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Deltares

Enabling Delta Life

How to best protect your coastline against flooding? A methodological approach

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Abstract

Coastal zones are among the most densely populated placed on earth, yet are increasingly more at risk due to climate change. Flood protection systems are more in need than ever, and there are several methods to provide this protection: Traditional hard engineering structures, natural protection systems and the combination of hard structures and natural flood protection systems. The main aim of this research is to develop a method to determine where on the globe what type of flood protection is most suitable. Several parameters were determined that influence the decision on whether a traditional protection system, an ecosystem of a combination thereof is most suitable. Additionally, variables were determined to assess the most suitable ecosystem for the location. The parameters used for the first decision between traditional, ecosystems or combined are the risk at the location in %GDP, the amount of space between the location and the coast in meter, and the cost of the solution compared to the wealth of the location. The variables for the ecosystem decision are temperature and sediment type.

All parameters and variables have been parameterized in a literature study. The parameterization was tested on the basis of several case studies; The Netherlands, the city of Khulna in Bangladesh and the city of New Orleans in the USA. A sensitivity analysis was then performed to test the robustness of the parameterization.

The results of the decision model determining between green, grey and hybrid show a great robustness, predicting the present protection system in most cases. Results of thedecision model determining the possibility of ecosystems are also found to be robust for temperature. However, the results show that the parameterization of the variable sediment had been oversimplified, and therefore needs to be reparameterized.

Our final conclusion is that the chosen parameters and variables are relevant to their respective models, and that their parameterizations in most cases represent reality in an adequate manner.

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1. Introduction

People and natural areas in coastal zones are increasingly at risk by coastal hazards (Spalding et al., 2014a). These zones are particularly vulnerable to impacts of extreme events, such as storms, floods and hurricanes (Allison et al., 2009; Bender et al., 2010; McIvor et al., 2012). Climate change will intensify this vulnerability, with projections of sea level rise between 0.4 meter and 0.8 meter (Church et al., 2013), thereby increasing storm surge and wave impact (Spalding et al., 2014b). This could lead to coastal erosion (Leatherman et al., 2000; Temmerman et al., 2013), flooding, inundantion of low-lying lands and consequently salinization of groundwater (Moore, 1999). Yet coastal zones are among the most densely populated places on earth, with about 10% of the world population living in the Low Elevation Coastal Zone (LECZ), a zone defined as the area along the coast that is less than 10 meters above sea level (McGranahan et al., 2007). Additionally, the LECZ is generally highly economically developed (Brown et al., 2009; Liu et al., 2013), adding an additional risk on top of the existing threat to natural systems and human lives.

The potential huge vulnerability of coastal zones gives an immediate need for more and better solutions. However, while the traditional "grey" solution of building levees, seawalls or bulkheads may work under certain circumstances (Borsje et al., 2011), these circumstances may not be the same for all coastal countries (Temmerman et al., 2013). Additionally, risk reduction scenarios such as levees are hard structures that do not adapt to changing boundary conditions, such as rising sea level. A need for more cost-effective and adaptive risk reduction scenarios, in addition to the traditional solutions, has therefore arisen (Temmerman et al., 2013).

The solution to relieve this need was found in nature, as it was noticed that some ecosystems provided coastal protection benefits, such as wave attenuation and sediment deposition (Borsje et al., 2011; Spalding et al., 2014a; Spalding et al., 2014b). These ecosystems can also be actively introduced, for example the Building with Nature approach, first introduced in the Netherlands (Van Slobbe et al., 2013; De Vriend et al., 2015).The potential for ecosystem coastal protection has been widely researched (Borsje et al., 2011; Ondiviela et al., 2014; Spalding et al., 2014a; Spalding et al., 2014b) and has shown a possible great value to protection but also as a more cost-effective method (Borsje et al., 2011; Spalding et al., 2014b). However, there is little knowledge on when ecosystem engineering or when classical engineering solutions are preferred, and what specific conditions this decision depend on. Additionally, in the case of ecosystem engineering, there are multiple ecosystems that can provide coastal protection (Borsje et al., 2011; Ondiviela et al., 2014; Spalding et al., 2014a; Spalding et al., 2014b), and a comprehensive manner to determine which one is most suitable in what locations does not exist. As this information is pivotal for the ensurance of proper coastal protection, in this project, we aim to provide a method to assess the suitability of different types of coastal protection for coasts around the globe.

2. State of the art

2.1 Type of flood protection

Broadly, there are 3 types of flood protection that can be differentiated: the traditional engineering solution which will be abbreviated to a “grey” solution; solutions that involve the use of ecosystems as methods against flooding, called “green” solutions; and solutions that involve both grey and green methods, called a “hybrid” solution. Different solutions exist for fresh- and saltwater systems, so the following definitions will be given in the context of saltwater systems, as the main interest of this research is on coastal systems.
In this report, grey solutions are defined as to be human built hard structures that prevent floodwater to penetrate either urban or agricultural area. Examples for grey solutions include levees, seawalls and bulkheads (Borsje et al., 2011).

Green solutions are ecosystems that through their natural behavior provide protection for land behind it. Green solutions can either be built by humans or can grow naturally. In this report, applying no intervention is also defined as a green solution.
In salt water systems, there are several ecosystems that can provide flood protection. We will list some of the most important ecosystems below, briefly explaining their mechanisms and value as flood protection ecosystem.

Sea grasses are a unique group of plants that have adapted to living fully submerged (Ondiviela et al., 2014). About 60 species exist worldwide, with species found in temperate and tropical waters, in coastal zones – both sheltered and exposed - and estuaries, and in zones ranging from tidal to subtidal (Ondiviela et al., 2014). Its interaction with hydrodynamics, which affects wave attenuation, current flow and sediment dynamics (Borsje et al., 2011; Ondiviela et al., 2014), make it a good example of a type of ecosystem that has characteristics to protect coastal zones against flooding. This combination of wave attenuation and sediment dynamics plays an important role on the water level penetrating the canopy. By catching sediments, sea grasses counter soil erosion, and also improve the water transparency and quality, eventually enabling more sunlight to reach the sea grass and promoting its own growth and reproduction, forming a positive feedback loop. But sea grasses are not effective everywhere. The depth of the grass in the water, the wavelength of the waves, sediment composition and the meadow width play an important role for its effectiveness. For example, sea grass performs better in shallow areas, where it occupies a large area of the water column. They are also difficult to plant and/or restore and their effectiveness on a large scale is so far unknown (Ondiviela et al., 2014). Sea grasses therefore have a great potential, but need further research before definitive implementation.

Mangroves and salt marshes are found in different parts of the world, but can provide flood protection in a similar manner. Mangroves and salt marshes can reduce surge water levels due to their dense vegetation, which reduces the water flow velocities and turbulent flows (Spalding et al., 2014a; Spalding et al., 2014b). They can also reduce coastal erosion and stimulate sediment deposition to counter sea level rise (Spalding et al., 2014a), as the vegetation catches particles in the water, promoting sediment deposition (Spalding et al., 2014b). A study by McIvor et al. (2012) has shown that mangroves can reduce wave heights between 12% and 66% over 100m mangroves; in absolute values showing between 0.4 and 4.8 centimeter of height reduction per 100m, depending on the thickness of the canopy. For salt marshes the reduction of wave heights were reported to be almost 61% per 100m (Möller et al., 1999). Coastal systems such as mangroves and salt marshes may have a clear advantageous position over grey solutions if these systems really are able to keep up with sea level rise through sediment deposition, which, according to Kirwan and Temmerman (2009) can be up to 5mm a year. However, a drawback is the fact that they require much more space than a grey solution before having a similar effect in flood protection (Golder Associates Ltd and Associated Engineering, 2003; Van Loon-Steensma, 2015).

The next group of ecosystems is *beaches, dunes and barrier islands.* This group consists of structures that are built out of sand and serve to dissipate wave energy and provide sediment deposition as a method to maintain coastlines (Defeo et al., 2009). An advantage to beaches and barrier islands is that its profile can be adjusted to dissipate the wave energy most efficiently (Prasetya, 2007). An example of barrier islands is the Wadden Islands in the northern part of the Netherlands. For dunes, an important factor for its effectiveness is the presence of vegetation. The vegetation catches loose flying sand, capturing and holding the dune together (Prasetya, 2007; Spalding et al., 2014b). A disadvantage for this group is the continuous erosion that takes place, through both natural processes (wind, waves and tides) and human activities (e.g. shrimp fishing) (Prasetya, 2007).

Finally, we discuss *mussel beds and coral reefs*. Mussel beds and coral reefs, through their intricate structure, can affect wave velocities and trap sediment (Van Leeuwen et al., 2010). Mussel beds have also shown to counter coastal erosion (Meyer et al., 1997), with reports up to 30-40cm of mussel bed rise in its first half year after building (Van Leeuwen et al., 2010). Its effectiveness, of course, depends on the thickness of the bed (Borsje et al., 2011). Coral reefs can also show rapid rates of accretion. Perry and Smithers (2011) show growth rates of 0.3 to 0.9m/100 years, strongly dependent on the health of the reef. Coral reefs suffer badly under coral bleaching due to ocean acidification, which threatens the long term value for these reefs. Even so, however, it is likely they will maintain their coastal protection value for at least another 20-50 years (Spalding et al., 2014a).

Hybrid solutions are defined as solutions that use both a green and a grey solution. Green protection solutions may not offer the amount of protection needed in many areas, but simultaneously it is possible that grey solutions may carry economic or social costs that are deemed unacceptable in some areas (Spalding et al., 2014b). Many ecosystems only reduce aspects such as wave height only by a certain degree, with a possibility that it is not enough. When combined with a levee, the land behind it can still be effectively protected while still maintaining the advantages of ecosystems such as sedimentation deposition. Additionally, levees can be built smaller as wave height is reduced (Spalding et al., 2014a), thereby also reducing production and operation costs. See Figure 1 for a general visual representation.

An example of a hybrid solution is the new coastal defense system in New Orleans, where wetlands have been restored as an additional coastal protection zone (Kazmierczak and Carter, 2010). Behind the wetlands, levees have been restored as a second line of defense, see Figure 2.

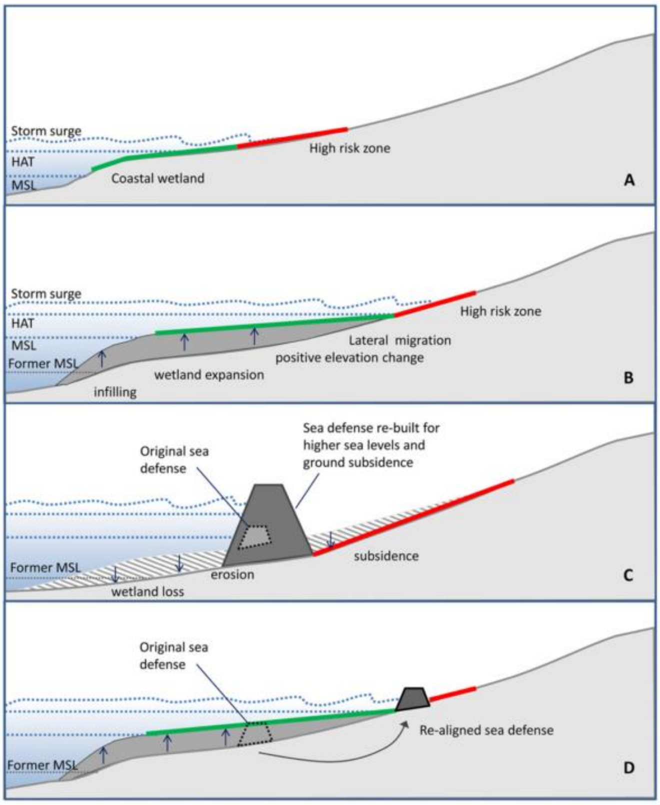

Figure 1. A: the situation in a coastal zone without any precautionary measures. B: coastal zone with a green precautionary measure, mean sea level (MSL) rise included. C: coastal zone with a grey precautionary measure, mean sea level (MSL) rise included. D: situation of the same coastal zone with a combination of a green and grey measure, mean sea level (MSL) rise included. Source: Spalding et al., 2014a.

