'STOCHASTIC ECONOMIC OPTIMISATION MODEL FOR THE COASTAL ZONE'

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Abstract

In this paper we present a stochastic optimisation model for sandy coasts. This model optimises the annual costs of maintenance (sand nourishment) and damage to societal activities due to coastal recession. The optimisation model combines the stochastic hydraulic and morphological processes in the natural coastal sub-system with the socio-economic and ecological activities. As a consequence, we obtain insight into the relation between physical processes, societal activities and sand nourishment. Ongoing structural coastal erosion and dune retreat cause damage to societal activities in the coastal zone. This damage will be larger when coastal recession increases or economic development takes place. The damage to societal activities is influenced by preventive maintenance measures like sand nourishment. However, the physical processes, societal activities and sand nourishment measures suffer from uncertainties. Variations and probabilities are included in the stochastic optimisation model, which helps to understand the impacts of these uncertainties.

The model can be used to optimise maintenance measures in the coastal zone and to give insight into the economic and ecological consequences of spatial decisions in the coastal zone.

Additional index keywords: *coastal zone management, stochastic modelling, climate change, cost-benefit analysis, soft shore protection, coastal processes, economic optimisation model, operation & maintenance*

1. Introduction

World-wide, coasts are subject to physical and societal changes. The development of a coastal policy which guide these (future) changes attract political attention. Physical changes include sea level rise and storm intensification, which might result into more intensive dune retreat and structural erosion. Societal changes like the development of the socio-economic and ecological sub-systems in the coastal zone claims additional space in this area. These activities consist among others of enlarging the recreation and tourism facilities, land reclamation for industry, infrastructure and residence. As a consequence of both physical and societal changes, the pressure upon the coast and the spatial claims increase almost everywhere.

Especially when space is limited, spatial decisions are important. The coast has to confront the future physical changes like sea level rise, but it is desirable that maximal profit is created from the economic opportunities offered by the coast and the beach. The landward pressure can create irreversible impacts, which can endanger future safety. Once, the limited space is allocated to societal-economic activities, nature and landscape, the allocated space can not be used to move or to enlarge the primary water barrier in the future. To avoid conflicts between these interests and to guide the developments in a responsible manner, spatial decisions along the coasts have to be taken cautiously.

In this paper we consider sandy coasts. Hence, the dune coast has a flexible character. The forces of nature cause constant moving of this barrier. Societal functions and interests in the coastal zone may experience problems due to ongoing structural erosion and dune retreat. The dynamics of the coast determine whether these functions can be fulfilled. Understanding of the dynamics of the coast is of great importance to assess the probability of damage in the coastal zone. The damage will be larger when coastal recession increases or economic development takes place. The damage to societal activities is influenced by preventive maintenance measures like sand nourishment. Preventive maintenance measures result in a reduction of the probability of damage, but introduces maintenance costs. Preventive maintenance costs and economic benefits have an important role in the relation between physical processes, societal activities and sand nourishment.

An economic optimisation model is proposed in this paper, which combines the hydraulic and morphological processes in the natural coastal sub-system and the preventive sand nourishment measures with the socio-economic and ecological activities. However, the physical processes, societal activities and sand nourishment measures hamper by uncertainty. The inclusion of variations and probabilities in a stochastic economic optimisation model contributes to understanding of these uncertainties.

The major aim of the stochastic model is to minimise the annual costs of maintenance (sand nourishment) and damage to societal activities due to coastal recession. Insight will be obtained into the economic and ecological consequences of spatial decisions in the coastal zone.

This paper consists of two parts. First the model framework for the economic stochastic optimisation model is presented. This framework is partly based on the model of Peerbolte and Wind *(1992)*. This model framework consists of an input file, three model parts and an optimisation module combining these model parts. In the second part of the paper the model framework is applied to the Dutch coast (Hook of Holland to Den Helder) to investigate economic and ecological consequences of relevant maintenance options in the Netherlands.

2. Stochastic economic optimisation model

2.1 Uncertainties

As stated in the introduction, the physical processes, the societal and ecological activities and sand nourishment measures hamper by uncertainties. The balance between the allocation of limited space in the coastal zone to societal-economic activities, nature and landscape on the one hand or the reservation of space, which can be used to guaranty safety in future, on the other hand, is a decision under uncertain conditions. Uncertainties exist among others in modelling of (extreme) hydraulic conditions and morphological processes. These processes cause coastal recession and coastal recession creates damage to societal activities in the coastal zone. The damage to societal activities in the coastal zone will be enlarged when coastal recession due to ‘uncertain’ climate changes increases or ‘uncertain’ economic development takes place. However damage to societal activities is also influenced by preventive maintenance measures like sand nourishment. The costs and the effectiveness of these maintenance measures vary.

To obtain a better understanding of these uncertainties the developed optimisation model is a stochastic model in which the variations of input variables in the model parts are included by probabilistic distribution functions.

2.2 Model Framework

The stochastic optimisation model consists of boundary conditions, three model parts (hydraulic morphological model, coastal defence measures-model, economic model) and an optimisation module combining these model parts. The results of the optimisation form the output of the model. Hydraulic and morphological processes, societal activities, ecology and coastal defence measures have central positions in this model. A clear overview of the damage to societal functions will be realised considering the connection between coastal dynamics and spatial claims of societal activities in the coastal zone. Based on the relation between the costs of coastal defence measures and damage to societal functions an optimal solution can be determined in which the total annual costs are minimised. The model framework is given in Figure 1.

In the stochastic optimisation model figures are included and calculations are carried out per linear meter coastal stretch, i.e. coastal recession, sand nourishment costs and the economic value of a coastal area are calculated per linear meter along the coastline. The equations given in the next sections have to be considered per linear meter coastal stretch.

2.3 Limitations and assumptions

Limitations and assumptions made in this paper include:

- The optimisation model is developed for dynamic sandy coasts.
- The coastal protection against flooding of the area behind the coast, i.e. safety is the most important function of the dune coast. Besides, coastal defence is inextricable linked with other societal functions in the coastal zone. Without harming the water protection function, the integrated coastal zone management is aimed at sustainable preservation of these functions in the coastal dune area. The awareness of the presence and appreciation of other functions in the coastal zone increases. Due to the importance of the societal functions and their spatial claims in the coastal zone, it is relevant to specify these functions.
- Only, beach nourishment is taken into account as a coastal defence measure.
- Both the present situation as an (arbitrary) point of time in the future is taken into consideration.
- In case of damage to the societal functions, reconstruction takes place at a location, which is not susceptible to damage. In this way, damage is charged once.
- Damage to the societal functions includes both investment costs and loss of profits. A period of two years is taken for loss of profits due to damage.
- Damage can be interpreted at different economic scales. At local scale damage affect the entrepreneur, who experiences damage and loss of profits. At macro-scale, this damage might be neglectable. This paper aims at nourishment costs and damage at a local economic scale.
- The plan-period over which the total costs of coastal defence measures and damage to societal functions will be optimised concerns 30 years.
- The stochastic optimisation model is a sequential model. The development of the input-conditions in time is not included in the model. Costs of coastal defence measures and damage to societal functions will be calculated in time steps of 1 year. From two starting points onwards (the present and a point of time in the future) the optimisation is based on constant input conditions. The feedback between

changing hydraulic conditions and their impact on morphological processes and visa versa is omitted in the model.

