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Management options for restoring estuarine dynamics and implications for ecosystems: A quantitative approach for the Southwest Delta in the Netherlands

Tom Ysebaert [a, b, *], Dirk-Jan van der Hoek [c], Rick Wortelboer [c, d], Jeroen W.M. Wijsman [a], Marijn Tangelder [a], Arno Nolte [d]

[a] IMARES – Wageningen UR, Institute for Marine Resources and Ecosystem Studies, PO Box 77, 4400 AB Yerseke, the Netherlands
[b] NIOZ Yerseke, Royal Netherlands Institute for Sea Research, PO 140, 4400 AC Yerseke, the Netherlands
[c] PBL Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, the Netherlands
[d] Deltares, PO Box 177, 2600 MH Delft, the Netherlands

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ABSTRACT

The Delta Works, a series of dams and barriers constructed in the 1960's–1980's changed the estuarine landscape of the Rhine-Meuse-Scheldt delta (SW Netherlands) into more stagnant and disengaged freshwater, brackish water or saltwater lakes. The remaining tidal systems were adapted by building a storm surge barrier in the Oosterschelde and dike reinforcement works along the Westerschelde. The Delta Works brought protection against flooding, but at the same time resulted in environmental and socio-economic problems, such as degradation of ecological quality and ecosystem functioning, disruption of fish migration routes, water and sediment quality problems.

In this study we explore in an integrated, quantitative way the consequences of a number of management options for the Southwest Delta and their implications for the occurrence and distribution of aquatic and estuarine habitats, considering the mutual coherence between the water basins. Five scenarios were evaluated using a 1D hydraulic, water quality and primary production numerical model and GIS habitat mapping. Scenarios vary from small-scale interventions, such as changes in day-to-day management of hydraulic infrastructures or creation of small inlets in dams, feasible in the short term, to restoration of an open delta by removing dams and barriers, as a long term potential. We evaluate the outcomes in relation to the restoration of estuarine dynamics, as this is in policy plans proposed as a generic solution for the current ecological and environmental problems. Net water flow rates show more complex patterns when connectivity between water basins is increased and when sluice management is less strict. Estuarine transition zones and fish migration routes are partly restored, but only fully develop when basins are in open connection with each other. Area of intertidal habitats, tidal flats and tidal marshes, increases in each scenario, ranging between 7 and 83%, 1–56%, and 8–100% respectively, depending on scenario. Large scale infrastructural adaptations are needed to restore estuarine dynamics at large scale.

The use of a 1D numerical model allowed to quantify the effect of different management measures for all water basins simultaneously, but also has its limitations. The model does not resolve more complex processes such as vertical mixing and morphodynamic changes. This requires expert judgment and more detailed 3D modelling.

1. Introduction

The devastating flood of 1953 prompted the construction of a series of dams and barriers, the so-called Delta Works, in the Southwest Netherlands to protect the Rhine-Meuse-Scheldt delta (Southwest Delta) from North Sea floods (Fig. 1). To achieve the

* Corresponding author. IMARES – Wageningen UR, Institute for Marine Resources and Ecosystem Studies, P.O. Box 77, 4400 AB Yerseke, The Netherlands.
E-mail address: tom.ysebaert@wur.nl (T. Ysebaert).

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Fig. 1. The Southwest Delta (Netherlands) with the main water basins and the main hydraulic infrastructures related to the Delta Works. Numbers indicate locations for which model results are presented: 1) Brienenoord, 2) Puttershoek, 3) Bovensluis, 4) Haringvliet center, 5) Steenbergen, 6) Zoom center, 7) Dreischor, 8) Zijpe, 9) Lodijkse Gat, 10) Hammen Oost, 11) Soelekerkepolder, 12) Hansweert. Except for 4) and 6), locations coincide with current routine monitoring stations.

desired safety levels the coastline was shortened through damming the estuary mouths and through dike reinforcements. Although the Delta Works increased safety against flooding for the local population (Pilarczyk, 2012), the environmental drawbacks are becoming increasingly evident, such as the degradation of ecological quality and ecosystem functioning, disruption of fish migration routes, and water and sediment quality problems (Nienhuis et al., 2002; Smits et al., 2006; van Wesenbeeck et al., 2014). Many of these problems and undesirable side effects result from the impact of these infrastructural measures on the natural processes, such as an imbalance between geometry (e.g., depth, surface area), water flows and its constituents, a disrupted sediment balance and a lack of connectivity (Mulder and Louters, 1994; van Wesenbeeck et al., 2014). Furthermore, the Delta Works split up the estuary into individual water basins of different sizes. As the new ecosystems developed, the estuarine landscape with natural transitions between tidal fresh, brackish and saline waters was replaced by more stagnant and disengaged fresh water, brackish water or salt water lakes (e.g. Saeijs and Stortelder, 1982; Wijnhoven et al., 2010; Paalvast and van der Velde, 2014). Each water basin has specific environmental problems (Table 1) (van Wesenbeeck et al., 2014). These problems also have an impact on socio-economic sectors such as recreation and shellfish aquaculture. Finally, climate change has prompted a reconsideration of the long-term safety measures against flooding in the Netherlands. A general policy movement towards working with natural processes as opposed to hard engineering solutions has paved the way to combine solutions for safety with solutions for environmental problems (Smits et al., 2006; Verspagen et al., 2006; van Wesenbeeck et al., 2014).

Increased awareness of these problems has led to a shift in thinking on management of the Southwest Delta as reflected in integrated water management policy plans launched since the 1990s. Already in the “Vierde Nota Waterhuishouding” (Fourth Memorandum on Water Management) (1998), the policy objective

Table 1
The main water basins in the Southwest Delta, their current characteristics and issues in relation to water quality and ecology.

Basin	Average tide[a] (m)	Salinity range[a] (psu)	Surface (ha)[b]	Issues in relation to water quality or ecology[c]
Northern rivers[d]	1.7–0.8	30–<0.5	7158	Salt intrusion
Biesbosch	0.3	<0.5	8278	Siltation, polluted river sediments
Hollands Diep	0.3	<0.5	4656	polluted river sediments
Haringvliet	0.3	<0.5	10,382	polluted river sediments, connection loss
Volkerak-Zoom	Non-tidal	0.6	7734	Extreme eutrophication, blue–green algae blooms, connection loss
Grevelingen	Non-tidal	28	13,446	Stratification, Oxygen problems, habitat loss
Lake Veere	0.1	25	2437	Oxygen depletion, macro-algae blooms
Oosterschelde	2.5–3.5	30–28	34,856	Morphological imbalance, habitat loss, erosion, invasive species, carrying capacity issues
Westerschelde	3.9–4.8	30–10	31,144	Eutrophication/oxygen, polluted sediments, habitat loss, dredging

[a] The first number in a range is the seaward average, the second number the landward average.
[b] Based on model calculations done in this study.
[c] Adapted from van Wesenbeeck et al., 2014.
[d] Northern rivers include Oude Maas, Nieuwe Maas and Nieuwe Waterweg.

for the Southwest Delta was to restore and strengthen natural processes by means of increased water exchange and gradual transitions between the water basins. This was further elaborated in the Delta Programme (Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2014) to achieve a climate proof, safe, ecologically resilient and socio-economic vital Delta area in the Southwest Netherlands. This programme includes proposals for national Delta Decisions and concrete preferential strategies as a guide to implement measures until 2050. Next to this programme, the central government (Ministry of Economic Affairs, 2014), the provinces (Province Zeeland, 2003; Province Zeeland et al., 2006), and non-governmental organizations (e.g. World Wide Fund for Nature, 2012) work on ambitions for the long term for the Southwest Delta.

In all policy plans, the 'restoration of estuarine dynamics' is a general term used to describe the overall goal for the Southwest Delta as a generic solution for many of the above mentioned environmental problems (Table 1). Natural estuarine ecosystems are complex systems characterized by the dynamic interplay between hydrodynamics, morphodynamics and ecodynamics, resulting in a large diversity of habitats. The main objective of restoration of estuarine dynamics is to enable gradual re-establishment of estuarine processes and functions, leading to the (re)installation of typical (and at the EU scale rare and endangered) estuarine habitats and biological communities as well as the ecosystem services associated with these habitats and systems. This can be accomplished through increasing fluxes of water and sediment circulating in the basins and re-establishing connections between water basins. Important structuring environmental factors in estuaries are water movements (vertically, horizontally), salinity, sediment transport, nutrients and turbidity. They affect the heterogeneity (or structure) of each estuarine ecosystem, as well as their complexity (in terms of relations between structural attributes).

Various visions and perspectives for the Southwest Delta have been sketched (H+N+S Landscape architects, 2009; World Wide Fund for Nature, 2010, 2012) and many studies carried out on solutions for each water basin (e.g. Paalvast and van der Velde, 2014). However, so far no quantification of the consequences of various management options for development of estuarine nature and dynamics in the Southwest Delta as a whole has been made. This restricts decision-making and planning because environmental and ecological benefits cannot be weighed objectively against socio-economic aspects. What would be possible consequences of various management options for the restoration of estuarine dynamics and estuarine habitats? What could be the implications for management? By computing and calculating surfaces of the different habitats present in a certain system, including geomorphological, hydrodynamic, ecological and quality aspects, one can qualitatively and quantitatively evaluate and compare different management options.

This study presents the first integrated, quantitative study that explores the possible consequences of a number of different management options for the Southwest Delta, considering the mutual coherence between the different water basins. The aim of this study is to quantify the effect of different management option on the occurrence and distribution of aquatic and estuarine habitats by changing and/or removing the existing infrastructures, and to evaluate the potential of these management options to restore estuarine dynamics. In addition, the consequences of these management options were evaluated against long-term policy ambitions.

Five distinct scenarios have been evaluated using a 1D hydraulic and water quality and primary production numerical model combined with GIS habitat mapping. The scenarios vary from small-scale interventions, such as changes in day-to-day management of infrastructures or creation of small inlets in dams, feasible in the short term, to restoration of an open delta by removing dams and barriers, as a potential scenario for the very long term.

