development of ecosystems has become an issue in water management. Figure 2 summarizes the changes in socio-economic needs in relationship to water management in the Rhine-Meuse estuary over the last 40 yr.

Since the area's ecosystem had become strongly dependent on the management of the Haringvliet sluices, their management had to be reconsidered with more emphasis on environment. This paper aims to analyze long-term developments since 1970 in morphology, water and sediment quality and ecology, to determine the impact of sluice management on these conditions, and to describe and evaluate alternative sluice management strategies from an ecological point of view and their impact on natural and human functions.

The Rhine-Meuse Delta Prior to Enclosure

The area considered comprises the Haringvliet, Hollandsch Diep, Biesbosch, and the Nieuwe Merwede and Amer rivers (Fig. 1). The Haringvliet is the main outlet of the Rhine and Meuse rivers. The area has experienced a complex history of inundation by the sea and rivers, land reclamation and diking (Lambert 1971), regulation, and channel construction. Until 1870, an important part of the Rhine water flowed through the Biesbosch area, depositing large amounts of suspended solids, and

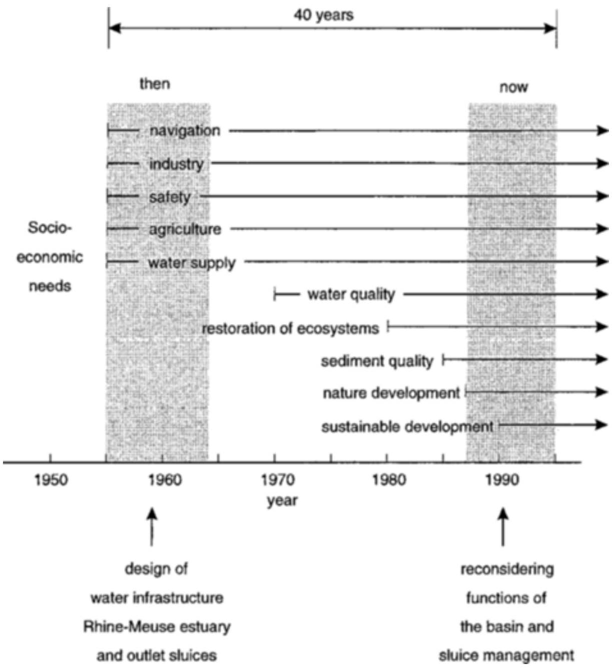

Fig. 2. Changes in socio-economic needs related to water management in the Rhine-Meuse estuary over the last 40 yr.

had its main outflow to the North Sea through the Haringvliet. Between 1860 and 1870 both the Nieuwe Merwede and the Nieuwe Waterweg, two navigational channels, were constructed to improve navigation and water discharge. The Meuse River, discharging into the Waal River, was given its own outlet to the Amer by the digging of the Bergsche Maas (Meuse River in Fig. 1) at the beginning of the 20th Century. Continuous sedimentation and diking of large intertidal areas decreased the water storage capacity. This, together with the channel digging, increased the average tidal range in the Biesbosch area from ca. 1 m in 1850 to ca. 2 m in 1960 (Zonneveld 1960). Before construction of the Volkerak and Haringvliet dams, a morphological equilibrium existed between depth profiles and currents; the marine and fluvial silt mainly accumulated in the intertidal areas.

The estuarine ecosystem consisted of a fresh- and brackish-water tidal system. It included a characteristic flora (Zonneveld 1960), and plankton (Peelen 1967), macroinvertebrate (Den Hartog 1961; Wolff 1973), fish (Vaas 1968), bird (Louman 1991), and mammalian (Anonymous 1989) fauna. The vegetation consisted of large stands of reeds and rushes, merging in the east into a large freshwater tidal area, the Biesbosch, with tidal forests and reed marsh areas. The freshwater tidal marshes were characterized by zonation of vegetation caused by tidal inundation and exposure to tidal currents (Zonneveld 1960). In the low intertidal areas, *Scirpus* marshes with *Scirpus lacustris, S. tabernaemontani, S. maritimus,* and *S. triqueter* dominated. At higher elevations these marshes were succeeded by reed marshes, ruderal vegetation, and alluvial forests with characteristic understory elements (Van de Rijt and Coops 1993). Vegetation succession has historically been strongly influenced by the exploitation of rushes, reed, and coppice wood (Smit and Coops 1990). Both the invertebrate and fish fauna followed an environmental gradient, with several marine species in the western Haringvliet, brackish-water species in the eastern Haringvliet and Hollandsch Diep, and freshwater species in the Biesbosch, Amer, and Nieuwe Merwede. Among the mammals, the otter (*Lutra lutra*) was still common around 1900 in the Hollandsch Diep and Biesbosch but had become extinct by 1940. Harbour seals (*Phoca vitulina*) were still common in 1953 but had nearly disappeared from the area at the end of the 1960s, mainly because of pollution (Reijnders 1982).

State and Developments After Enclosure

Hydrodynamics

The construction of the Volkerak Dam (finished in 1969) and Haringvliet Dam (finished in November 1970) converted the estuary into an inland freshwater basin. The Haringvliet sluices have regulated the water distribution in the enclosed Rhine-Meuse Delta since then. At low Rhine discharges ($Q < 1{,}700\ m^3\ s^{-1}$), the sluices are closed to prevent salt intrusion. With increasing Rhine discharge the sluices are gradually opened during low tide on the North Sea. At high Rhine discharges ($Q > 9{,}000\ m^3\ s^{-1}$), the sluices are completely open. Consequently, current velocities and residence times vary greatly with Rhine discharge (Table 1).

Morphology

After the closure, channel profiles in the enclosed area have become oversized and consequently large amounts of sediments have been deposited in the former tidal channels (Van Berghem et al. 1992). These sediments mainly originated from the Rhine and Meuse rivers. The tidal channels of the upstream part of the delta, including the Nieuwe Merwede, filled up first, in the early 1970s. In subsequent years, sediment was deposited further west as the upstream parts reached equilibrium with new flow rates. Today, about 5 million m^3 of sediment are deposited annually in the Amer, Nieuwe Merwede, Hollandsch Diep, and Haringvliet. Sand is mainly deposited in the Amer and Nieuwe Merwede, while silt is deposited in the Hollandsch Diep. The finest silt particles settle in the Haringvliet. However, this pattern is depen-

TABLE 1. Residual current velocities and residence times in parts of the enclosed Rhine-Meuse Delta, in relation to the discharge of the river Rhine at the German-Dutch border. Current velocities are cross sectional and tidal averaged, and calculated with the one-dimensional ZWENDL model. The fraction of time in which river Rhine discharge is exceeded is also given.

Parameter (unit)	Part of R-M Delta (Rhine km)	River Rhine Discharge (m^3 s^{-1})				
		1200	2000[1]	3000	6000	8000
Current velocity (m s^{-1})	Nieuwe Merwede (968–980)	0.25	0.38	0.53	1.01	1.25
	Hollandsch Diep East (980–984)	0.08	0.13	0.20	0.42	0.55
	Hollandsch Diep West (995–999)	0.02	0.05	0.10	0.26	0.35
	Haringvliet West (1018–1030)	0.00	0.03	0.09	0.26	0.36
Residence time (days)	Hollandsch Diep (980–999)	9.1	3.5	1.8	0.71	0.50
	Haringvliet East (999–1018)	7.5	2.8	1.3	0.50	0.38
	Haringvliet West (1018–1030)	41.5	6.9	2.3	0.79	0.58
	Hollandsch Diep + Haringvliet	58	13	5	2	1.5
Fraction of time (%) in which River Rhine discharge was exceeded (average over the period 1901–1980)		77	57	15	1.4	0.3

[1] 2200 m^3 s^{-1} is the average discharge over the period 1901–1980.

dent on river discharge. When river discharges are high, the depositional gradient shifts to the west; silt which was deposited in the east may be resuspended and transported further west.