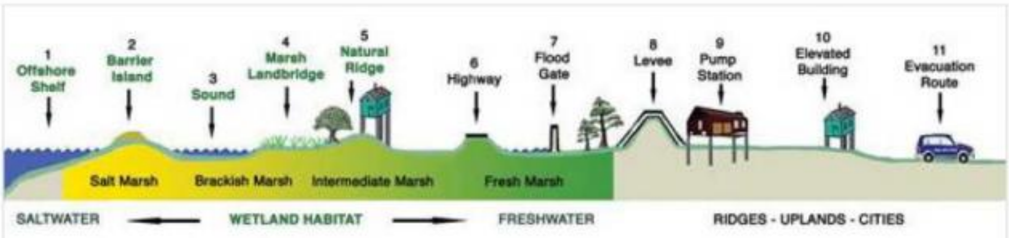

Figure 2. Schematic representation of the New Orleans flood defense, showing multiple lines of defense against hurricanes, flooding and sea rise. Source: Kazmierczak and Carter, 2010.

2.2 Aqueduct global flood analyzer

This project has been done as a daughter project of Aqueduct. Aqueduct is a global flood analyzer, which measures river flood impacts in terms of urban damage, affected GDP and affected population (Ward et al., 2013). These impacts can be calculated on different scales: country, state and river basin across the globe. The analyzer can then estimate the current flood risk for a specific location, taking into account a protection level which can be set by the user which ranges from a once every 2 year flood event and a once every 1000 year flood event. Additionally, the user can identify how that flood risk would project 20 years into the future, and how this can differ between varying decisions in socio-economic development. This last feature is specifically designed to assist decision makes to identify the drivers for future change and thereby assisting them in strategic planning.

The current version of Aqueduct contains some limitations, however, that are of great importance. First, the current version of Aqueduct only simulates large-scale river flooding, and no coastal flooding as of yet (Ward et al., 2013). Secondly, the risk values returned by Aqueduct do not include current flood protection, and is therefore often overestimated where flood protection measures are in place (Ward et al., 2013, Winsemius et al., 2013).

This thesis is designed to be a future addition to Aqueduct, where decision makers will simply select the country, state or river basin they wish to investigate, and will receive a recommendation on which type of intervention is most suitable with respect to coastal flooding, and which ecosystem would suit their needs in the case of a hybrid or green solution. Due to the fact that Aqueduct is an open source, free to access tool, the model therefore has the prerequisite to remain fairly simple, as any full hydro dynamical modeling that would require a large amount of computational effort would greatly slow the tool down and reduce ease of use.

2.3 Research Questions and Aim

The main aim of this research is to develop a method to succesfully determine where on the globe what type of flood protection is most suitable.

This leads to our main research question with the following subquestions:
How can we determine the most adequate coastal protection system for a given location?

> Sub question 1: what factors determine when classical engineering and when ecosystem protection solutions are used? And what environmental factors play a role when choosing for the most appropriate ecosystem?
>
> Sub question 2: How are these factors parameterised to create an accurate and adequate decision model?

3. Methods

3.1 General explanation decision model

The goal of this research is to develop a method to succesfully determine where on the globe what type of flood protection is most suitable. The possible types of protection are the green, grey and hybrid methods, as explained in Section 2.1. Additionally, when a green or hybrid solution is favored, it is useful to know what type of ecosystem is then possible in this location. This means there are 2 types of decisions that need to be made: the type of solution, and then the type of ecosystem. We have therefore chosen to develop two separate decision models.
Model 1, which helps deciding between a green, grey and hybrid solution, and returns a compatibility percentage for each type of solution. The lowest achievable compatibility is 0.0%, the highest compatibility 100%. This compatibility is determined through the interdependence of several parameters that are important in the decision which solution is best. Section 3.2 is dedicated to the elaboration on important parameters and the parameterization of model 1.
Model 2, which is the ecosystem model, is deterministic of nature. This model determines if an ecosystem is either possible or not. The choice for a deterministic model stems from the fact that a lower compatibility with for example a type of sediment leads to the fact that the ecosystem is unable to grow, and will eventually wither. For this reason, an ecosystem can either exist or not exist. The determination of the relevant variables for the ecosystem model and their parameterization can be found in Section 3.3.
The results of both models will be combined to give a final recommendation for a specific location. A combined result will have the form of a list of compatibility percentages for each type of solution, together with a list of ecosystems that are possible in this location.
Finally, in Section 3.4, several locations will be introduced on which both above described models will be tested.

3.2 Decision model part 1. Green/grey/ hybrid model

First, the green/grey/hybrid section of the decision model will be discussed. The decision factors that determine what choice is optimal are the following: Risk (avoided damage, in %GDP), available space (in meters), spendable GDP on a solution (in %GDP), sediment availability, governance and rate of subsidence. The decision factors have been chosen based on expert knowledge within Deltares (Deltares private meeting, 2015) and literature research. In this thesis, only the first three decision factors are modeled, which were determined to be the most important in the decision (Deltares private meeting, 2015). The other potential decision factors are more elaborately explained in Section 3.2.4.
When the model is applied to a given location, the location specific values for the parameters listed above are compared to when a certain solution is most preferable. For every parameter, for every type of solution, the model returns a percentage between 0 and 100%, identifying how compatible the type of solution is for that location, where 0% represents no compatibility and 100% maximum compatibility. This percentage is calculated as follows; the decision of the type of intervention is determined by the parameters, where we assume them all to be of equal importance. For all parameters it is determined until what value of this parameter a green, hybrid or grey intervention is most suitable, and thresholds are determined. Thresholds are defined as when the solution is the least attractive, and when the solution is the most attractive. Between these values, a linear relation between the compatibility and the parameter is assumed. However, when more than one point of either minimum or maximum attractiveness is identified, a Gaussian relation is used. When the proper relation is identified, either linear or Gaussian, a compatibility percentage is calculated per intervention per parameter. The final compatibility percentage per intervention is finally calculated by determining the mean of these individual percentages. For example, a possible result for a location could be a 30% compatibility with green, 45% with hybrid and 2% with grey.

Below, all parameters will be explained in detail as to why they have been chosen. Furthermore, the parameterization for each chosen parameter will be discussed.

3.2.1 Risk Parameterization

Traditionally, risk is defined as the product of three components: hazard intensity, vulnerability and values at stake (Kron et al., 2005). Hazard is the natural phenomenon that is threatening a certain area, including its probability of occurrence and the intensity of the hazard. Vulnerability is the degree to which a system is susceptible to harm from exposure to stresses associated with environmental and social change, and from the absence of capacity to adapt (Adger, 2006). Values at risk (in USD) are defined as the people/buildings/valuables that are present in that particular area (Kron et al., 2005). In this report, the term risk is used for potentially avoided damage, given a certain hazard and vulnerability. So risk will be synonymously used as the possible avoided damage. The possible avoided damage will be expressed in %GDP, and not GDP/capita, as Aqueduct also calculates its risk in %GDP.
Risk was chosen as an important factor to implement, as different flood risks consequently mean different solutions, due to the difference in protection ability between the possible interventions (McGranahan et al., 2007; Sutton-Grier et al., 2015).

Out of the three possible solutions (green, grey and hybrid), we estimated boundaries above and below which the solution is likely not the most feasible option. These estimates of boundaries, including their explanations, are found below, and are based on when a particular solution is the most and least attractive given a similar hazard. A visual representation is given in Figure 3; a summary of the thresholds is given in Table 1.

Table 1. Summary of the thresholds, in %GDP, for minimum and maximum attractiveness for a green, grey and hybrid solution, for the parameter Risk.

	Maximum attractiveness	Minimum attractiveness
Green	0% GDP	0.7% GDP
Grey	3% GDP	1% GDP
Hybrid	0.5% GDP	2% GDP

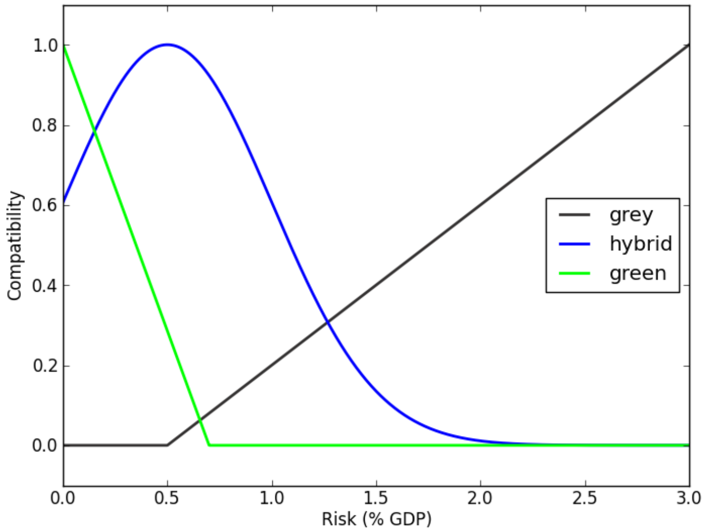

Figure 3. 2D representation of the compatibility on the y-axis of all solutions with respect to the risk, on the x-axis, of the area in % GDP. The grey line represents the change in compatibility for a grey solution, the blue line the compatibility for a blue solution and the green line the compatibility for a green solution.

Green

The minimum attractiveness of a green solution is when the risk is high. An ecosystem in itself often does not provide the protection that is needed on its own (Spalding et al., 2014a), as it often only lessens the waves and not stops them (wave attenuation for mangroves is between 13 and 66% over 100 meters (McIvor et al., 2012), and about 61% for salt marshes (Möller et al., 1999)). Green solutions are able to protect high value areas (Cruz et al., 2007), yet due to dependency on the biotic and abiotic features of the specific location, the level of protection per location varies widely (Sutton-Grier et al., 2015). The minimum attractiveness is therefore chosen in between a very severe flood event and weak flooding; minimum attractiveness is when risk reaches 0.7% GDP.
Maximum attractiveness is when the risk is low, but when flood hazard does exist. In these cases, wave attenuation through the green option is sufficient to bring down the risk. In addition, a green solution in these cases leads to an array of co-benefits, such as increased biodiversity, recreational use and carbon sequestration (Sutton-Grier et al., 2015; Spalding et al., 2014a; Barbier et al., 2011 ; Grabowski et al., 2012).

Grey

Maximum attractiveness of a grey solution is when there is a high risk. A grey solution is defined as the most effective solution in high risk situations compared to green and hybrid solutions (see hybrid for elaboration), partially due to significant knowledge and experience with grey solutions (Sutton-Grier et al., 2015). The maximum risk in our model is defined as 3% of GDP. This number is based on the annual cost of flooding in Bangladesh, calculated by Majumder (2013), who calculated the annual average cost between 1980 and 2010. It must be noted, however, that this cost includes river flooding, and therefore may be slightly overestimated. Minimum attractiveness is when risk is low, as a grey approach may sustain more damage during small storm events than natural approaches, due to nature’s ability to self-repair (Sutton-Grier et al., 2015). In these cases, a green or hybrid solution would make more sense, and would provide co-benefits additional to flood protection.