2. Materials and methods

2.1. Study area

The area where rivers Rhine, Meuse and Schelde converge, used to consist of an interconnected estuarine landscape. The Delta Works completely changed this landscape. Nowadays, three main areas can be distinguished. Firstly, the northern area consists of the Rhine and Meuse river branches with average discharges to the North Sea of 1960 m^3/s and 230 m^3/s respectively. The rivers Oude Maas and Nieuwe Maas confluence into Nieuwe Waterweg (hereafter called Northern Rivers) that forms the entrance to Rotterdam harbour and is permanently open, except for occasional closure of the Maeslant storm surge barrier. At low river discharge, salt intrusion is a major concern for inland intake locations for fresh water used for drinking water, industrial water, irrigation and flushing of polder areas. The Haringvliet and Hollands Diep are fresh water basins closed off from the North Sea by the Haringvlietdam (Fig. 1) (Paalvast and van der Velde, 2014). The water distribution is nowadays largely regulated by the Haringvlietdam sluice, which is operated in such a way that the Nieuwe Waterweg can discharge 1500 m^3/s for as long as possible to minimize salt intrusion.

Secondly, the central part consists of four water basins (Volkerak-Zoom, Grevelingen, Oosterschelde and lake Veere) that behave largely independent from each other (Fig. 1). Therefore each water basin has its own characteristics and problems. Volkerak-Zoom is a fresh water lake that it is part of the intensively used shipping connection between the Rotterdam and Antwerp harbours. Only a tiny 5–10 m^3/s fraction of the Rhine and Meuse discharge enters Volkerak-Zoom at the Volkerakdam sluices. With furthermore two regional streams draining agricultural land, Volkerak-Zoom is a lake with a long residence time and relatively high nutrient concentrations. Massive blooms of toxic algae, initiated by the high nutrient input into these stagnant systems, hamper freshwater supply for agriculture (Verspagen et al., 2006) as well as recreation and have caused in substantial bird kills. Problems with toxic algae have subsided in recent years, probably related to the entry of the exotic filter feeding Quagga mussel (*Dreissena bugensis*) which appears to limit algae growth through grazing control (Deltares, 2013).

The salt water lake Grevelingen has equally long residence times, as the Brouwer sluice is the only connection to the North Sea resulting in a tidal range of 0.03 m on average only; this small tidal influence has hardly an effect on the mixing in the lake. Fresh water discharge from the adjacent polders is limited to 1–2 m^3/s and hence the salinity is high and rather constant at 28–30 psu. Due to the stagnant situation, a weak thermal and/or salinity stratification already results in dissolved oxygen depletion and subsequent damage to the benthic community (Ministry of Infrastructure and the Environment, 2014). When Grevelingen and Volkerak-Zoom became stagnant, non-tidal systems, the entire intertidal landscape disappeared. Tidal flats became islands that were rapidly overgrown with vegetation. Some of them are now actively managed with large grazers. With tides and natural sedimentation absent, the shorelines were strengthened with low embankments to prevent erosion by waves.

The brackish/salt water lake Veere experienced severe eutrophication and macro-algae blooms as well as dissolved oxygen depletion due to strong stratification until the opening in 2004 of the Katse Heule connection. The re-establishment of a microtidal influence (0.1 m) in lake Veere increased flushing, increased salinity and reduced the nutrient concentration (Wijnhoven et al., 2010). This measure is now seen as a successful example of restoration of estuarine dynamics. The Oosterschelde was not closed off, instead a half-open storm surge barrier was constructed, to maintain a reduced tidal regime (Smaal and Nienhuis, 1992) (Fig. 1).

The Oosterschelde is nowadays a salt water sea inlet with a daily 2.5–3.5 m tide (Nienhuis and Smaal, 1994). The Oosterschelde is extensively used for shellfish bottom culture (Smaal et al., 2013). Despite the Oosterschelde remaining a tidal ecosystem, the geomorphology of the area is still adapting to the decreased tidal water volume and tidal currents. The gullies are too wide and too deep for the reduced water volume resulting in erosion and loss of intertidal area. During storm events sediment of the tidal flats is eroded away, whereas tidal currents are too weak to bring back sediments on the tidal flats (Mulder and Louters, 1994). As a consequence, there is a net transport of sediments from the intertidal zone into the gullies and many tidal flats are eroding. This process is known as the 'sand starvation' problem of the Oosterschelde. From 1987 to 2001, on average 0.5 km^2 of the intertidal area eroded each year (van Zanten and Adriaanse, 2008). About 35% of the entire intertidal area of the Oosterschelde estuary is predicted to disappear by 2060 (de Ronde et al., 2013).

Finally, the southern part is the Westerschelde; the only remaining true estuary in the Southwest Delta (Fig. 1). It is disconnected from the Rhine-Meuse estuary except for the water discharged from the Volkerak-Zoom via the Bathse sluice. The Westerschelde is the Dutch part of the Schelde estuary that stretches through the Netherlands and Belgium over a distance of 350 km (Meire et al., 2005). The freshwater input from the river Schelde is small (on average 105 m^3/s), hence the brackish part is limited to the area between Hansweert and Antwerp (Meire et al., 2005). From the mouth towards Antwerp a gradient of decreasing salinity and transparency, and of increasing suspended matter and nutrients is found (van Damme et al., 2005). Large mud and sand flats occur all over the estuary (Table 1). The "Verdronken Land van Saefthinge", situated in the brackish part, is the largest salt marsh of the whole Southwest Delta and one of the largest brackish marshes in Europe. Two categories of human activities influenced the eco-morphological development of the Westerschelde estuary: (1) activities related to shoreline management, especially land reclamation, and (2) activities for improving and maintaining navigability. Initially, human activity in the Schelde estuary was restricted to reclaiming land that had silted up by natural processes. This reclamation resulted in a permanent loss of intertidal areas, creation of embankments, and permanently fixing the overall alignment of the estuary (Meire et al., 2005; de Vriend et al., 2011). Since the beginning of the 20th century, human activities have shifted from land reclamation to sand extractions, as well as dredging and dumping to deepen and maintain the navigation channel to the port of Antwerp (de Vriend et al., 2011).

Although the estuarine character largely disappeared in most branches and basins, each water basin still has important nature values, and all are Natura 2000-sites designated under the EU Birds Directive and the EU Habitats Directive. As an example, the loss of tidal influence turned tidal flats into islands, creating interesting pioneer vegetation like humid dune slacks with rare plant species. The remaining tidal flats in the Oosterschelde and Westerschelde are still of international importance for many wader species, that use the area during migration or as wintering ground (e.g. Ysebaert et al., 2000).

2.2. Scenario building

Five scenarios have been evaluated in this study and compared with the current situation. These scenarios vary from small-scale interventions, feasible in the short term, to restoration of an open delta by removing dams and barriers, as a potential scenario for the very long term. Changes in current management strategies and infrastructural changes are added in each scenario, such that higher scenarios differ more from the current situation. The scenarios distinguish themselves by an increasing level of connectivity between the basins. Table 2 gives the main measures taken within each scenario.

Scenarios 1, 2 and 3 introduce management options and increasing adaptations to the existing infrastructure (Table 2). These scenarios reflect some of the currently investigated management plans in the Southwest Delta. Scenario 1 (Adapted Management) foresees in adaptations that can be achieved with the existing infrastructure. A small inlet in the Haringvlietdam allows seawater to enter the Haringvliet basin. In the Volkerak-Zoom basin a larger flushing (25 m^3/s) is realized. In Grevelingen, exchange of North Sea seawater through the Brouwersdam is maximized, and at the east side an exchange between Grevelingen and Oosterschelde is realized by opening the Flakkeese sluice gate in the Grevelingendam. The adaptations in scenario 1 do not result in a change in tidal level in the basins. In scenario 2 (Small Infrastructural Changes) more seawater is allowed to enter the Haringvliet basin by further opening the sluice gates in the Haringvlietdam. This creates a brackish zone and reduced tide in Haringvliet. In the Volkerak-Zoom basin a larger flushing of 100 m^3/s is realized, which is further distributed to the Oosterschelde basin through new openings in the Philipsdam and Oesterdam. An open inlet in the Brouwersdam allows

Table 2
Water management in the current situation and in five scenarios. An inlet or outlet can be controlled in two ways. When a flow rate is given, this flow rate is enforced; else water level management determines resulting flow rates. At exchange sluices, the flow rate is two-directional and determined by parameters including flow-through surface area and hydraulic resistance. The same holds for a storm surge barrier, the difference being that the flow-through area is maximized. 'Open' indicates that there is no blocking structure and water flows freely.

Scenario		1	2	3	4	5
	Current situation	Adapted management	Small infrastructural changes	Major infrastructural changes	Storm surge barriers	Estuary
Northern rivers	Open	Open	Open	Open	Open	Open
Haringvlietdam-sluice	Outlet	Outlet + small exchange	Outlet + increased exchange	Barrier	Barrier	Open
Volkerakdam-sluice	Inlet (5 m^3/s)	Inlet (25 m^3/s)	Inlet (100 m^3/s)	Inlet (25 m^3/s)	Open	Open
Fresh water inlet to Volkerak-Zoom from Hollandsch Diep						
Brouwersdam-sluice	Exchange	Optimised Exchange	Increased Exchange	Increased Exchange	Barrier	Open
Oosterschelde storm surge barrier	Barrier	Barrier	Barrier	Barrier	Barrier	Open
Veerse Gatdam	Closed	Closed	Exchange	Exchange	Barrier	Open
Grevelingendam north	Closed	Closed	Closed	Open	Open	Open
Grevelingendam south-sluice	Closed	Exchange	Exchange	Exchange	Open	Open
Philipsdam-sluice	Outlet (10 m^3/s)	Outlet (10 m^3/s)	Outlet (55 m^3/s)	Exchange	Exchange	Open
Fresh water outlet to Ooster-schelde from Volkerak-Zoom						
Oesterdam-sluice	Closed	Closed	Outlet (45 m^3/s)	Exchange	Exchange	Open
Fresh water outlet to Ooster-schelde from Volkerak-Zoom						
Bathse sluice	Outlet	Outlet	Outlet	Outlet	Outlet	Open
Fresh water outlet to Wester-schelde from Volkerak-Zoom						
Zandkreekdam-sluice	Exchange	Exchange	Increased exchange	Increased exchange	Open	Open

800 m^3/s of seawater to enter Grevelingen during flood, creating a 0.5 m tide. In lake Veere, a new inlet in the Veerse Gatdam and the enlarged inlet in the Zandkreekdam results in a net flushing of 60 m^3/s and a 0.6 m tide. Scenario 3 (Major Infrastructural Changes) introduces extensive physical changes within the Delta area. The sluice gates in the Haringvlietdam are opened to their maximum, in fact creating a storm surge barrier. An open connection between Grevelingen and Volkerak-Zoom is realized by removing the Grevelingendam North.

