Estimating the effects of restoration on ecosystem services in the Haringvliet Mapping current and future regulating ecosystem services

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ABSTRACT

To improve the state of the ecosystem of the Haringvliet, an estuary in the Southwest Delta of the Netherlands, the dam, which cuts off the estuary from the sea, will be opened a little in 2018. My research aims to quantify plausible changes of the ecosystem services supply following this water management modification and accompanying habitat restoration measures. For this purpose, values of ecosystem services supply for the relevant ecosystems were collected from the literature and GIS mapping was applied. The study shows clearly that the ecosystem services supply is expected to increase in general following the restoration scenarios. The results can be used for the planning of additional restoration measures aiming to provide the highest possible supply of the ecosystem services.

1. INTRODUCTION

Estuaries are among the most productive natural habitats in the world (McLusky, 2004). An estuarine ecosystem benefits from inflows of nutrients both from the sea and from a river. However, presently many estuaries suffer degradation by many anthropogenic factors (Wolanski, 2007). One of the main reasons of estuarine ecosystems degradation is damming of estuaries for flood control or water diversion (Silva, Lowry, Macaya-Solis, Byatt, & Lucas, 2017). Wellknown examples of estuarine ecosystems deterioration caused by damming include La Rance in northern France (Retiere, 1994) and Sihwa Lake in South Korea (Han & Park, 1999).

The Haringvliet was one of the biggest estuaries in the Southwest Delta (SWD) in the Netherlands. The rich estuarine ecosystem severely deteriorated since 1971, when the estuary was closed off from the sea by the Haringvlietdam to prevent flooding of the SWD (Nienhuis, Bakker, Grootjans, Gulati, & de Jonge, 2002; Smits, Nienhuis, & Saeijs, 2006; van Wesenbeeck et al., 2014). The most important problems include pollution of water and river sediments with heavy metals and organic compounds (Bijlsma & Kuipers, 1989; van Wesenbeeck et al., 2014), disappearance of marsh vegetation (Van Haperen, 1989), decrease of migration possibilities for migratory fish, like salmon and eel (Ferguson & Wolff, 1984), and seasonal algae bloom (Verspagen et al., 2006). Since the mid-1990s, different suggestions about ecological restoration of the estuary have been made ("Ecological restoration of the rhine/maas estuary", 1995; Smit, van der Velde, Smits, & Coops, 1997; Kerkhofs, Tiebosch, van der Velden, & Kuijpers, 2005). In 2011, the Dutch government decided to open the Haringvlietdam sluices a little in 2018 to allow limited saltwater intru sion in the Haringvliet, aiming to improve the state of the ecosystem (Troost, Tangelder, Van den Ende, & & Ysebaert, 2012). In addition, the Droomfonds ('Dream fund') coalition of six nature conservation NGO's received €13.5 million for restoration and strengthening the region's recreational value (WWF, 2015). Therefore, information about plausible consequences of the Haringvlietdam's partial opening and accompanying habitat restoration measures for economy, society and environment were needed.

Issues related to this project have been discussed widely in the literature. Several studies discuss the Haringvliet opening from the sociological point of view. van Meerkerk, van Buuren, and Edelenbos (2013) say that water managers predominantly made tight boundary judgements related to the Haringvliet sluices.Keessen, Hamer, Rijswick, and Wiering (2013) describe the social resistance to the partial opening of the Haringvlietdam. Marks, Gerrits, Bakker, and Tromp (2014) and Vermoolen and Hermans (2016) claim that contradictory interests of different stakeholders made the process of making the decision about the Haringvliet opening unexpectedly long.

Other studies are dedicated to assessing plausible changes of biophysical conditions after the Haringvliet opening. Paalvast and van der Velde (2014), who dedicated their study to the northern part of the SWD, discuss potential changes of the water regime of the Haringvliet as they can significantly affect other parts of the delta. Zegwaard and Wester (2014) consider the potential opening of the Haringvlietdam in relation with the debates concerning the reopening of the Philipsdam, another dam in the SWD. Breukelaar (2015) focuses on the optimal use of the Haringvliet opening for migratory fish. Ysebaert et al (2013; 2016). presented a comprehensive description of potential changes of hydrodynamic and ecodynamic conditions (including habitats) in the SWD (including the Haringvliet)