Between 1970 and 1987 the cross-sectional profile of the area was considerably reduced (Fig. 3), resulting in an average net sedimentation of 0.5–2 m in 17 yr. With the present sluice management, the sedimentation process will continue and move further westward until a new equilibrium in the entire delta has been established. This will occur within one or two centuries.

Directly after the closure, the former intertidal flats, which still had gentle slopes, were not adapted to the small vertical tidal amplitude and the lower current velocities. During the decades after enclosure, erosion by wind-induced waves gradually changed the gentle slopes in most intertidal areas into steep slopes between 0.0 m and 0.6 m above mean sea level. The ecologically important intertidal zone practically disappeared in most places. The vegetation border of wind-exposed intertidal areas in the Haringvliet, for example, has receded by about 100 m between 1970 and 1984. Sediments eroded during this process also contributed to the filling of the channels.

Human activities have also changed the area's morphology directly. Several underwater sand pits testify to the construction of the Haringvliet sluices and the Volkerak dam complex during the 1960s.

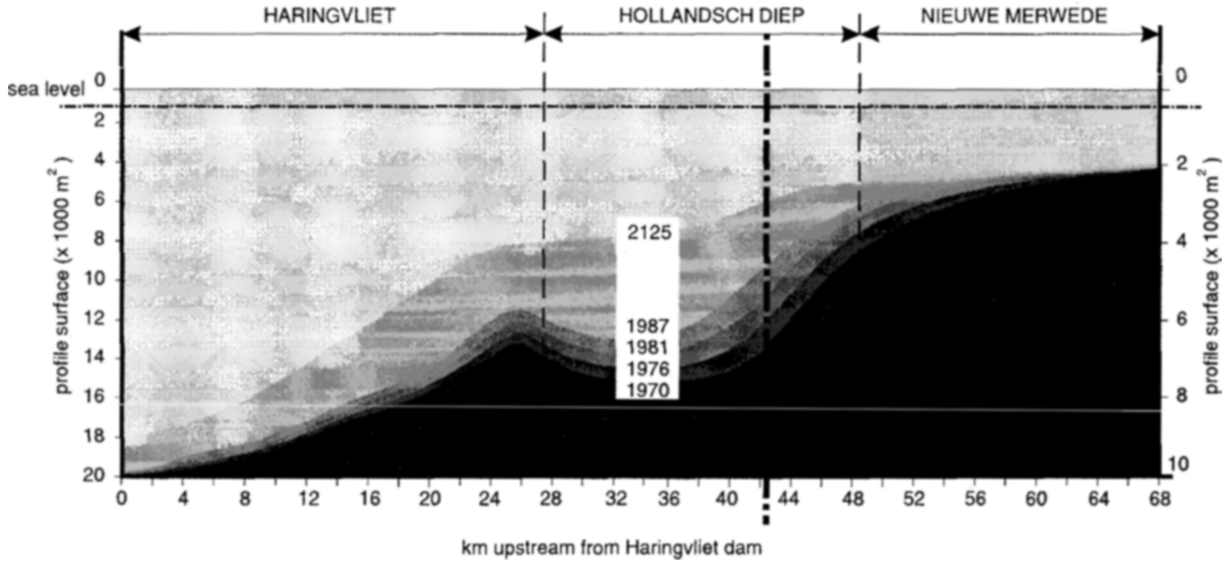

Fig. 3. Surface of cross-sectional profiles in the enclosed Rhine-Meuse Delta between 1970 and 1987, and a prediction for the year 2125. Surface area of the eastern Hollandsch Diep (to the right of the bold line) refers to the North side, connected to the Nieuwe Merwede. Adapted from Van Berghem et al. (1992).

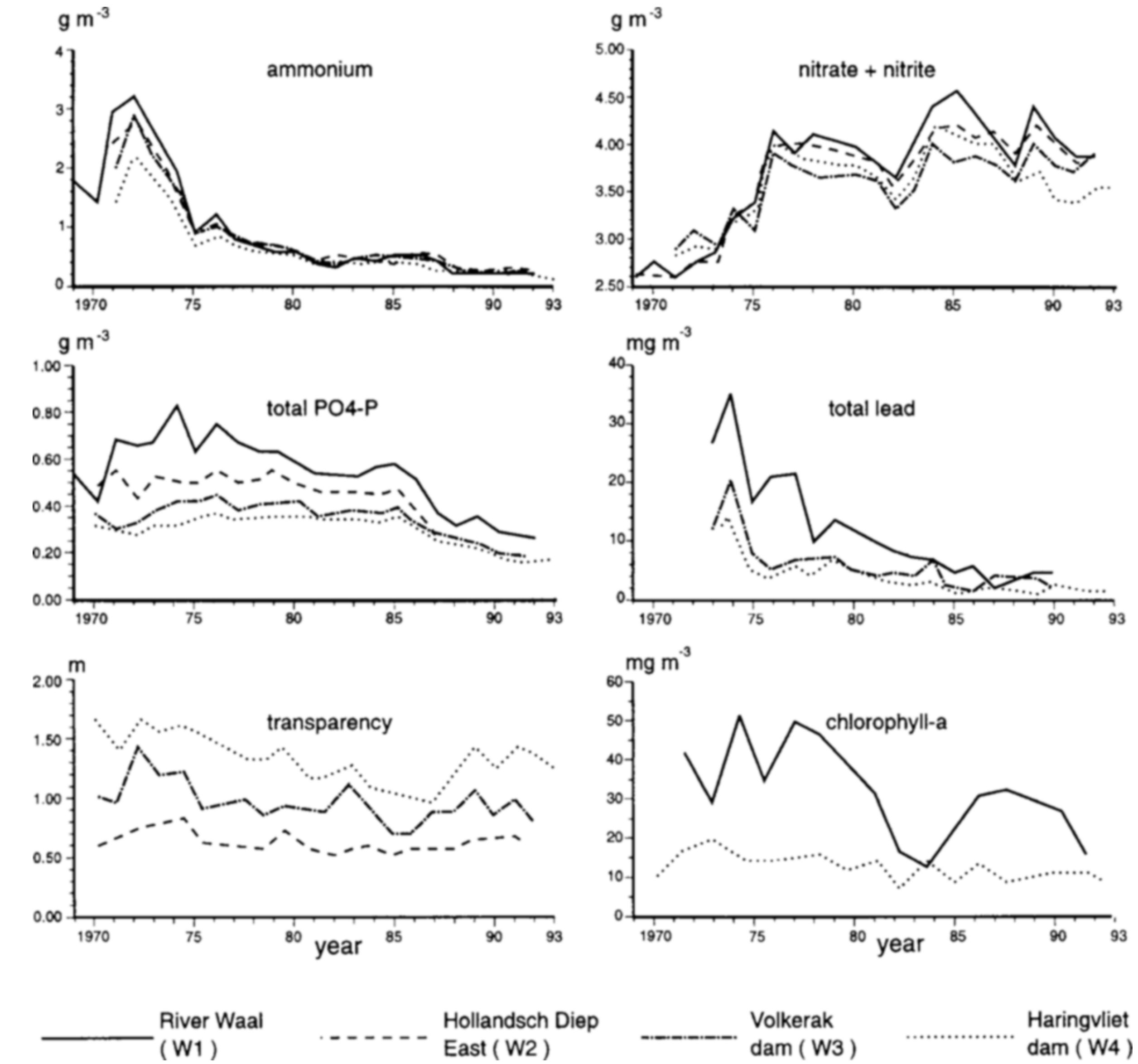

Fig. 4. Annual average values of some water quality parameters between 1970 and 1993 at four sampling sites from the Waal River (W1) to the Haringvliet sluices (W4). See Fig. 2 for the position of the sampling sites. Data from Rijkswaterstaat, DONAR database.