Hybrid

For hybrid solutions, quantification of its storm and erosion protection is still very much in process and (as of August 2015) no documentation can be found on this (Sutton-Grier et al., 2015). In this research we have searched for information as well, but came to the same conclusion as Sutton-Grier et al (2015). This means that the values used for the hybrid solution, which will be based on literature of both green and grey solutions, are subjected to a higher level of uncertainty than the values found for green and grey solutions.

Maximum attractiveness for a hybrid solution is when risk levels are getting higher, since natural coastal protection may not offer sufficient security in some areas (Spalding et al., 2014b). They do quickly become attractive as a solution, as they provide more services than grey flood protection alone (Sutton-Grier et al., 2015 ; Spalding et al., 2014a; Barbier et al., 2011 ; Grabowski et al., 2012); this means that attractiveness increases until a maximum, which we will set at 0.5%, and then decreases. Minimum attractiveness is when the risk is becoming very high. Due to its design, it capitalizes on the best characteristics of both green and grey solutions, so can withstand high risk situations (Sutton-Grier et al., 2015). However, due to uncertainty in the performance of hybrid systems, and the fact that the benefits to the green part will be less with a higher possible risk, this risk will not be set at out upper limit of 3%, but estimated at 2% (Sutton-Grier et al., 2015).

As mentioned, due to the large uncertainty in the performance of hybrid systems, the chosen thresholds are simply estimates. It is therefore possible that a hybrid solution is able to withstand much higher risk levels and that its peak compatibility is wider than shown in Figure 3.

3.2.2 Space Parameterization

Space has been chosen as a parameter as the required space for the different solutions differs widely. Green solutions tend to require much more space than conventional grey structures (Temmerman et al., 2013). In highly urbanized areas such as New York, space is so scarce that only a grey solution would seem feasible, due to the amount of space ecosystems require (Temmerman et al., 2013). This means that not all solutions are applicable in every situation, and it is necessary to know when our three solutions can be applied, and when not.

In this report, the parameter Space is the amount of meters from the shore to a point inland. For every solution, we have determined a minimum and maximum limit. These limits are expressed in attractiveness, i.e. the minimum attractiveness is the amount of meters when the solution is still possible, but the least advisable. Table 2 shows a summary of the chosen thresholds for the parameter Space. In Figure 4, the thresholds are visualized.

Table 2. Summary of the thresholds, in m, for minimum and maximum attractiveness for a green, grey and hybrid solution, for the parameter Space.

	Maximum attractiveness	Minimum attractiveness
Green	3000m	500m
Grey	500m	0m
Hybrid	1000m	250m

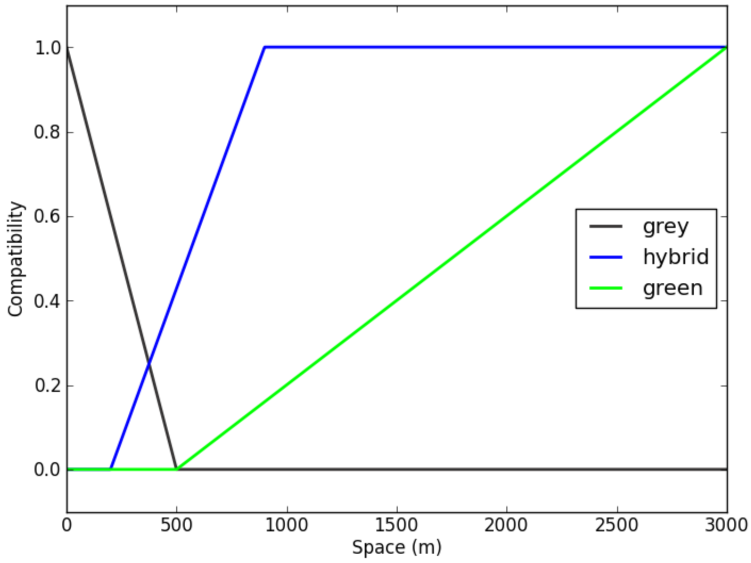

Figure 4. 2D representation of the compatibility, on the y-axis, of all solutions with respect to the space (in m) available, which is plotted on the x-axis. The grey line represents the change in compatibility for a grey solution, the blue line the compatibility for a blue solution and the green line the compatibility for a green solution.

Green

The more space available between an urbanized area and the sea, the higher the efficiency of a green solution (Temmerman et al., 2013). Green solutions such as mangroves and salt marshes offer flood protection by attenuation of waves over wide expanses, and with increasing width the attenuation increases (Spalding et al., 2014a). Wave attenuation for mangroves is between 13% and 66% over 100m, depending, among others, on the density of the canopy (McIvor et al., 2012). Mangroves also have a potential in reducing tsunami waves, if the forest spans many kilometers (Spalding et al., 2014a). Salt marshes attenuate about 37% of the waves in the first 200m, but as the increase in attenuation over increased space is not linear, a wide expanse is necessary (Van Loon-Steensma, 2015). Dunes block the water directly, but need considerable space to allow natural dynamics such as erosion and accretion take place. A green solution is therefore the most attractive when there is a lot of space available, a limit we will place at a maximum of 3 kilometers.
A green solution is therefore the least attractive when there is little space for the waves to be attenuated. The space for a system of dunes to effectively operate lies around 800+ meters (Defeo et al., 2009), yet for a mangrove system much less is needed (McIvor et al., 2012). We therefore place a minimum amount of space necessary at 500 meters.

Grey

A grey solution is attractive due to its limited use of space and ability to immediately withstand storm events after construction (Spalding et al., 2014a); Sutton-Grier et al., 2015). The space necessary for a grey solution depends on the height of the dike. A dike needs roughly three times its height in horizontal space (Golder Associates Ltd and Associated Engineering, 2003). This size is without taking into account the size of the crest of the dike, which can vary widely per location. So for a small dike, the space needed is about 10 meters. However, we choose our threshold at 0.0, to make sure no situations are accidentally left out. Our maximum attractiveness is therefore set at 0m. The minimum attractiveness is when there is a lot of space available, as a grey solution only offers storm protection benefits when a storm is approaching, but does not add additional benefits in good weather conditions as green and hybrid solutions do (Sutton-Grier et al., 2015; Spalding et al., 2014a; Barbier et al., 2011; Grabowski et al., 2012). The minimum attractiveness limit is therefore placed when both a green and hybrid solution are (becoming) attractive.

Hybrid

For cities closer to the sea, a combination of grey and green would be more appropriate (Temmerman et al., 2013). According to Temmerman et al. (2013), in the case of hybrid solutions with off-shore possibilities, seaward ecosystem creation is also an option. In this study, however, we only focus on landward available space due to a lack of knowledge on foreshore bathymetry.

When a green solution and grey solution are combined, the combination requires less space (Spalding et al., 2014a). As ecosystems attenuate wave action, a less powerful wave will reach the dike, so a smaller dike will suffice. Conversely, when a dike is present to stop the remaining wave after it has passed through an ecosystem, it is possible to somewhat shorten the amount of ecosystem present as the waves don't have to be attenuated as much as when a green solution stands alone. This means that a hybrid solution is already attractive when a green one is not, but still needs more space than a stand-alone grey solution. The minimum attractiveness is therefore set at 250 meters. The maximum attractiveness is when a longer stretch of ecosystem precedes the dike, offering higher levels of wave attenuation thereby reducing damage to the dike from small storm events (Sutton-Grier et al., 2015). In total, this offers a higher protection level. This maximum attractiveness threshold is set at 1000 meters, since a green solution beyond this point might hold more benefits as a hybrid system can still have some – but limited- negative effects on biodiversity and ecosystem functioning.

3.2.3 Cost of a Solution Parameterization

The cost of a solution is a very important parameter, as the different solutions vary widely in their projected expense. Grey solutions are highly effective, but are also very costly to build and maintain (Spalding et al., 2014b; Anthony and Gratiot, 2012; Bosello et al., 2012). Green solutions often come at a much lower cost (De Vriend et al., 2015), while hybrid solutions have a cost lying between grey and green solutions.

The cost of a solution is also important as different countries are not able to spend the same amount of money on coastal protection as others. The Netherlands spend about 1.1 billion USD each year on flood protection by dikes (Delta Commissie, 2008; Eijgenraam et al., 2012), which is about 0.13% of their GDP. This is an expense that for a country such as Albania, with a similar length coastline (Eftimi, 2010; U.S. CIA Factbook, 2000) but with a GDP of only 13 billion USD, is not as feasible. The GDP of a particular country is therefore very important in deciding if the cost of a solution is too high or not.

Hinkel et al. (2010) find that adaptation costs relative to GDP differ largely per country. For example, Estonia invests 0.16% GDP and Ireland 0.05%, where Estonia has a much lower GDP than Ireland (World Bank, 2015). It is, however, unclear what the exact relation is between spendable GDP and GDP height. Additionally, the exact cost of the individual solutions per country would be needed, which is currently unavailable (Committee on U.S. Army Corps of Engineers Water Resources Science, 2014). We therefore use the GDP of a country as a proxy, based on the assumption that richer countries have the wealth and will therefore use it, and relate this to the attractiveness of the solution. As the height of GDP on state/province- and city level are of similar order of magnitude as the GDP of countries (Parilla et al., 2014), this parameter can also be applied on city and state/province level, if other parameters have values covering a similar geographical area.

We have set thresholds when a solution is the most attractive and when they are the least attractive. Figure 5 shows a visual representation of the chosen thresholds, and Table 3 a summary.

Table 3. Summary of the thresholds, in USD, for minimum and maximum attractiveness for a green, grey and hybrid solution, for the parameter Cost.

	Maximum attractiveness	Minimum attractiveness
Green	0 USD	75 billion USD
Grey	1600 billion USD	400 billion USD
Hybrid	400 billion USD	1 billion USD

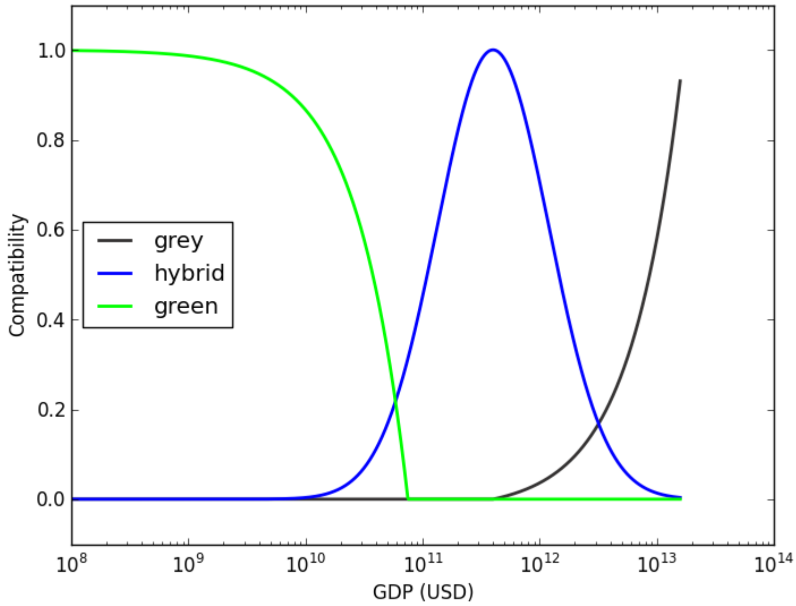

Figure 5. 2D representation of the compatibility, on the y-axis, of all solutions with respect to the GDP of a country, on the logarithmic x-axis. The grey line represents the change in compatibility for a grey solution, the blue line the compatibility for a blue solution and the green line the compatibility for a green solution.