2.4 Boundary conditions

The boundary condition concerns the coastal dune area. Here a representative coastal cross-section is defined based on historical data. Societal functions and coastal dynamics are considered within the coastal dune area of this representative coastal cross-section. The coastal dune area stretches out from the dune crest till the landward boundary of the coastal dune area (see Figure 2). The dune crest is a reference point for coastal dynamics and the position of societal functions in the dune area.

2.5 Hydraulic morphological model

The morphological development of the coast is rather irregular, as it is a superposition of the effects of different processes and human interference. Morphological processes occur at different scales. The hydraulic morphological model focuses at meso-macro scale level. This level includes the principal morphological features and the interaction between these features. The principal forcings are seasonal and interannual variations in tide and weather conditions, human activities (sand mining) and extreme events. In this model two types of coastal development are considered: structural and incidental erosion *(van Rijn, 1998)*.

Structural erosion includes the ongoing sand loss in the coastal zone due to waves and flows. General effects of ongoing structural erosion are predictable within uncertainty bounds. Therefore, the coastal manager is able to anticipate structural erosion on time. However, the influences of the future climate changes (and involving sea level change and storm intensification) on structural erosion is uncertain.

Structural erosion is expressed as follows:

$$\underline{x}_s(t) = \underline{b} \cdot t \qquad :1$$

In which:

$\underline{x}_s(t)$	stochastic variable of cumulative structural erosion in year t	[m]
$\underline{b}$	stochastic variable of annual structural erosion	[m/yr.]
t	time	[yr.]

The stochastic variable consists of an average annual coastal recession (or coastal extension) trend and a standard deviation. Using a regression analysis the parameters of the stochastic variable of structural erosion can be determined based on coastal measurements (if available). The coastal recession (extension) due to structural erosion is schematised in Figure 3.

Incidental erosion results from severe storm surges. Incidental erosion is a fast elapsing process. A significant sand loss in the top part of the cross section occurs within a short period of time. The declined sand out of the dunes deposits on the fore shore, see the schematic representation of incidental erosion in Figure 4 *(TAW, 1995)*.

To calculate the extent of incidental erosion, dynamic equilibrium is assumed at the annual scale. This means that the dune retreat in a certain year is assumed to be restored the same year in a natural manner. The cumulated coastal recession over several years due to incidental erosion is equal to the annual contribution of dune retreat to coastal recession. So, dune retreat is temporal. The deposited sand will be transported back to the dunes in a natural way. Natural recovery takes place under calm weather conditions.

The Bruun-rule of erosion is important, while calculating the future dune retreat. *(Bruun, 1983)* This Bruun-rule concerns the long-term budget of onshore/offshore movement of sediment due to the future sea level rise. The Bruun-rule includes a translation of the beach profile by a distance *s* following a sea level rise *a*, which results in shore erosion and a deposition of sediments. The cross-section profile changes. These profile changes have impact on the dune retreat calculations.

$$\underline{x}_i = \underline{a} \qquad :2$$

In which:

$\underline{x_i}$	stochastic variable of incidental erosion	[m]
$\underline{a}$	stochastic variable of incidental erosion	[m]

Superposition of both structural erosion and dune retreat results in the total coastal recession (see Figure 5):

$$\underline{x_{tot}}(t) = \underline{x_s}(t) + \underline{x_i} = \underline{b} \cdot t + \underline{a} \qquad : 3$$

2.6 Coastal defence measures

Coastal protection measures are taken to compensate for or to resist against structural coastal recession. Incidental dune retreat will be restored in an natural manner. The coastal protection measures are limited. Only sand nourishments are taken into account. *(TAW, 1995)* Sand nourishments yield profit compared to other coastal defence measures, like seawalls, groyne:

- Sand nourishment is cheaper in comparison with other coastal protection schemes. This is mainly because sand is a relatively cheap material, despite the fact that sand nourishment is a temporal solution and has to be repeated on a regular basis.
- Sand nourishment is appropriate to the natural character of the coast. The natural processes along the coast remain virtually undisturbed.
- Sand nourishment is a very flexible approach to combating coastal recession: the method can be utilised virtually everywhere.

The costs of beach nourishment per linear meter coastal stretch are divided into constant starting costs and variable costs per meter coastal extension. Increase in return period leads to the increase of sand nourishment volume. The average costs will decrease. The relative large starting costs will be spread over a larger sand nourishment volume. Though the probability of damage to societal activities in the coastal zone increases. The relation between sand nourishment costs and coastal extension is described by:

$$\underline{C_T} = \underline{c} + \underline{d} \cdot \underline{x_n} \qquad : 4$$

In which:

$\underline{C_T}$	stochastic variable of total sand nourishment costs	[$]
$\underline{c}$	stochastic variable of the constant starting costs	[$]
$\underline{d}$	stochastic variable of the variable costs per meter coastal extension	[$/m]
$\underline{x_n}$	stochastic variable of coastal extension	[m]

The coastal extension is linked with the erosion rate. Sand nourishment is a preventive and corrective measure against structural coastal erosion. The coastal extension will be determined using the stochastic variable of structural erosion:

$$\underline{x_n} = \underline{b} \cdot T_R \qquad : 5$$

In which:

$\underline{x_n}$	stochastic variable of coastal extension	[m]
$\underline{b}$	stochastic variable of structural erosion	[m/yr.]
T_R	return period sand nourishment	[yr.]

Therefore, the relation between sand nourishment and structural erosion corresponds with:

$$\underline{C_T} = \underline{c} + \underline{d} \cdot \underline{b} \cdot T_R \qquad : 6$$

2.7 Economic model

Several societal functions are selected and value functions of these functions over the cross sections are determined in the economic model. Both the investment costs and the profits are included in these functions.