One pit in the western Hollandsch Diep is currently used for the disposal of sediment dredged to maintain the Nieuwe Merwede and eastern Hollandsch Diep as navigable channels. During the 1980s most banks were protected with wave breaks at some distance from the borders. The protection programme will be finished by 1997. The intertidal gradient has been restored on two flats in the Haringvliet by means of sand supply.

Water Quality, Spatial Changes

In the 1970s the Rhine river was known as a heavily polluted, large river. Its water quality has improved substantially since. From the upstream Waal river (Rhine river; W1, sample point in the east) to the Haringvliet Dam (W4) in the west (for locations see Fig. 1), considerable changes in water quality took place. Most changes are related to the above mentioned sedimentation processes. Parameters related to the presence of suspended particles, such as total phosphate, total lead, and chlorophyll *a* (Fig. 4), decreased in a downstream direction. Transparency also increased in this direction (Fig. 4).

Water Quality, Temporal Changes

Increased rates of purification of domestic wastewater in the Rhine basin led to decreasing ammonium and increasing nitrate concentrations in the enclosed Rhine-Meuse Delta between 1972 and 1976 at the sediment-water interface (Van Eck 1982). Since 1976, nitrate concentrations have decreased in a westerly direction (from W1 to W4), probably because denitrification at the sediment-water interface exceeded nitrification in the surface water from 1976 onward. Nitrate uptake by algae also may have contributed. Total phosphate concentrations have shown a remarkable decrease from 1986 onwards, mainly because of dephosphatation in wastewater treatment plants upstream and the increased use of detergents without phosphate. Concentrations of heavy metals, such as cadmium, chromium, copper, lead, mercury, nickel, zinc, and arsenic, decreased from the 1970s onward (Beurskens 1995; Hendriks 1995), illustrated here for lead. Several polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins, dibenzofurans, and polycyclic aromatic hydrocarbons followed a similar pattern of decreasing concentration since 1970 (Beurskens 1995). However, concentrations of many micropollutants in the Rhine are still above acceptable levels (Hendriks 1995).

Chlorophyll-*a* concentrations in the Haringvliet were low throughout the period 1970–1990 (< 20 mg m^{-3}), and transparency high (1–1.5 m) in spite of the eutrophic conditions. The low chlorophyll-*a* concentrations in the Haringvliet are remarkable, since conditions for algal growth seem very favourable: nutrient levels are high and light conditions are good. Several explanations have been proposed for this phenomenon, such as iron limitation of algal growth (personal communication G. T. M. Van Eck), the sedimentation of river plankton combined with a short residence time (De Hoog and Steenkamp 1989), and sedimentation combined with consumption by zooplankton (De Ruyter van Steveninck et al. 1990a, 1990b) and zebra mussels (*Dreissena polymorpha*) (Smit unpublished data).

Sediment Quality

Sediment quality is mainly determined by the pollution level of sediments deposited after 1970. Sediments deposited in the early 1970s have the poorest quality (pollution class 4), since pollution was then at its peak. The most recent sediments are less polluted (class 2 or 3). Consequently, sediment quality at the surface should improve going downstream from the Amer and Nieuwe Merwede to the Hollandsch Diep. However, at high river discharges polluted silts are resuspended and transported downstream. Most of the 90 million m^3 deposited between 1970 and 1989 is polluted (class 3) or extremely polluted (class 4), and is settled in the Hollandsch Diep (Fig. 5).

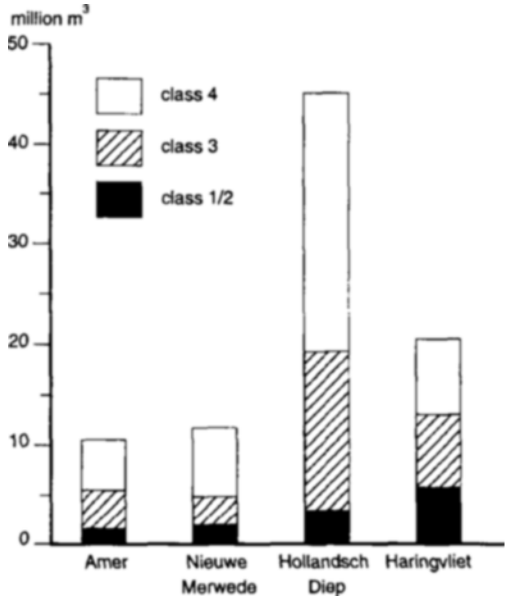

Fig. 5. Amounts and quality of sediments deposited in the Amer, Nieuwe Merwede, Hollandsch Diep, and Haringvliet between 1970 and 1989. Quality classes according to the Ministry of Transport and Public Works (1989); class 1: meets the standards of environmental quality (AMK 2000); class 2: moderately polluted; class 3: polluted; class 4: extremely polluted. Sediments are classified using corrected concentrations of contaminants according to the Ministry of Transport and Public Works (1989). Data from Rijkswaterstaat, Zuid-Holland Directorate.

Vegetation

The closure reduced the water-level variation and transport of silt to the intertidal area and thus eliminated a crucial factor in the existence of the extended fresh- and brackish-water tidal marshes. As a consequence, the vegetation changed drastically (Beeftink 1975; De Boois 1982). The *Scirpus* zone gradually deteriorated throughout the enclosed Rhine-Meuse Delta: between 1970 and 1989, the *Scirpus* stands in the Haringvliet and Hollandsch Diep declined from several hundreds of hectares to less than 0.1 ha (Smit and Coops 1990). A similar decline occurred in the Biesbosch (Coops 1992). Most of the reduction was caused by permanent inundation, accompanied by erosion and heavy grazing by geese.

After the disappearance of *Scirpus* stands, wave attack affected the reed (*Phragmites australis*) vegetation. Local wave action led to the formation of steep shoreline cliffs without emergent vegetation at the water's edge. It was only after the construction of protective wave breaks during the 1980s, that the shoreline retreat was halted.

At higher elevations, the absence of frequent inundation led to oxygen penetration into the soil and hence to an increased availability of nutrients. These areas were soon invaded by terrestrial ru-