In scenario 4 (Storm Surge Barriers), all outermost sea defenses are converted to storm surge barriers assuming equal hydraulic resistances as the Oosterschelde storm surge barrier. Most inland dams and structures are removed completely, resulting in a free flow of water not steered by human control. The three exceptions are the Philipsdam sluice and the Oesterdam sluice that were set to maximum exchange capacity and the Bathse sluice that is set to maximum outlet to the Westerschelde. This scenario encompasses the minimum management level. In the final scenario (scenario 5, Estuary), all dams, storm barriers and sluices are removed, i.e. there is no more water management. Estuarine gradients develop freely and undisturbed.

2.3. Modelling approach

To evaluate the consequences of the different scenarios for water quantity and quality (water balance and physico-chemical characteristics) and habitat development, a combination of 1D modelling and GIS habitat mapping was performed. The approach does not include morphodynamics (i.e. no change in bed level is considered).

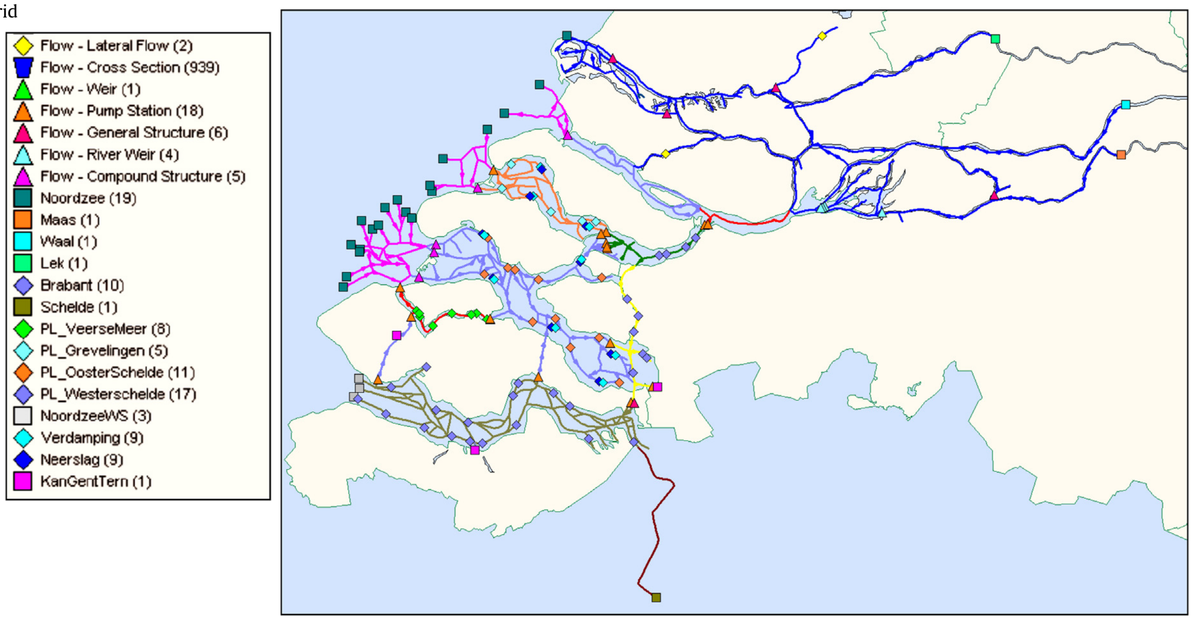
2.4. Modelling of hydrodynamics, water quality and primary production

Water flows, water quality and primary production are modelled with the SOBEK 1D package (Stelling and Verwey, 2005). The model consists of a SOBEK 1D hydraulic numerical model coupled to a DELWAQ water quality model. SOBEK 1D solves the cross-sectional integrated non-linear equations for open channel flow (Saint Venant equations). DELWAQ is the computational engine of the D-Water Quality and D-Ecology routines of the SOBEK 1D and Delft3D suites and has been coupled to other hydrodynamic models such as TELEMAC (Jeuken et al., 2013). It is based on an extensive processes library that covers many aspects of water quality and ecology, from basic tracers, dissolved oxygen, nutrients, organic matter, inorganic suspended matter, heavy metals, bacteria and organic micro-pollutants, to complex algae and macrophyte dynamics (e.g. Blauw et al., 2009). A summarized description of the model set-up is given in Table 3. The model is calibrated on monthly measurements in all water basins.

The goodness-of-fit for water levels is demonstrated in cumulative occurrence functions in Fig. 2. Note that none of the locations in stagnant basins are shown as these are fully controlled by the imposed water balance. Obviously, locations close to the model boundary are simulated well as the imposed boundary is still dominant for the simulated water level. The Zijpe location (northern branch) in the Oosterschelde, reproduces observed water levels reasonably well with slight underestimation of the flood water levels. Potentially, the 28-day spring-neap cycle should be expanded to include this. In the Westerschelde, the tidal amplification that increases the tidal amplitude from about 4.7 m at Vlissingen to about 5.7 m at Bath is not reproduced. The Bovensluis location in the Hollands Diep is presented as a location where both the river discharge and the tidal influence interact. The cumulative occurrence shows that the model underestimates the water level variation, probably as spring-neap variation and storm surges are insufficiently included. For further scenario studies, this has to be considered for improvement.

The goodness-of-fit for water quality is demonstrated in target diagrams for chloride, total nitrogen and chlorophyll-a in Fig. 2. Noting the wide variation in riverine, estuarine and marine characteristics (Table 1), the Southwest Delta model is well suited for

Table 3
Summary of model input and output for the SOBEK 1D hydrodynamic and DELWAQ water quality model of the Southwest Delta.

Simulation period	2005–2009 (2005 is used as initialization year in scenarios)
Grid	 Symbols: □ = boundary, Δ = structure (inlet, sluice or pump), ◊ = lateral discharge
Modeled parameters	Nutrients (Nitrate, Ammonia, Ortho-phosphate and Silicon), Phytoplankton: freshwater diatoms, saltwater diatoms, Organic matter, Inorganic suspended sediment, Dissolved oxygen
Modeled water quality processes	Nitrification and denitrification, Primary production and algae mortality, Decay of organic matter, Shell fish grazing, Sedimentation
River input	Daily flow rate at upstream Rhine and Meuse boundaries Hagestein, Tiel and Lith are derived from DONAR database (live.waterbase.nl). The Scheldt river discharge is taken as 10-day averages from Schaar van Ouden Doel at the Netherlands-Belgium border. The shift to upstream boundary is assumed to be acceptable. Water quality measurements are taken as monthly averages from station Lobith for Hagestein and Tiel and from station Eijsden for Lith. Water quality measurements from station Schaar van Ouden Doel were used at the Scheldt river boundary. A salinity correction was applied to convert brackish water nutrient concentrations at Schaar van Ouden Doel to fresh water input, assuming conservative mixing.
Lateral inflows	Water quality measurements for the Dintel and Vliet streams that discharge into Volkerak-Zoom were available on a monthly basis. For polder discharges, only actual year loads were available. Available monthly data for the period 1995–2000 was scaled to the year load, so that both actual load and seasonal variation could be represented.
North Sea	A representative 28-day spring-neap tide cycle is imposed on the North Sea boundaries. The cycle is repeated for the whole simulation period. Water quality measurements from station Vlissingen are used for the Westerschelde seaward boundary. Station Walcheren 2 is used for the other North Sea boundaries (Nieuwe Waterweg, Haringvliet, Grevelingen, Oosterschelde).
Meteorological data	Precipitation/evaporation are included in Oosterschelde and Grevelingen. Solar radiation and water temperature are included for all basins. Data from a reference year are repeated yearly.
Water management and structures	Most structures are controlled by hydrodynamic parameters such as water level, water level differences, and discharge rates. These structures react dynamically to scenario induced changes. For the Volkerak, Philipsdam-sluice and Kreekrak sluices, monthly averaged flow rates are available and imposed on these structures in the model.
Shellfish grazing	Filtration by shellfish is relevant for nutrient cycling and phytoplankton control in Volkerak-Zoom, Grevelingen, Lake Veere and the Oosterschelde. Shellfish biomass is not modeled dynamically, but a measured maximum filtration capacity is imposed.
Phosphate exchange with the sediment	The release of phosphate from the sediment in the summer half year and the fixation in the sediment in the winter half year is imposed based on measurements.
Generated model output parameter	
Water level (m NAP)	Cumulative distribution over 2006–2009
Stagnant or tidal	If water level variation within a single tidal cycle > 0.1 m, a location is identified as tidal.
Salinity	10% annual exceedance, Annual average, and 90% annual exceedance
Current velocity	Cumulative distribution over 2006–2009
Water transparency	Summer average (April 1 – September 30)
Primary production	Annual average 2006–2009
Chlorophyll-a	Annual average 2006–2009 (Summer average April 1 – September 30)
POM	Annual average 2006–2009 (Summer average April 1 – September 30)
Total N and P	Annual average 2006–2009 (Summer average April 1 – September 30)

the calculation of nutrient concentrations and nutrient budgets (Deltares, 2014). Chlorophyll-a is less well reproduced, probably because of high spatial and temporal variation. In the scenarios, simulated chlorophyll-a is evaluated on relative changes instead of absolute values.