Green

While restoration and management of ecosystems of a green solution will incur some costs, existing ecosystems already provide protection with no installation costs needed (Barbier et al., 2013). The maximum attractiveness of a green solution is therefore when there is no installation cost, most suitable for countries with very low GDP. Ecosystems are the least attractive as a solution when their costs rise, as beyond a certain threshold, a hybrid solution is already affordable and becomes more attractive due to its higher defense level. Due to a lack of precise data on costs of all solutions, we estimate this limit at 75 billion USD GDP. This limit is chosen as this covers the poorest 50% of the world (The World Bank, 2015).

Grey

Grey solutions are defined as the most expensive solution of the three, and are most attractive when a country has a very high GDP. As a maximum, we take the highest global GDP, which is the US GDP at 1600 billion USD (The World Bank, 2015). Minimum attractiveness, we estimate, is with a GDP of 400 billion USD, covering the world's richest 15%. With less money available, combinations of the (cheaper) green solution (Barbier et al., 2013; Sutton-Grier et al., 2015; Committee on U.S. Army Corps of Engineers Water Resources Science, 2014) with a built infrastructure is then more attractive, as the costs drop and risk attenuation is not compromised.

Hybrid
Due to a lack of cost-benefit analyses and general estimates of costs for hybrid solutions (Sutton-Grier et al., 2015), our thresholds are based on the substantiated estimates of green and grey solutions. A hybrid solution is the most attractive with a GDP of $4.0*10^{11}$ USD, as the country has a substantial amount to spend on a hybrid solution, the solution offers additional benefits over a grey solution, but also offers more protection than a green solution. A hybrid solution is the least attractive when the costs become very high, so we will see a decrease in attractiveness as cost goes up. There is also a minimum attractiveness when the GDP is $1*10^{9}$ USD, as the cost is then considered quite high, but the protection of a hybrid solution is considered higher than of green solutions.

3.2.4 Additional parameters
The current green/grey/hybrid decision model has three parameters. However, to more accurately be able to make a recommendation, more parameters are preferred. Some of the parameters that can be used are sediment availability, rate of subsidence and governance. A short summary of possible additional parameters is given below.

Sediment availability
For each type of solution, different types of sediment are needed, which all cost differently (Maryland Department of Inspections and Permits, 2012). Additionally, if sediment is needed that cannot be found close to the location the solution needs to be implemented, additional sediment needs to be shipped to location, adding to organization and cost of the particular solution. Also, it is often not possible to ship sediment across large distances. The availability for the necessary sediment is therefore important to take into account.

Rate of subsidence
Coastal subsidence affects many countries across the world, and can exacerbate the threats of coastal flooding. Grey solutions often increase the effects of coastal subsidence (Temmerman et al., 2013), while green and hybrid interventions can counter this (Defeo et al., 2009; Kirwan and Temmerman, 2009; Spalding et al., 2014a). The existence of a high subsidence level can therefore be an additional reason to implement green or hybrid interventions, and has therefore been identified as an interesting parameter. As no global subsidence maps are available yet, this parameter was not yet implemented. However, this map is currently under construction at Deltares (Deltares private meeting, 2015), so remains a viable parameter.

Governance
Governance consists of the traditions and institutions that organize influence in a country. This includes how governments are formed, monitored and replaced when necessary; the capacity of the government to formulate and implement policies and how to execute them (The World Bank Group, 2015). The governance of a country is an important aspect as strong institutions are necessary to guide the implementation and maintenance of any intervention (The World Bank Group, 2015). According to Crowder et al. (2006) marine ecosystem governance is often fragmented and poorly coordinated, creating a strong need for integrated approaches for the management on regional and international level of these ecosystems (Dimitrov, 2002). A country with weak institutions can therefore handle the implementation of any solution differently than a rich country. Furthermore, ecosystems can be maintained and implemented on a local scale, while dikes would need more supervision from higher forms of governance (Dimitrov, 2002).
The exact thresholds, however, are possibly hard to determine, due to a lack of information on the subject, and was therefore not implemented in the model.

3.3 Decision model part 2. Ecosystem model.

3.3.1 Ecosystem variables

In contrast to our green/grey/hybrid model, the ecosystem model is deterministic. In our model, ecosystems are only able to grow under a certain set of specific conditions, categorized under several variables. We use the following variables: Annual average temperature and sediment type. Additional possible variables – salinity and water depth –, including a short description, can be found in Section 3.3.2.

For each variable, we have determined for each ecosystem the limits in which they are able to live, based on literature. The final result of this decision model, under the given constraints, is simply either "yes", this ecosystem is possible or "no", this ecosystem is not possible. For example, if sediment conditions in The Netherlands are suitable for a mangrove forest, but the average annual temperature isn't, mangroves will receive a "no" for The Netherlands.

A list of possible ecosystems is found in Table 4. This list, which has been determined through a literature research previously done at Deltares (Deltares private meeting, 2015), is a narrowed down version of all possible ecosystems found in Section 2.1, as ecosystems such as sea grasses have been excluded due to their yet unknown potential on large scales.

The model is divided in three steps to determine the suitability of each ecosystem. Each step is a variable which tests the boundary conditions of an ecosystem.

Table 4. Summary of all possible ecosystems in the ecosystem model.

Ecosystem
Coral Reef
Shellfish Reef
Beach and Dunes
Mangroves
Salt Marsh

Step 1: Existing ecosystems

Import an ecosystem map to determine whether the location currently has one out of the possibly 5 ecosystems already present. If yes, this ecosystem will be indicated as having a preference over the remaining ecosystems. However, steps 2 and 3 will still be executed to determine whether others are possible as well. Due to a lack of global availability maps of all ecosystems, however, this step was skipped while testing the model.

Step 2: Variable: mean annual temperature

Within the variable of mean annual temperature, we identify a difference in aquatic ecosystems and wetland/hybrid ecosystems, which are partially land based and partially water based. For aquatic ecosystems, we use the mean annual water temperature in degrees Celsius. For the wetland/hybrid ecosystems, we use mean annual air temperature, also in degrees Celsius.

In this report, the variable mean annual temperature has been chosen as we define this temperature to be when that ecosystem is dominant, and not merely surviving (Osland et al., 2013). If temperature ranges are low for that particular ecosystem, the system is perhaps surviving, but with higher possibility of it not being a complete and healthy system that is capable of proper flood protection. If a system is dominant, the system is to be expected to be a healthy system as a whole, and therefore more suitable for flood protection. Secondly, for annual mean water temperatures we do not take into account seasonal variation in temperature, as this range is only several degrees (Roemmich and Gilson, 2009). To investigate whether a change of a few degrees changes our results, a sensitivity analysis will be performed in Section 4.3.

Limits for both the average annual water and air temperature have been retrieved from a wide array of literary sources, and are summarized below. First, we will discuss the aquatic ecosystems.

Aquatic ecosystems
The two aquatic ecosystems are coral reefs and shellfish reefs. Coral reefs can tolerate extreme temperatures as low as 18°C and as high as 40°C, yet not for extended periods of time (NOAA, 2015a; Kleypas et al., 1999). The most optimal temperature for coral reefs is found to be between 23°C and 29°C (NOAA, 2015a; Kleypas et al., 1999). Shellfish reefs have a broader range in temperatures in which they are able to grow, due to a wide variety of different shellfish. Temperatures between 6°C and 32°C have been observed (Bartol et al., 1999; Coen et al., 2000), but optimal growth temperatures lie around 25°C (Galtsoff, 1964). The ranges with their possible ecosystems can be found in Table 5. A visual representation of the values in Table 5 can be found in Figure 6.

Table 5. Summary of the possibility of Shellfish Reefs and Coral Reefs with respect to the average annual water temperature.

Water temperature range	Possible ecosystem
< 6°C	None
>6°C & <23°C	Shellfish Reef
>23°C	Coral Reef and Shellfish Reef

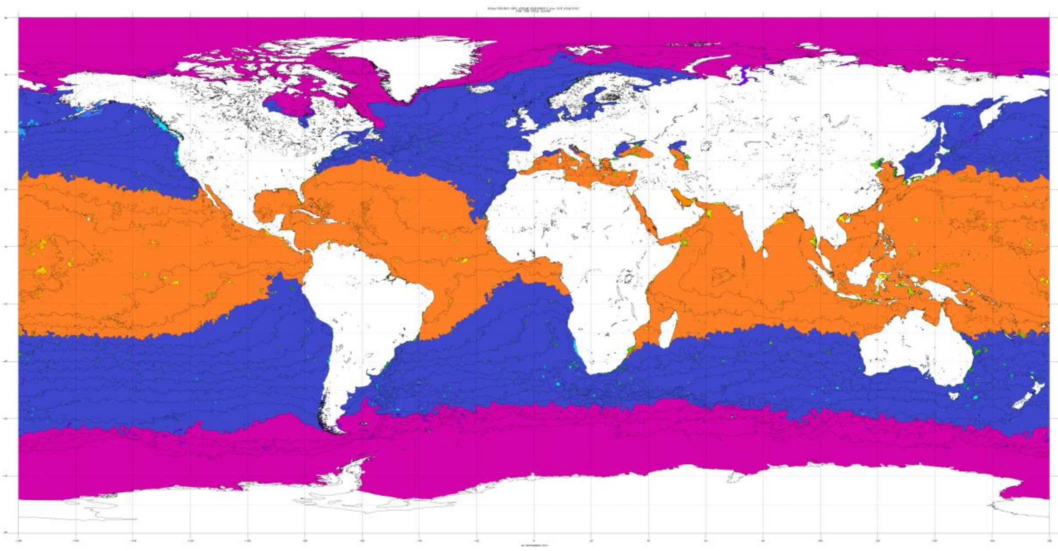

Figure 6: possible areas where aquatic ecosystems are able to live. Pink is the area where both Shellfish reefs and Coral reefs are not able to live, blue where Shellfish reefs can exist and orange where both Shellfish reefs and coral reefs are able to exist. Adapted from NOAA annual SST contour chart (NOAA, 2015b).

Wetland/hybrid ecosystem
For our remaining ecosystems – beaches and dunes, salt marshes and mangroves – the average air temperatures were taken to assess when the ecosystems were able to survive. Salt marshes can tolerate a wide range of temperatures, from 0°C in winter to 32°C in summer (Weis, 2010). Mangrove forests are more sensitive to temperature. Quisthoudt et al. (2012) finds a possible range between 15°C and 28°C, with a mean of 22°C. Higher temperatures are possible, but not for extended periods of time (Quisthoudt et al., 2012). Mangroves are also able to survive short frost periods of several days (Quisthoudt et al., 2012).
Finally, with respect to the available temperature range of the final ecosystem, dunes and beaches are similar to salt marshes. A map, produced by Martinez et al. (2004) (from data from van der

Maarel et al., 1993), shows that coastal dune and beach systems exist from northern Russia to coasts along Ivory Coast and Nigeria. The temperature range of a dune and beach system will therefore be set at -5°C to 30°C.
The ranges with their possible ecosystems can be found in Table 6. A visual representation of the values in Table 6 can be found in Figure 7.

Table 6. Summary of the possibility of Dunes, Salt Marshes and Mangroves with respect to the average annual air temperature.