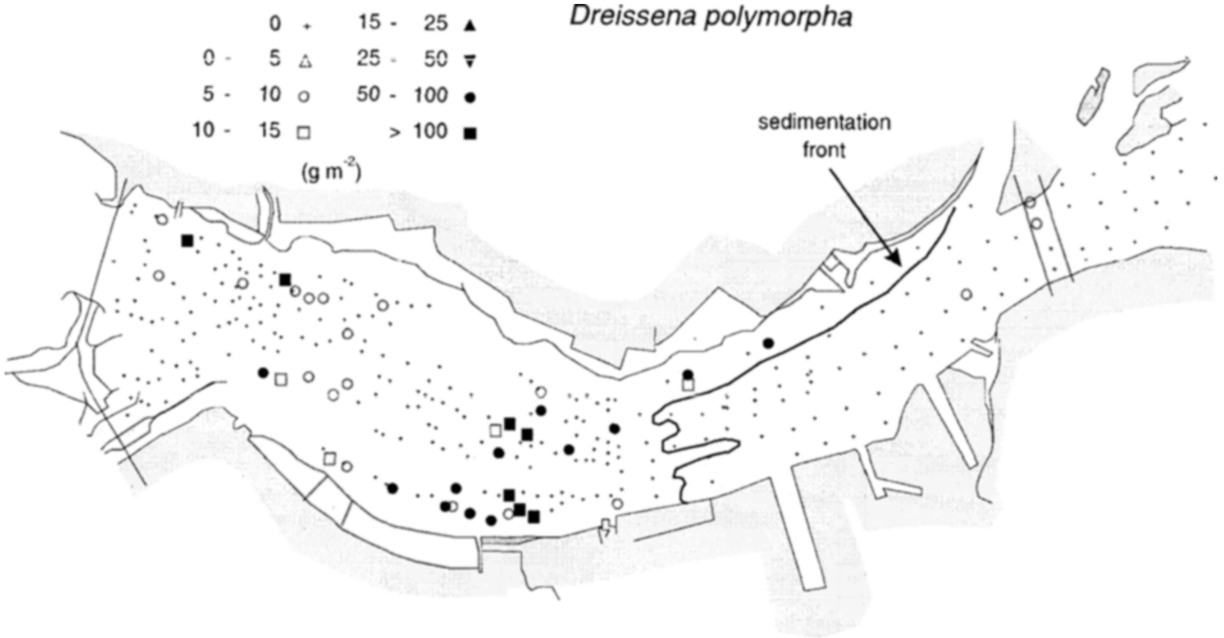

Fig. 6. Distribution of zebra mussels (*Dreissena polymorpha*) (g AFDW m^{-2}) in the Hollandsch Diep. The 'sedimentation front' denotes the barrier between areas with higher (> 1 m between 1970 and 1987) and lower (< 1 m) sedimentation rates. The northeastern bank includes former intertidal areas, which have been subject to heavy erosion by wind waves. Consequently, sedimentation rates have been low and zebra mussels could settle. Adapted from Dudok van Heel et al. (1992).

deral plant species, such as common nettle (*Urtica dioica*), great hairy willow-herb (*Epilobium hirsutum*), and goldenrod (*Solidago gigantea*). Along the Haringvliet, some characteristic brackish-marsh species disappeared (e.g., Parsley water-dropwort, *Oenanthe lachenalii*) or decreased significantly (e.g., wild celery, *Apium graveolens*), while others persisted over 20 yr (e.g., marshmallow, (*Althaea officinalis*) and common scurvy-grass (*Cochlearia officinalis*). The lower current velocities and increased transparency compared to the former estuarine situation favoured the establishment of extensive stands of fennel-leaved pondweed (*Potamogeton pectinatus*) and perfoliate pondweed (*P. perfoliatus*) in shallow water. Between 1970 and the present, almost all terrestrial, formerly intertidal areas have become nature conservation areas. Parts of the former reed marshes have been transformed into grassland (496 ha) in order to expand the foraging terrain for wintering geese, mainly of barnacle goose (*Branta leucopsis*) and greylag goose (*Anser anser*).

Macroinvertebrates

Since the enclosure of the Rhine-Meuse estuary, the macroinvertebrate fauna of this area has been rather poor in species diversity, with low biomass, and has been generally dominated by a few tolerant tubificid worm species (Verdonschot 1981; Smit et al. 1995). Exceptions are the western Hollandsch Diep and eastern Haringvliet, where high biomasses of zebra mussel (*Dreissena polymorpha*) occur. Here, clusters of zebra mussels are found attached to solid structures where the net sedimentation is not too high. The highest biomass values have been found in the Hollandsch Diep, west of the silt sedimentation front (Fig. 6). The mussels seem to utilize the high food availability in the sedimentation area of the two large eutrophic rivers more than other macroinvertebrate species. The mussels are an important food source for waterbirds (e.g., tufted duck, *Aythya fuligula*). As the sedimentation front moves further westward, zebra mussel biomass is expected to decline in the future because their habitat (i.e., solid substrates to which they attach) will become more scarce.

Fish

Directly after the closure in 1970, anadromous fish species such as twaite (*Alosa fallax*) disappeared from the enclosed Rhine-Meuse Delta. All marine species disappeared, except for the catadromous flounder (*Platichthys flesus*) and small numbers of smelt (*Osmerus eperlanus*). Ruffe (*Gymnocephalus cernuus*) was one of the fastest colonizers after desalination but never became dominant. A rapid colonization by common freshwater species such as perch (*Perca fluviatilis*), roach (*Rutilus rutilus*), and bream (*Abramis brama*) followed (Fig. 7). Between 1971 and 1974 the importance of floun-

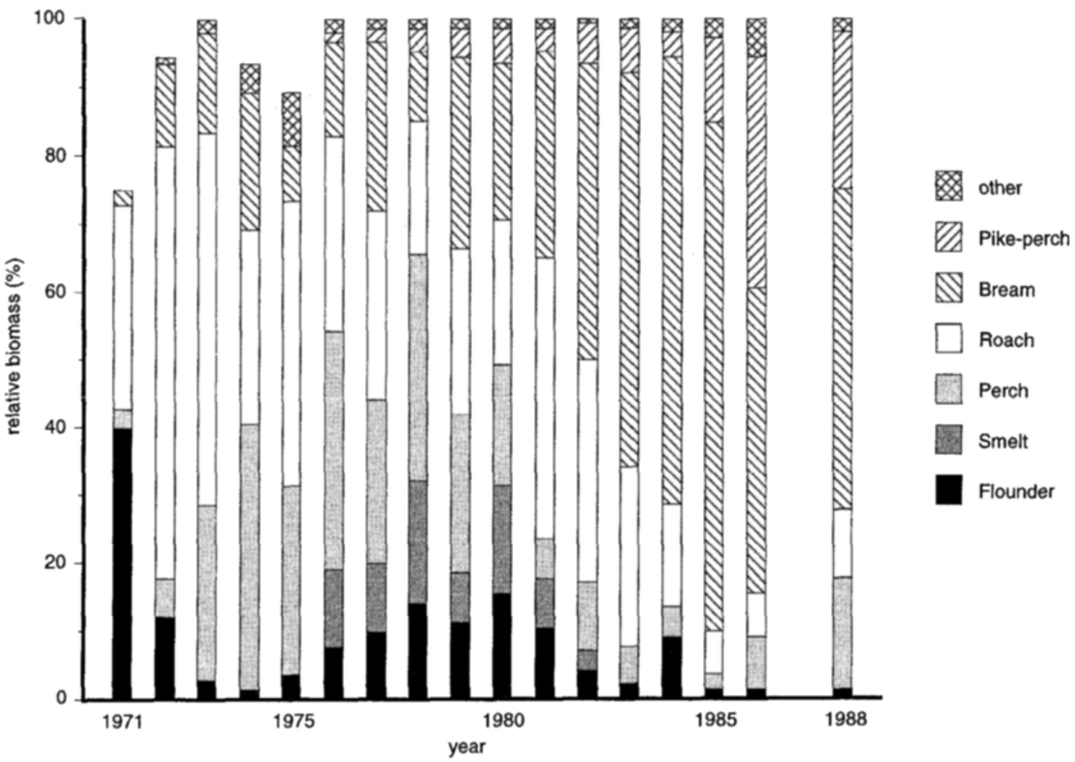

Fig. 7. Relative biomass of the most abundant freshwater fish species in the Haringvliet. Data courtesy Netherlands Institute for Fishery Investigations, IJmuiden.

der decreased. An initial dominance of roach in 1972 was superseded by perch in 1974. From 1976 onward, pike-perch (*Stizostedion lucioperca*) appeared; its importance gradually increased in the course of the following decade. After 1980, bream became dominant, replacing roach (Wiegerinck and Heesen 1988).