We made a distinction between coastal types: urban coastal areas (coastal resorts with recreation, recreation, harbours and industry), areas with nature and landscape, coastal areas with agriculture. Due to the variation in the width of the cross sections along a coast the damage functions have to be determined for the different types of coastal areas with different widths. For each of the selected societal functions economic values have to be included in the damage function. Though, the economic value of nature and landscape will not be included. The economic value of supplementary functions, like extensive recreation and drinking water supply, are taken into account in the damage function for coastal areas with nature and landscape. After the optimal situation has been determined, the effects on the different types of nature will be considered.

An example of a damage function is shown in Figure 6. The damage function shows the cumulative damage in the coastal zone due to coastal recession $\underline{x_{tot}}(t)$.

The damage to societal functions depends on the coastal recession measured from the dune crest. The coastal recession is a function of time. The damage function can be used to determine the damage as it contains the cumulative economic value for an arbitrary point at a distance x from the dune crest. The total damage at time t can be described as follows:

$$\underline{D} = f\left(\underline{x_{tot}}(t)\right) = f\left(\underline{b} \cdot t + \underline{a}\right) \quad : 7$$

In which:

$\underline{D}$	stochastic variable of damage in year t	[$]
$f(\cdot)$	damage function	[$]
$\underline{x_{tot}}(t)$	stochastic variable of total coastal recession	[m]
$\underline{b}$	stochastic variable of structural erosion	[m/yr.]
$\underline{a}$	stochastic variable of incidental erosion	[m]
t	time	[yr.]

For the future value functions, different development possibilities can be investigated. The scenarios for future value functions depend on the paper area. For future scenarios an increase of capital value (inflation) or/and economic developments can be taken into account.

2.8 Optimisation module

The various model parts are linked in the optimisation module. The optimal situation is a matter of nourishment costs and societal benefits. Nourishment costs and damage may occur at different points in time. By discounting, their values are made comparable. In case no coastal defence measures will be taken, the damage after the plan-period corresponds with:

$$\underline{NPV_D} = \sum_{t=0}^{T}\left[\frac{\left(f\left(\underline{x_{tot}}(t)\right) - f\left(\underline{x_{tot}}(t-1)\right)\right)}{(1+r)^t}\right] \quad : 8$$

In which:

$\underline{NPV_D}$	stochastic variable of the Net Present Value	[$]
$f(\cdot)$	damage function	[$]
$\underline{x_{tot}}(t)$	stochastic variable of total coastal recession	[m]
T	plan-period	[yr.]
r	net interest rate,	[-]
t	time	[yr.]

Postponing or cancelling coastal defence measures have financial impacts on the societal functions in the coastal zone. However, taking coastal defence measures involves costs. The cumulative discounted costs of coastal defence measures and damage after the plan-period depend on the return period of sand nourishment. The first sand nourishment takes place after the first return period.

$$\underline{NPV}_{D+C_T} = \sum_{t=1}^{T_R}\left[\frac{\left(f\left(\underline{x}_{tot}(t)\right) - f\left(\underline{x}_{tot}(t-1)\right)\right)}{(1+r)^t}\right] + \sum_{k=1}^{n_s}\left[\frac{\underline{C}_T(T_R)}{(1+r)^{k\cdot T_R}}\right] \qquad :9$$

In which:

$\underline{NPV}_{D+C_T}$	stochastic variable of the Net Present Value of damage and sand nourishment costs	[\$]
$\underline{C}_T(T_R)$	stochastic variable of sand nourishment costs	[\$]
$f(\cdot)$	damage function	[\$]
$\underline{x}_{tot}(t)$	stochastic variable of total coastal recession	[m]
T	plan-period	[yr.]
T_R	return period sand nourishment	[yr.]
r	net interest rate	[-]
t	time	[yr.]
n_s	amount of sand nourishment in plan-period T: $n_s = \frac{T}{T_R}$	[-]
k	k^{th} sand nourishment from k=1 to n_s	[-]

By systematically changing the return period of sand nourishment, the total costs of sand nourishment and damage in the coastal zone can be minimised.

$$\underset{T_R}{MIN}\left\{\underline{NPV}_{D+C_T}\right\} = \\ = \underset{T_R}{MIN}\left\{\sum_{t=1}^{T_R}\left[\frac{\left(f\left(\underline{x}_{tot}(t)\right) - f\left(\underline{x}_{tot}(t-1)\right)\right)}{(1+r)^t}\right] + \sum_{k=1}^{n_s}\left[\frac{\underline{C}_T(T_R)}{(1+r)^{k\cdot T_R}}\right]\right\} \qquad :10$$

3. Coastal zone management in the netherlands

3.1 The Dutch coast

The Dutch coast has a total length of 432km of which the straight coast from Hook of Holland to Den Helder covers 118km. The main part of the Dutch North Sea coast is made up of dunes, which vary in width from less than a hundred metres up to a few kilometres. This flexible dune-coast together with the beach and the coastline protect the western part of the Netherlands against flooding. Failure of this coastal protection would have disastrous impacts for the Netherlands.

Along the coast, the forces of nature, wind and sea, cause constant moving of this dune-coast barrier. Societal activities and ecology in the coastal zone can be harmed due to the dynamics of the coast. Erosive coasts and coasts with accretion alternate along the coast. Alternately urban coastal areas and coasts with nature reserves be situated along the coast. The combination of both dynamic characteristics and coastal area types show a varied view from Hook of Holland to Den Helder. In order to have a responsible coastal policy and coastal management, insight into the dynamics of the coast and the consequences of spatial decisions has to be obtained.

3.2 Coastal zone policy in the Netherlands

Dynamic preservation and natural processes have an important role in the current Dutch policy. However, if the entire coast was left to natural processes the safety of the polders behind the dunes would be endangered by erosion. Therefore the policy was adopted to preserve the coastline at its position of 1990, in order to stop ongoing structural coastal recession. This reference line is known as basal coastline. In case the coastline recedes across the basal coastline preventive measures have to be taken (see Figure 7). The main instrument of the manager in this dynamic preservation policy is sand nourishment *(Ebbing, 1996)*.

Besides protection against flooding, integrated coastal zone management is aimed at sustainable preservation of functions in the dunes area. Attention is focused on maintaining and strengthening the position of the functions in the coastal zone.

The Dutch coast is subjected to future changes. The question arises whether, given the expected physical and societal changes, it is still possible and economic attractive to reconciliate coastal defence and increasing spatial claims of other interests and values under the basal coastline policy. As a result of the basal coastline policy, societal activities in the coastal zone tend to develop seaward till the designated basal coastline. Besides, physical changes will claim additional space in the coastal zone.

