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Estuarine management strategies and the predictability of ecosystem changes

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Abstract. The Dutch Delta Region (S-W Netherlands) originally consisted of interconnected estuaries, interfacing the rivers Rhine, Meuse and Schelde with the North Sea. The ecosystems were immature, with physical rather than biological control of population dynamics. Main functions were shipping and shellfisheries. An emergent function of the interconnected estuaries was the buffering and upgrading of riverborne substances before they entered the sea.

Execution of the Delta Project in the period 1960-1986 resulted in isolation of several water systems disconnected from rivers and sea, and loss of gradients within these systems. Population dynamics were now controlled by chemical and biological rather than physical factors. Vulnerability to external perturbation increased. These changes also affected the buffering capacity, i.e. reduced the utility of the area as stabiliser of the geosystem. Recreational use and appreciation of natural values increased, potentially conflicting with shipping and shellfisheries.

Retrospective analysis of the environmental policy and management revealed three consecutive strategies in the Delta Project. 1. Reactive one-issue management, focusing on safety against flooding only. This strategy aimed at complete closure of the estuaries thus transforming them into fresh water lakes. It has destroyed feed-backs and buffering between coastal and inland waters. This strategy has not promoted sustainable development and has increased the vulnerability of the area to future catastrophes. 2. Protective bio-ecological management focused on the preservation of existing values of landscape and environment, and resulted in the maintenance of saline conditions and preservation of marshes by shore protection measures. The drawback of this passive orientation to existing values Ôwhere they are nowÕ is the necessity of continuous intensive care because the natural adaptive ability is not being restored. 3. Constructive geo-ecological management is based on understanding functional properties within and between ecosystems as integrated elements of the landscape structure. This strategy aims at environmental protection, restoration and development of values Ôwhere they must beÕ. Re-establishment of gradients by e.g. re-introducing tidal influence and by restoring salt marshes should contribute to sustainable development.

Keywords: Delta region; Nitrogen budget; Shell fishery; Socio-economic function.

Introduction

The Dutch Delta region is created by the rivers Rhine, Meuse and Schelde and interfaces these rivers with the southern North Sea. Like most delta-estuarine environments, this region represents open interconnected estuaries with dynamic gradients between riverine and marine systems, and different ecotopes such as salt marshes, tidal flats, shallow subtidal areas, gullies and artificial rocky shores. These gradients and ecotopes represent a carrying capacity (i.e. the ability of the ecosystem to offer food and habitat) for a variety of populations, and for other functional ecosystem characteristics such as:

1. system productivity, supporting e.g. fish nurseries, shellfish cultivation and nourishment of waders and coastal breeding birds;
2. transformation capacity through mass cycling, supporting retention and removal of river borne substances and the upgrading of terrestrially derived organic material;
3. the combination of productivity and ecotope diversity, supporting estuarine biodiversity.

Because of these functional characteristics, estuaries are important areas with regard to environmental values, recreation, fisheries, shipping, waste discharge etc.

On February 1, 1953, a northwesterly storm breached 180 km of coastal defences in the Dutch Delta region and flooded 160 000 ha of polderland. The catastrophe caused 1835 casualties and inundated most of the region. The Delta Project, formalized in 1957 by an act of law, was formulated as an answer to the continuous risk of flooding in this low lying region. The core of the Delta Project called for the closure of the main tidal estuaries and inlets, except for the Westerschelde where the existing dikes were raised to allow continued shipping access to Antwerp.

In the original plan the complete closure of estuaries was envisaged, thus transforming them into stagnant lakes filled with fresh water originating from the river Rhine and Meuse. These freshwater reserves were