2.5. Habitat mapping

The ecological potential has been calculated on the basis of the changes in the dynamics of the tides (vertically) and salinity, that results in changes in the occurrence and area of habitats present in

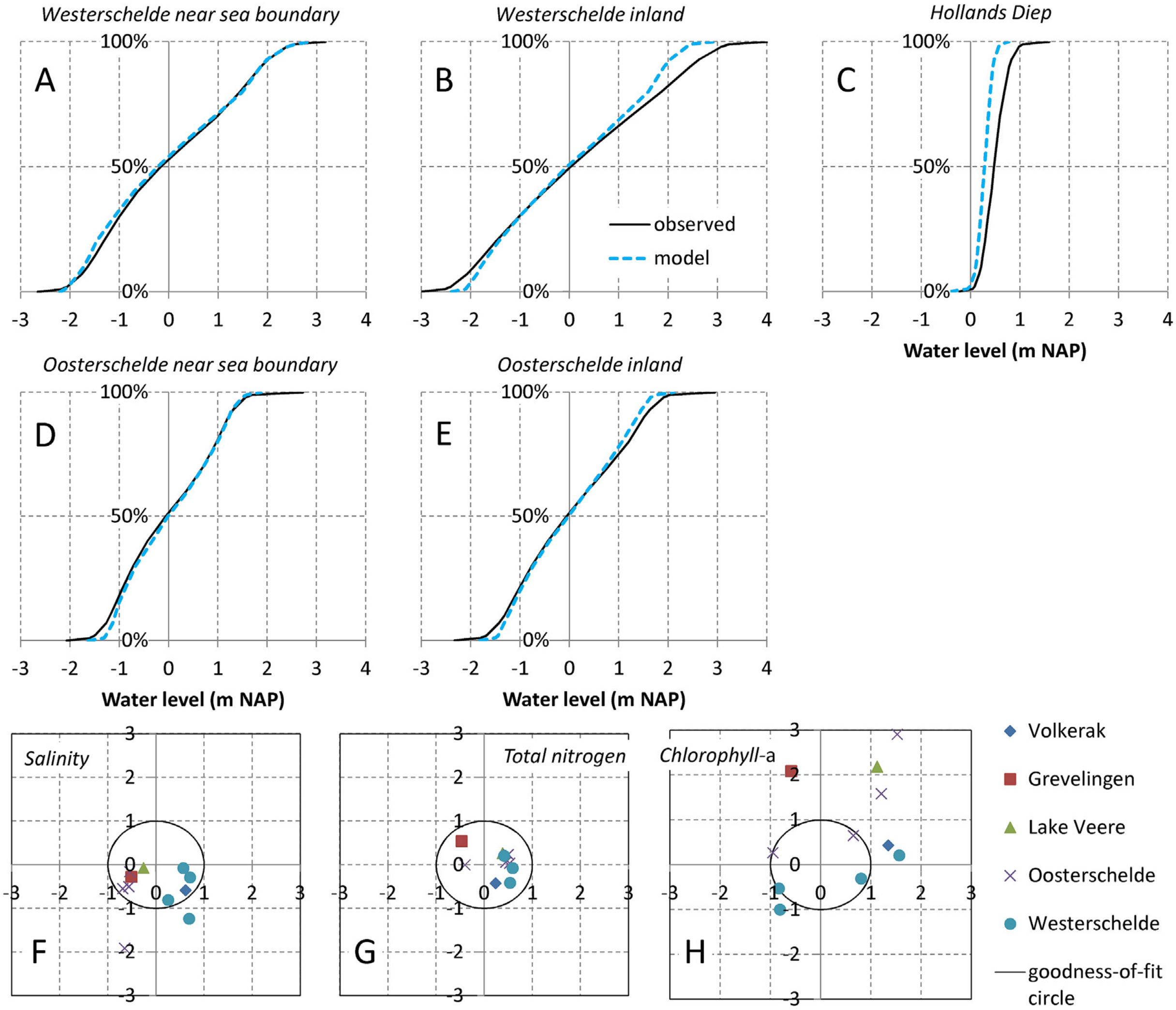


Fig. 2. Goodness-of-fit for water levels (cumulative occurrence function figures A–E) and salinity, total nitrogen and chlorophyll-a (target diagrams, figures F–H). Target diagrams show seasonal variation (x-axis) and absolute values (y-as). Markers enclosed by the circle indicate good model reproduction.

each basin. Firstly, a bathymetry/elevation map of the Southwest Delta was constructed based on a combination of topographic charts (the Actual Height model of the Netherlands AHN) and bathymetric charts of the different basins, and converted into a 20 × 20 m grid raster map for the whole study area. Interpolation of elevations was made for the shallow zones in the transition between land and water. Model results were aggregated using a total of 99 segments of 4–5 km length in all the basins and river stretches. Tidal amplitude, salinity, nutrient concentrations and chlorophyll-a were averaged over all model calculation points within one segment. Secondly, habitats were classified using class boundaries as indicated in Fig. 3. A further distinction of brackish waters into oligohaline (salinity between 0.5 and 5) and mesohaline (salinity between 5 and 18) was done when evaluating more in detail the presence of brackish transition zones. Thirdly, based on the bathymetry/elevation map and the SOBEK 1D modelling results, each grid cell of 20 × 20 m was denoted to a certain habitat type, resulting for each scenario in an areal coverage (in hectares) of each habitat in each water system. Terrestrial habitat in the tidal environment is defined as the area above Mean High Water Spring. This means that very high marshes (above MHWS), currently present in Westerschelde and Oosterschelde, are not classified as tidal marshes, but as terrestrial habitat. In non-tidal conditions, the terrestrial habitat can consist of adjoining catchment flood plains, including hydrophilous tall herb fringe communities, humid dune slacks, dunes, etc. The habitat calculations were done using PCraster (PCRaster-Team, 2011).

3. Results

3.1. Water balance

The water balance in the scenarios is shown in Fig. 4 as net discharge rate through cross-sections averaged over the four year simulation period 2006–2009. Cross-sections are placed at sluice and barrier sites and at logical open sites such as the Westerschelde estuary mouth. Colour coding indicates if the net discharge is the residual result of inflow and outflow – such as at the Oosterschelde storm surge barrier where average inflow and outflow are both around 21,000 m^3/s, while the net discharge rate is only 21 m^3/s in the present situation – or the average of one directional flow such as at the Haringvliet sluices that discharge 750 m^3/s to the North Sea in the present situation.

As the tide and river discharge remain the same in all scenarios, the change in water flows is the sole result of adapted management of existing structures and/or the construction or removal of

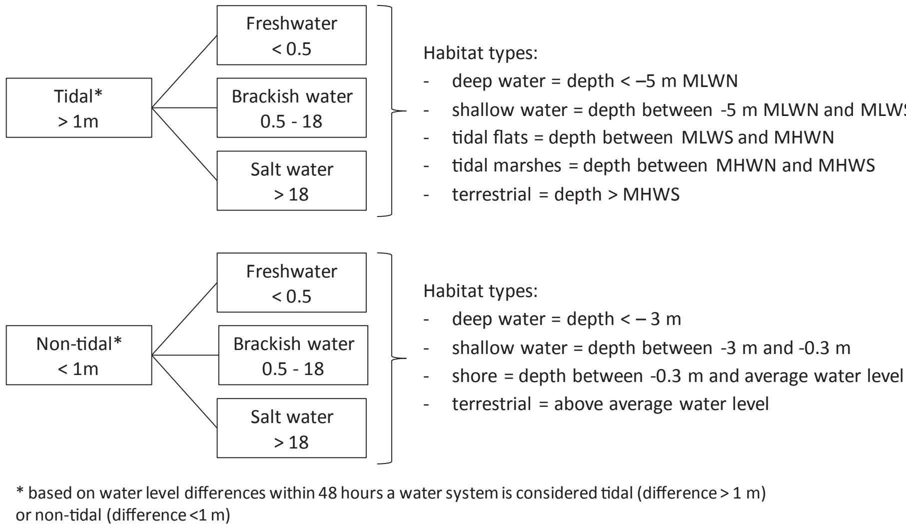


Fig. 3. Classification of habitats as a function of tidal range (left), salinity (middle) and depth/elevation gradients (right). Fresh water, brackish water and salt water habitats are classified based on salinity. MLWN: Mean Low Water Neap, MLWS: Mean Low Water Spring, MLWN: Mean Low Water Neap, MHWN: Mean High Water Neap, MHWS: Mean High Water Spring.

waterworks. Results are not described and discussed in detail, as this is not the objective of this paper (see Nolte et al., 2013 for more detailed information). The major trends and observations are described.

In the northern area of Oude Maas, Nieuwe Maas, Haringvliet and Hollands Diep, the scenarios change the distribution of Rhine-Meuse discharges. The increasing inlet of the tide through the Haringvliet sluices in scenarios 1-3 decreases the net discharge to the sea, which is counteracted by an increased net discharge through Oude Maas and Nieuwe Maas to Nieuwe Waterweg. In scenario 4 (Storm Surge Barriers) and scenario 5 (Estuary), a substantial part of the river discharge is flowing south to the Volkerak-Zoom.

The key position of the Volkerak-Zoom is further emphasized as water flows (blue arrows) remain controlled in all scenarios except scenario 5. In scenarios 1 (Adapted management) and 2 (Small Infrastructural Changes), the water balance remains fully controlled as the two-step increased inlet (25 m^3/s and 100 m^3/s) of fresh water at the Volkerak sluice is distributed over 2 and 3 outlets respectively. Scenario 3 (Major Infrastructural Changes) introduces tide and salt water in this lake, but the tidal variation is still controlled at 0.3 m and the salinity level is controlled at 20 psu at the Volkerak sluices. In the present situation, the Grevelingen and lake Veere only have one connection to one other water basin (North Sea and Oosterschelde respectively). The scenarios increase the number of connections and net flushing increases and residence time decreases substantially. In scenario 5, Grevelingen becomes order-of-magnitude equal in net flow rate to the North Sea as the Haringvliet and Nieuwe Waterweg. The scenarios appear to have relatively limited effect on the net water flows in the Oosterschelde.

Apparently, water flows in the Westerschelde change relatively little. In scenarios 1, 3 and 4, an increased discharge via the Bathse sluice adds an additional fresh water flow to the brackish part of the estuary. As the long-term average Scheldt river discharge is 105 m^3/s, the additional flow reaches order-of-magnitude similar levels. In scenario 4, the additional flow will not be fresh, as the Volkerak-Zoom is saline. In scenario 5, the Bathse sluice acts as an extra 'inlet' of water (104 m^3/s) to the central area.

Overall, the net water flow rate through the Southwest Delta shows more and more complex patterns when the connectivity between the water basins is increased and when the sluice management (on net flow or water level) is less strict.

3.2. Physico-chemical changes

Fig. 5 presents how four simulated indicators change in the five scenarios for the Southwest Delta. The indicators tidal amplitude, salinity, total nitrogen and chlorophyll-a are defined in Table 3 and location numbers are shown in Fig. 1. Each water basin is represented by one location, except for the Oosterschelde that is represented by three locations (NE, SE and W) to distinguish the effects of scenarios for inland locations from the seaward location.