Willemsen (1980), relating the dominance of fish species to the trophic status of water bodies, allocated a higher trophic status to bream and pike-perch compared to roach and perch, based on findings in shallow lakes in The Netherlands. However, chlorophyll-*a* concentrations in the enclosed Rhine-Meuse Delta were much lower than those in most large eutrophic water bodies.

The observed succession patterns show a remarkable similarity to those observed in Lake IJsselmeer in the first years after the enclosure of the Zuiderzee (De Beaufort 1954) and those in Lake Volkerak-Zoommeer after the separation from the Oosterschelde in southwest Netherlands (Ligtvoet 1993). The conversion from an estuarine to a freshwater ecosystem generates large amounts of detritus, of which opportunistic macrozoobenthic species take advantage. In the enclosed Rhine-Meuse Delta, considerable amounts of organic pollutants from the rivers Rhine and Meuse were deposited as well. Consequently, tubificids—consumers of detritus rich in food—were highly abundant in the Nieuwe Merwede and Hollandsch Diep in 1971–1972, which benefitted roach (personal communication K. Peeters). In Lake Volkerak-Zoommeer another invertebrate species peaked shortly after enclosure. Here high densities of midge larvae (*Chironomus balatonicus*), on which flounders fed (personal communication G. van Beek), were observed (Van Nes and Smit 1993; Van der Velden et al. 1996). Peeters and Van Beek both observed very large and heavy individuals of these fish species, whose stomachs were filled with the above mentioned macroinvertebrates. In later years, biomasses of tubificids as well as chironomids declined in both waters. The replacement of roach and flounder by bream may, however, be attributed to many simultaneously developing processes. A proposed explanation of events leading to the eventual dominance of bream in the enclosed Rhine-Meuse Delta is given in Fig. 8.

Water Birds

The former estuary had an important function for various geese, duck, tern, and wading bird species (Louman 1991). Since 1972, systematic bird censuses in the area have been carried out during the winter months, from October through March. The abundance of water bird species has become

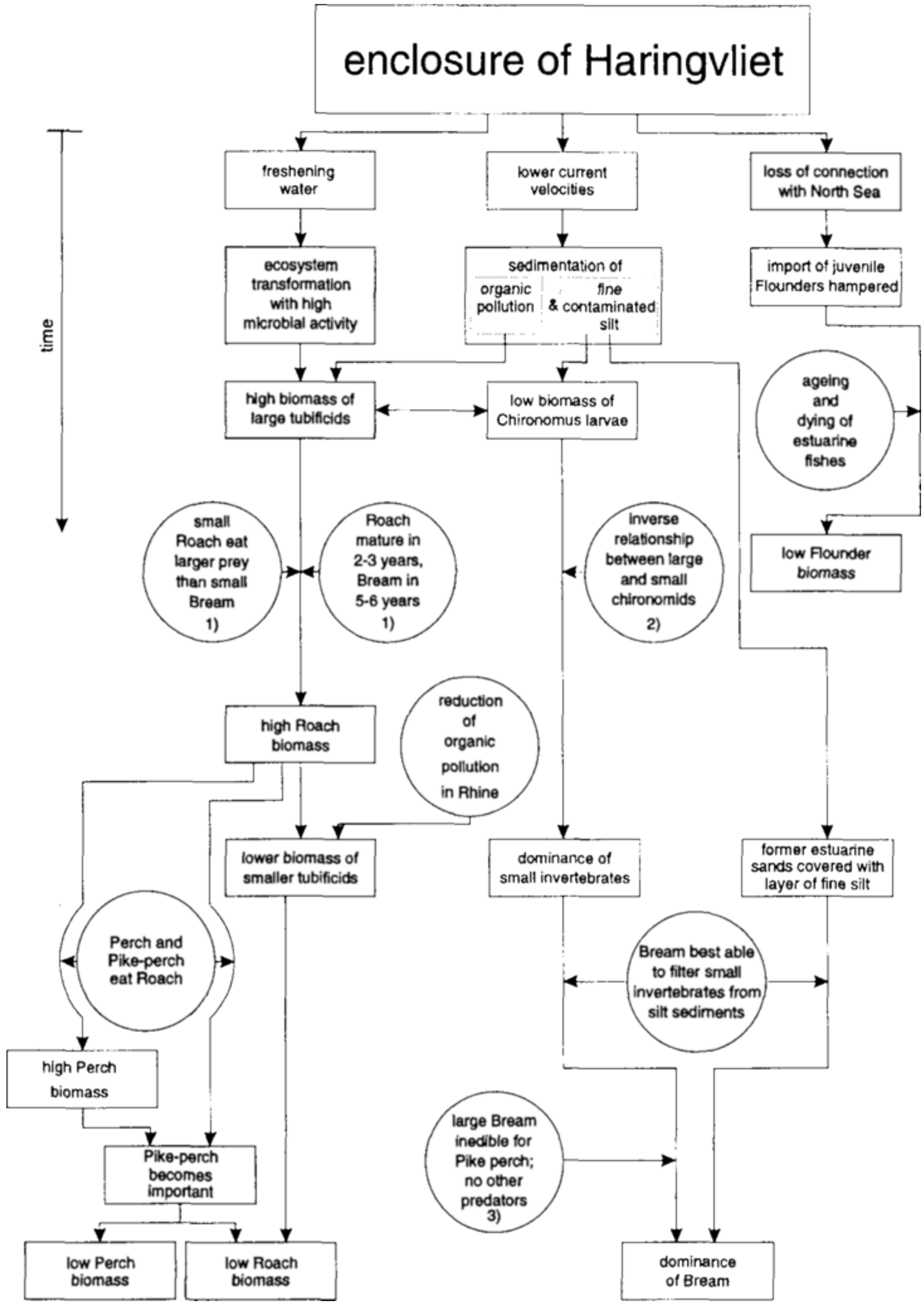

Fig. 8. Possible ecosystem interactions and events, which occurred in the Haringvliet after the enclosure in 1970, leading to the dominance of bream (*Abramis brama*). 1) personal communication E. Lammens; 2) Heinis (1993); 3) Lammens (1986).

an important parameter indicating the ecological status of water bodies since the 1% standard was accepted as a criterion for the designation of wetlands as internationally important. The status 'wetland of international importance' is given to any wetland in which more than 1% of the west European population of a water bird species is encountered on a regular basis. For this area the criterion 'more than 1 % on a regular basis' was considered true when a species exceeded the 1% standard in five consecutive years between October 1988 and March 1993. This was the case for three species: barnacle goose (*Branta leucopsis*, range of winter maxima: 20–34 % of the west European population), Greylag goose (*Anser anser*, 2.7–6.1 %), and wigeon (*Anas penelope*, 1.4–3.3 %). However, these species mainly live on the surrounding grasslands, which function largely independently from the aquatic ecosystem. During the last four years (October 1989–March 1993), tufted duck (*Aythya fuligula*, 1.0–2.0 %) also exceeded the 1% standard. The tufted duck lives on the open water and feeds on zebra mussels (*Dreissena polymorpha*).

Water Bird Trends Between 1972 and 1993

Figure 9 illustrates the temporal patterns for a selection of six water bird species (based on the bird censuses) having different feeding habits and living in different habitats. Greylag goose and wigeon were observed most often on grasslands in the area. The decrease of Greylag goose in the 1970s was caused by the decline of the *Scirpus* stands during in this period (Kuijpers 1976). However, the animals have shifted their habitat to agricultural and grasslands and numbers have increased since 1983–1984. The occurrence of dunlin (*Calidris alpina*) and shelduck (*Tadorna tadorna*) was confined to the littoral zone. Although their numbers show considerable fluctuations because of the irregular changes in water levels (Boudewijn and Mes 1986), numbers of both species have decreased during the observation period. This is probably related to habitat loss caused by progressive bank erosion. The decreased numbers of these littoral species are consistent with observations of other wading and duck species in the area, which are confined to the intertidal and shallow-water zone. Numbers of tufted duck increased from the late 1970s onwards. The ducks mainly forage on zebra mussels, which also increased in abundance during the same period.