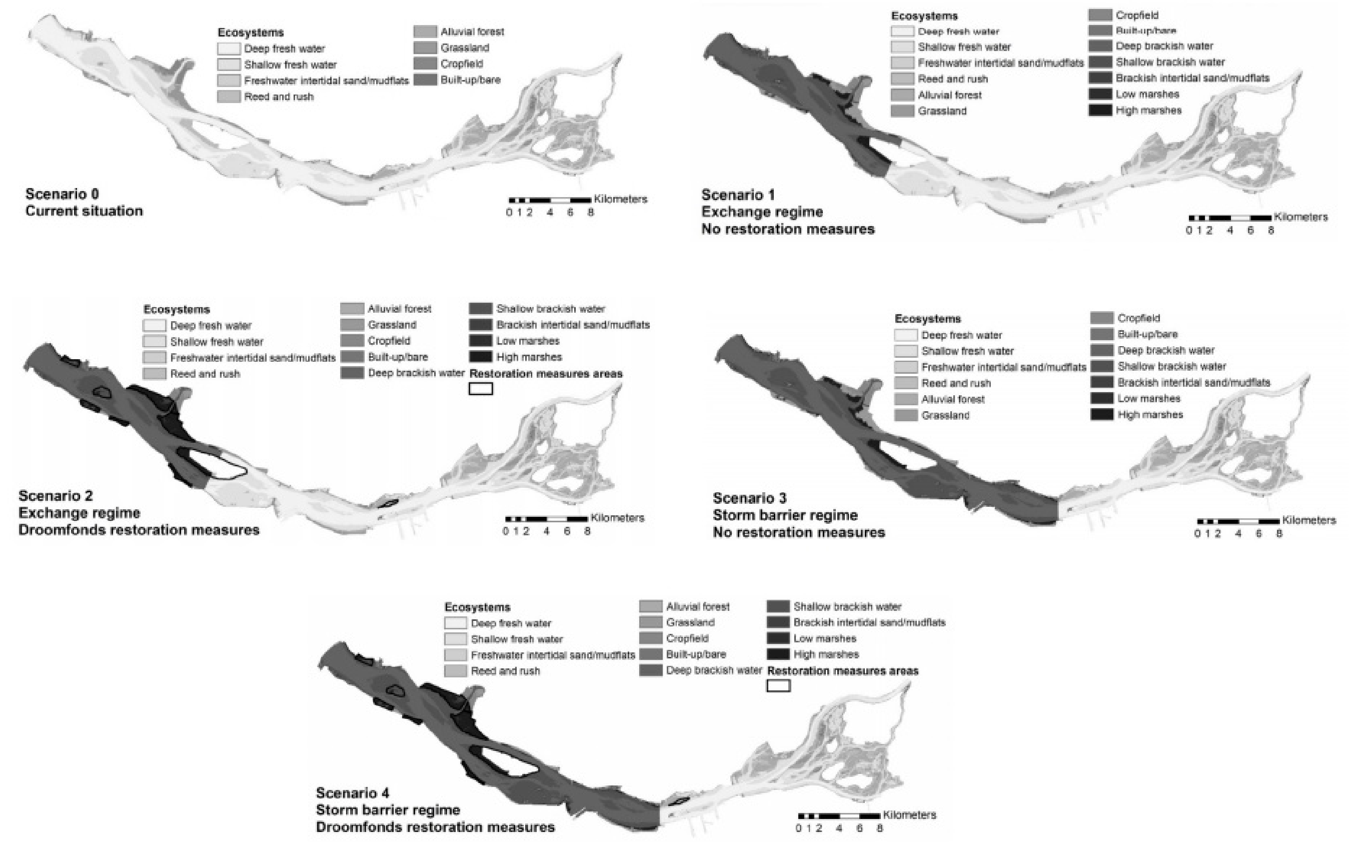

Figure 1: Ecosystems

under different water management scenarios, developed by A.J. Nolte (2013). One of the important aspects of the proposed Haringvliet's restoration is potential changes in benefits, which the Haringvliet's ecosystem can provide to people. Such benefits are known as 'ecosystem services' (ES) (MEA, 2005). Actually, ES provided by estuaries are described in the literature relatively well (De Groot, Stuip, Finlayson, & Davidson, 2006; Molnar, Clarke-Murray, & Whitworth, 2009; Barbier et al., 2011). However, for the Haringvliet only one study of ES is available (Bönhke-Heinrichs & De Groot, 2010). This study identified changes in ES related to estuarine restoration in this region under one restoration scenario that combines water management and habitat restoration measures. However, the scenario used was extreme. It implied total removal of all dams in the SWD, which is not plausible at present. In addition, it provided values of ES mainly in monetary terms, but did not explicitly report on the changes in the capacity of ES to supply services in biophysical terms. In this way, the impact of the Haringvliet dam partial opening and accompanying habitat restoration measures on the supply of ES in biophysical terms under plausible restoration scenarios remains uncertain. My research aims to contribute bridging this knowledge gap.

2. MATERIALS AND METHODS

The approach I used in my study consists of eight main steps: 1) study area definition and description; 2) scenarios selection; 3) ecosystem typology development and obtaining spatial landscape data; 4) ES typology development and ES selection and operationalization; 5) searching for numerical values of ES supply and quantifying ES supply; 6) mapping ES; 7) total ES supply calculation; 8) quantification of differences between present and future ES. These steps are described in the following paragraphs.

2.1 STUDY AREA DEFINITION AND DESCRIPTION

The main water basins of the SWD are defined and described in the study by Ysebaert et al. (2016). This study defines the Haringvliet as the basin bounded by the Volkerakdam upstream and the Haringvlietdam downstream with a total area of 10,382 ha. However, I enlarged the study area by adding two upstream basins, where the impact of the Haringvlietdam sluices opening might be significant: the Hollands Diep and the Biesbosch. As this study focusses on (semi)natural estuarine habitats, I considered only the outerdike areas. The total surface of the study area determined in this way amounts 23,316 ha. All considered basins are currently characterized by an average tide of 0.3-0.5 m and a salinity level of approximately 0.2 psu (A.J. Nolte, 2013; Ysebaert et al., 2016).