Air temperature range	Possible ecosystem
>-5°C & < 0°C	Beaches and Dunes
>0°C & <22°C	Salt Marshes and Beaches and Dunes
>22°C	Mangroves, Salt Marshes and Beaches and Dunes

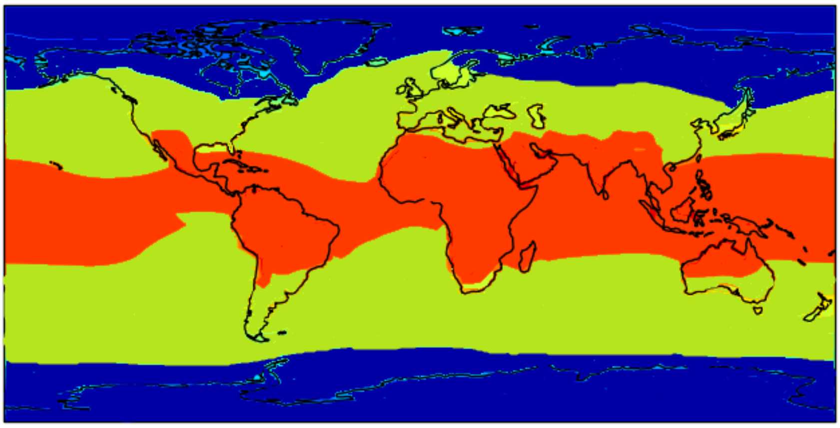

Figure 7. Possible areas where wetland/hybrid ecosystems are able to live. Blue is the area where only dune systems are possible. Green is the area where salt marshes and dune systems are possible, and red is where dune systems, salt marshes and mangroves are possible. Adapted from the Iris Python package, using the annual average air temperature contour chart (Iris, 2015).

Step 3: Sediment

Finally, the model tests for sediment compatibility. The Naval Oceanographic Office provides a list of 65 standard sediment categories (Navo, 2003), which we reduce to the following 3 overarching types to avoid unnecessary complication: sandy, muddy and rocky. Having been unable to identify a global sediment database that could be used to identify locations with these sediment types, for now, the type of sediment per location will have to be found in literature. Below, the determination of what ecosystems match what sediment type can be found.
Mangroves are ecosystems that are very diverse in nature; their vegetation can differ from location to location with vegetation types that prefer different sediment (Karleskint et al., 2012; Matthijs et al., 1999). Research by Karleskint et al. (2012) and Matthijs et al (1999) have shown that both sandy and muddy soils are suitable for growth of a mangrove forest. Salt marshes are similar to mangroves with respect to diversity, as salt marshes can be found all over the world in different temperature regions harboring many different types of vegetation (Weis, 2010). Both sandy and muddy soils have been found to be suitable for salt marsh construction (Van Wijnen et al., 1999; Daleo and Iribarne, 2009; La Pierre, 2015). Shellfish reefs and coral reefs, however, do not grow well on very loose soil,

and need hard rocky substrates to be able to create a reef (Brumbaugh et al., 2006). Finally, beaches and dunes are characteristically made out of sand, so their necessary sediment type is sand (Lancaster, 1988). A summary of the type of ecosystems with respect to sediment type can be found in Table 7.

Table 7. Summary of the possibility of all ecosystems with respect to the type of sediment available.

Sediment type	Possible ecosystem
Rocky	Shellfish Reef and Coral Reef
Sandy	Mangroves, Salt Marsh and Beaches and Dunes
Muddy	Mangroves and Salt Marsh

3.3.2 Additional variables

The model takes only takes two abiotic variables into account that influence the existence of ecosystems. However, using only two abiotic variables to determine the possible ecosystems results in a highly simplified representation of reality. Additional biotic and abiotic variables, to be able to more thoroughly narrow down the list of possible ecosystems, were also identified, and are listed below, including a short summary as to why they would be suitable.

Salinity

The first variable recommended would be the salinity of both water and soil. As this research concerns coastal flood protection, all possible ecosystems are subjected to saline conditions. However, for all ecosystems except beaches and dunes, a too high salinity level can have detrimental effects on the growth and survival of the ecosystem. Mangroves can experience low seedling emergence rate with high salt content, reducing seedling establishment and eventually compromising the health and vitality of the mangrove forest (Chen and Ye, 2014; Duke et al., 1998). Salt marshes show retarded and reduced germination in response too high salinity (Clarke and Hannon, 1970). Coral reefs vary in their response to increased salinity, depending on their location. Generally, coral reef diversity is severely affected when salinity rises above 50 ppm (Barnes et al., 1979). When salinity levels are too low, coral reefs are unable to establish a stable reef (Bell et al., 1989). Finally, shellfish reefs are able to live under a wide range of salinity concentrations (Brumbaugh et al, 2006), with differences found in intertidal reefs and permanently inundated reefs (Troost, 2010). Concluding, a proper salinity level is very important to the health of an ecosystem and its ability to establish seedlings and grow.

Water depth

Another variable important to consider is bathymetry. As beaches and dunes are based entirely on land, the water depth before the coast is irrelevant, but it is all the more important for shellfish reefs and coral reefs. Coral and shellfish reefs are able to grow up to a depth of 10 meters (La Peyre et al., 2014), but a reef in shallower waters has a greater wave breaking ability (Van Zanten and Van Beukering, 2012). Salt marshes develop naturally when the ecosystem is around mean high water level, with external effort needed when bathymetry is close around mean low water level (Van Loon-Steensma, 2015). Mangroves need to be constantly partially flooded, with water depths from maximum of 2.5 meters to being completely on dry land (Ritchie, 1990).
With such varying necessary water depths for the varying ecosystems, bathymetry is a valuable variable for the ecosystem decision model.

3.4 Validation: Location Description

To determine if our model is working accordingly, it needs to be tested for various possible outcomes. We will do so by choosing 3 locations, determining all values needed to run both models for all locations and determine whether a green, grey or hybrid solution is preferred, and which ecosystem is optimal for the location. Additionally, we will perform a sensitivity analysis to determine how sensitive the model is. In the discussion, we will compare the outcome of the model, and the variations in the parameters/variables, with reality (i.e. what currently is present at the location). For the parameter Risk, two values will be listed per location. The first risk value is taken from literary sources, calculating the risk values of the chosen locations in the present state of the locations. This means that these risk values have current protection taken into account (Rijkswaterstaat VNK Project, 2015; Hallegatte et al., 2013). The second risk value is taken from the Global Flood Risk Analyzer Aqueduct. Aqueduct calculates risk using hydrological, inundation and impact models, where the protection level of a country, state or river basin can be altered from a 2-year protection level (can withstand a once in every 2 year flood event; low severity flood event) to a 1000-year protection level (can withstand a once in every 1000 year flood event; very severe flood event). The risk values extracted from Aqueduct are with the assumption of a 2-year protection level, hence with little to no protection. We wish to compare these two situations to see what kind of impact the assumption of present flood protection has on the final result. The outcome will be presented in the results, in the discussion the results will be compared and discussed.
The locations have been chosen based on the amount of existing literature. The first location is the Dutch coast, with a combination of dune systems and hard structures protecting its shores. The second location is New Orleans, as the city has adopted one of the first hybrid solutions scientists after the devastation of Hurricane Katrina (Kazmierczak and Carter, 2010). The final location is Khulna in Bangladeshi, due to its location behind the Sundarbans, a large mangrove forest that covers half of the Bangladeshi coast.

Netherlands

The Netherlands is a country in Western Europe bordering the North Sea, comprising of about 40.000 square kilometers, of which 2/3rd is below sea level (Jonkhoff, 2009). GDP of the Netherlands was calculated by the World Bank (2015) to be 853 billion USD in 2014, 46% of which was generated in the Randstad area (CBS, 2015), which lies within the area below sea level. The risk, including all current protection, is estimated at approximately 660 million USD, which is about 0.08% of Dutch GDP (Rijkswaterstaat VNK Project, 2015). The annual average damage, as calculated by Aqueduct, is 71.3 billion USD, which is 8% GDP. The damage calculated by Aqueduct is the average annual damage per year assuming the lowest flood protection level possible.
The country was considered compact enough to assume the country wide annual average temperature as accurate for the entire coast. The average annual air temperature, averaged over 28 years, is 9.3°C (Weatherbase, 2015). The annual average sea surface temperature, measured off the coast of Scheveningen, is 12.1°C (Seatemperatures, 2015). Along the coastal stretch from Zeeland up to North Holland and across the Wadden Islands, the main sediment type is sandy soil (Hartemink and Sonneveld, 2013; Sistermans & Nieuwenhuis, 2004a). In the provinces of Friesland and Groningen, which border the Waddensea, the main type of coastal soil is muddy (Hartemink and Sonneveld, 2013). Distance between the coastline and populated areas vary from less than 100m up to several kilometers (rough estimate from aerial maps found in Google maps). For our calculation, we will use a rough average of 500m.

Table 8. Summary of the input values for both the green/grey/hybrid model and the ecosystem model, for the The Netherlands case study.

Parameter/variable	Value
Space	500 meter
Risk	0.08% (literature) / 8% (Aqueduct)
GDP	853 billion USD
Temperature- air	9.3°C
Temperature – water	12.1°C
Sediment type	Sandy

New Orleans, USA

New Orleans is a city in the state of Louisiana, United States. In 2005, hurricane Katrina hit New Orleans, devastating the city, causing failures of levees and floodwalls protecting the city (Kazmierczak and Carter, 2010). Since 2005, New Orleans has adopted a hybrid solution, implementing a series of dikes and floodwalls in combination with large stretches of salt marsh (Kazmierczak and Carter, 2010).

New Orleans has an annual average air temperature of 20.4°C, averaged over 57 years (Weatherbase, 2015). The annual average water temperature is 23.1°C (NOAA, 2015b), and sediment is found to be muddy (Independent Levee Investigation Team, 2006). The distance between urbanized area and the coast differs between 0m between New Orleans and Lake Pontchartrain, 2000m for Lake Borgne and on average 5000m from New Orleans to the Gulf of Mexico. For our calculation, we will use the value for the distance between the urbanized area of New Orleans and Lake Borgne, as this lake is the direct connection from the Gulf of Mexico to Lake Pontchartrain and any wave reduction around Lake Borgne will therefore also affect Lake Pontchartrain.

The GDP of the United States is 16770 billion USD, but since the calculation will be compared to the entire Dutch coast, we will take into account just the GDP of New Orleans in comparison. According to Hallegatte et al. (2013), New Orleans has an annual average loss of 558 million USD, taking into account all potential floods and existing protection. The annual average loss of 558 million USD corresponds to approximately 0.003% US GDP, and 1.21% of New Orleans GDP (Hallegatte et al., 2013). The fluvial flood risk for Louisiana, as calculated by Aqueduct, is 23.6 billion USD, which corresponds to a 9.64% risk for the state of Louisiana. We assume the risk constant across the state, therefore also assuming a risk of 9.64% for New Orleans. The damage calculated by Aqueduct is the average annual damage per year assuming the lowest flood protection level possible.

Table 9. Summary of the input values for both the green/grey/hybrid model and the ecosystem model, for the New Orleans case study.

Parameter/variable	Value
Space	2000 meter
Risk	1.21% (literature) / 9.64% (Aqueduct)
GDP	41.4 billion USD (New Orleans)/216 billion USD (Louisiana)
Temperature- air	20.4°C
Temperature – water	23.1°C
Sediment type	Muddy

Khulna, Bangladesh

Khulna in Bangladesh is the third largest city in Bangladesh, located right behind the Sundarbans, a large mangrove forest on the south-western coast of Bangladesh. Khulna is about 80 kilometers from the Bay of Bengal, the closest large body of water to Khulna. The 30-year annual average air temperature is 26.3°C (Weatherbase, 2015), the annual average water temperature is 27.1°C (Seatemperatures, 2015). The sediment found around Khulna and to the south towards the Bay of Bengal, is muddy (Imamul Huq and Shoaib, 2013). Bangladesh has a GDP of 150 billion USD (The World Bank, 2015), but, comparable to New Orleans, we will use the GDP of Khulna in this comparison. The average annual loss, according to Hallegatte et al. (2013) with current flood potential and protection level, is 13 million dollars, which is 0.008% Bangladeshi GDP, and 0.43% of the GDP of Khulna (Hallegatte et al., 2013). The fluvial flood risk for the Khulna Division, as calculated by Aqueduct, is 2 billion USD, which corresponds to a 10.2% risk for the entire Khulna Division. We assume the risk constant across the province, therefore also assuming a risk of 10.2% for the city of Khulna. The damage calculated by Aqueduct is the average annual damage per year assuming the lowest flood protection level possible.