Numbers of great crested grebe (*Podiceps cristatus*) increased from 1972–1973 until 1976–1977 but then showed a sharp decline. These birds probably changed their wintering area to the neighbouring saltwater Lake Grevelingen, where food conditions were better. Lake Grevelingen contains a large population of small fish (Doornbos 1984), which are a more suitable prey than the large bream dominating the Haringvliet and Hollandsch Diep. The cormorant (*Phalacrocorax carbo sinensis*) population increased during the observation period. In the period 1989–1993, several hundred cormorants wintered on the area's breakwaters, which provided them with good protection against predatory mammals.

Ecological Impacts of the Present Sluice Management

This section summarizes the main ecological impacts of the present sluice management practices both on the system itself and on the connected rivers and the North Sea.

Disturbed Silt Balance

Silt, including organic material, has accumulated in the former tidal channels and river beds of the Nieuwe Merwede and the eastern Hollandsch Diep, where it has become largely unavailable to both the local ecosystem and the North Sea. In the study area the organic material remains unused. Sluice management allows only small quantities to reach the North Sea, thus the former tidal flats have been deprived of building materials and of their main food source, the organic fraction of the sedimenting silt.

Accumulation of Contaminated Sediments

Most of the 90 million m^3 of sediment accumulated in the area is severely polluted (Fig. 5). This produces a hazardous situation for both man and nature. Several toxic compounds reach high levels in the sediment. Polychlorinated biphenyls (PCBs), for example, approached and sometimes even exceeded the allowed level for consumption in eel (*Anguilla anguilla*) in recent years (Hendriks and Pieters 1993; personal communication H. Pieters 1996). Eel is commercially fished in the area. The allowed total PCB level in eel for consumption in The Netherlands is similar to that in the United States (5 mg kg^{-1}) and less severe than the Canadian standard (2 mg kg^{-1}). Negative impacts on various components of the ecosystem have also been revealed in recent years: the reproduction of cormorants (Dirksen et al. 1995) and tufted ducks (De Kock and Bowmer 1992) was negatively affected; there was a high incidence of malformations in mouth parts of chironomids (Van Urk and Kerkum 1986) and densities of chironomids were low (Smit et al. 1995) compared to levels found normally in sediments of rivers and lakes in The Netherlands. The otter (*Lutra lutra*) is an indigenous species in the Rhine-Meuse Delta but has been absent for a long time. Concentrations of PCBs in water and sediment of the entire Netherlands part of the Rhine-Meuse catchment area are too high to allow an otter population to reproduce and survive (Van der Linde 1996). Since the Biesbosch area is a suitable otter habitat, the high PCB levels accumulated in the polluted sediments are probably the main restricting factor for the return of this species.

Disappearance of Intertidal Areas

After the enclosure, most of the intertidal areas became either permanently submerged or exposed. The brackish tidal areas have disappeared completely. The remaining freshwater intertidal areas declined further, due to the erosional power of wind and waves. Consequently, only a few hundred hectares of freshwater tidal area remain 20 yr after

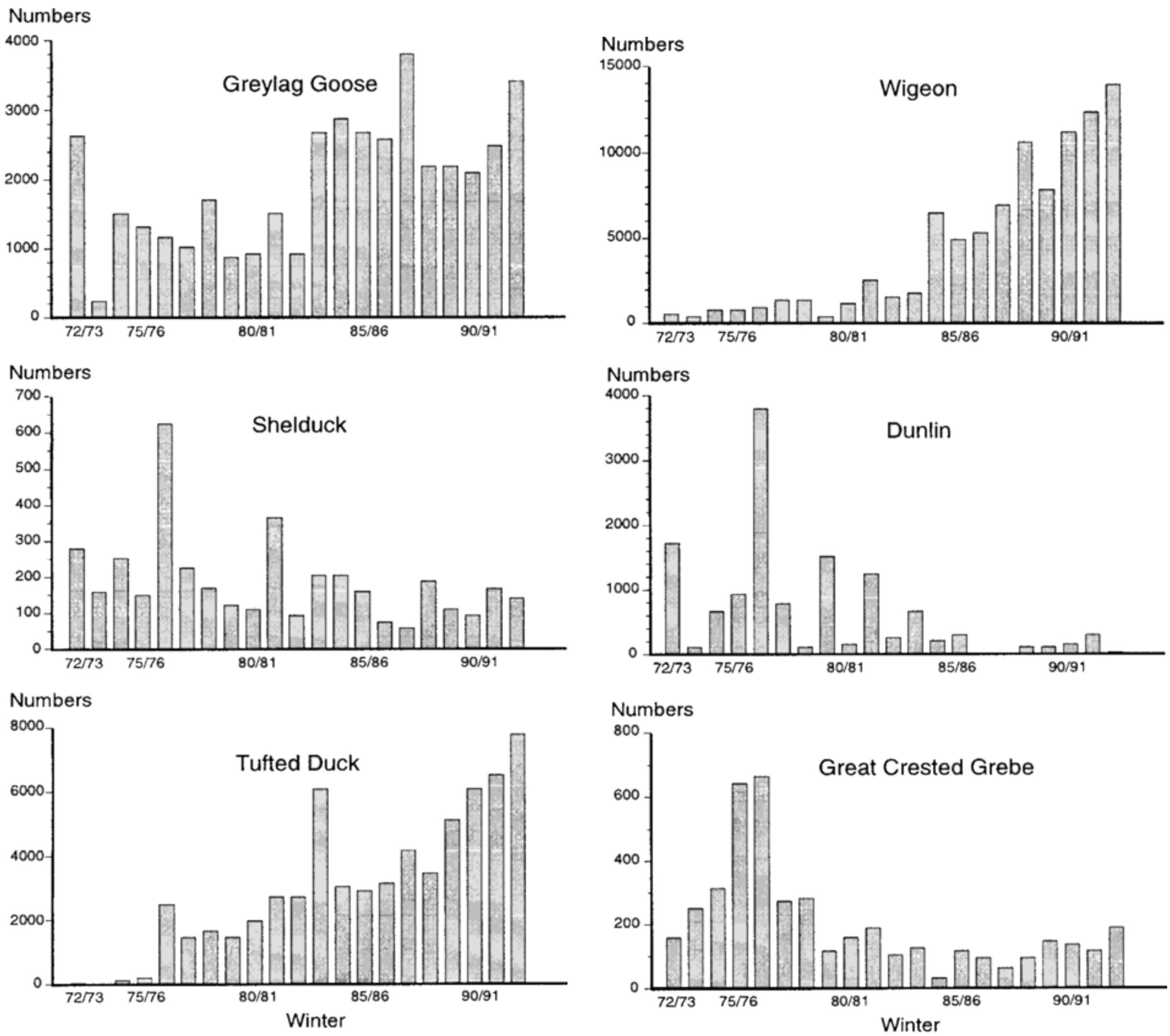

Fig. 9. Numbers of a selection of bird species between 1972 and 1992 in the Haringvliet and Hollandsch Diep area. Numbers are averages of monthly counts from October to March. For methodological details see Boudewijn and Mes (1986). Data courtesy Province of Zuid-Holland.

enclosure. Both the freshwater and brackish intertidal areas were of international importance (e.g., for migrating water bird species) and their decline or disappearance is regarded as a serious ecological loss.