In the northern basins Haringvliet and Hollands Diep, the tidal amplitude increases substantially only when scenario 4 (Storm Surge Barriers) or scenario 5 (Estuary) are created. The other scenarios have a minimal effect on tidal amplitude only, even though the salinity in the Haringvliet does increase when flood tide is allowed to enter through the Haringvliet sluice (scenarios 2 and 3). On average, salinity intrusion does not seem to reach the Bovensluis location in Hollands Diep. However, as fresh water criteria at intakes are stringent (150 or 250 mg/l chloride, or about 0.27–0.45 psu salinity), these model results indicate that intake locations are likely to be impacted more when the Haringvliet sluice is opened longer. Curiously, salinity in Haringvliet and Hollands Diep decreases again in scenario 4 and 5. This is explained by the southwards redistribution of the Rhine-Meuse river discharges that increase net flushing of these water basins (1082 m^3/s and 869 m^3/s respectively in Hollands Diep) as compared to the scenarios 1–3 (687–786 m^3/s range). Total nitrogen concentrations vary slightly, but remain non-limiting for primary production. The alterations in the simulated chlorophyll-a concentrations are related to longer residence times in the scenarios 1–3 that allow for more production before the water is flushed out to the North Sea. The lower chlorophyll-a in scenario 4 and 5 results from a combination of change in residence time and shift in algae composition due to the higher salinity in Haringvliet.

The central area lakes Volkerak-Zoom, Grevelingen and lake Veere, that have no or limited tidal influence in the present situation, undergo the restoration of tidal amplitude in several levels with progressing scenarios up to the maximum tides in scenario 5. The Oosterschelde that is also located in the central

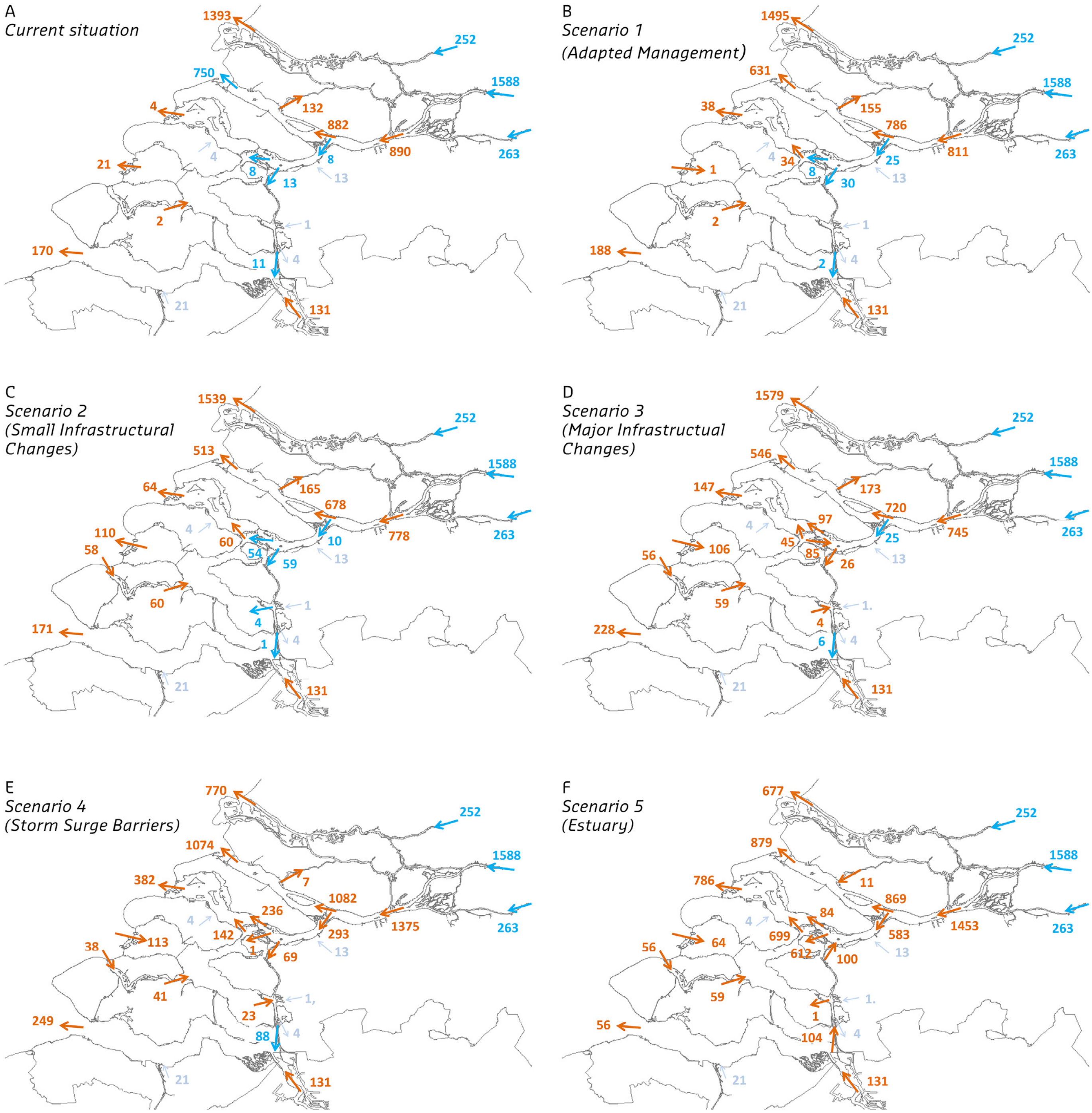


Fig. 4. Net flow rates (in m^3/s) averaged over the simulation period 2006–2009. Red arrows and numbers indicate the residual flow (i.e. net result of inflow and outflow); Blue arrows and numbers indicate one-directional flow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area, shows relatively little effect on the tidal amplitude except in scenario 5 where the tidal amplitude is some 10% decreased due to increased tidal capacity of the whole Southwest Delta. Salinity in Volkerak-Zoom is highest in scenario 3 (Management Option 3), when the fresh water inlet through the Volkerak-sluice is limited to 25 m^3/s and 0.3 m tide results in relatively large salt water flows. The net inflow through the Philipsdam-sluice of 85 m^3/s is the result of 360 m^3/s inlet to Volkerak-Zoom and 275 m^3/s outlet to the Oosterschelde. The mixing of a relatively small fresh water inlet and relatively large tidal flow rates, results in high salinity. In scenario 4 and 5, fresh water inflow is substantially larger and although the tide and thus the tidal volumes are higher as well, this combination results in a salinity gradient that is pushed further towards the North Sea. Total nitrogen concentrations show the inverse as salinity, as the total nitrogen concentration is mainly the result of mixing of fresh water with a high concentration and seawater with a low(er) concentration of total nitrogen. The overall effect on chlorophyll-a is rather small. Increased flushing in scenarios 1 and 2 reduces chlorophyll-a slightly. When Volkerak-Zoom is made salt, chlorophyll-a increases in particular in the southern Zoom part of the lake. In scenarios 4 and 5, chlorophyll-a

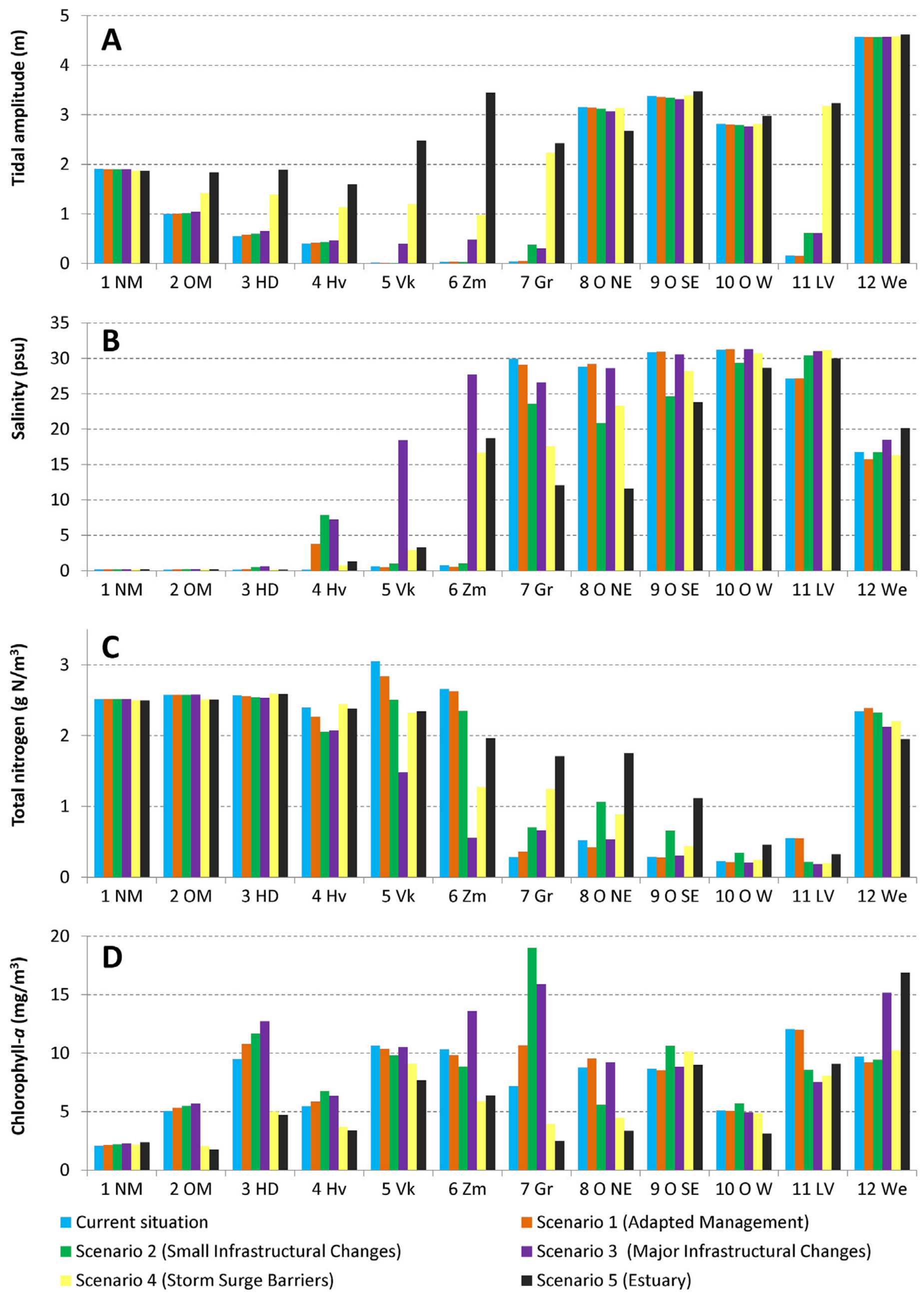


Fig. 5. Calculated indicators (A: Tidal amplitude; B: Salinity; C: Total nitrogen; D: Chlorophyll-a) for the current situation and five scenarios. Locations: 1 NM: Nieuwe Maas, 2 OM: Oude Maas, 3 HD: Hollands Diep, 4 Hv: Haringvliet, 5 Vk: Volkerak, 6 Zm: Zoom, 7 Gr: Grevelingen, 8 O NE: Oosterschelde Northeast, 9 O SE: Oosterschelde Southeast, 10 O W: Oosterschelde West, 11 LV: Lake Veere, 12 We: Westerschelde.

decreases as a result of shorter residence times.