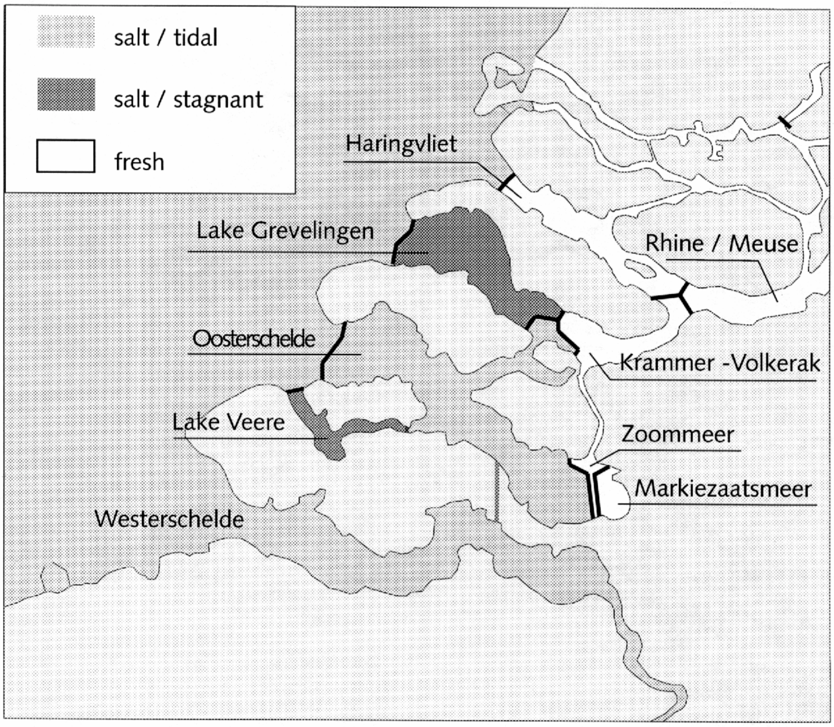

Fig. 1. The Delta region with various water systems resulting from the Delta Project.

planned to be used for irrigation of agricultural land. However, throughout the 1960s and 1970s environmentalists stirred public awareness for the need to protect marine natural resources in the region, including an extensive shellfish industry. This resulted in the decision to maintain saline conditions in Lake Grevelingen. For the Oosterschelde, a compromise solution was finally accepted after several years of desk studies and public debate: a storm-surge barrier. The barrier guarantees protection against flooding while still allowing the tide to enter the estuary freely, thus safeguarding the tidal marine ecosystem. Fig. 1 shows the region after completion of the Delta works. The engineering scheme resulted in stagnant fresh water lakes (Krammer-Volkerak, Zoommeer, Markizaatsmeer) partly connected to the regulated river mouth of Rhine and Meuse (Haringvliet), a stagnant brackish lake (Lake Veere), a stagnant saline lake (Lake Grevelingen), a saline bay with reduced tide (Oosterschelde) and one remaining estuary (Westerschelde).

The Delta Project has fundamentally changed the hydraulic, morphological and ecological characteristics of the region. The overall change can be summarized as the loss of dynamic gradients. The open and interconnected estuaries interfacing rivers and sea were replaced by isolated lakes and lagoons, disconnected from rivers and the sea. Gradients were replaced by discrete boundaries. Within these new physical boundaries new ecosystems developed with different characteristics. Some of these characteristics were expected or designed, others arose by coincidence. Moreover, the new management aims which were established for nature conservation, recreation and fisheries and the consequent developments required intensified management of the area.

In this paper we present a retrospective analysis of the Delta Project as a case study of estuarine management, focusing on:

- the characteristics of the different water systems evolving from the project: predicted and unpredicted events as a result of changes from natural water systems to man-made and managed systems;
- the utility of the different systems and the region as a whole: which functions disappeared or became less important, and which functions were new or increased in importance;
- evaluation of management: achievements, failures and challenges.

The analysis is restricted to the southern part of the region with remaining influence of the sea, i.e. the two brackish-saline lakes (Lake Veere and Grevelingen), the bay with reduced tide (Oosterschelde) and the Westerschelde estuary.

Methods

Four water systems in the southern part of the region with remaining marine influence are considered on the basis of model analysis and a literature review. The hydrographical and hydrochemical characteristics of the water systems are summarized in Table 1.

Lake Grevelingen

Lake Grevelingen was disconnected (by dams) from the rivers Rhine and Meuse in 1964 and from the North Sea in 1971. The connection with the North Sea was partly re-established in 1978 by means of a small exchange sluice, which is opened during winter to prevent salinity stratification. The restricted flushing with sea water has reduced the flushing time (or water residence time) of the lake to its present value (Table 1). The bathymetry, with large shallow areas and several deep gullies, reflects the estuarine origin: approximately 60% of the area has a depth of less than 2.5 m. The freshwater input from polders is small compared to the volume of the lake. Nutrient input is small because of the almost complete hydrological isolation from rivers and surrounding polders. The total nutrient input, presented in Table 1, includes atmospheric deposition. The lake has developed into an oligotrophic ecosystem with high water transparency. Phytoplankton concentrations generally are low (chlorophyll-a rarely exceeds 10 µg/l) and macrophytes, dominated by eelgrass (*Zostera marina*), cover the shallow areas.