Based on experiences, the present coastal policy shows in some cases less flexibility. It might be recommendable to relax the basal coastline policy and permit the coastline to move within a designated zone. Two additional coastal policy options are defined (see Figure 8 and Figure 9), the coastal zone policy with the landward strategy and the coastal zone policy with the seaward strategy. The coastal zone policy with the landward strategy allow the coastline to recede across the basal coastline in landward direction. A seaward sand buffer will be created under the coastal zone policy option with seaward strategy. The economic and ecological consequences of both new policy options and the current basal coastline policy will be analysed by the application of stochastic optimisation model to the Dutch coast.

4. Stochastic optimisation model applied to the Dutch coast

World-wide a great variety in coasts can be distinguished. Due to the different dynamic coasts with their specific characters the stochastic optimisation model might be adapted for a good application to a specified coast. The necessary adaptations to make the stochastic optimisation model applicable for the Dutch coast are explained below.

4.1 Limitations and assumptions

The Dutch coastal zone is intensely occupied with human activities. The sea has always been attractive to people for its beauty and its economic advantages. A limited number of functions is considered. The functions included in the optimisation model applied to the Dutch coast are safety, nature and landscape, recreation and tourism, residence, industry and water catchment (drinking water supply).

The optimisation is performed at two points in time. These points concern the present (in 2000) and the future (in the year 2100).

Many different combinations of both hydraulic and morphological characteristics and economic development are present in the coastal zone along the Dutch coast. Representative morphological classes, storm conditions, cross-sections, economic distribution functions are developed for the varying situations along the Dutch coast. The representative cross-section is shown in Figure 10.

4.2 Boundary conditions

In addition to the boundary condition in section 2.4 a second restriction is imposed on the coastal zone. The Dutch coastal policy is aimed at the safety of the low-situated western part of the Netherlands. Subsequent to the storm surge disaster in 1953 the Netherlands introduced safety-norms to establish safety constraints by law. This safety constraint results in an additional boundary condition in the optimisation model.

According to this safety constraint the probability of failure equals 10^{-5}. That means that once in 100,000 years failure is expected. To fulfil this safety condition, the law imposes a limiting cross section in additional to the 10^{-5}-dune retreat zone to be present in the coastal zone at all times (see Figure 11). This constraint limits the space for dynamics. To meet this constraint, the distance over which the coastline is allowed to recede is calculated and included as boundary condition in the model *(DWW, 1996)*.

4.3 Hydraulic morphological model

The structural erosion is determined using annual coastline measurement data. The annual erosion or accretion trend is determined by a linear trend analysis *(Bolle et al., 1983)*. The trend for structural erosion or accretion is normal distributed.

The incidental erosion is calculated for three storm climates along the Dutch coast: Den Helder, IJmuiden and Hook of Holland. Retreat calculations are executed by a dune-retreat program called Super Dune. The calculations are repeated for different storm surge levels and corresponding significant wave heights. The relation between the dune retreat calculations and the storm surge levels is determined with a curve fit-program. Using this relation and the probability distribution of the storm surge level, the probability distribution of dune retreat is calculated with a Monte Carlo simulation. The dune retreat is Gumbel-distributed.

The structural and incidental erosion are also predicted for the future (2100). Climate changes might result into a(n) (accelerated) sea level rise and intensification of storms. This will influence the morphological processes. It is possible to have a long-term perspective and to outline a recommendable long-term policy in the future. Table 1, 2 and Table 3 show the values of structural erosion and incidental erosion in the present and in the future.

The total coastal recession is a superposition of structural erosion and dune retreat, see equation (3). In case a sand buffer is created in the coastal zone policy with the seaward strategy equation (3) is modified:

$$\underline{x_{tot}}(t) = -x_{buffer} + \underline{b} \cdot t + \underline{a} \qquad : 11$$

4.4 Coastal defence measures

The relation between the costs of beach nourishment per linear meter coastal stretch and the coastal extension due to sand nourishment is described by equation (6). Based on information about nourishment cost the constant starting costs and the variable costs are described as triangle distribution functions (See Table 4 and Table 5).

The costs of sand nourishment measures will increase in time as a function of the growth rate of capital:

$$\frac{dC}{dt} = r \cdot C \qquad : 12$$

$$C(t) = C_0 \cdot e^{r \cdot t} \qquad : 13$$

In which:

$C(t)$:	costs at t	[$]
C_0:	present sand nourishment costs	[$]
r:	real interest rate, growth rate of capital	[%]

Taking a growth rate of 3% into account, the sand nourishment costs in the future (2100) will increase by a factor 20.

4.5 Economic model

For the Dutch coast economic value functions over the cross sections are determined. Therefore, based on an inventory along the Dutch coast, a distinction is made between urban coastal areas and coastal areas with nature reserves. Urban coastal areas are subdivided into three types: coastal resorts with small-scale recreation, coastal resorts with large-scale recreation and areas with large-scale recreation, harbours and industry.

Nature type varies over the dune cross-section (see Figure 12). Characteristic nature for dynamic coastal areas appears in the seaward region of the dune cross-section and nature with genesis for hundreds of years appears in the landward region of the dune cross-section.

The assumption is made that nature in coastal areas with nature reserves coincides with the functions extensive recreation and drinking water supply. The economic value of extensive recreation and drinking water supply is taken into account, while the economic value of nature is not included. The economic value of coastal areas with nature and landscape is relatively low. After the optimal situation has been determined, the effects on the different types of nature are considered.

The economic value per function in the coastal area is based on standard economic values per unity or square measure for each given function. In Vrisou van Eck et al *(1999)* information is provided about these standard economic values.

There is no doubt that changes in spatial claims and economic value of societal functions will occur in future. For the Netherlands, two scenarios for societal changes are developed. The economic value increases with a factor 20 (see section 4.4) for both scenarios. Providing a stop to the development of societal functions in the present Dutch policy, the first scenario considers a situation in which the increase of capital value is taken into account and in which no economical development takes place compared to the present situation. The second scenario considers a case in which both inflation and economical developments are taken into account. In fact, many scenarios for future societal development in the coastal zone can be thought of.

4.6 Optimisation module

The optimisation module links the model parts.

Subsequent to the remarks to the general optimisation module the following comment on the module applied to the Dutch coast has to be made. When a sand buffer is created the net present value of coastal defence measures costs and damage after the plan-period is given by equation (9). Tough, the index k in the second term starts at zero instead of one and stops at n_s-1 instead of n_s. The first sand nourishment takes place at the beginning to create the sand buffer.

5. Optimisation

The Dutch coast shows much variety. Some representative situations are optimised. Optimisation are carried out for:

- a narrow and a broad urban coastal area
- a broad coastal area with nature reserves

The optimisations with the stochastic economical optimisation model give insight into the economic and ecological consequences of dynamic preservation of the basal coastline and the two basal coastal zone policies.