Increased Flat Formation in the Outer Delta

On the North Sea side of the outer Haringvliet Delta, channels have filled up and new intertidal sandbanks have developed as a result of the decreased tidal currents. These areas also have high natural values, since they harbour large numbers of several water bird species, provide a nursery function for fish, and house a characteristic macroinvertebrate fauna (Rijkswaterstaat 1989).

Disappearance of Nursery Function for Fish

The former estuary had a nursery function for several marine fish species such as sole (*Solea solea*) and plaice (*Pleuronectes platessa*) (Vaas 1968). This nursery function has disappeared and is now restricted to the outer delta.

Disturbance of Fish Migration

Formerly common anadromous fish species have disappeared from the rivers Rhine and Meuse for several reasons. One was the closure of most river outlets. Only the Nieuwe Waterweg, the main shipping route to the industrialized harbour of Rotterdam, constitutes an open connection between the

Rhine and the North Sea. This is not a natural estuary.

The present functioning of the Haringvliet sluices forms an important obstacle to the return of anadromous fish species such as salmon (*Salmo salar*) in the Rhine basin (Van Dijk and Marteijn 1993). When the sluices discharge, current velocities are too high to allow any significant upstream migration. At low Rhine discharges (< 700 m^3 s^{-1}) the sluices are closed and no passage is possible at all.

Recovery of anadromous fish populations depends not only on management of the sluices to permit their passage but also on the restoration of migration routes (fish ladders) and spawning habitats in the upstream rivers, on further improvement of water and sediment quality in the river basins, and on an adequate control of fishing intensities in the North Sea and Atlantic Ocean (De Groot 1990, 1992).

Reduced Mixing of River and Seawater

Before closure, an intensive mixing of river water and seawater occurred in the estuary. The enclosure of the estuaries in the southwest of the Netherlands (the Delta area) has dramatically diminished the rate of mixing. Since the enclosure of the Haringvliet, a larger proportion of the river water flows through the Nieuwe Waterweg, a narrow and deep channel, where conditions for mixing are unfavourable. Consequently, fresh water is now being injected into the North Sea, where most of the mixing with seawater takes place. Laane et al. (1994) showed that the average salinity measured at a group of nearshore stations (< 10 km from the coastline) along the Dutch coast has dropped since 1970, while nutrient concentrations (e.g., dissolved inorganic nitrogen, DIN), have increased (Fig. 10). The increase in DIN concentrations is probably also attributable to the increased nitrogen loads of the rivers Rhine and Meuse. Nutrient-rich river water remains close to the Dutch coast and is transported to the Wadden Sea, a large, internationally important intertidal area in the northern Netherlands. These results indicate that the enclosure of the estuaries in the southwest of The Netherlands, of which the Haringvliet sluices constitute an important component, may have contributed to the existing eutrophication problems along the Dutch coast, including the Wadden Sea.

In conclusion, the present management of the Haringvliet sluices has an impact on the Rhine ecosystem up to central Germany and on the North Sea ecosystem along the Dutch coast, as well as a major impact on the ecosystem of the Rhine-Meuse Delta itself.

Steps Towards Estuary Restoration

Recent Policy and Management Developments

Recent years have seen the publication of a number of national policy documents, emphasizing ecology in physical planning and water management, and a new approach to nature conservation. The National Policy Document on Water Management (Ministry of Transport and Public Works 1989) was the first to include water quantity, water and sediment quality, and ecology in water management. In this document, the Dutch government promised a new policy for the enclosed Rhine-Meuse Delta, including a reconsideration of the management of the Haringvliet sluices. The Rhine Action Programme was adopted in 1987 by the countries along this river (IKSR 1987). It included an agreement on the reduction of discharges, which would improve the water and sediment qual-

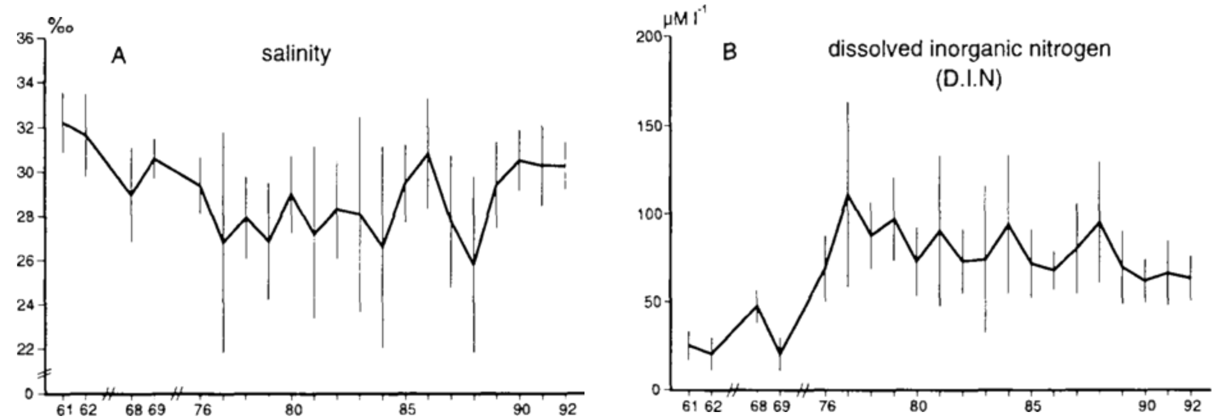

Fig. 10. Annual variation in salinity (‰) and dissolved inorganic nitrogen (DIN, μM l^{-1}) during the winter (January–March) in the North Sea from 1961 to 1992. Data are averages (± 1 SD) of a group of localities along the Dutch coast (<10 km offshore). Courtesy Laane et al. (1994).

ity in the enclosed Rhine-Meuse Delta. An ecological objective is the return of anadromous fish species such as the salmon. Numerous measures are presently being taken in the Rhine basin to prepare it for the return of this fish species. The Haringvliet sluices, however, present an important obstacle to the salmon migration route. The Integrated Policy Document on the Haringvliet, Hollandsch Diep, and Biesbosch (IPDH). This document provides an inventory of general properties and functions of this area (Rijkswaterstaat 1990), an analysis of sluice management options and selection procedures (Rijkswaterstaat 1991), and a detailed description of the selected policy for the management of the Haringvliet sluices and the removal of contaminated sediments (Rijkswaterstaat 1994).

These documents have resulted in two concrete policy steps. An Environmental Impact Assessment (EIA) of the Haringvliet sluices started. The national law for water management requires an EIA for proposed changes in water levels greater than 16 cm. Consequently, an EIA was initiated in 1994 by the Zuid-Holland Directorate of Rijkswaterstaat, the authority responsible for the sluice management. It will result in a final report by 1997. Removal and storage of contaminated sediments. Studies for the IPDH have shown that modified sluice management would remobilize contaminated sediment and transport it to the North Sea. This was widely considered unacceptable, therefore, the most contaminated sediments must be removed before sluice management can be changed.

The possibilities for removal of contaminated sediments from the Rhine-Meuse Delta are now under study. A study of the Nieuwe Merwede has recently been completed (Rijkswaterstaat 1992; Den Besten 1993), while a study of the Hollandsch Diep has been initiated and studies of the Haringvliet and Biesbosch began in 1995 and 1997 respectively. The actual removal is expected to start in 1997 and last about 20 yr. A large-scale sludge disposal that could store about 30 million m^3 of contaminated sediment has been proposed for the centre of the basin, the western Hollandsch Diep.