2.2 SCENARIOS SELECTION

I used water management scenarios for the whole SWD developed by A.J. Nolte (2013), which were used also in the studies by Ysebaert et al. (2013, 2016). These studies consider five scenarios, in addition to the current situation. These scenarios evaluate hydrodynamic and ecodynamic conditions (including habitats) under different water management options (changing of regime and/or removing the existing infrastructure). For the current study two of these scenarios were used, namely 'Adapted Management' and 'Major infrastructural changes' (titles of the scenarios are provided according to Ysebaert et al. (2016)).

'Adapted Management' scenario implies a small inlet in the Haringvlietdam (regime of exchange) allowing the seawater to enter the Haringvliet basin. 'Major infrastructural changes' scenario involves opening of the sluices in the Haringvlietdam to their maximum (regime of storm barrier) – as well as important infrastructural changes in other dams around the SWD, which significantly influence biophysical conditions of the Haringvliet. Under this scenario, more seawater enters the Haringvliet. From the current situation through 'Adapted Management' scenario to 'Major infrastructural changes' scenario, exchange between the sea and the Haringvliet increases, while the net discharge to the sea through the Haringvlietdam decreases. Following the increase of water exchange, salinity in the Haringvliet increases in 'Adapted Management' scenario up to 2.2 psu on average, when tidal amplitude hardly changes (A.J. Nolte, 2013). In 'Major infrastructural changes' scenario, salinity in the Haringvliet increases even more – up to 4.6 psu on average, and brackish water reaches also the Hollands Diep, where salinity increases up to 0.7 psu on average (A.J. Nolte, 2013). Tidal amplitude in this scenario increases by several centimeters in the Haringvliet, by 0.1 m in the Hollands Diep and by 0.15 m in the Biesbosch(A.J. Nolte, 2013). In addition, I used the habitat restoration scenario developed by the Droomfonds (B. Roels & M. van de Berg pers. comm. Table version [21.04.2017]). This scenario implies restoration of natural ecosystems in particular areas in the Haringvliet. Considering each of two water management scenarios both with and without implementation of habitat restoration measures, I obtained four scenarios in total, in addition to the current situation (Table 1).

2.3 ECOSYSTEMS: TYPOLOGY DEVELOPMENT AND MAPPING

As a primary data source for ecosystems typology and maps I used the current ecotopes map obtained from Rijkswaterstaat (RWS, 2013). This map defines within the study area 48 types of ecotopes. However, this level of detail cannot be maintained in this study given that both the ES knowledge base and the restoration scenarios are less detailed in terms of ecosystems and habitat types considered. Therefore, I generalized this map, combining these 48 types of ecotopes into eight more general types of ecosystems: 1) fresh deep water, 2) fresh shallow water, 3) freshwater intertidal sand and mudflats, 4) reed and rush, 5) alluvial forest, 6) grassland, 7) crop field and 8) built-up or bare area. In this way, I obtained the ecosystem map for the current situation (scenario 0). To develop ecosystem maps for the restoration scenarios, I had to make assumptions about changes of the current ecosystems under these scenarios. First, I developed ecosystem maps for the scenarios, which imply only changes in water management and no habitat restoration measures (scenarios 1 and 3). For this purpose, I used maps of habitats for both scenarios considered in my study from the paper by Ysebaert et al. (2013). This study defined 27 estuarine habitats in the SWD based on different combinations of tidal range, salinity and depth/elevation. However, only ten of them occur in my study area in two water management scenarios, which I consider here. The criteria of definition of these habitats are shown at the Table 2. Ysebaert et al. (2013) developed maps of habitats for both scenarios considered in my study as well. These maps in GIS format have kindly been provided by the authors of the study.

As some types of habitats in the considered water management scenarios are brackish, it seems that some new types of ecosystems will appear. According to the papers by Bönhke-Heinrichs and De Groot (2010) and by Paalvast and van der Velde (2014), the following ecosystems are typical for brackish habitats in the SWD: 1) brackish deep water, 2) brackish shallow water, 3) brackish intertidal sand and mudflats, 4) low brackish marshes and 5) high brackish marshes (estuarine meadows). The potential spatial distribution of new brackish ecosystems among the Haringvliet under the restoration scenarios is unknown, and, to my knowledge, was never modelled. Therefore, I had to make the following assumptions about changes of the current ecosystems under the restoration scenarios, depending on the habitat category they would fall into in the scenario:

Regime of the Haringvlietdam	Nature restoration measures	
	No measures	Droomfonds measures
Current (only outlet)	0	
Exchange	1	2
Storm surge barrier	3	4

Table 1: Scenarios of the Haringvliet restoration

Salinity (psu)	**Depth/elevation**	**Habitat**
Freshwater (<0.5)	Deep water (depth <-5 m MLWM)	Fresh deep water
	Shallow water (depth between -5 m MLWN and MLWS)	Fresh shallow water
	Tidal flats (elevation between MLWS and MHWN)	Freshwater tidal flats
	Tidal marshes (elevation between MHWN and MHWS)	Freshwater marshes
	Terrestrial (elevation >MHWS)	Freshwater terrestrial
Brackish (0.5-18)	Deep water (depth <-5 m MLWN)	Brackish deep water
	Shallow water (depth between -5 m MLWN and MLWS)	Brackish shallow water
	Tidal flats (elevation between MLWS and MHWN)	Brackish tidal flats
	Tidal marshes (elevation between MHWN and MHWS)	Brackish marshes
	Terrestrial (elevation >MHWS)	Brackish terrestrial

Table 2: Criteria of habitats definition (Ysebaert et al., 2013, 2016) All habitats are tidal, with tidal range approximately 0.3 m. MLWN: Mean Low Water Neap, MLWS: Mean Low Water Spring, MHWN: Mean High Water Neap, MHWS: Mean High Water Spring

1. If any ecosystem falls into one of the following categories of habitat: 'fresh deep water', 'fresh shallow water', 'brackish deep water' or 'brackish shallow water', it converts into (or remains) the ecosystem 'fresh deep water', 'fresh shallow water', 'brackish deep water' or 'brackish shallow water', respectively.