5.1 Urban coastal area

The optimisation results show that for urban coastal areas it is recommendable to relax the basal coastline policy and permit the coastline to move within a designated zone as well in the present as in the future. This designated zone has to be created by a seaward sand buffer. Compared to the present, the size of this buffer is larger for the future circumstances. Allowance of the coastline to recede across the basal coastline in landward direction has to be avoided. In that case, the damage increases due to the high economic value of urban coastal areas.

A module, in which the additional profits due to the economic developments in future are included, is absent in the optimisation model. That is why based on this model the question about whether it is attractive from economic point of view to allow further economic development in the coastal zone or to maintain the policy that economic development is not allowed cannot be answered.

5.2 Coastal area with nature reserves

The economic value given to these areas is low. As a consequences it is attractive to permit the coastline to move within a designated zone landward. This zone is broad. The damage due to coastal recession is relatively low. The nourishment costs to maintain the coast at his position are compared to the damage high. The coastal zone policy with the landward strategy is the cheapest maintenance option.

The zone over which the coast is permit to move landward is broad (50-110 metres). As the type of nature varies over the cross-section, coastal recession might influence the type of nature. Due to the great coastal recession, nature with genesis for hundreds of years will disappear. 'Dynamic' nature will evolve. Besides this economic consideration, in practice a society widespread acceptance is important to allow that a certain type of nature rises at the expense of the overall disappearance of another type of nature. The economic optimisation model cannot be applied unlimitedly in coastal areas dominated by nature reserves and landscape.

5.3 Feedback to Dutch coast: Hook of Holland to Den Helder

To guaranty safety and liveability in the Netherlands for the future generations as well, a lasting vision to coastal protection against flooding is important. Therefore, anticipation of future changes is advisable. Based on the optimisations results, insight into the significance of the different policy options is gained. The optimisation model provides clarity about the flexibility towards expected future changes in the coastal zone and economic consequences of decisions.

As well for an urban coast area whereas for a coastal area with nature reserves it is advisable to relax the basal coastline policy and to introduce a coastal zone policy. The designated zone has to be found seaward in case of an urban coastal area. The coast is allowed to recede landward, across the basal coastline, in case of a coastal area with nature reserve. The optimal situation along the Dutch coast gives a varying view due to the fact that urban coastal areas and coastal areas with nature reserves alternate along the Dutch coast. The discontinuity in the 'optimal' coastline (see Figure 13) causes sand losses in longshore direction for the coastal areas which have to be maintained at their position along the coast. Maintenance problems will occur in maintaining the optimal situation along the Dutch Coast. In practice a solution will be chosen which leads to less extreme transitional areas.

If this optimisation model will be applied, societal acceptation of the results have to be taken into account. In practice decisions are not only based upon cost-benefit analysis. Besides societal views, opinions and ideas can change in time which can result in different future choices.

6. Discussion and recommendations

6.1 Significance of the optimisation model for coastal areas world-wide

The optimisation model is a useful instrument to create insight into the relation between societal activities and coastal dynamics. The economic and ecological consequences of spatial decisions related to different policy maintenance options for sandy coasts world-wide can be cleared up.

The stochastic model gives indicative answers to questions like:

- What kind of coastal zone policy is attractive from both an economical point of view and an ecological point of view in an arbitrary sandy coast world-wide?
- How to deal with the pressure upon coasts and the increase of spatial claims due to both future physical changes and societal changes?
- How to ascertain that the future safety is guarantied for the lowlands behind the coastal dunes, while at the other hand maximum profit is desired from the economic opportunities offered by the coast and the sea?

- Is it advisable to adapt the present coastal policy to anticipate of future changes?

The stochastic optimisation model provides insight into the present and the anticipation of the future changes.

6.2 Shortcomings of the model and recommendation

This model obtains insight into the interaction of the physical processes and the societal activities in the coastal zone. The model estimates the consequences of the future changes. In practice decisions are not only based on a cost-benefit analyses. Therefore the shortcomings of the model consist among others of the limited applicability of the model in coastal areas with nature and landscape. An additional consideration is often important to investigate societal acceptance of the model results.

Societal acceptance is not only important for coastal areas with nature and landscape. Societal objection might rise when extreme coastal recession is allowed based on model results. Lack of understanding and trust in the safety of the coasts are realistic consequences. Societal uncertainties have an important role. The societal ideas and views change in time and might lead to different choices and decisions in the future. This change might be the result of new insights after analysing the foreseen and unforeseen effects of policies and civil engineering works *(*see *Dubbeldam, 2000*). An interesting point for further research is how to cope with these future changes in societal preferences.

It is recommended to improve the model at the following points:

- the present optimisation model is a sequential model. The developments in time from the starting-point onwards (the input time series) in the present and in the future are not included. Improvements concerned to the evolution of input variables and morphological processes in time are important.
- the model has to be expanded with a module, in which the additional benefits of economic development alternatives are included. In that way it is possible to evaluate the economic consequences of future economic development strategies.

7. Acknowledgements

During this paper valuable contributions and comments have been made by H.J de Vriend and C.M. Dohmen-Janssen. The National Institute for Coastal and Marine Management in the Netherlands provided useful comments on and information for the structural erosion computations.

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Figure 1: Stochastic economic optimisation model framework