Oosterschelde

The storm-surge barrier was constructed between 1979 and 1986 in the western mouth of the estuary. The auxiliary dams in the rear end of the estuary Ð the Oesterdam in the east and the Philipsdam in the northern branchÐ were built between 1977 and 1987. These dams separated the saline bay from the freshwater inflow. The hydrodynamics of the bay are dominated by the tidal influence of the North Sea, although the tidal volume has decreased by 30 % and the tidal amplitude by 12 % compared to the pre-barrier situation. The fresh-water input from the surrounding polders is small, resulting in a relatively high salinity, absence of salinity stratification and low nutrient input. The surface area of intertidal flats decreased by 36 % and the area of salt marshes, mainly situated in the rear end of the former estuary, by 63 %. Water transparency increased because of reduced current velocities, especially in the eastern and northern branch. Phytoplankton concentrations are relatively low, with occasional peak values of chlorophyll-a exceeding 20 µg/l.

Lake Veere

Lake Veere originated in 1960-1961 after isolation from the adjacent Oosterschelde estuary and the North sea by dams (Fig. 1). The water level is controlled by water exchange with the Oosterschelde estuary through the ship-lock in the eastern dam. The lake is small and shallow. As in Lake Grevelingen, the former intertidal and shallow subtidal areas comprise at least 50 % of the area of the lake. During winter the lake receives excess water from the surrounding polders. To facilitate this function, the water level is artificially maintained at 0.7 m below mean sea level during winter, reducing the water surface area to 18 km^2. As a consequence, the hydrology of the lake is dominated by the input of fresh water which causes a strong and almost permanent salinity stratification in parts of the lake. The freshwater input also results in a considerable nutrient input due to the agricultural use of the polderland. Conditions in the

Table 1. Hydrographical and hydrochemical properties of Lake Grevelingen, Oosterschelde, Lake Veere and Westerschelde.

	Lake Grevelingen	Ooster-schelde	Lake Veere	Wester schelde
Area (km^2)	108[a]	351[b]	21[a]	300[a]
Volume ($m^3.10^6$)	575[a]	2750[b]	89[a]	n.d.
Average depth (m)	5.4[a]	7.8	4.2[a]	n.d.
Flushing time (days)	180-360[a]	20-60 [b]	180[a]	30-90 [a]
Salinity (ä)	30-33 [a]	25-31 [b]	15-25 [a]	12-33 [f]
Fresh water load (m^3/s)	5[a]	25[b]	3[a]	120[f]
Average tidal amplitude (m)	-	3.25[b]	-	3.82[f]
Extinction ($m^{Ð1}$)	0.2-0.5 [a]	0.4-1.5 [a]	0.3-1.4 [a]	0.5-7.0 [a]
N-total input ($g/m^2/yr$)	4.5[c]	9.5[a]	35[d]	263[e]
P-total input ($g/m^2/yr$)	0.4[c]	n.d.	6[d]	n.d.
N/P ratio of input (by atoms)	25	n.d.	13	n.d.

[a]Nienhuis 1993; [b]Nienhuis & Smaal 1994; [c]de Vries et al. 1988a; [d]de Vries et al. 1990; [e]de Vries et al. 1988b;[f] CadŽe 1994; n.d. = not determined.

lake are eutrophic with dense phytoplankton blooms (spring chlorophyll-a exceeds 100µg/l), excessive growth of macrophytes (*Ulva* spec.) and prolonged oxygen depletion in the bottom water layer below 6-10 m.

Westerschelde

The Westerschelde is the only remaining real estuary in the region. The tidal influence from the sea and the freshwater flow from the Schelde cause large and dynamic gradients in salinity, turbidity and nutrient concentrations. Freshwater input is large compared to other water systems in the region, but compared to other European estuaries the riverine influence is small. The estuary number (ratio of average river discharge per tidal cycle and tidal volume) is 0.25% for the Westerschelde, compared to 2.5 - 7.5% for the Elbe, Loire and Gironde (CadŽe 1994). The estuary is in a morphological non-equilibrium state due to continuous dredging activities necessary to maintain the required depth in the shipping lane to Antwerp. From the Schelde river the estuary receives a high nutrient load, 1-2 orders of magnitude higher than the other water systems in the region. The Westerschelde is completely mixed and has a high turbidity. As a consequence, primary production and chlorophyll-a levels are low (Kromkamp et al. 1992).