Table 10. Summary of the input values for both the green/grey/hybrid model and the ecosystem model, for the Khulna case study.

Parameter/variable	Value
Space	80.000 meter
Risk	0.43% (literature) / 10.2% (Aqueduct)
GDP	3 billion USD (Khulna) / 16.8 billion USD (Khulna Division)
Temperature- air	26.3°C
Temperature – water	27.1°C
Sediment type	Muddy

4. Results

4.1 Base model runs

4.1.1 Green/grey/hybrid model

The acquired parameters in the Tables 8, 9 and 10 have been implemented in the model deciding on the type of solution. The results of the base run with the risk values found in literature can be found in Table 11. The results of the base model run with the risk values found in Aqueduct are in Table 12. I will first present the results of the model run with the literature risk values, and then the model with the Aqueduct values.

For risk values taken from literature, the model finds that for Netherlands, the optimal solution is a hybrid solution, with 64.1% compatibility, followed by a green solution with 30.4% compatibility, and grey with just 1.8%. The base run of the model returns that for New Orleans, the most suitable solution is a hybrid model, showing a compatibility percentage of 48.7%. Green solutions are found to be 36.7% compatible, and grey solutions 9.5%. The results for Bangladesh show a high compatibility of 78.6% with green solutions, a compatibility of 66.3% with hybrid solutions and 0.0% with grey solutions. Figure 8 shows the normalized results of Table 11.

Table 11. Results for the base model run of the green/grey/hybrid model, using risk values taken from literature. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands	New Orleans	Khulna
Green	30.4%	36.7%	78.6%
Hybrid	64.1%	48.7%	66.3%
Grey	1.8%	9.5%	0.0%

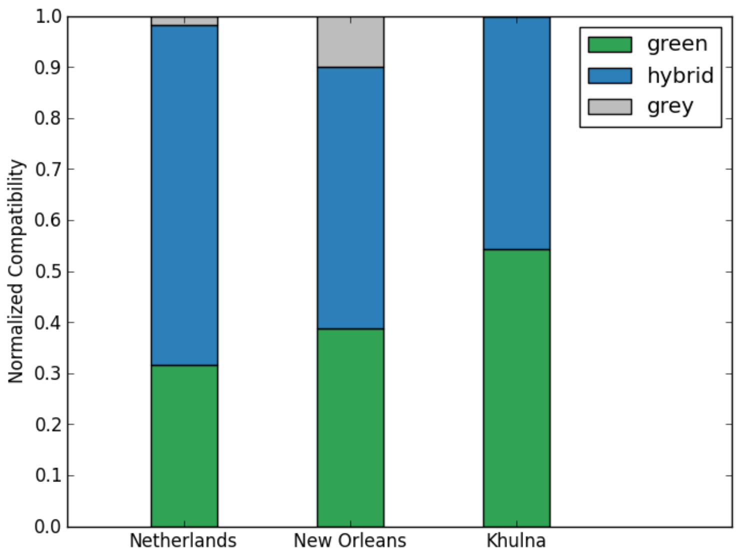

Figure 8. Bar chart visualizing the normalized results of the green/grey/hybrid model run for the risk value taken from literature. Grey indicates the normalized compatibility for a grey solution, blue the normalized compatibility for a hybrid solution, and green the normalized compatibility for a green solution.

The base model run with the risk values calculated in Aqueduct shows that for the Netherlands, the most optimal solution is a hybrid solution, with a compatibility of 41.5%. Grey solutions are the second most compatible with 35.1%, finishing off with 0% compatibility for greens solutions.
New Orleans also has the highest compatibility with hybrid solutions, with a percentage of 59%. Grey solutions, again, come in second at 33.3%, with green at 20% at third.
Bangladesh has the highest compatibility with a green solution, at 59.5%. Hybrid and grey solutions are found close in compatibility, with respectively 33.8% and 33.3%.
In all case studies, the most compatible solution is similar to the results of the model run with risk values from literature. Figure 9 shows the normalized results of Table 12.

Table 12. Results for the base model run of the green/grey/hybrid model, using risk values taken from the Global Flood Risk Analyzer Aqueduct. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands	New Orleans	Khulna
Green	0.0%	20.0%	59.5%
Hybrid	41.5%	59.0%	33.8%
Grey	35.1%	33.3%	33.3%

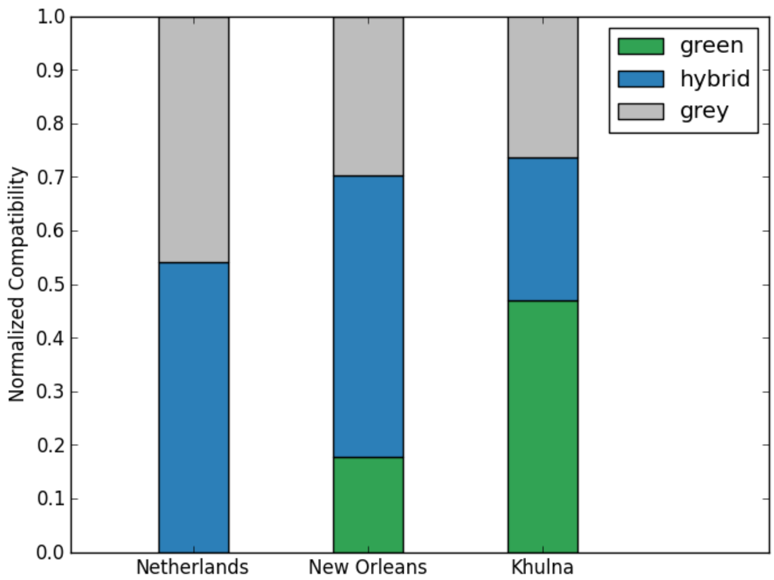

Figure 9. Bar chart visualizing the normalized results of the green/grey/hybrid model run for the risk value taken from the Global Flood Risk Analyzer Aqueduct. Grey indicates the normalized compatibility for a grey solution, blue the normalized compatibility for a hybrid solution, and green the normalized compatibility for a green solution.

4.1.2 Ecosystem model

Applying the ecosystem decision model on the values in Tables 8, 9 and 10, we obtain the results described below; for a summary see table 13.
The Netherlands' air temperature value is high enough to sustain dune systems and salt marshes, but is too low to be able to sustain mangrove forests. The water temperature is suitable for shellfish reefs, but too cold for coral reefs. However, due to the sediment necessary for both coral reefs and shellfish reefs, these are found to not be applicable in the Netherlands.
New Orleans can sustain dune systems and salt marshes due to a suitable air temperature and suitable sediment availability. Air temperatures, however, are too low to be able to sustain

mangrove forests. Water temperatures are also suitable for coral reefs and shellfish reefs, but the necessary sediment, however, is unavailable.
In Khulna, Bangladesh, despite having suitable air and water temperatures, dune systems, coral reefs and shellfish reefs are deemed not suitable due to unsuitable sediment. Mangroves and salt marshes are found to be applicable.

Table 13. Results of the base model run of the ecosystem model. In the case of a "No", an (S) or a (T) indicates whether this is due to either the available sediment or the present temperature. An (S+T) indicates the result was limited by both variables.

	Netherlands	New Orleans	Khulna
Mangroves	No (T)	No (T)	Yes
Beaches/Dunes	Yes	Yes	No (S)
Salt Marsh	Yes	Yes	Yes
Coral Reef	No (S+T)	No (S)	No (S)
Shellfish Reef	No (S)	No (S)	No (S)

4.2 Sensitivity – Green/grey/hybrid model

To determine how sensitive the chosen thresholds of our parameters are, a sensitivity analysis was performed on all parameters. This analysis was performed in a very crude fashion. From the values found in the Tables 8, 9 and 10, we take the literature risk values, the space values and the GDP values, and increase respectively decrease this value by 50%. These altered values will then be entered into the model, and compatibility percentages will be calculated. When a single parameter is being tested, all other parameters are kept constant. These analyses results in a table where the values for risk have increased 50%, a table where they have decreased 50%, a table with 50% decreased space, 50% increased space, 50% increased GDP and 50% decreased GDP; a total of 6 tables.
The results of all analyses can be found in Tables 14, 15, 16, 17, 18 and 19. The tables are divided into columns representing the country, where the first column per country is the compatibility percentage in the new run, and the second column is the variation between the base model run and the new run. If this value is negative, it means that compared to the base model run, the compatibility has gone down. Conversely, if this value is positive, the compatibility has increased.

4.2.1 Risk

The results of the sensitivity analysis of the Risk parameter show that for a high initial risk, variation on this value leads to high change in compatibility. The Netherlands has a low initial risk (0.08%), and with +50% and -50% change in this risk, the compatibility changes 3% at most across all solutions. A hybrid solution remains the most compatible amongst the solutions.
Bangladesh, with an initial risk of 0.43%, sees a sharp decrease in compatibility with a green solution if its risk increases, while all other solutions stay fairly constant. However, despite the sharp decrease in compatibility, green remains the highest recommended solution. When the risk is decreased, we see a sharp increase in compatibility for a green solution. The compatibility with a hybrid solution decreases due to the decreased risk. A green solution remains the most compatible in all situations.
New Orleans has the highest risk out of the three case studies, with a value of 1.21%. When this risk increases further, a grey solution immediately becomes a much more viable solution. A hybrid solution, however, remains the most compatible solution, despite a sharp decrease of over 11%. Conversely, when the risk decreases, a hybrid solution increases sharply by 20%, and a grey solution becomes much less compatible. In all cases, a hybrid solution remains the most compatible with the situation present.

Table 14. Results for the sensitivity analysis for all case studies for the green, grey and hybrid solutions, where the values for the parameter Risk was increased by 50%. The first column in each case study represents the new compatibility, the second column the deviation from the base model run in Table 11. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands		New Orleans		Khulna	
Green	27.6%	- 2.8	36.7%	- 0	68.5%	- 10.1
Hybrid	66.5%	+ 2.4	37.6%	- 11.1	65.5%	- 0.8
Grey	1.8%	- 0	17.6%	+ 8.1	1.8%	+ 1.8

Table 15. Results for the sensitivity analysis for all case studies for the green, grey and hybrid solutions, where the values for the parameter Risk was reduced by 50%. The first column in each case study represents the new compatibility, the second column the deviation from the base model run in Table 11. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands		New Orleans		Khulna	
Green	31.9%	+ 1.5	41.2%	+ 4.5	88.7%	+ 10.1
Hybrid	62.9%	- 1.2	69.2%	+ 20.5	61.6%	- 4.7
Grey	1.8%	- 0	1.4%	- 8.1	0%	- 0

4.2.2 Space

The results of the sensitivity analyses of the parameter Space show a great variability, indicating a strong dependency on space in at least two of our case studies. In Bangladesh, none of the compatibility percentages change in both analyses. In contrast, the results for the Netherlands are highly variable, showing a sharp increase in compatibility for hybrid solutions with an increase in space. Conversely, when the amount of space decreases, the compatibility of hybrid sharply decreases and a grey solution's compatibility increases. In all cases, however, a hybrid solution remains the most compatible with the conditions in the Netherlands.

New Orleans is the only location where the most optimal solution does not remain constant. With an increase in space, the compatibility of a green solution becomes greater than of a hybrid solution. If the amount of space decreases, the compatibility of a green solution decreases sharply, with a hybrid solution remaining the most compatible solution.