Management Alternatives

In the IPDH, various sluice management alternatives were studied: from continuing the present management to opening the sluices and using them as a storm surge barrier only. Three alternatives are presented here to describe the full range of alternatives (Rijkswaterstaat 1991): 1) the 'present management' alternative, referred to below as HV0; 2) the intermediate alternative, referred to as HV2, and 3) the 'storm surge barrier' alternative, referred to as HV4.

Characteristics of the three alternatives and their impacts on the ecology and various anthropogenic functions have been summarized in Table 2. From an ecological point of view, the storm surge barrier alternative (HV4) is most attractive, since it leads to a true restoration of estuarine conditions and the creation of large areas of very valuable biotopes. The costs, however, are estimated to be very high. The intermediate alternative (HV2) also provides a great increase in valuable habitat but lacks the regularity of estuarine conditions. During low Rhine discharges the sluices close and the area is temporarily managed as it has been until present. In the IPDH, HV2 has been proposed as the preferred alternative, since it combines some profit for nature with reasonable costs to the parties involved. In the EIA the intention is to present a modified version of HV2, an "Ecological alternative." In this alternative the sluices have a smaller opening (about 2,000 m^2) and close at lower Rhine discharges (at 1,000 m^3 s^{-1} instead of 1,700 m^3 s^{-1}). This results in less estuarine characteristics but a greater constancy in conditions. This will probably be the new preferred alternative of Rijkswaterstaat, but this depends on political decisions of the joint actors involved.

Discussion

Significance of Estuary Restoration

Since the Rhine-Meuse estuary connects the Rhine and Meuse rivers to the North Sea, its management is highly relevant to the rehabilitation programs of these large rivers (the Rhine Action Programme, IKSR 1987) and the North Sea (North Sea Action Programme, (ICONA 1986). The severe degradation of the estuarine ecosystem over the last 25 yr is hampering the completion of both action programs. Good possibilities for the passage of migratory fish species are necessary to meet one of the main objectives of the Rhine Action Programme: the return of indigenous fish species such as the salmon. Better mixing of fresh and salt water in the estuary will help to solve eutrophication problems in the North Sea, a major objective of the North Sea Action Programme. Moreover, an estuary can be considered as a large-scale nutrient filter (Kennedy 1984). Both chemical and biological processes contribute to this filter function. The mixing of fresh and salt water enhances flocculation of suspended matter and hence the removal of phosphate. In the same zone, denitrification at the sediment-water interface can remove a significant part of the nitrogen load (cf., Admiraal and Botermans 1989). Extensive surfaces of highly productive helophyte stands and a high intertidal macroinvertebrate biomass production may also en-

TABLE 2. Characteristics of three management alternatives of the Haringvliet sluices. Surface areas of biotopes denote areas which have the potential for development as such. MHW: mean high water level; MLW: mean low water level; mfl: million guilders (1 guilder = 0.6 US $).

Sluice Management Alternative	Present Management HV0	Intermediate HV2	Storm Surge Barrier HV4
Physical characteristics			
Mean tidal range (m)	0.3	0.55–0.95	1–1.4
Tidal movement	restricted	larger but irregular	largest and regular
Average period of salt water inlet (months)	0	6	12
Salt intrusion up to	sluices	Spui-river	Hollandsch Diep
Water and sediment quality in the area	poor	intermediate	good
Mobility of contaminated sediments	little	limited	considerable
Important biotopes (km^2)			
Brackish marshes	0	3.5	4
Reed, weed vegetation and grassland from MHW to dike	43	46.5	39
Helophyte stands (reeds and rushes)	16.5	15.5	18
Softwood floodplain forest (*Salix*)	5	8	5
Hardwood floodplain forest	30	35	25
Intertidal area (MLW–MHW)	10.5	19.5	32.5
Submerged waterplant vegetation (MLW–75 cm–MLW)	16.5	7	8.5
Functions			
Navigational depth	unchanged	some reduction	reduction at Volkeraksluices
Conditions for fisheries	poor	intermediate	good
Recreation, adaptation costs	0	4.2	6.8
Swimming water quality	poor	intermediate	good
General attractiveness	unchanged	slight increase	increase
Costs (million Dutch guilders)			
Adaptation costs Haringvliet sluices	0	18	18
Agricultural compensation costs	0	52–176	909
Drinking water compensation costs	0	18	103–123

hance the storage and internal cycling of nutrients and organic matter, thereby reducing the discharge of these constituents into the North Sea. High biomass productivity in estuaries increases natural values at the higher trophic levels. High biomass production in helophyte stands promotes sedimentation, retention, and succession of vegetation, leading to a higher diversity of estuarine wetlands. Both plant and macrozoobenthos production may feed increased numbers of water birds. High macroinvertebrate biomass enhances the function of the estuary as a nursery for marine fish species. The intertidal areas in the entire delta area have a very important function as a feeding site for migrating birds and as a wintering site for birds breeding in Northern Europe.

If the Rhine-Meuse Delta is to be managed as an estuary, the 'storm surge barrier' alternative (HV4) is the only valid option. Only HV4 offers a considerable and regular exchange of tidal volumes, a large intertidal area, and a constant tidal rhythm. These factors are essential for the existence of estuarine communities. In contrast, the intermediate alternative (HV2) is less ecologically attractive than it would appear from the biotope surfaces created. HV2 is not merely an intermediate between a continuation of the present management (HV0) and the 'storm surge barrier' alternative (HV4); regular tidal movement is completely lacking, since the sluices close at low Rhine discharges. The duration of sluice closure under HV2 is far too long for most intertidal species to survive, and during this period fish migration is blocked.

The Path to Restoration

If the estuary is to be restored, it should be done as soon as possible, before irreversible processes including geomorphological changes and the extinction of relict species have proceeded too far. On the other hand, the problem of polluted sediments must be solved first, so as to prevent their spread. The costs of removing the contaminated sediments are very high: 125 million US $ to remove all class 4 sediments (the category of most polluted sediments) and about 400 million US $ to remove all class 3 and 4 sediments. Thanks to the sluices, however, the contaminated sediments have not spread into the North Sea, which has created the possibility of removal or in situ treatment. The ideal restoration pathway would involve si-

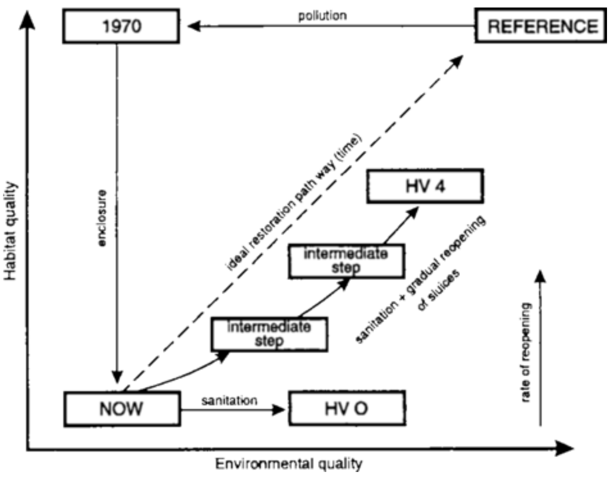

Fig. 11. Conceptual model of the pathways of ecosystem degradation including pollution and habitat destruction, and of possible restoration including the removal of polluted sediments (sanitation) and a stepwise reopening of the sluices.

multaneous approaches to both the habitat and the pollution problems (Fig. 11). Investing in one without the other will lead to less than optimal returns. Hence, the polluted sediment removal programme should be followed as soon as possible by gradual opening of the sluices, ultimately ending with a complete opening (HV4). Simultaneous progress on both problems can be regarded as the pathway to sustainable development; it develops the area in a sustainable way by working with the natural processes rather than against them.

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