Mass balance analysis

The mass balances of the four water systems were quantified by means of a descriptive model analysis, resulting in annual carbon and nutrient budgets. Existing applications of ecological models have been used for this purpose (Anon. 1990; de Vries et al. 1988a, 1990; Klepper et al. 1994; van der Tol & Scholten 1992; Soetaert et al. 1992). Each model consists of a transport module and an ecological module. The transport module deals with the transport of dissolved and suspended substances between the computational elements (model segments) in one, two or three directions. Within each computational element, the ecological module describes the most important processes between substances and functional groups of organisms.

Schematization of Lake Veere resulted in 18 segments in horizontal and vertical directions, including nine water segments which allowed a distinction between shallow and deeper parts, and water layers above and below the halocline. Each water segment had an adjacent bottom segment. Information on the hydrodynamical environment was obtained from a detailed stratification model (Bollebakker & van de Kamer 1989). Schematization of Lake Grevelingen resulted in 11 model segments in horizontal and vertical directions. Four water segments and seven benthic segments were distinguished. All mass transport by water movement was formulated as dispersive transport because of wind driven circulation and absence of stratification. The Oosterschelde was schematized into four segments in horizontal

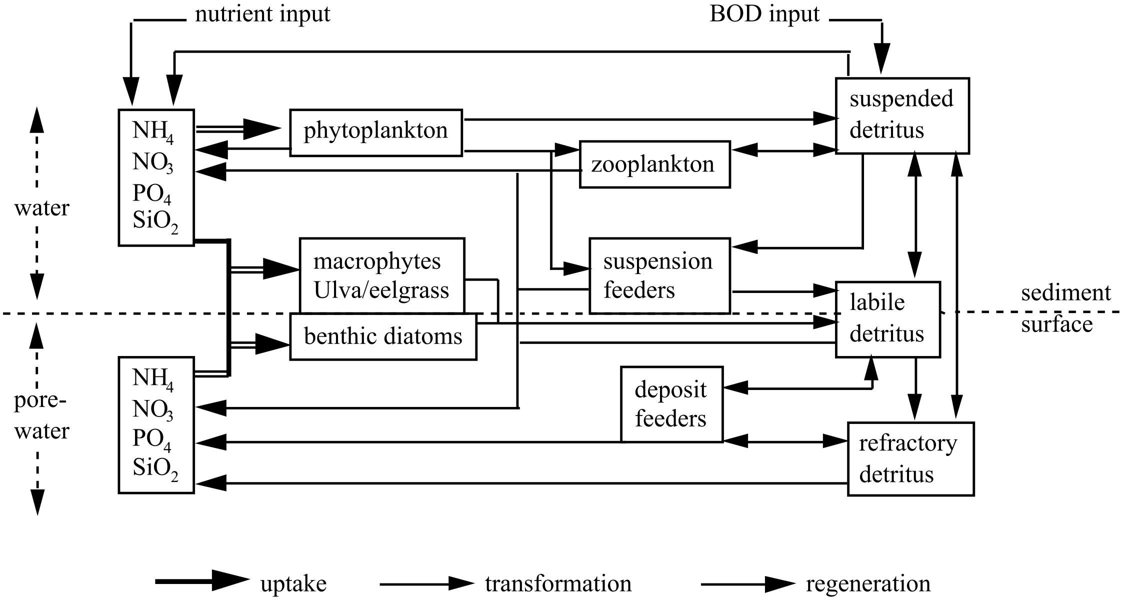

Fig. 2. State variables and processes in the ecological models. BOD input = input of oxygen-demanding substances.

Table 2. Simplified equations of the state variables of the ecological models.

State variable	Equation
Primary producers:	
Phytoplankton	dX/dt = prd-exc-mor-gra-sed
Microphytobenthos	dX/dt=prd-mor-gra-res-bur
Macrophytes	dX/dt=prd-mor
Consumers:	
Zooplankton	dX/dt=gra-exc-fae-mor
Suspension feeders	dX/dt=gra-exc-fae-mor
Deposit feeders	dX/dt=gra-exc-fae-mor
Detritus:	
Suspended detritus	dX/dt=mor+fae+res-gra-min-sed
Labile detritus sediment surface	dX/dt=mor+fae+sed-gra-min-res-bur
Bottom detritus	dX/dt=bur-gra-min
Dissolved nutrients - water	
Nitrate	dX/dt=inp+nit-den-prd ±exh
Ammonium	dX/dt=inp-nit+min+exc-prd ±exh
Phosphate	dX/dt=inp+min+exc-prd ±exh
Silicate	dX/dt=inp+min-prd ±exh
Dissolved nutrients - bottom	
Nitrate	dX/dt=nit-den ±exh
Ammonium	dX/dt=min-nit ±exh
Phosphate	dX/dt=min ±exh
Silicate	dX/dt=min ±exh