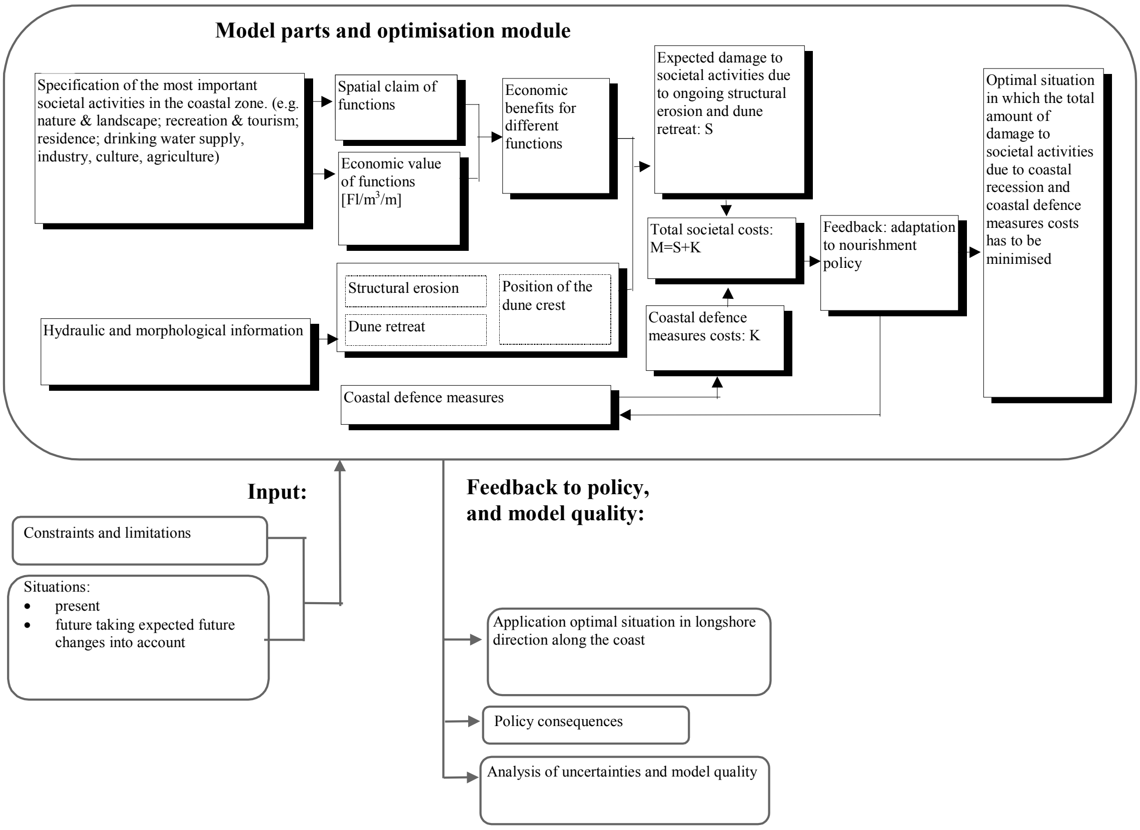


Figure 2: Coastal zone

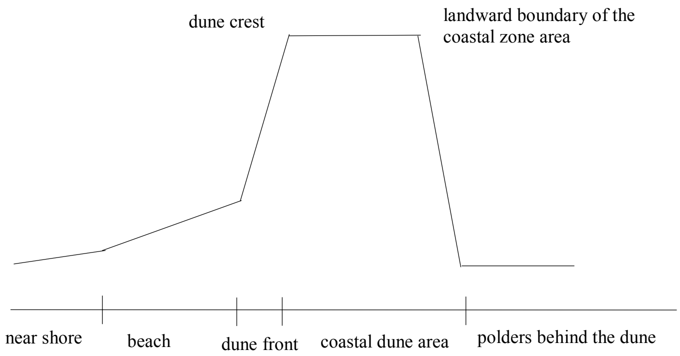


Figure 3: Schematisation of structural erosion in the coastal zone

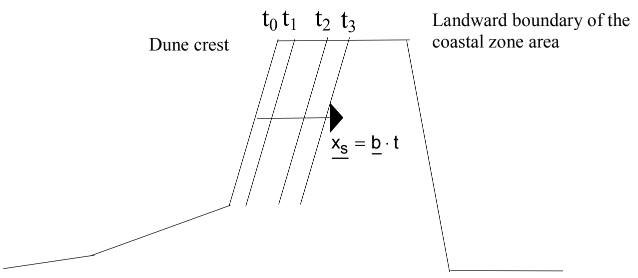


Figure 4: Schematisation of Incidental erosion in the coastal zone

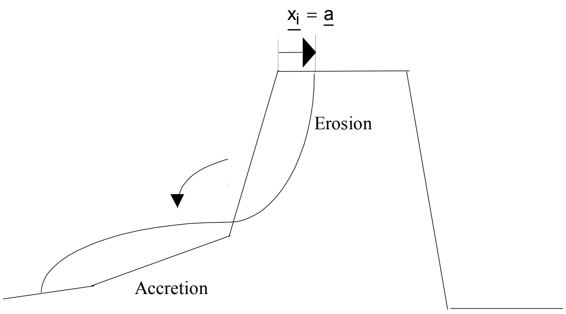


Figure 5: coastal recession: superposition structural and incidental erosion

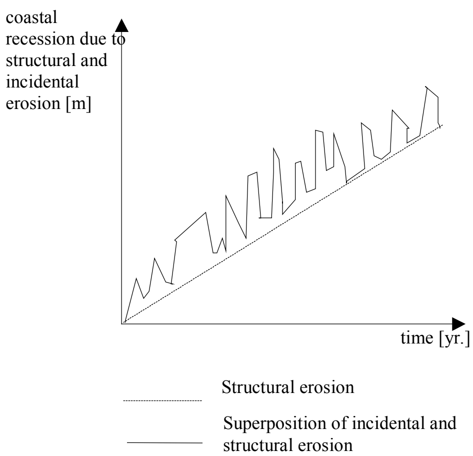
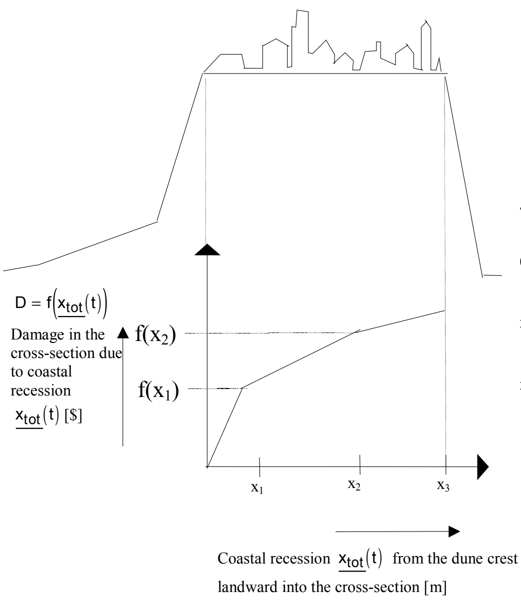


Figure 6: Damage function



The cumulative damage due to coastal recession $\underline{x_{tot}}(t)$ measured from the dune crest:

$0 \le \underline{x_{tot}}(t) \le x_1$: $$f(\underline{x_{tot}}(t)) = \frac{f(x_1)}{x_1}\cdot \underline{x_{tot}}(t) \quad (1.)$$

$x_1 \le \underline{x_{tot}}(t) \le x_2$: $$f(\underline{x_{tot}}(t)) = f(x_1) + \frac{(f(x_2) - f(x_1))}{(x_2 - x_1)}\cdot (\underline{x_{tot}}(t) - x_1) \quad (2.)$$