Table 16. Results for the sensitivity analysis for all case studies for the green, grey and hybrid solutions, where the values for the parameter Space was increased by 50%. The first column in each case study represents the new compatibility, the second column the deviation from the base model run in Table 11. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands		New Orleans		Khulna	
Green	33.9%	+ 3.5	50.0%	+ 13.3	78.6%	- 0
Hybrid	77.1%	+ 13	48.7%	- 0	66.3%	- 0
Grey	0.7%	- 1.1	9.5%	- 0	0%	- 0

Table 17. Results for the sensitivity analysis for all case studies for the green, grey and hybrid solutions, where the values for the parameter Space was reduced by 50%. The first column in each case study represents the new compatibility, the second column the deviation from the base model run in Table 11. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands		New Orleans		Khulna	
Green	30.4%	- 0	23.3%	- 13.4	78.6%	- 0
Hybrid	52.6%	- 11.5	48.7%	- 0	66.3%	- 0
Grey	17.9%	+ 16.1	9.5%	- 0	0%	- 0

4.2.3 Cost

The results of the sensitivity analyses of the Cost parameter show that the parameter is fairly stable. For the Netherlands, the most compatible solution remains the hybrid option.
The results for Bangladesh remain almost exactly the same to the base run, with only a small change in the compatibility for a green solution of +/- 0.6%. In all cases, a green solution is the most compatible with the present conditions in Bangladesh.
The most variation can be found in the results of New Orleans, where the compatibility of a green solution varies with approximately 8%. However, despite this large variation of a green solution's compatibility, in all cases a hybrid solution remains the most compatible.

Table 18. Results for the sensitivity analysis for all case studies for the green, grey and hybrid solutions, where the values for the parameter Cost was increased by 50%. The first column in each case study represents the new compatibility, the second column the deviation from the base model run in Table 11. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands		New Orleans		Khulna	
Green	30.4%	- 0	29.4%	- 7.3	77.9%	- 0.7
Hybrid	57.9%	- 6.2	51.7%	+ 3	66.3%	- 0
Grey	2.4%	+ 0.6	9.5%	- 0	0%	- 0

Table 19. Results for the sensitivity analysis for all case studies for the green, grey and hybrid solutions, where the values for the parameter Cost was reduced by 50%. The first column in each case study represents the new compatibility, the second column the deviation from the base model run in Table 11. The results show a compatibility percentage between 0% and 100%, the combined percentages per case study site are not normalized.

	Netherlands		New Orleans		Khulna	
Green	30.4%	- 0	45.3%	+ 8.6	79.2%	+ 0.6
Hybrid	69.5%	+ 5.4	46.1%	- 2.6	66.3%	- 0
Grey	1.0%	- 0.8	9.5%	- 0	0%	- 0

4.3 Sensitivity – Ecosystem model

For the ecosystem model, we perform a sensitivity analysis on the air- and water temperature thresholds, to determine if it's possible to include/exclude an ecosystem with minor changes in threshold. For both variables, a test is run calculating the difference in result with a change of +/- 1°C, and a test is run for +/- 3°C. The results are shown below, and will be more elaborately discussed in the discussion.

4.3.1 Air temperature threshold variation

Tables 20 and 21 show the results for the air temperature sensitivity analysis of +/- 1°C and +/- 3°C respectively. The results of the +/- 1°C air temperature variation shows no variation compared to the base model results found in Table 13. The results of the +/- 3°C temperature change, however, shows a change in the possibility of mangrove settlement in New Orleans, as the lower range of mangrove forest temperature becomes wide enough to overlap with the annual average air temperature of New Orleans.. The remaining results remain the same compared to the base model results.

Table 20. Results of the ecosystem model for Mangroves, Beaches/Dunes and Salt Marshes, for the annual average air temperature threshold variation of +/- 1°C. When the result is written in red this indicates a change with respect to the base model result found in Table 13.

	Netherlands	New Orleans	Khulna
Mangroves	No	No	Yes
Beaches/dunes	Yes	Yes	No
Salt Marsh	Yes	Yes	Yes

Table 21. Results of the ecosystem model for Mangroves, Beaches/Dunes and Salt Marshes, for the annual average air temperature threshold variation of +/- 3°C. When the result is written in red this indicates a change with respect to the base model result found in Table 13.

	Netherlands	New Orleans	Khulna
Mangroves	No	**Yes**	Yes
Beaches/Dunes	Yes	Yes	No
Salt Marsh	Yes	Yes	Yes

4.3.2 Water temperature threshold variation

As the results of the ecosystem model showed all aquatic ecosystems are sediment limited, the sensitivity analysis was run without sediment as a variable in the model. Table 22 is therefore the result if sediment is not taken into account, and solely based on temperature limitations. When we execute the ecosystem model without the sediment variable, we find that shellfish reefs are possible in the Netherlands, and that both coral reefs and shellfish reefs are possible for both New Orleans and Khulna.

As we perform the sensitivity analyses of 1°C and 3°C, we see that for most possibilities the results show no change. The possibility of the existence of coral reefs, however, becomes debatable, as with a lowering of 1°C tips this possibility over the threshold of no coral reefs possible.

Table 22. Results for the base run of the ecosystem model for Coral Reef and Shellfish Reef, for annual average water temperature, without taking sediment into account.

	Netherlands	New Orleans	Khulna
Coral Reef	No	Yes	Yes
Shellfish Reef	Yes	Yes	Yes

Table 23 Results of the ecosystem model for Coral Reefs and Shellfish Reefs, for the annual average water temperature threshold variation of +/- 1°C. When the result is written in red this indicates a change with respect to the base model result found in Table 22.

	Netherlands	New Orleans	Khulna
Coral Reef	No	**No**	Yes
Shellfish Reef	Yes	Yes	Yes

Table 24. Results of the ecosystem model for Coral Reefs and Shellfish Reefs, for the annual average water temperature threshold variation of +/- 3°C. When the result is written in red this indicates a change with respect to the base model result found in Table 22.

	Netherlands	New Orleans	Khulna
Coral Reef	No	**No**	Yes
Shellfish Reef	Yes	Yes	Yes

5. Discussion

Considering the results of both models, both the green/grey/hybrid model and the ecosystem model show great robustness when a sensitivity analysis is applied. However, it is important to know if the returned results by the models in fact correspond to reality, and if they do not, what the cause is for this discrepancy. To do this, we will first compare the results of the green/grey/hybrid model to reality, and assess the model's parameterization. Afterwards, in a similar manner, the results of the ecosystem model will be elaborated upon.

5.1 Green/grey/hybrid model

In this section, we will first compare the results of the model with risk values from literature and the model with risk values from Aqueduct. The model using Aqueduct values will then be compared to reality, and possible discrepancies will be explained. However, as the exact compatibility percentages cannot be directly tested for their accuracy, we will compare if the interventions that are possible according to the model are indeed found at the location, and if the intervention with the highest compatibility percentage is indeed the most used solution. We define an intervention to be possible when the compatibility percentage is greater than 0%. Further, a list of considerations per parameter will be given. Finally, recommendations for future research are listed.

Risk values in literature and Aqueduct

Comparing the model results with risk values from literature to the model with risk values from Aqueduct, we see that the most compatible solution in the three case studies – The Netherlands, New Orleans and Khulna - is similar for both models. However, the compatibility percentages of the interventions vary 20-30% between the two models.

These large differences are mainly explained due to the nature of the risk values from Aqueduct and the ones calculated in literature studies. The risk values taken from literature are values calculating the risk at a certain location, taking all current infrastructure into account. Hence, these values include current flood protection. The risk values taken from Aqueduct are with the assumption of no flood protection. If the model is run with the values from literature, the results take the form of an advice for the future: what is the best option to improve on the current infrastructure. If the model is run with the values from Aqueduct, however, the results of the model can be seen as a validation of currently present flood protection, or what would be more suitable than the already present flood protection. An example of the latter is for example the "Room for the river" project (Borsje et al., 2011; Van Vuren et al., 2005), where a grey solution was replaced with a hybrid solution. The two models therefore represent completely different situations, explaining the large difference in results. Also, to assess the validity of the model results compared to reality, the model results with Aqueduct risk values will be used.

Comparison to existing infrastructure

The Netherlands

For The Netherlands, the model using risk values from Aqueduct returns a 0.0% compatibility percentage for green, 41.5% for hybrid and 35.1% for grey. Comparing the results of the model to reality, we indeed find a lot of grey protection systems for The Netherlands. A well-known example is the Delta Works in Zeeland (Delta Commissie, 2008; Rijkswaterstaat VNK project, 2015) and the Afsluitdijk in de Wadden Sea area. Green ecosystem solutions are also widely used as flood protection. The west coast and barrier islands are mainly protected by dunes, and in the Wadden Sea area and in Zeeland salt marsh systems can be found (Sistermans & Nieuwenhuis, 2004a; Sistermans & Nieuwenhuis, 2004b; Schoeman, 2006; Temmerman et al., 2013). Hybrid options were not found to be used in coastal protection in The Netherlands.

We see that the results for green and hybrid contrast what is found in reality. The large discrepancy between the result of a green intervention and reality is due to two reasons. For the The Netherlands case study, an average available distance of 500 meters was determined. Yet as this was an average over the entire coast, it is highly likely that there are many areas with more space than 500 meters. For these areas, a green intervention would have a high compatibility in terms of Space, while on average over the entire Dutch coast it does not. The second reason lies in the parameter Cost and its parameterization. When an intervention is expensive, a poor country is not able to afford the intervention. However, when a country is rich – such as The Netherlands- and the intervention cheap, they, in fact, are able to afford it. The Cost compatibility of green interventions for rich countries should hence be 100%, and not 0% as currently is parameterized.

New Orleans

Our second case study, New Orleans, shows compatibility percentages of 20.0%, 59.0% and 33.3% with green, hybrid and grey respectively. According to Kazmierczak and Carter (2010), New Orleans is home to the first intervention officially called a hybrid intervention, and has become the main flood protection system protecting New Orleans. Grey interventions are hardly used independently (Kazmierczak and Carter, 2010), but systems consisting of dunes and salt marshes can be found south of New Orleans, bordering the Gulf of Mexico. The results are therefore in complete agreement to reality.

Khulna

The results of our final case study show that Khulna has a 59.5% compatibility with green interventions, 33.8% with hybrid interventions and finally 33.3% with grey interventions. Being home to one of the largest mangrove forests in the world, the model result is in complete agreement with reality. No evidence was found for grey and hybrid use in the space between Khulna and the Bay of Bengal. However, in the neighboring district of Patuakhali, several projects involving grey and hybrid interventions are being developed (Cordaid, 2013). We therefore conclude that the results of the model are in agreement with reality.

Discussion of model parameters

Based on the results of the comparison between the model's result and reality, we can conclude that the parameters Risk, Space and Cost are important parameters in the decision between green, grey and hybrid interventions. Furthermore, the current parameterization leads to an adequate representation of reality in most cases. However, the model also returns incorrect results, such as the incorrectly predicted lack of green solutions in The Netherlands, and the existence of grey and hybrid solutions in Khulna. Therefore, several aspects of the used parameters Risk, Space and Cost need to be taken into account.

First, considering the parameterization of the parameter Risk with a maximum of 3% GDP and the large difference between literature risk values and Aqueduct risk values that were found, it is clear that while parameterizing the model, a bias was implemented. Hence, applying the model with risk values from Aqueduct may in fact be less suitable when considering the risk of an unprotected coastline. Developing and testing an Aqueduct-based parameterization is therefore recommended as comparison to the current parameterization. This can be done in a similar manner as previously done in the methods, but then with a different maximum for Risk. Additionally, the results show that in all cases a hybrid solution is a highly suitable intervention. However, due to the unknown potential of hybrid interventions, the thresholds for hybrid were estimations, based on the values for green and grey solutions. It is therefore possible that the potential for the hybrid solutions were either over- or underestimated. As soon as more information is available on the potential of hybrid solutions, for example its ability to withstand extremely high risk situations compared to grey and green interventions, the thresholds of the model should be updated.