In general, Grevelingen shows an increasing tidal amplitude and a decreasing salinity with progressing scenarios (i.e. progressing restoration of estuarine dynamics). Also, the total nitrogen concentration increases. In the present situation, the nitrogen load to the lake is the lowest of all water basins in the Southwest Delta. Hence, any connection with other water basins will increase the nitrogen load. The nitrogen limitation that limits primary production almost the whole summer period, is reduced and chlorophyll-a increases substantially with progressing scenarios 1, 2 and 3. As in Volkerak-Zoom, only the shorter residence times of scenarios 4 and 5 limit chlorophyll-a concentration below the present concentration.

The Oosterschelde tidal amplitude changes slightly in the scenarios. When the inlet of river water through the Volkerak-Zoom increases, a salinity gradient is established in the Oosterschelde with salinity in the northern Zijpe location dropping to 11 psu in scenario 5. The additional inflow of river water increases the total-nitrogen concentration in the Oosterschelde.

Of all the large water basins in the Southwest Delta, the Westerschelde is least influenced by all scenarios. No significant impact on the tidal amplitude is simulated, as the tide dominates the extra water flow through the Bathse sluice. This flow does influence the salinity gradient, resulting in a 1–4 psu salinity change at Hansweert. In scenario 5, the flow through Bathse sluice (i.e. an open channel in this scenario) reverses and becomes an inlet the Volkerak-Zoom thereby reducing the Scheldt river water input to the Westerschelde. Chlorophyll-a concentrations follow the salinity gradient.

3.3. Estuarine transition zones (salinity gradients)

In the present situation the basins are largely separated from each other and gradual transition zones between salt water, brackish water and fresh water zones are absent, except for the Westerschelde (Fig. 6). In scenarios 2, 3 and 4 transition zones are partly restored, but only in scenario 5 (Estuary), when all basins are in open connection with each other, transition zones fully develop (Fig. 6).

3.4. Habitat mapping

The habitat mapping of the current situation showed the following distribution with respect to salinity: 60% salt water, 14% brackish water and 25% fresh water habitats. Only the Westerschelde has a transition between salt and brackish water, all the other basins have only one salinity type (Table 1). The Volkerak-Zoom basin is characterized as brackish, although salinity is very low (0.6–0.7). Based on the depth distribution, 66% of the area is permanently covered by water (41% deep habitat and 25% shallow habitat), 20% partly exposed (18% sand and mud flats, 1.3% tidal marshes and 0.4% shores), and 14% terrestrial. Terrestrial habitats are present in all basins, but especially in the Biesbosch and Grevelingen basins. Due to the imposed water levels and used classification criteria, large parts of the salt marshes in the Westerschelde and Oosterschelde are classified as terrestrial, because of the highly elevated nature of these marshes (i.e. above Mean High Water Spring).

Depending on the scenario, habitat changes range from rather small to relatively big. Here the changes for three types of estuarine habitats (brackish habitat, tidal flat habitat and marsh habitat) are presented. Scenario 5 (Estuary) is described in more detail. With respect to brackish habitats, all scenarios show an increase compared to the current situation (Table 4), although considerable variation is observed due to differences in the water balance. Tidal flat habitat increases in each scenario, although the increase in scenario 1 (Adapted management) is very small (Table 5, Fig. 7). The largest increase is observed in scenario 4 and 5. Similar trends are observed for tidal marsh habitat (Table 6, Fig. 7). The surface area of tidal marshes in the Oosterschelde and Westerschelde appears underestimated, because very high marshland (above MHWS) is not classified as tidal marsh based on the criteria used, but as terrestrial habitat instead. Indeed, in both systems high, mature marshes, here classified as terrestrial habitat, occur that are only rarely flooded. In the Westerschelde this is about 2000 ha, in the Oosterschelde about 330 ha.

In scenario 5 (Estuary) the situation before the Delta Works is to a large extent restored with the removal of all dams and other infrastructures (sluices, gates). All basins become tidal, and the river discharge is equally distributed over Nieuwe Waterweg, Haringvliet and Grevelingen. In this scenario brackish habitat increases, especially in the Grevelingen (+9400 ha) and Haringvliet (+2900 ha) (Fig. 8). The salt water habitat decreases, especially in Grevelingen (−9400 ha) and Oosterschelde (−3300 ha). The freshwater habitat decreases in Haringvliet, and remains unchanged in Hollands Diep and Biesbosch. Because of the change in water levels and the re-introduction of tides, the habitats defined by depth strata and tidal influence change drastically in scenario 5 (Estuary). Deep water habitat decreases in all basins, except for Oosterschelde and Westerschelde where it largely remains the same. Shallow habitat remains on average the same, but there are differences between basins. The largest changes are observed at the level of the intertidal habitats (Figs. 7 and 9). Tidal flats increase (+12,200 ha), especially in Grevelingen (+4250 ha), Biesbosch (+2800 ha) and Volkerak-Zoom (+2450 ha) (Fig. 7). Tidal marshes double in surface, and new tidal marsh habitat is mainly created in Haringvliet (+500 ha), Biesbosch (+400 ha), Grevelingen (+310 ha), and Volkerak-Zoom (+260 ha).

4. Discussion

Although the Delta Works brought protection against flooding in the Southwest Delta, estuarine branches were cut off from the sea and (partly) from the rivers and turned into separated water basins resulting into different environmental and socio-economic

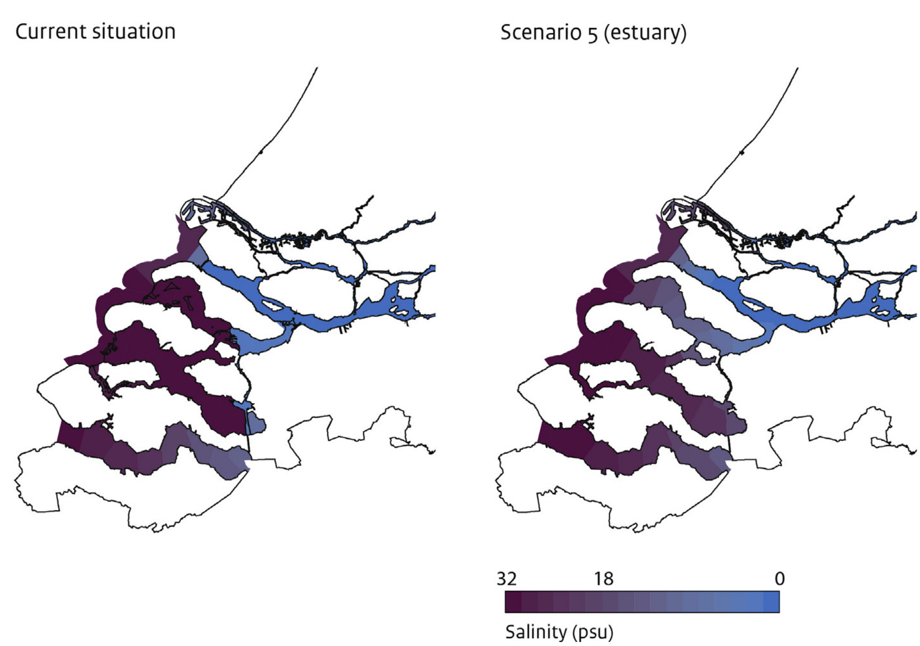


Fig. 6. Estuarine salinity gradients in the Southwest Delta: current situation (left) and the situation in scenario 5 (Estuary) (right).

Table 4
Realised brackish habitat (ha) in the water basins for the current situation and five scenarios.

Water basin	Current situation	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Westerschelde	9616	9616	9616	9616	9616	8321
Oosterschelde	0	0	0	0	0	3264
Lake Veere	0	0	0	0	0	0
Grevelingen	0	0	0	0	0	9396
Volkerak-Zoom	7734	4256	7734	3479	7734	7303
Haringvliet	0	8018	10,382	10,382	1143	2929
Hollands Diep	0	0	1550	2879	0	0
Biesbosch	0	0	0	0	0	0
Northern rivers	0	855	855	855	0	466
TOTAL	17,351	22,745	30,138	27,210	18,494	31,679

Table 5
Realised tidal flat habitat (ha) in the water basins for the current situation and five scenarios.