$x_2 \le \underline{x_{tot}}(t) \le x_3$: $$f(\underline{x_{tot}}(t)) = f(x_1) + f(x_2) + \frac{(f(x_3) - f(x_2))}{(x_3 - x_2)}\cdot (\underline{x_{tot}}(t) - x_2) \quad (3.)$$

figure 7: Basal coastline policy

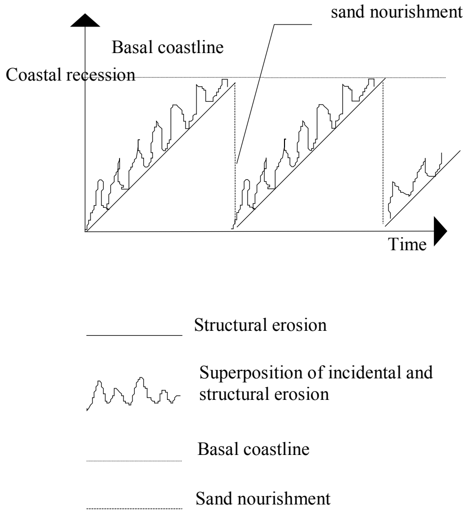
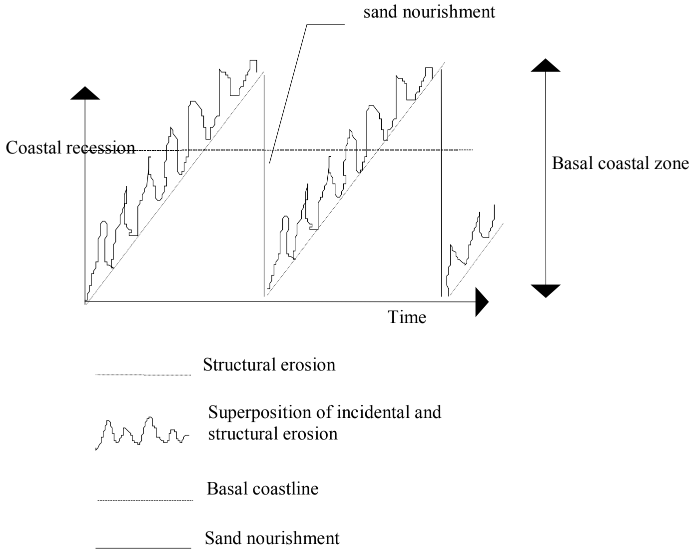
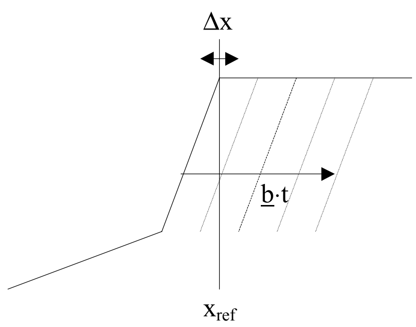
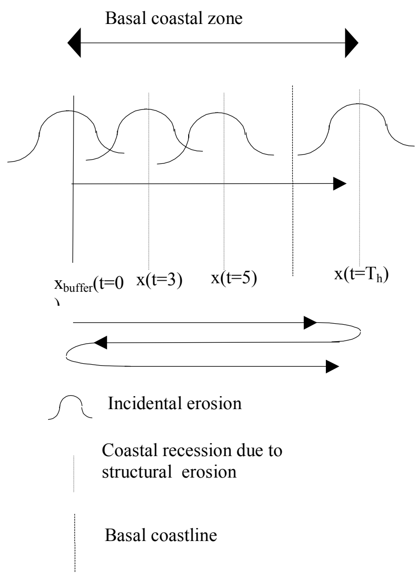


Figure 8: Basal coastal zone policy - landward strategy





Coastal recession in the cross-section



Fgure 9: Basal coasal zone policy - seaward strategy

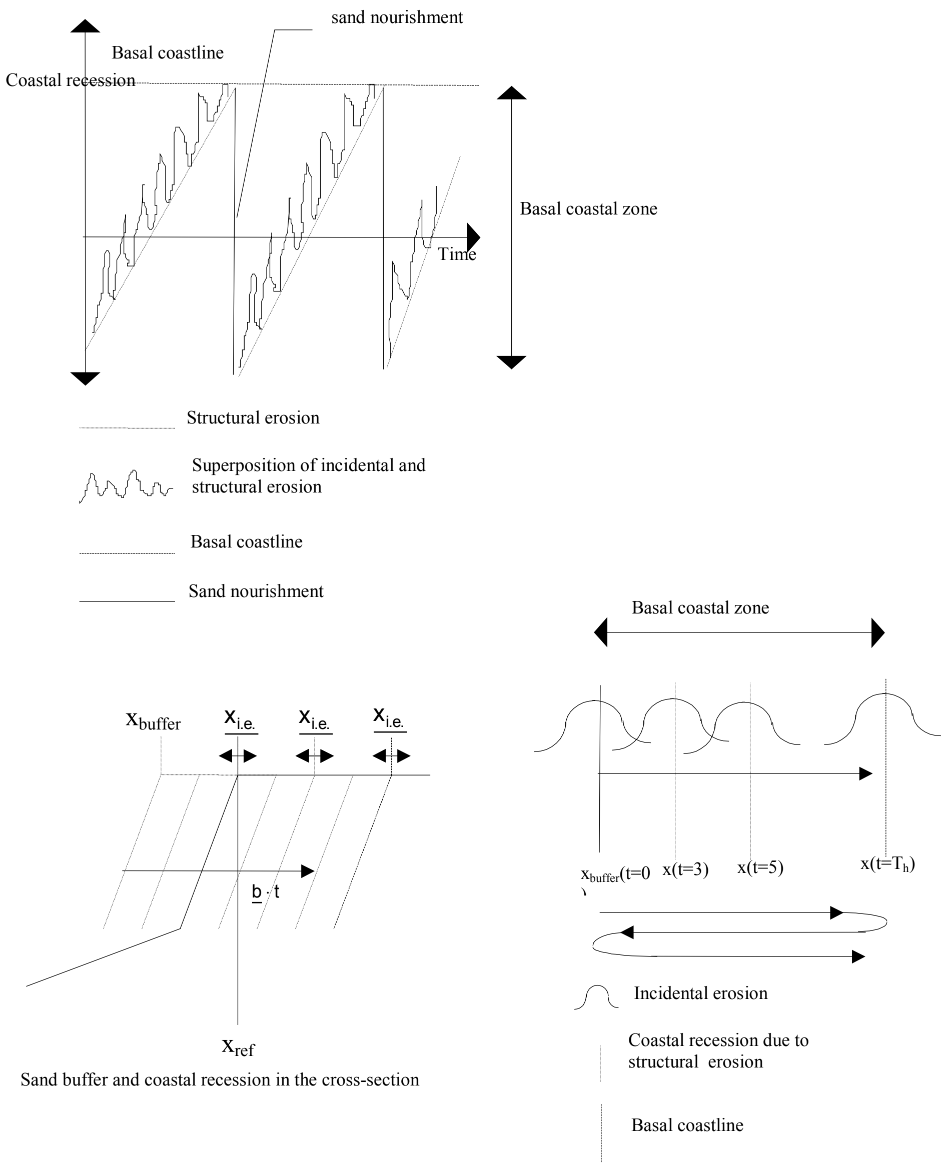
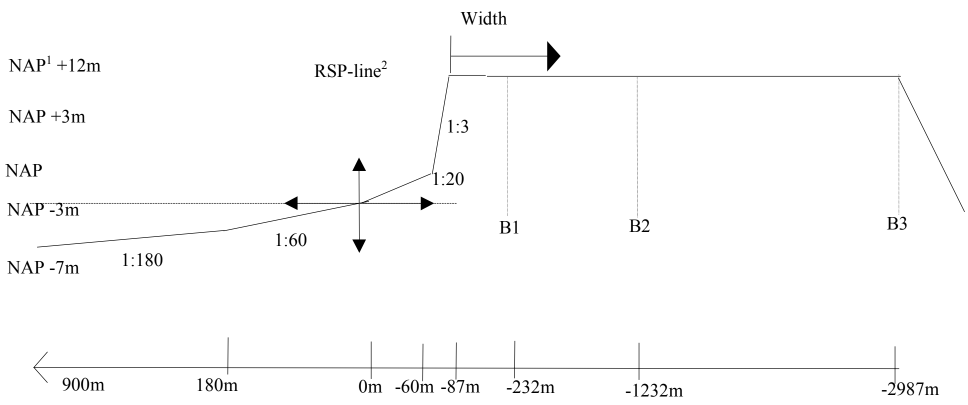
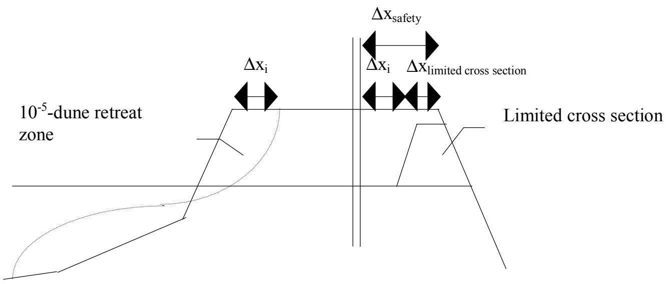