Legend:
prd = primary production
exc = excretion (producers and consumers)
mor = mortality
gra = grazing
fae = faeces and pseudofaeces biodeposition
min = mineralization
sed = sedimentation
res = resuspension
bur = burial
inp = input of nutrients (loading)
nit = nitrification
den = denitrification
exh = sediment/water exchange

directions only, without separate bottom segments. Mass transport was formulated as tidally averaged advective transport and dispersive transport. The Westerschelde was divided into 18 segments which allowed representation of longitudinal concentration gradients. Mass transport was described with tidally averaged advective and dispersive transport.

The choice of state variables in the ecological models was based on their estimated involvement in mass cycling (Fig. 2). Only functional groups of organisms which contributed more than 10 % to the total mass flow (or total pool size of organic carbon and nutrients) were distinguished in the model. Consequently, organisms at higher trophic levels such as birds and fishes and other organisms with a low biomass such as benthic meiofauna and epibenthic crustaceans were not incorporated in the model analysis. Some of the variables were not incorporated as prognostic state variables but imposed as forcing functions derived from empirical data. This was the case for benthic primary consumers as well as for eelgrass and *Ulva* spp. in Lake Grevelingen and Lake Veere. Table 2 lists the simplified budget equations for the state variables. Processes such as denitrification, which directly influences mass balances by taking nitrogen out of the system, have been emphasized in the model development and application. In addition to state variables and processes depicted in Fig. 2 and Table 2, an oxygen balance was included in the models. Further details, parameter values and calibration/validation results are given in the references listed above.

Results

Ecosystem characteristics and expectations

The four water systems responded differently to changes imposed by the Delta Project. The most obvious changes to be described focusing on (1) productivity, (2) habitats and biodiversity and (3) transformation capacity.

Productivity

In Lake Veere, increased transparency and high nutrient input stimulate primary production by pelagic phytoplankton as well as by benthic diatoms and macrophytes. The long water residence time and permanent stratification has turned the lake into a system susceptible to eutrophication. Chlorophyll concentrations are high and cannot be controlled by pelagic and benthic grazers, and the consequent deposition of organic material on the bottom has extended the anaerobic sediment surface to more than 25 % of the bottom area. As a result of eutrophication eelgrass (*Zostera marina*) has been replaced by macroalgae (*Ulva* spp.).

Lake Grevelingen has a low nutrient input, and the low phytoplankton biomass is controlled by benthic suspension feeders. Due to the high turnover of available nutrients, expressed as a high cycling index (7/yr; see Table 3), there is still considerable primary production supporting normal levels of secondary and tertiary production. Prolonged periods of warm and stable weather may cause temperature stratification due to water stagnancy and the estuarine bathymetry with deep gullies. Despite the low nutrient input, stratification events may cause oxygen depletion reaching more than 5 % of the bottom area, as occurred in 1993 and 1994.

Primary and secondary production in the Oosterschelde has not significantly changed after construction of the barrrier and auxiliary dams. Transparency increased and nutrient availability decreased, especially in the inner parts of the bay (Wetsteijn & Kromkamp 1994). East-west gradients in transparency, nutrient concentrations, biomass and production levels of primary and secondary producers disappeared or even reversed. The system showed functional stability, or homeostasis, due to changes in phytoplankton species composition and extension of the growing season (starting earlier and ending later) without the original gradual transitions (Bakker et al. 1994). Biological control increased through increased grazing pressure by zooplankton (from 10 % to 30 % of primary production, van der Tol & Scholten 1992; Tackx et al. 1994), keeping phytoplankton summer biomass at low levels (Bakker & Vink 1994). Decreased physical control and increased transparency increased the percentage of benthic diatoms contributing to total primary production (from 16 % to 30 %, de Jong et al. 1994a). The shift from physical to chemical and biological control was also evident in the factors governing shellfish production (van Stralen & Dijkema 1994).