Water basin	Current situation	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Westerschelde	8321	8319	8319	8317	8339	8357
Oosterschelde	10,740	10,684	10,643	10,589	10,696	10,630
Lake Veere	9	9	130	125	825	823
Grevelingen	0	0	1587	1565	4030	4243
Volkerak-Zoom	0	0	0	608	1519	2457
Haringvliet	803	842	870	856	1409	1860
Hollands Diep	129	156	172	185	365	581
Biesbosch	959	1054	1126	1218	2619	3875
Northern rivers	669	677	686	704	855	1000
TOTAL	21,630	21,740	23,535	24,166	30,656	33,826

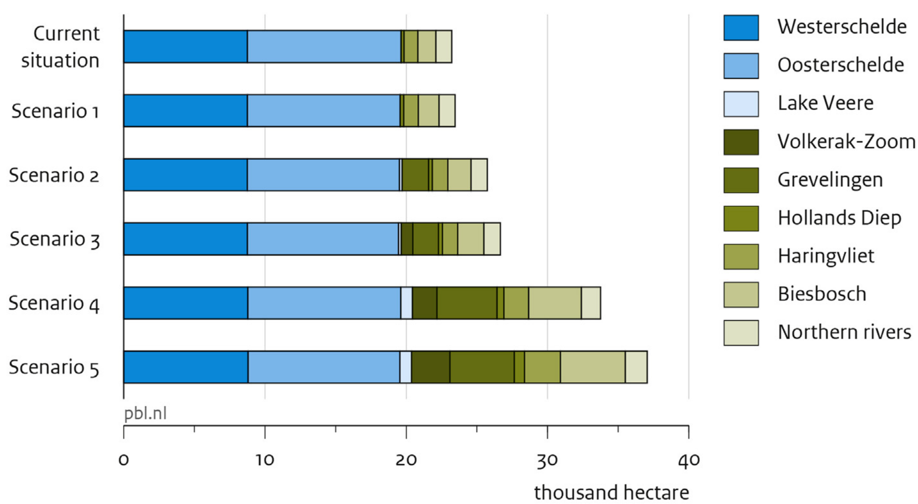


Fig. 7. Area of intertidal habitats (tidal flats and tidal marshes combined) in the different basins in the Southwest Delta in the different scenarios.

Table 6
Realised tidal marsh habitat (ha) in the water basins for the current situation and five scenarios. It should be noted that for the calculation of tidal marsh surface the area between MHWN and MHWS was used. As a result, very high marshland (above MHWS), is not considered as tidal marsh habitat (see text).

Water basin	Current situation	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Westerschelde	437	436	434	438	449	448
Oosterschelde	131	127	124	115	128	112
Lake Veere	0	1	62	64	4	4
Grevelingen	0	0	281	253	222	311
Volkerak-Zoom	0	0	0	208	210	258
Haringvliet	179	200	228	217	346	678
Hollands Diep	75	84	94	96	118	145
Biesbosch	319	409	517	642	1115	727
Northern rivers	445	456	463	465	499	542
TOTAL	1586	1712	2203	2497	3091	3224

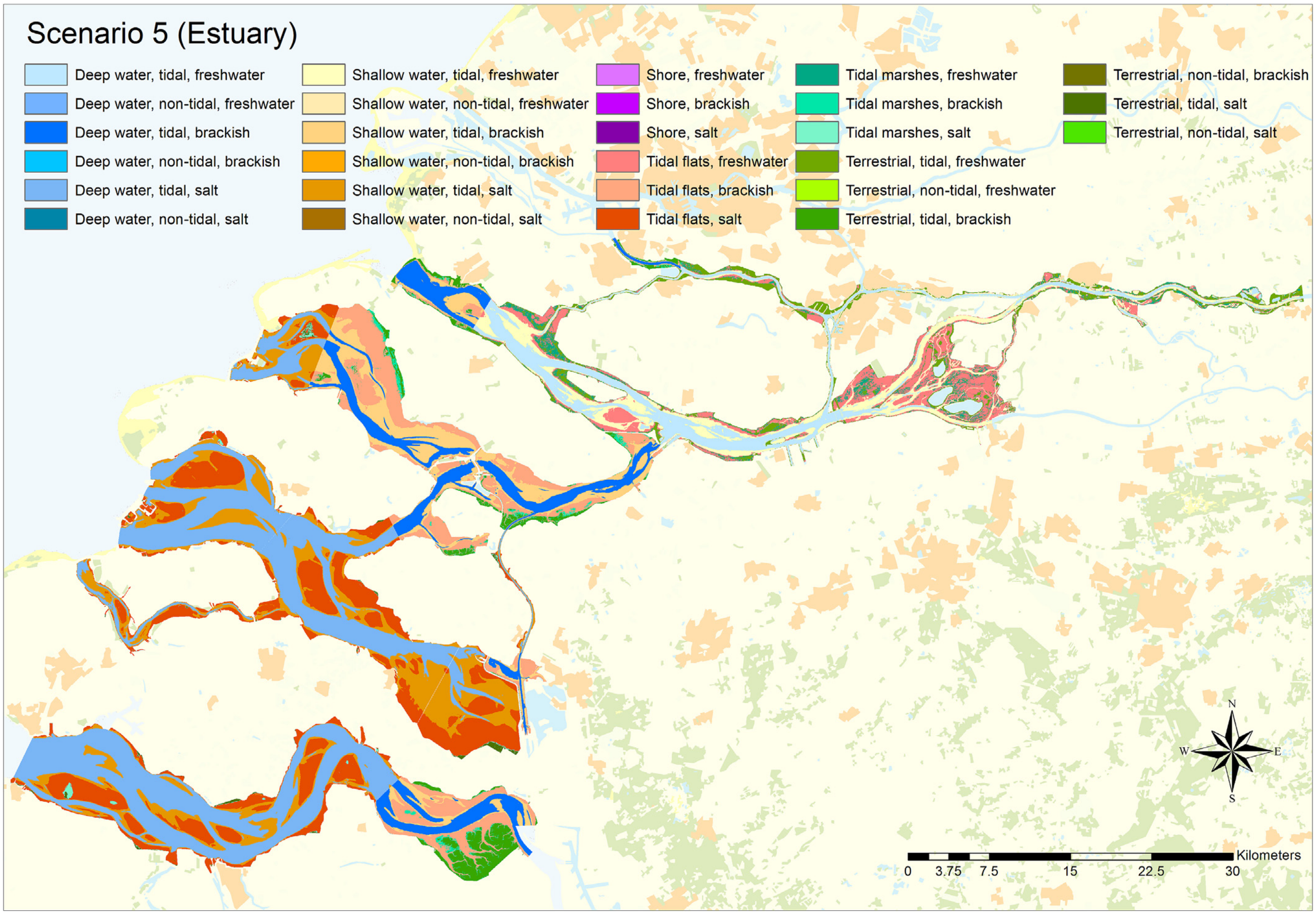


Fig. 8. Habitat map of the Southwest Delta in scenario 5 (Estuary). For the classification of habitats, see Fig. 3.

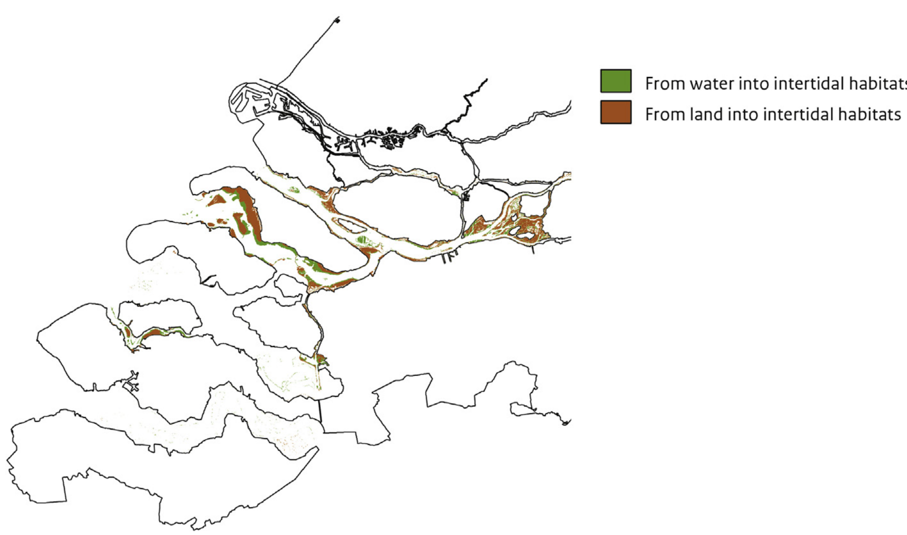


Fig. 9. Potential new intertidal habitats (tidal flats and tidal marshes) in the case of scenario 5 (Estuary).

problems. This study is the first integrated, quantitative study that explores the consequences of a number of different management options for the Southwest Delta, considering the mutual coherence between the different water basins.

4.1. Restoring estuarine dynamics and implications for ecology

Water management policy plans for the Southwest Delta nowadays aim at solving the environmental problems in the Southwest Delta, based on an integrated approach that not only guarantees safety against floods, but also makes the region ecologically resilient and socio-economically vital (e.g. Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2014). The re-establishment of estuarine dynamics is often proposed as the general solution by the regional and national governments. This is, however, a very broad goal for the very long term, and management policy plans often do not give a clear definition of what estuarine dynamics imply. Natural estuarine ecosystems are complex systems characterized by the dynamic interplay between hydrodynamics, morphodynamics and ecodynamics. In mesotidal, coastal plain estuaries, like for instance the Westerschelde, longitudinal gradients caused by salinity and other related biogeochemical variables and vertical gradients caused by tides are the two major gradients determining the diversity of habitats and species present in an estuary (e.g. Heip et al., 1995; Ysebaert et al., 2003; Elliott and Whitfield, 2011). As places where seawater and freshwater mix, a gradient in salinity is an essential characteristic of estuarine ecosystems. Within salinity zones, other important gradients are determining the distribution and development of habitats and populations. Vertically, strong gradients occur between the deep channels and the high intertidal. Extensive tidal flats and tidal marshes are characteristic for mesotidal systems like the Westerschelde and Oosterschelde. This vertical gradient correlates with emersion and submersion stress, presence of predators, variations in temperature, desiccation, rainfall and ice scour. Strong physical gradients are also present at different spatial scales, for example in current velocity, sediment composition, intensity of waves. For many organisms, estuaries and their habitats play key roles in their life cycles and fulfil important nursery, feeding, or reproductive functions (e.g. Gillanders et al., 2003; Seitz et al., 2014). Many species rely on different habitats to fulfil their life cycle; therefore, habitat quality and connectivity are considered essential characteristics of coastal ecosystems (Seitz et al., 2014). Dependent on the type or life stage of organisms, different (functional and structural) aspects of the estuarine environment are important. For migratory, diadromous fish the channels in estuaries are essential migration routes between the sea and the rivers. These organisms need an open connection between the sea and the river, and gradual transition zones are needed to adjust to changes in salinity. For many birds, especially wader species (e.g. *Haematopus ostralegus*, *Calidris canutus*, *Numenius arquata*, etc.), the extensive tidal flats present in estuaries and along coasts are essential feeding habitats along their migration routes between high-latitude breeding areas and temperate or tropical wintering grounds (Delany et al., 2009). At low tide these birds forage on the tidal flats, looking for benthic macrofauna like bivalves, polychaetes and crustaceans, to rebuild their reserves. At high tide, tidal flats are used as foraging grounds by many fish species (e.g. *Platichthys flesus, Solea solea*). Tidal marsh creeks are important nursery grounds for several fish species (e.g. *Dicentrarchus labrax*) and crustaceans, and in the marsh vegetation birds breed.