2. If any ecosystem falls into one of the following categories of habitat: 'freshwater tidal flats', 'freshwater marshes', or 'freshwater terrestrial', the original classification is kept.

3. If any natural freshwater ecosystem falls into one of the following categories of habitat: 'brackish tidal flats', 'brackish marshes' or 'brackish terrestrial', it converts into 'brackish intertidal sand and mudflats', 'low brackish marshes' or 'high brackish marshes', respectively.

4. If any anthropogenic ecosystem falls into one of these categories of habitat, it does not change.

Using these assumptions, I superimposed the habitat maps for each of two considered water management scenarios on the current ecosystem map. From ten types of habitats and eight types of current ecosystems, I obtained 80 types of their combinations. Then, I reclassified them into 13 ecosystem types, according to the above-mentioned assumptions. In this way, I obtained ecosystem maps for the scenarios 1 and 3.

Then, I developed ecosystem maps for the scenarios, which imply habitat restoration measures (scenarios 2 and 4). For this purpose, I created first the map of the areas, where habitat restoration measures are planned, using the corresponding data, kindly provided by WWF (Bureau Stroming, 2015). Then, I superimposed the created maps on the maps of combinations of habitats and ecosystems, obtained during development of the ecosystem maps for scenarios 1 and 3. Then, I reclassified this map. For the areas, where habitat restoration measures are not planned, the principles of the reclassification were the same as for scenarios 1 and 3. However, for the areas of planned habitat restoration measures, I assumed that within these areas grasslands and crop fields are replaced with natural ecosystems. The particular type of the natural ecosystem is determined by the type of habitat. In this way, I obtained ecosystem maps for the scenarios 2 and 4. Using derived ecosystem maps for the current situation and for the scenarios, I calculated areas of each ecosystem for each scenario (including the current situation). It allowed me to calculate changes in ecosystem areas in each scenario compared with the current situation.

2.4 ES: TYPOLOGY DEVELOPMENT, SELECTION AND OPERATIONALIZATION

I used the ES typology proposed for the Haringvliet by Bönhke-Heinrichs and De Groot (2010), who considered 50 ecosystem sub-services (ESS). For this study, not all these ESS were used. Given the focus on outerdike (semi-

)natural areas, the set of services considered here was limited to regulating services only. I also did not take into account the ESS 'Storm surge protection / coastal flood prevention', as it is relevant neither for the current situation nor for scenarios considered in my research, because in all these cases the Haringvlietdam performs this function. In this way, 15 ESS remained. I selected for my research six of them, which are sufficiently provided with literature data on ESS supply by ecosystems typical for the Haringvliet, and determined units of measure (Table 3).

2.5 QUANTIFYING ES SUPPLY

Having identified the relevant ES, the next step is to quantify the contribution of the different ecosystems in the Haringvliet region to providing these ES. Bönhke-Heinrichs and De Groot (2010) already reported which ecosystems link to what (sub)services.

To obtain ES supply per unit of area per year for the relevant ecosystems, I first searched for numerical values of ES supply. For this purpose, I conducted a literature analysis of peer-reviewed and 'grey' literature on quantifying supply of the ES I have selected for my research and then derived one indicator value per ES per ecosystem type from the set of available values from the literature.

The literature review showed that regulating ES in estuaries are widely discussed in the literature. Many papers are focused on monetary valuation of estuarine ES, but they of ten include supply as well. Directly for the Haringvliet, data on supply of some ES are available in the paper by Bönhke-Heinrichs and De Groot (2010). A comprehensive review on monetary valuation of estuarine ES provided by Barbier et al. (2011) contains some data on supply of ES for other regions. Considering studies, which focus on estuarine regulating ES in biophysical terms, there are many studies dedicated to carbon sequestration and sediment fixation in estuaries, but fewer for water treatment, and almost none for air quality control. Due to the recent developments of estuaries restoration plans around the world, some studies of ES associated with estuarine restoration are available as well.

I collected numerical values of ES supply per unit of area per year for each combination of the considered ES and the relevant ecosystem from different papers. Then, I used the collected values to quantify supply of ES in my study area per unit of area per year. For this purpose, I chose for each combination of the considered ES and the relevant ecosystem one of the values reported in the literature (in case of multiple values available), which I used further in my research. I applied the following criteria for the choice: reliability of the paper (peer-reviewed papers preferred); region and type of landscape, where the study was done (the closer natural conditions to the Haringvliet, the better); accordance with other studies. I assumed the ES supply in the ecosystems, which are not considered as most relevant for a given ESS according to Bönhke-Heinrichs and De Groot (2010), to be zero.

2.6 MAPPING ES

At this step, I used spatial data on ecosystems obtained in the step 3 and attributive data on ESS in each of these ecosystems obtained in step 5 to map ESS supply for the study area. I developed five maps for each ESS: one for the current situation (scenario 0) and one for each of four considered scenarios. These maps show the spatial distribution of the supply of each separate ESS across the study area per unit of area per year.