In the Westerschelde, autochthonous primary production is low due to light limitation caused by high turbidity. Probably a significant part of secondary and tertiary production is based on terrestrially derived organic matter carried into the estuary by the river. This material is processed and upgraded by bacterial activity, which is especially high in the brackish region of the estuary (Goossen et al. 1992). Also, the hyperbenthic mysids, occurring in high densities in the turbid brackish water zone, are probably direct grazers on the imported organic matter (Mann 1988). The mysids are consumed by fish and shrimp and may well be a characteristic link between river borne detritus and higher trophic levels in the estuarine foodchain (Mees et al. 1992).

We can conclude that changes in productivity were generally smaller than expected because adaptive or structural changes buffered the functional response. Physical limitations to primary as well as secondary production were replaced by chemical limitations and biological control. Susceptibility to eutrophication increased in the stagnant water systems, even when nutrient input was low.

Habitats and biodiversity

In Lake Veere and Grevelingen, as well as in the other northern and eastern water systems in the region, exclusion of the tidal influence caused loss of intertidal areas and periodically flooded salt marshes. The temporary reduction of the tidal range in the Oosterschelde during construction (by 35 % over 18 months) and the permanent tidal range reduction by 12 % caused serious erosion of intertidal areas and salt marsh edges, a process which continues today. The overall tendency is a decrease of smooth gradients (de Jong et al. 1994b).

The benthic fauna shows a resilient response to these changes, which could be explained by the tolerance of species to environmental variation and by the fact that estuarine benthic populations are nonequilibrium communities (Meire et al. 1994a). However, other populations are seriously affected. The morphological and hydraulic changes have caused considerable habitat loss for waders and coastal breeding birds. The carrying capacity for overwintering intertidally foraging waders is probably determined by bird density and availability of food (Meire et al. 1994b). Maximum density of overwintering waders is remarkably constant at ca. 10-12 individuals/ha intertidal area in a variety of estuaries (Oosterschelde: Meire et al. 1994b; Westerschelde, Humber, Mersey, Dee: CadŽe 1994). The density of intertidal foragers is close to carrying capacity in the Delta region. Consequently, numbers declined proportional to habitat loss (Meire et al. 1994b).

Increased transparency and decreased current velocities promoted the development of benthic macrophytes in Lake Veere and Lake Grevelingen. In the oligotrophic Lake Grevelingen eelgrass (*Zostera marina*) dominates; in eutrophic Lake Veere eelgrass is replaced by a comparable standing stock and production of macroalgae (*Ulva* spp., de Vries et al. 1995). Colonization and extension of eelgrass to 20 % of the area in Lake Grevelingen until 1989 was followed by an unexpected decline to near extinction in the 1990s. The most probable cause of this example of unpredictable behaviour in a ÔmanagedÕ ecosystem is the hypersalinity due to consecutive years with warm and dry summers, in combination with shortage of silicon due to diversion of polderwater discharges (pers. comm. de Jong).

Zostera and *Ulva* areas are the new habitats in the region for a variety of herbivorous birds, notably swans, geese and dabbling ducks (Meire et al. 1989). Increased transparency, together with a shift in fish fauna to smaller species, has led to a considerable increase in diving piscivorous birds. Waders nearly disappeared from the lakes (Meire et al. 1989).

In conclusion, hydraulic and morphological changes caused significant loss of habitats, which still continues due to the morphological non-equilibrium state of the newly created water basins. Some communities show resilient responses, notably the benthic fauna. Numbers of benthivorous bird species, mainly waders, declined proportionally to habitat loss because their density was close to carrying capacity. Also, new habitats were created which increased the diversity of herbivorous and piscivorous bird species in the Delta.

Transformation capacity

The overall characteristics of modelled nutrient cycling in the four water systems are illustrated by the annual nitrogen budgets in Table 3, which compares external balances and internal cycling. The total annual uptake of nitrogen by primary production as calculated by the models illustrates the intensity of internal cycling through the biological components. The differences in cycling intensity between the four water systems are smaller than the differences in external input, except for the Westerschelde. The concept of new and regenerated production, originally formulated by Dugdale & Goering (1967) is applicable to this cycling intensity. Dugdale and GoeringÕs definition is based on the chemical distinction between nitrogen sources:

¥ new production, i.e. production based on nitrate as nitrogen source;

¥ regenerated or old production, i.e. production based on ammonium as nitrogen source.