When the different scenarios are evaluated based on the different aspects governing estuarine dynamics, and the different needs estuarine organisms pose, it becomes clear that most scenarios only partly recover estuarine dynamics and therefore only partly realize the overall goal for the Southwest Delta (Table 7). Not surprisingly, from scenario 1 (Adapted Management) to scenario 5 (Estuary) recovery of estuarine dynamics increases. Aspects like connectivity, estuarine transition zones, and area of intertidal habitats increase. Especially scenarios 1 and 2 contribute only in a limited way to the recovery of estuarine dynamics in the Southwest Delta.

An important annotation for our study is that morphodynamics were not included, as we limited our study to the hydrodynamics (tide, salinity, etc.) and ecodynamics (nutrients, primary production, habitats). It should be noted that for a long-term sustainable management based on estuarine dynamics, the morphodynamics will need to be considered as well. Management options like storm surge barriers or the creation of reduced tidal influence in the basins might lead to morphological disequilibrium, resulting in e.g. erosion of intertidal habitats like observed in the Oosterschelde, or to remobilization/resuspension of fine sediments that have built up in the deeper parts of the stagnant lakes, affecting habitat and water quality.

4.2. Management implications

Restoring estuarine dynamics should counteract the ecological degradation of the SouthWest Delta and support a more robust and sustainable ecological environment. As the current rational is to counteract the negative ecological impacts of the Delta Works, the implicitly assumed reference situation is '1952' (i.e. before the 1953 flooding disaster). This leads to the following considerations on the potential of restoring estuarine dynamics.

Firstly, changes in the Southwest Delta have a history of many centuries, both due to natural processes and human interventions. For example, land reclamations have connected the tens of islands present in the Southwest Delta to the current four big islands. The 1952 situation is therefore much different from the 1850 or 1650 situation. This historical context shows that the restoration of estuarine dynamics will to a large extent be constrained by current (land) boundaries. Scenario 5 (Estuary) results in the maximal restoration of estuarine dynamics feasible within the current (land) boundaries. Depoldering or managed realignment, i.e. returning land to the sea, can additionally contribute to restoration of estuarine dynamics in the Southwest Delta. Although a very sensitive and controversial topic, several hundreds of hectares of agricultural land and freshwater wetlands along the Westerschelde and Oosterschelde are nowadays being transformed into intertidal habitats like tidal flats and marshes.

Secondly, the current Southwest Delta is a delta in imbalance. In particular, the geomorphology is still adapting to the Delta Works, and as a consequence also the habitats and species in these systems. The ecosystem is adapting, for example in the vegetation succession of former intertidal areas in the stagnant lakes or the sand starvation in the Oosterschelde, but also through establishment of non-indigenous, invasive species such as the Pacific oyster (*Crassostrea gigas*) in the Oosterschelde and the Quagga mussel (*D. bugensis*) in Volkerak-Zoom. In scenarios 1–4 that do not establish the maximum feasible estuarine dynamics, this imbalance will largely remain.

Also, water managers and the general public have to be aware that time scales of natural change are tens to hundreds of years, easily exceeding the typical 4 year political period or the 6 year Water Framework Directive cycle. The challenge is to incorporate the long term natural time scales into the much shorter management time scales. Modelling studies like this one can help to envision the management consequences for long term development of the Southwest Delta.

Furthermore, on the basis of the management options evaluated in this study, sustainable restoration of full estuarine dynamics seems a very difficult goal to reach. The implication for other estuaries in the world, where similar developments takes place, is that for conservation or restoration of the estuarine ecosystem choices must be made in an early development stage to prevent a situation where the hydromorphological situation as well as the socio-economic situation has changed beyond return.

In addition, other goals (i.e. benefits) may be achieved by the proposed management options. The provision of ecosystem services and the interaction with human welfare should be part of the

Table 7
Changes in different aspects governing estuarine dynamics, for each of the five scenarios, based on the model and habitat mapping results (habitats) and expert judgement (connectivity). 0 = no change compared to current situation, + = 10–50% increase compared to current situation, ++ = 50–100% increase compared to current situation, +++ ≥ 100% increase compared to current situation, - = 10–50% decrease compared to current situation.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Salinity and connectivity					
Saltwater tidal habitat	0	+	+	0	0
Brackish tidal habitat	++	+++	+++	++	+++
Freshwater tidal habitat	-	-	-	+	-
Connectivity	0	0	+	++	+++
Intertidal habitats					
Tidal flat habitat	0	0	+	+	++
Tidal marsh habitat	0	+	++	++	+++

evaluation (e.g. Atkins et al., 2011; Elliott and Whitfield, 2011). Additional analyses are needed to define and quantify these benefits. In this context, maintaining or recovering biodiversity may be a goal to strive for, even if not all aspects of estuarine dynamics can be restored. From a biodiversity point of view, it would be very interesting to be able to translate changes in habitat area (i.e. the results of this study) into habitat quality, both in terms of structure and functioning. Habitat quality at a specific location may differ between scenarios, due to differences in tidal ranges, salinity, nutrient concentrations, and differences in connectivity between water basins. Therefore the species present and the extent of occurrence may be different although the broad habitat classification is the same, affecting the overall ecosystem functioning. This requires more detailed approaches using for instance mechanistic or correlative species distribution models and ecological indicators.

A change in water management of the Southwest Delta will have consequences for the national and international status of the different water basins, for instance with respect to the European Water Framework Directive or Natura 2000. Targets for habitats and species are designated based on the current status of the basins, and will have to be adapted based on the implied management option. E.g. introduction of tides may lead to different environmental conditions and thus to different habitats and species. A well described scientific baseline and an extensive monitoring programme should accompany the implementation of new management options. Good data management is a prerequisite for the evaluation of management options. It may prevent the unselective application of the precautionary principle leading to blanket protection and disenfranchised stakeholders.

Finally, as the Southwest Delta is the confluence of three major rivers (Rhine, Meuse, Scheldt), there is also an international aspect involved in managing this area. All the water basins are assigned as Natura 2000-areas. Several (migratory) bird populations use it as a living, breeding or foraging habitat. Moreover, nature targets like fish population targets in upstream countries (e.g. for salmon) are affected by management decisions concerning fish migration routes in the Southwest Delta. On the contrary, upstream water regime changes in the major rivers may also affect fresh water quantity and quality in the delta with associated ecological implications.

4.3. Limitations of the study

The presented results on the effects of the different management options should be made with care. The quantitative analysis as performed in this study gives insight into the general effects of the proposed management options. However, additional modelling will be needed for detailed design decisions such as dimensioning of water works for counteracting oxygen depletion and mass mortality of organisms such as in Grevelingen.

Mathematical models have limitations, especially when used for predicting effects of management options for restoring such complex processes as estuarine dynamics for the Southwest Delta. Although the SOBEK 1D model did not describe dynamic morphogenetic processes in the Delta area, the benefit of using this model is that the effect of a management measure can be quantified for all water basins at the same time, even if a measure is intended to improve water quality in a single water basin only. In policy and stakeholder processes, it shows that water basins are not stand alone systems but that the future of the basins is strongly intertwined. As such, the modelling approach supports the mindset of the people that are formulating measures for the area. This necessity for a joint and shared mindset will increase when restoration of estuarine dynamics is progressing as – by definition – the water basin connectivity and interdependency increases. In this process, user participation and communication between scientists and policy makers are key aspects that will determine the acceptability, credibility and the correct use of modelling results in policy making (Wassen et al., 2011).

Any model has limitations and the SOBEK 1D model is no exception. One conceptual and one practical limitation is mentioned here. The conceptual limitation is the 1D resolution. As the model is 1D, the vertical dimension of the water column is not included. Many water basins in the Southwest Delta are deep and low in dynamics, so that temperature and salt stratification can occur, which can lead to dissolved oxygen depletion and extensive mortality of benthic animals. Stratification can influence algae growth in particular the onset of toxic algae blooms. Also, although intertidal areas are included in the schematization of cross-sections for each link, the physics and biochemistry of intertidal areas are poorly resolved in a 1D model. These potential effects on water quality have to be assessed through expert judgement or through 3D studies. As several 3D modelling studies have been done for water basins, information from these studies can be used to support and strengthen expert judgement. The practical limitation of the modelling approach used in this study is the limited model validation which leaves uncertainty in the calculated values. Therefore, presented numbers are indications only as further model validation is pending. A validation of the model on the pre 1953 Delta Works situation is prepared.

5. Conclusions

Dutch policy aims at a climate proof and safe, but at the same time ecologically resilient and socio-economically vital Southwest Delta. This study is the first integrated, quantitative study that explores the consequences of a number of management options for the Southwest Delta, considering the mutual coherence between the water basins. The results of this study were presented to the government by PBL Netherlands Environmental Assessment Agency in a policy document about coherence in the Southwest

Delta (PBL, 2013). The study was discussed with authorities of the different provinces of the Southwest Delta. They have embraced some of the recommendations. Also the central government did use and still uses this study in the development of the Delta Programme (Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2014) and the development of ambitions for the very long term (Ministry of Economic Affairs, 2014).

For a real understanding of the complexity of the current problems and the implications of management options, it is recommended to look at all the aspects of estuarine dynamics, including ecomorphodynamics and socio-economic aspects. An ecosystem based approach could help to achieve the goal of restoration of estuarine dynamics. Restoring and creating room for natural processes and strengthening spatial connectivity will also increase the adaptive capacity of the ecosystems to climate change (Vos et al., 2010). In this way the Southwest Delta will be more climate resilient. The (partial) re-establishment of estuarine processes and functions will also enable the ecosystem services associated with these habitats and systems to be delivered.

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