2.7 CALCULATING TOTAL ES SUPPLY

To obtain a total value of supply of a given ESS for the whole study area, I multiplied values of supply of this ESS in each type of ecosystem, expressed in values per unit of area per year, by the area of this type of ecosystem and then summed the values obtained for each type of ecosystem. Then, I repeated this procedure for each ESS for the current situation and for each of the four scenarios.

2.8 QUANTIFYING DIFFERENCES BETWEEN CURRENT AND FUTURE ES

In order to answer the principal question of my research about changes of ES supply, I compared the map of a given ESS for the current situation with the maps of the same ESS for each of the four scenarios. For this purpose, I subtracted the values of the current ES supply from the ES supply as projected under each of the scenarios. I did it for each ESS. In this way, I obtained maps of changes of values of supply of each ESS under each of the four scenarios. Using these maps, I calculated changes in the total values of ESS supply under these scenarios.

3. RESULTS

3.1 ECOSYSTEMS

The ecosystem mapping of the current situation shows that 71% of the study area is covered by water, almost equally by deep and shallow. Anthropogenic ecosystems, presented mainly by grasslands, cover less than 11% of the total area – but more than 1/3, if water is excluded. Natural intertidal and terrestrial ecosystems (mainly reed & rush and alluvial willow forests) cover 18%, primarily in the eastern part of the study area (Figure 1).

ES	ESS	Unit of measure
Air quality regulation	Capturing particulate matter (PM)	$kg(PM10) \cdot ha^{-1} \cdot yr^{-1}$
	Capturing NOx	$kg(N) \cdot ha^{-1} \cdot yr^{-1}$
Climate regulation	Carbon sequestration	$t(C) \cdot ha^{-1} \cdot yr^{-1}$
Water treatment	Water purification (nitrogen)	$kg(N) \cdot ha^{-1} \cdot yr^{-1}$
	Water purification (phosphate)	$kg(P) \cdot ha^{-1} \cdot yr^{-1}$
Adaptation to sea level rise	Sediment fixation	$m^3 \cdot ha^{-1} \cdot yr^{-1}$

Table 3: The ESS, selected for the study, and the units of measure

Almost all ecosystem changes under the considered scenarios occur in the western half of the study area (Figure 1). The eastern half of the area is virtually not exposed to these changes.

Ecosystem changes increase from exchange regime scenarios to storm barrier regime scenarios and from scenarios with no restoration measures to scenarios with Droomfonds restoration measures. Accordingly, changes are smallest in scenario 1 and generally increase up to scenario 4.

The main change observed is the replacement of freshwater ecosystems with brackish ecosystems. In the scenarios with exchange regime (1 and 2), 6,800 ha of freshwater ecosystems in the western part of the Haringvliet convert into brackish ecosystems, and in the scenarios with storm barrier regime (3 and 4) this change covers the whole Haringvliet as well as the western part of the Hollands Diep – 11,600 ha in total. Approximately 90% of this change in both water management scenarios is the conversion of fresh water into brackish water, and the remaining is mainly conversion of reed & rush into high marshes.

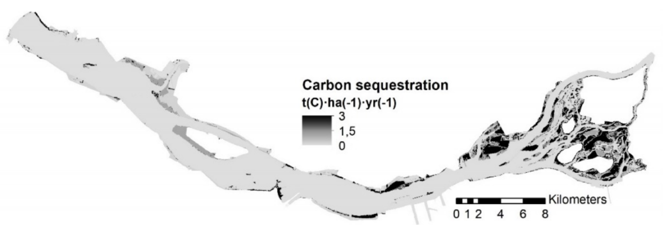

Figure 2: Spatial distribution of carbon sequestration in the current situation (scenario 0)

In scenarios with no restoration measures (1 and 3) ecosystem changes are driven exclusively by the above-mentioned change. However, in scenarios with Droomfonds restoration measures (2 and 4), conversion of agricultural ecosystems (grassland and cropland) into natural ecosystems occurs as well. As almost all restoration measures areas are situated in the locations that are exposed to brackish water even under the exchange regime scenario, agricultural ecosystems convert almost exclusively into brackish ecosystems. Actually, under both restoration measures scenarios, 590 ha of grassland and 90 ha of cropland convert into brackish ecosystems, mainly into high brackish marshes.

3.2 VALUES OF ES SUPPLY PER UNIT OF AREA

ES supply varies considerably in different ecosystems within the study area. Water and artificial ecosystems do not provide significant supply of any of the considered ES. Natural intertidal and terrestrial ecosystems are much more productive in this sense. Freshwater intertidal sand and mud flats provide significant amounts of carbon sequestration and water treatment. Reed & rush provide all considered ES, but the supply per unit of area for most of them, except for capturing NOx and water purification from nitrogen, is not very high. Alluvial forests, providing all considered ES as well, stand out in high supply of the most of them. For air quality regulation and carbon sequestration, they provide the highest supply per area unit, while their supply of water treatment from nitrogen is significant as well. Brackish intertidal sand and mud flats provide high supply of water treatment and sediment fixation. Brackish marshes are characterized by the highest values of supply of water purification from nitrogen and sediment fixation.