For the pelagic oceanic ecosystem, the ratio of old versus new production can be interpreted as an index of the number of times nitrogen cycles before being exported from the upper water column as particulate nitrogen. On the shelf at the middle Atlantic Bight, nitrogen cycles twice on average before sinking (Harrison et al. 1983). This original definition, however, cannot be applied to shallow coastal ecosystems such as tidal bays and estuaries because (1) external input from land runoff and rivers consists partly of ammonium (see also Wassmann 1986) and (2) the pelagic subsystem cannot be considered independent of the benthic subsystem, due to the strong interaction between sediment and water. We therefore propose the following definition:

¥ new production is the production based on the external input of nitrogen;

¥ old production is the production based on pelagic and benthic regeneration of nitrogen, i.e. internal input or loading.

The cycling index (Table 3) is based on this definition, and is defined as the ratio of uptake by primary producers and external input. When comparing the four water systems, this cycling index shows a strong inverse relation with the external input per unit volume.

The external input of nitrogen per unit area into the four water systems is different by about two orders of magnitude. Nitrogen input in Lake Grevelingen is balanced by removal through denitrification and retention in refractory detritus. This results in lower DIN concentrations than in the adjacent coastal zone of the North Sea, which in turn results in a small net import of nitrogen through water exchange with the North Sea. The nitrogen removal calculated for the Oosterschelde is comparable, taking into account the larger water exchange with the North Sea, levelling the nutrient concentrations.

Nitrogen removal calculated for Lake Veere and Westerschelde compensates for only part of the external input. As a consequence, average DIN concentrations of these water systems are higher than in the North Sea, resulting in export of a significant part of the input.

The efficiency of nitrogen removal by denitrification increases at longer water residence time (Nielsen et al. 1995) and is based on two pathways:

¥ Direct denitrification of nitrate after diffusion into the anaerobic layers of the sediment. In the upstream parts of the Westerschelde with near anoxic conditions, denitrification probably occurs essentially in the pelagic realm (Soetaert et al. 1992). This pathway is important at high nitrate concentrations, i.e. in the Westerschelde (with a calculated efficiency of 25 % of the input) and partly in Lake Veere, and is promoted by anaerobic conditions.

¥ Denitrification coupled to organic matter cycling, determined by the organic matter flux through the sediment in combination with the efficiency of the coupling ammonification - nitrification - denitrification. The removal efficiency of this pathway increases with higher turnover (cf. cycling index in Table 3) and benthic-pelagic coupling via an aerobic sediment top layer.

The efficiency of nitrogen removal via these pathways is higher than for phosphorus removal. The phosphate buffer mechanism (Froelich 1988) may control dissolved concentrations in the low salinity and turbid upper region of estuaries by interaction with sediment and suspended solids. However, release at the seaward

Table 3. Modelled nitrogen budgets of four water systems (units gN/m^2/yr). Cycling index is the ratio of uptake by primary producers and external input.

	Lake Grevelingen	Oosterschelde	Lake Veere	Westerschelde
External balance:				
External input	4.5	9.5	35	263
Net export	Ð 0.5	3.0	18	197
Denitrification + retention	5	6.5	17	66
Internal cycling:				
Uptake primary producers	32	35	72	7
Cycling index	7.1	3.7	2.1	0.03

end by increasing pH and salinity and release from reducing sediments may increase concentrations (Balls 1994; Conley et al. 1995). Consequently, estuaries tend to reduce the high N:P ratios (> 20) occurring in fresh waters and polluted rivers to low N:P ratios (< 16) which are normal for the marine environment. This transformation capacity is underexploited in the water systems in the Delta area, which were isolated from the rivers.

Changes in socio-economic functions

The implementation of the Delta Project caused changes in the functions of the water systems in the Delta region; some functions were lost or decreased in importance, others arose or became more important (Table 4). One has to bear in mind that concomittant socio-economic changes ocurred, especially increased recreational demand and environmental awareness.

The function of river water discharge almost disappeared from the Delta region proper since river water has been diverted to the north. Fisheries and shellfisheries decreased in area, but increased in intensity (Smaal & Nienhuis 1992). Protection against flooding, recreation and nature reserve areas are the main new functions.

Conflicts between functions arise more frequently in the new situation, for example the increased competition for shellfish between waders (particularly oystercatchers) and commercial exploitation by man. This is caused by increased shellfisheries, the large and unpredictable natural variability of wild shellfish stocks, and the decreased carrying capacity for waders due to the reduced surface area and foraging time on the tidal flats (Smaal & Nienhuis 1992).