Secondly, the main consideration for the parameter Space is its definition. This thesis defines space as the amount of meters from the shore to a point inland. However, this definition doesn't take into account tidal and subtidal areas in which predominantly coral and shellfish reefs exist. This exclusion affects the possibility for a green and hybrid ecosystem in a negative way. This aspect was not yet taken into account due to unavailable knowledge on local bathymetry, but it is recommended to implement this as the knowledge becomes available. In addition, as seen in the The Netherland case study results, when a large coastline is examined which has a highly variable amount of available space, it is recommended to split this coastline in smaller pieces of similar amount of space. This would return a more accurate recommendation per coastal stretch, compared to an average of the entire coastline.

For the last parameter, Cost, it is most important to keep in mind that the thresholds for this parameter have not been substantiated with robust literary sources, despite the model showing robust results. Additionally, it is important to consider if the GDP of a country can be used as a proxy for the cost of a solution and used to consider when certain interventions are used. This includes the situation when the GDP of an area is very low, but the desire to protect this area very high, as can be with for example sites with important cultural heritage.

Recommendations and future research

To conclude, we have several recommendations for future research. The first recommendation is to change the parameter Cost. In the green/grey/hybrid model estimates are given when a certain solution is preferable taking only into account how rich a country is, assuming that when a country is richer, they will implement the more expensive – grey- solution. Yet as we have seen while discussing the Dutch case study results, the parameter contains parameterization issues that draw into question the practicality and usability of the current definition and parameterization. Therefore, one solution would be to adjust the parameterization of the parameter Cost, as described in the discussion of the case study of The Netherlands. This alteration would entail the possibility for rich countries to be able to afford all interventions and not only the most expensive ones, and poor countries only the cheaper solutions. A second solution, and perhaps a more accurate method, would be to change the definition of the parameter Cost to implement the coastal stretch length and the precise cost of a solution as a part of the parameter. This method would take into account how much a country would be able to spend (Hinkel et al., 2010), with a very rough estimate on how expensive a solution would be. However, the exact cost of a solution varies per country, and depends on the final length of the structure. Therefore, a more accurate calculation can be made if representative prices per unit length for all countries per solution can be estimated. For this calculation, the length of the location’s coast is then also a necessary input. This method was not yet used in this report as the exact cost per solution is yet unknown, but soon might become available due to new research results of a project done within Deltares (Deltares private meeting, 2015).

A second recommendation for future research is to update the definition of the parameter Space to include the possibility of space available in tidal and intertidal waters. This is important as to allow for the aquatic ecosystems to be taken into account as a part of a green or hybrid solution. Additionally, as we’ve seen in the The Netherlands case study, averaging over large stretches adds noise to the results. Hence, the implementation of shorter coastal stretches would benefit the parameter Space, to more accurately be able to determine the amount of space available.

Furthermore, an Aqueduct-based parameterization for the parameter Risk should be tested, with a higher upper threshold, as the results have shown that the risk values from literature and Aqueduct are very different. Moreover, it is recommended to implement - within Aqueduct - the option to determine both the most optimal solution including current flood protection and excluding current flood protection. The first as this gives a recommendation on what to implement with the current flood protection already in place, and the latter as this can give a recommendation on what to do different and if the current flood protection is really the most suitable given the risk of that area. As a final recommendation additional parameters should be investigated and added to the model. Previously suggested in the methods are the parameters sediment availability, rate of subsidence and governance.

5.2 Ecosystem model

In this section we will compare the results of the ecosystem model to the ecosystems found in reality. We will discuss each of the case study sites – The Netherlands, New Orleans and Khulna –, and identify and explain discrepancies. Further, we will discuss the general workings of the model. Finally, recommendations for future research will be given.

Comparison to existing ecosystems

The Netherlands

For The Netherlands case study, the model predicts the possibility of salt marshes and dune systems. Mangrove forests, shellfish reefs and coral reefs are predicted not to occur.

Dune systems are mainly found along the western coastline, and northern border of the barrier islands to the North Sea (Van de Graaff, 1985; Klijn, 1981; Sistermans & Nieuwenhuis 2004a). These areas are subjected to high wave action, which would wash any other ecosystem away. Therefore, only dune systems are able to be sustained in these regions. The Western Scheldt and the Wadden Sea contain salt marshes, as these areas are sheltered, estuarine and silty, but still provide sufficient sediment supply (Bakker et al. 1993; Bakker et al., 2002; Sistermans &Nieuwenhuis, 2004b; Schoeman, 2006). Temperatures in The Netherlands are found to be too low for mangroves and coral reefs.

The only discrepancy between the model results and literature is the presence of shellfish reefs. The model predicts that shellfish reefs are not possible due to the sandy substrate determined for The Netherlands, while in reality shellfish reefs are found in the Eastern Scheldt and the Wadden Sea (Borsje et al., 2013; Sistermans & Nieuwenhuis, 2004b). A reason for this discrepancy is that shellfish reefs can be built on artificial structures, which essentially makes the ecosystem independent of the variable sediment (Temmerman et al., 2013; Fikes, 2013).

New Orleans

In New Orleans, it is predicted that dune systems and salt marshes are possible ecosystems in the region. Mangroves, shellfish reefs and coral reefs are, again, predicted not to occur.

As the areas subjected to the highest wave action, a strip of dune systems and a variety of barrier islands are found directly bordering the Gulf of Mexico (Tibbetts, 2006; Conservation Habitats & Species Assessments, 2005). The land behind this strip of dunes experiences lesser wave action, allowing salt marshes and mangroves to survive (Tibbetts, 2006; Conservation Habitats & Species Assessments, 2005; IPA, 2014).

For New Orleans, the model shows several discrepancies. The first is the possibility of coral and shellfish reefs. Similar to The Netherlands, the main sediment type identified for New Orleans is sandy substrate. Coral reefs, similar to shellfish reefs, are able to be built on artificial structures, making both ecosystems independent of sediment type (Temmerman et al., 2013; Fikes, 2013). The second discrepancy is the presence of mangroves in New Orleans, as the model predicts the weather simply to be too cold for mangroves. However, we see that after performing a sensitivity analysis of an increase of 3°C, mangroves suddenly do become a possibility. This result can be explained in two parts: the first aspect that influences this prediction is the data used for the average annual temperatures. The source used for determining the annual average temperature for New Orleans was based on a 57-year average. Due to climate change, global temperatures have risen, therefore shifting the threshold lines where ecosystems are able to exist in real life compared to literature annual averages (Pachauri et al., 2014). The sensitivity analysis shows that New Orleans lies close to this threshold line, explaining, in part, the model's wrong prediction. This effect does not explain the entire 3 degrees difference, however. An additional explanation can be found in the use of annual average temperatures, and our assumption that an ecosystem is dominant in our determined ecosystem temperature ranges. The result of the ecosystem model can be attributed to the fact that while mangrove forests do occur in New Orleans, they are not the most dominant ecosystem present. When the average annual temperature increases by approximately 3°C, mangroves are expected then to be the most dominant ecosystem.

Khulna

For our final case study site, the model predicts dune systems, coral reefs and shellfish reefs not to be possible. Mangroves and salt marshes are predicted to occur.

Mangroves forests are found in great abundance in between Khulna and the Bay of Bengal, with dune systems protecting forests from severe wave impact, and a myriad of rivers providing sufficient nutrient and sediment transportation to the forest (Mangroves for the future, 2015). Salt marshes are mostly found in the eastern part of Bangladesh, near Cox's Bazar. They are mostly located in estuaries, sheltered behind dune systems and barrier islands (Abu Hena et al., 2007). Coral reefs and shellfish reefs are mostly found in tidal and intertidal zones (Chowduhry et al., 2014).

In Khulna, three ecosystems – dune systems, coral reefs and shellfish reefs – were wrongly predicted not to occur. The explanation for this discrepancy for coral reefs and shellfish reefs is similar to the explanation for The Netherlands and New Orleans: both types of reefs are able to be built on artificial structures. For dune systems, this explanation lies in the parameterization of the model. The model has been parameterized using only three sediment types: sandy, muddy and rocky. Furthermore, the model then simplifies a region of interest to just one of those sediment types. If a region is sufficiently large, this simplification can lead to incorrect estimates to the system as a whole.

Recommendations and future research

To conclude, we have several recommendations for the future. First, during the application of the ecosystem model to the three case study sites, it is shown that sediment and substrate are not represented well. Two reasons are identified. First, mainly in the case of coral and shellfish reefs, is the possibility for both types of reefs to be built on artificial structures. This means that both types of reefs are essentially independent from the variable sediment. Secondly, the parameterization simplification to three sediment types can lead to incorrect estimations if the area of interest is too large. Applying the model to smaller spatial scales or using a detailed global sediment map to identify local sediment types would solve this problem (ISRIC, 2015).

In addition, the New Orleans case study showed to wrongly predict the mangrove system present due to temperature considerations. An explanation previously offered is the use of an annual average temperature, taking an average over 57 years. Averaging over a large number of years diminishes the effect of global rising temperatures on the average, resulting in a lower average annual temperature (Pachauri et al., 2014). Especially for regions close to the threshold lines between an ecosystems possibility, this can result in wrong predictions. A solution may be to take an average over a smaller time period. The wrong prediction may also lie in the use of annual average temperatures, in contrast to monthly average temperatures. In this report, the variable mean annual temperature had been chosen as it was defined when a system was dominant, and not merely surviving (Osland et al., 2013). However, as the use of mean monthly temperatures can vary several degrees from the annual average temperature, the possible effects on the model results with the use of monthly mean temperatures needs to be investigated (Zhuang et al., 2001; O'Donnell and Ignizio, 2012). Further, the first step of the ecosystem model – to check if an ecosystem is already present – needs to be implemented. To do this, world data maps with information on existing mangrove forests, salt marshes, dune systems, coral and shellfish reefs are needed.

As a final recommendation additional variables should be investigated and added to the model. Previously suggested in the methods are the variables salinity and water depth.

6. Conclusion

The main question of this research was how to determine the most adequate coastal protection system for a given location. To answer this main question, two subquestions were asked. The first question was what factors determined the choice between the green, grey and hybrid solutions, and what environmental factors were important to determine the most suitable ecosystem. In this report, we have determined that important factors in the decision between green, grey and hybrid solutions are the risk of an area, the amount empty space between the built area and the sea and finally the cost of a solution, where the GDP of the country was used as a proxy. Additional factors, such as governance, sediment availability and subsidence rate, were also determined to be important, but not yet tested. The environmental variables that were determined to have an important influence are sediment and temperature, both water and air. Further variables that were found, but not yet implemented, are salinity and water depth.

The second question asked how these factors could then be parameterised to represent reality as close as possible.For the parameters Risk, Space and Cost, and the variable temperature, upper and lower boundary limits were determined for each different type of intervention/ecosystem. For the variable sediment, three main sediment types were determined, and correlated to when the ecosystems were able to grow.

When tested on three different locations – The Netherlands, New Orleans and Khulna – results for the green/grey/hybrid choice corresponds to the currently used intervention, and results are found to be robust. The results for the determination of the optimal ecosystem have found to be mostly correct, and results are found to be robust. However, most incorrect estimations were due to the sediment variable, so the parameterization of this variable is found to be incorrect.

Building on our results, we can therefore conclude that the chosen parameters and variables are relevant to their respective models, and that their parameterizations in most cases represent reality in an adequate manner.

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