3.3 SPATIAL DISTRIBUTION OF ES SUPPLY AND ITS CHANGES FOLLOWING THE SCENARIOS

At the Figure 2, a map of spatial distribution of carbon sequestration in the current situation is shown. Similar maps were developed for other considered ES and for other considered scenarios: 30 maps in total. These maps show that most of the ES supply currently concentrates in the eastern part of the study area, where the share of alluvial forests, which provide the highest per-area supply of the most of considered ES, is higher. Supply of water treatment is also significant in some bank locations in the western part of the study area, where relatively large reed and rush beds exist. Maps of spatial distribution of ES for the four scenarios show that while the supply of air quality regulation remains concentrating in the eastern part of the study area in all four scenarios, supply of other ES, especially of sediment fixation, becomes significant in its western part as well.

At the Figure 3, maps of changes in carbon sequestration supply are shown. Similar maps were developed for other considered ES: 24 maps in total. These maps show that ES in the eastern half of the study area remain virtually unchanged in all considered scenarios. The reason for it is that ecosystems there hardly change. In the western half, on the contrary, significant changes of spatial distribution of ES follow changes of ecosystems. The following description of changes in ES supply concerns only the western half.

The supply of air quality control, both capturing PM and capturing NOx, decreases in many sites, but increases almost nowhere. The reduction occurs mainly in intertidal and terrestrial habitats, where marshes replace reed & rush and alluvial forests. Under the restoration scenarios, the air quality control supply reduces even more – in locations, where grasslands convert into marshes.

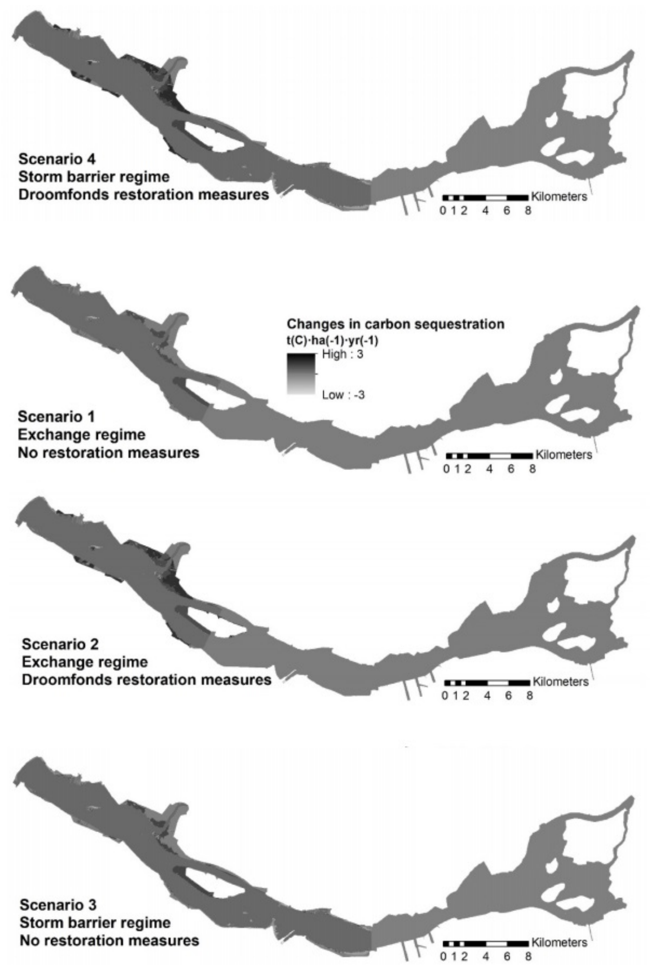

Figure 3: Changes in carbon sequestration

Except for air quality control, other ES mainly increase their supply under the scenarios. However, the patterns of changes are different for different ES. Carbon sequestration supply increases a little in aquatic ecosystems and much higher – in some intertidal habitats, for example, where reed & rush convert into high marshes. Under the restoration scenarios, one can also observe the substantial magnification of this ES supply in locations, where grasslands and croplands convert into marshes. However, in some locations carbon sequestration supply decreases. That happens, for instance, where freshwater sand & mudflats convert into brackish ones, or where marshes replace alluvial forests.

Supply of water purification from nitrogen almost only increases, mainly following conversion of intertidal and terrestrial ecosystems from freshwater into brackish. Major magnification of this ES supply occurs under restoration scenarios, in locations, where grasslands and croplands are replaced with marshes. Supply of water purification from phosphate mostly increases, mainly in locations, where reed & rush and alluvial forests convert into marshes. However, this increase is relatively small. Conversion of grasslands and croplands into marshes under restoration scenarios provides much higher magnification of this ES. In some locations, the decrease of water purification from phosphate occurs, for example, where freshwater sand & mud flats convert into brackish ones.

Sediment fixation supply experiences only an increase under all four scenarios. The increase is substantial and occurs mainly in locations, where various freshwater intertidal, terrestrial and anthropogenic ecosystems convert into marshes.

3.4 TOTAL ES SUPPLY AND ITS CHANGES FOLLOWING THE SCENARIOS

Total ES supply in current situation and in four considered scenarios was calculated in this study. Based on these calculations, relative changes were derived (Figure 4). They show clearly the main patterns of ES supply development under the scenarios.