Discussion

Comparison of the Delta region before and after the establishment of the Delta Project reveals the following main findings:

1. Functional stability or homeostasis with respect to productivity, due to partly unpredictable adaptive or structural responses.
2. Significant loss of estuarine habitats, gradients within and between water systems, and resulting biodiversity; partly compensated by ÔnewÕ non-estuarine biodiversity.
3. Loss (underexploitation) of transformation capacity for river-borne substances.
4. Loss of robustness and resilience, i.e. increased vulnerability or susceptibility to external perturbation.

These four findings are discussed below with regard to estuarine environmental policy planning and management. In retrospect, three consecutive management strategies can be discerned, leaving their scars in the landscape and the utility of the Delta.

Reactive one-issue management

The first stage of the Delta Project focused on safety only: disastrous flooding Òshould never happen againÓ.

Table 4. Socio-economic functions of the water systems in the Delta Region before and after the establishment of the Delta Project. The water systems are arranged according to the phasing of the project (years are indicated).

	Before Delta Project	After Delta Project
Lake Veere (1961)	Polder water discharge (fisheries)	Safety Polder water discharge Recreation (Fisheries)
Haringvliet (1970)	River water discharge	Safety River water discharge recreation Fresh water supply
Lake Grevelingen (1971)	River water discharge Shell fisheries (fisheries)	Safety Recreation (Shell fisheries) (Fisheries) Nature reserve areas
Oosterschelde (1987)	River water discharge Shell fisheries Fisheries	Safety Shell fisheries Fisheries Recreation Nature reserve areas
Westerschelde (ongoing)	Shipping River water discharge	Shipping River water discharge

This strategy is reflected in the discharge sluices of the Haringvliet and in the closures of Grevelingen and Lake Veere. These measures have not promoted sustainable development, because buffering feedbacks between coastal and inland waters and natural adaptation processes were destroyed. Loss of robustness and resilience and increased vulnerability are particularly evident in the water systems created in this stage of the Delta Project (Haringvliet, Lake Veere and Lake Grevelingen).

Protective bio-ecological management

In the second stage, protection and conservation of existing, remaining values of landscape and nature were added to the main aim of safety. The decision to maintain saline conditions in Lake Grevelingen, and the decision to built a storm-surge barrier in the Oosterschelde instead of closing this estuary, were based on nature protection arguments. It is not unimportant to say that the transition to this protective management strategy was provoked by increasing environmental awareness in the seventies. This strategy has some serious drawbacks which are apparent in the Delta region. According to Kavaliauskas (1995), the bio-ecological approach focuses on threatened nature values Ôwhere they are nowÕ, without satisfying the actual needs of integrated landscape management. This approach results in isolated subsystems and systems which are not functionally integrated in the landscape. Examples on the subsystem level are the former intertidal areas and salt marshes with artificial shore protection. An example of the system level is Lake Grevelingen. Continuous and intensive management is needed to maintain these isolated natural values. Despite intensive care, these (sub)systems remain susceptible to external perturbation.

Constructive geo-ecological management

The third strategy, constructive geo-ecological management, has not been implemented yet but plans are being formulated and experiments conducted. Ideally, the strategy should be based on the functional relations in the landscape, focusing on protection and on restoration and development of functional natural values Ôwhere they must beÕ (Kavaliauskas 1995). Estuaries are stabilisers of geosystems, they form a natural buffer or filter between upstream rivers and downstream marine environments. To restore this function, gradients should be re-established within the water systems. For example, the envisaged reclamation of salt marshes in Oosterschelde and Westerschelde will intensify the land-sea interactions. Enclosed water systems can be reconnected to the rivers and the sea; therefore sluice manipulation experiments to re-introduce the tide in the Haringvliet and plans to restore river water discharge into the Oosterschelde are currently being carried out. In general, this strategy aims at re-establishment of feedbacks within and between watersystems, contributing to the self-organizing capacity of the geosystem.

Conclusions

Reactive and protective management strategies as applied in the Delta Project have serious drawbacks. They assume predictable functional system responses on implemented measures, whereas in reality responses are often adaptive and unpredictable. The increased vulnerability and loss of resilience which resulted from the Delta Project has even increased the risk of unpredictable system behaviour. Estuarine management should be adaptive in itself, by taking into account the functional position of estuaries in the landscape. The key-issue of future estuarine management is the maintenance of connectivity between upstream rivers, estuaries and the downstream sea.

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