Supplies of different ES have different patterns of changes in the scenarios. Supply of air quality control, both capturing PM and capturing NOx, decreases moderately (from 6 to 20 percent depending on the scenario). The decrease in the capturing PM supply is influenced approximately equally by water management and habitat restoration measures. However, the reduction in capturing NOx supply is influenced almost only by changes in water management, and it virtually does not depend on habitat restoration measures. In contrast, the total supply of all other ES considered increases in all scenarios. For carbon sequestration, this increase is quite high – 30-60%, influenced more or less equally by water management and habitat restoration measures. Supply of water purification (both from nitrogen and from phosphate) increases only by 2-6% by water management measures, but much stronger (about 20 percent) by habitat restoration measures. Finally, supply of sediment fixation increases dramatically (60-150%) in all scenarios, and the input of habitat restoration measures seems to be more important than the input of water management measures. high – 30-60%, influenced more or less equally by water management and habitat restoration measures. Supply of water purification (both from nitrogen and from phosphate) increases only by 2-6% by water management measures, but much stronger (about 20 percent) by habitat restoration measures. Finally, supply of sediment fixation increases dramatically (60-150%) in all scenarios, and the input of habitat restoration measures seems to be more important than the input of water management measures.

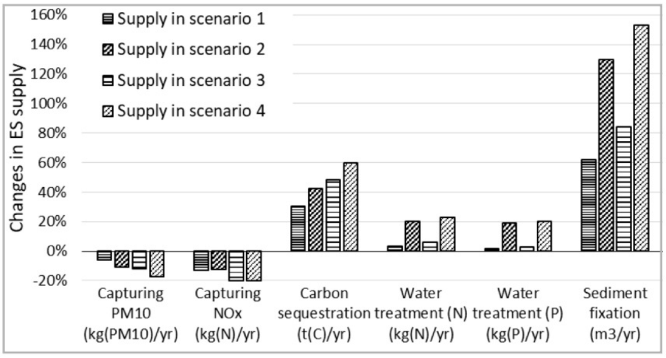

Figure 4: Changes in carbon sequestration

4. DISCUSSION

This study aims to assess the impact of the water management interventions and accompanying habitat restoration measures on the supply of ES in the Haringvliet area. I found that the supply of most of the considered ES increases under all four considered scenarios. The effectiveness of storm barrier regime scenarios is higher than that of exchange regime scenarios. The Droomfonds habitat restoration measures have approximately the same impact on the ES supply as the considered water management measures, which means that habitat restoration measures in general are a quite effective way to support ES supply.

4.1 COMPARISON OF THE RESULTS AGAINST A MORE EXTREME SCENARIO

The paper by Bönhke-Heinrichs and De Groot (2010) is also dedicated to the potential changes in ES in the same water basin. However, unlike the present study, it uses an extreme restoration scenario. Therefore, it is interesting to see, how the results obtained by Bönhke-Heinrichs & De Groot differ from the results of my research.

Bönhke-Heinrichs & De Groot provide only monetary values of ES and do not consider their spatial distribution. However, as the monetary values of the regulating ES, which are considered in my study, are proportional to their supply in biophysical terms, it is possible to compare relative changes of ES according to two studies. As Bönhke-Heinrichs & De Groot use a radical scenario, I compare against their results the results of scenario 4, which is the most extreme among the scenarios considered in my study.

The results obtained from two studies differ considerably. First, according to Bönhke-Heinrichs & De Groot, the supply of all ES considered increases following the restoration scenario, while the present study shows the decrease of the air pollution control supply under the restoration scenarios. Second, Bönhke-Heinrichs & De Groot claim that the supply of water treatment will increase under the restoration scenario by approximately 2.5 times that is much higher than the increase in the supply of this ES according to the present study (20% for nitrogen and 23% for phosphates) . Finally, despite of the substantial increase in the supply of air pollution control and water treatment reported by Bönhke-Heinrichs & De Groot, the increase in the supply of carbon sequestration projected in their study (33%) is almost two times lower than in the present study (60%).

There are several reasons for these considerable differences in changes of ES supply in the two studies. First, the considered scenarios are very different. While in scenario 4 in the present study the Haringvliet dam persists (although, functioning in storm barrier regime) and habitat restoration measures are relatively modest, the scenario used by Bönhke-Heinrichs & De Groot implies the total removal of the dam and the complete change in the land use of the whole Haringvliet area. It is clear that in the last case changes in ES supply will be much higher.

Another reason is the difference in study area. The area, considered in the study by Bönhke-Heinrichs & De Groot is 3.5 times higher than the study area in this research (82,000 ha against 23,000 ha). This substantial difference in the areas mainly due to including in the study by Bönhke-Heinrichs & De Groot terrestrial landscapes (mainly croplands, grasslands and cultivated forests), which are assumed to be converted into intertidal ecosystems under the considered scenario, and extensive surface of coastal seawaters. Of course, such a difference in the areas (and, consequently, in the composition and spatial distribution of the ecosystems) affects the supply of ES considerably. Finally, the present study and the study by Bönhke-Heinrichs & De Groot have different assumptions about values/supplies of the ES in different ecosystems. This also causes differences in changes of ES supply in two studies.

4.2 LIMITATIONS OF THE STUDY

The presented results of the effects of different combinations of water management and habitat restoration scenarios on values and spatial patterns of the ES supply in the Haringvliet should be interpreted with care. This study only shows a general picture and has several important limitations related to the study area, assumptions about the ecosystem changes under the scenarios and selection of the values of ES supply.

First, this study considers only the outerdike area (area that is currently not protected by dikes). However, Droomfonds plans some restoration measures related to the Haringvliet in the areas, which are protected by dikes now. Some of these areas are to be converted into artificial marshes; others are intended for the development of natural terrestrial ecosystems, like forests. These measures would significantly affect the ES supply in the Haringvliet area, but they are not taken into account in this study (section 2.1).

Second, an important limitation is related to the assumptions about the ecosystem changes in restoration scenarios. I assumed that the ecosystems will change following the habitat changes (mainly from freshwater to brackish), and the type of the new ecosystem will be determined exclusively by the elevation above water level. However, this might not always be the case. For example, at present reed and rush ecosystems occur at very different elevations. Consequently, the spatial distribution and the total area of any ecosystem in the scenarios are quite uncertain, causing uncertainty in ES supply.

Finally, the uncertainty, related with the selection of values of ES, seems to be the most important limitation of the present study. For most combinations of ecosystems and ES, I have found several values of ES supply. Even for the well-studied combinations, for which different sources of data are matched relatively well (e.g., carbon sequestration by deciduous forests), the variation between values of ES supply provided by different sources can be threefold (for example, compare the results by Sikkema (1994) with the results by Bernal and Mitsch (2012)). And for the poorer-studied combinations (e.g., carbon sequestration by brackish intertidal sand and mud flats), the ES supply in similar ecosystems in different locations (which can be quite close to each other) even within one study can differ twentyfold (Ruiz-Fernández et al., 2007). It is especially the case for the sediment fixation, for which supply can change more than tenfold at a very short distance.

Therefore, the total supply of the ES and its spatial distribution are influenced considerably by the selection of values of ES. However, the transfer of these values from other locations inevitably causes an error, which is difficult to estimate (Costanza et al., 1997; Daily, 2003; Johnson, Polasky, Nelson, & Pennington, 2012). To obtain more precise data, field studies of ES within the study area (or, for brackish ecosystems, which are not presently existing in the study area, as close to the study area, as possible) are needed.

4.3 IMPLICATIONS FOR MANAGEMENT AND POLICY MAKING

Despite of the limitations described above, the results of this study still can be applied for making management and policy decisions. The main goal of the restoration measures analysed in this study is to provide a more robust and sustainable ecological environ ment for the Haringvliet and the connected water basins. In terms of ES, it means the increase of the total ES supply in the area. While the study shows clearly that all considered restoration measures, both water management and habitat restoration, are in general beneficial for the ES supply, some additional habitat restoration measures might make the changes even more environmental-friendly. This study shows that the restoration measures do not automatically result in the increase of the supply of each ES. Of the six sub-types of ES considered in this study, supply of two sub-types (capturing of PM and NOx) decreases following the restoration measures. Therefore, environmental managers and policy-makers should not think that the restoration measures is a 'silver bullet', which will increase the supply of all ES. For each ES, thorough research should be implemented to find how this particular ES would change following the proposed restoration scenario. The main reason for the decrease of air quality control supply under the restoration scenarios is the reduction of the area of forests, which currently supply most of this ES within the study area. It is very likely that other ES supplied mainly by forests (not considered in this study) will decline as well following the considered restoration scenarios. Probably, environmental managers should come up with some additional habitat restoration measures in order to reduce the decrease of the total supply of the ES, which are specific for forests. One of the evident measures to reach this goal is the planting of new forests – either within the study area or in its neighbourhood. However, before the implementation of such measures a rigorous analysis should be done as well – to reduce potential trade-offs with other ES.

Fortunately, for the total supply of the ES considered in this study, most ES are currently provided at the eastern part of the study area. And this part of the study area is virtually not influenced by the considered restoration measures. It means that the substantial decrease of any type of ES following all the scenarios considered in this study in unlikely. However, the spatial distribution of changes in ES supply has a great importance as well, at least for some types of ES. For example, the reduction of the PM capturing following scenario 1 is quite small – only 6 percent. However, one can observe a considerable reduction of this ES supply near Hellevoetsluis city. While this city is quite small – only 39 thousand people, the reduction of PM capturing in its neighbourhood still might matter for the air quality in this settlement. Therefo re, the restoration measures, which will help at least to conserve the current level of PM capturing supply around Hellevoetsluis, are very welcome.

5. CONCLUSION

The Dutch government and the Droomfonds coalition plan to improve the Haringvliet's ecosystem state by partial opening of the Haringvlietdam and accompanying habitat restoration measures. The present study is the first attempt to assess the impact of these measures on the supply of ES in biophysical terms under plausible restoration scenarios. Its results can be used for the assessment of the Droomfonds restoration plan in order to provide the highest possible supply of the ES in the Haringvliet area. However, for a really comprehensive analysis of changes in ES supply following the restoration scenarios additional research should be done. It should consider more types of ES, take into account habitat restoration measures in the areas protected by dikes and preferably use the values of ES supply obtained directly in the Haringvliet area or in the vicinity.

In addition, assessment of the ES changes in biophysical terms only is not sufficient for the full understanding of the impact of these changes on the environment, society and economy. Social and economic assessment should be done as well. In this way, my study is only small, though hopefully important, part of a comprehensive research that should be implemented to provide thorough, detailed and precise assessment of the ES changes in the Haringvliet area following restoration scenarios.

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