Figure 10: Representative cross-section: dune area varying in width from B1 till B3



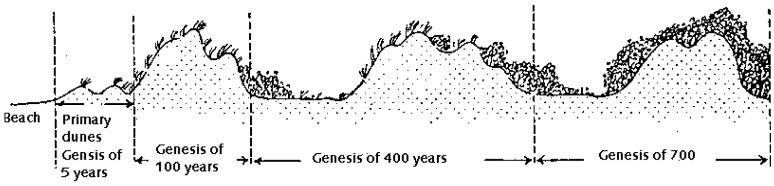
[1]NAP (Normaal Amsterdams Peil): reference line in the Netherlands for object altitudes
RSP-line reference line for object distances perpendicular to the coast

figure 11: Safety-conditions



Δx_{safety} = safety zone (superposition of limited cross section and 10^{-5} dune retreat zone) which have to be present in the coastal zone at all times

Figure 12: Nature type varying over the cross-section



From beach to more landward situated dunes:

Climate:	decrease influence wind-forces decrease salt-supply
Soil conditions:	increase organic material increase descaling
Vegetation:	from pioneer vegetation (helm-grass) to forest with oak trees

Figure 13: results

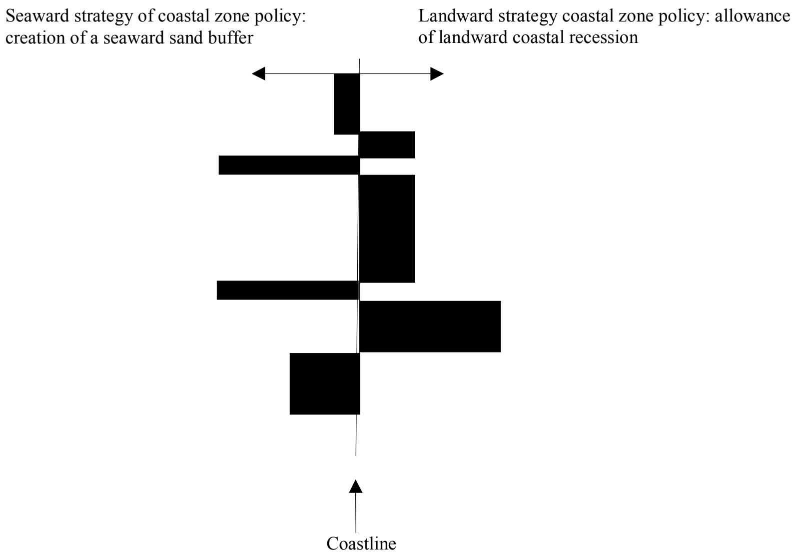


Table 1: Trend of structural erosion in the present and in the future along the Dutch coast

Coastal area stretches	Trend [m/yr.]	Trend [m/yr.] 100+	Coastal area stretches	Trend [m/yr.]	Trend [m/yr.] 100+
Den Helder	-5.1	-15.2	Zandvoort	-1.1	-3.4
Callantsoog	-0.4	-1.3	Zandvoort Z.	0.7	2.0
Petten	-1.4	-4.1	Noordwijk	0.5	1.6
Bergen a. Zee	-1.4	-4.1	Katwijk	0.3	1.0
Egmond a. Zee	0.9	2.7	Scheveningen. N.	-0.7	-2.1
Wijk aan Zee	-0.8	-2.5	Scheveningen	0.2	0.5
IJmuiden N.	2.8	8.4	Ter Heijde	-0.5	-1.6
IJmuiden Z.	7.4	22.3			

Table 2: Parameters Gumbel-distribution function for Incidental erosion in the present along the Dutch coast

Gumbel-distribution function, $F(x_i) = e^{-e^{-\frac{x_i - A}{B}}}$, with parameters:

Location	A	B
Den Helder	-15.2	6.5
IJmuiden	-17.7	6.2
Hook van Holland	-19.9	6.1

Table 3: Parameters Gumbel-distribution function for Incidental erosion in the future along the Dutch coast

Gumbel-distribution function, $F(x_i) = e^{-e^{-\frac{x_i - A}{B}}}$, with parameters:

Location	A	B
Den Helder	-15.21	7.03
IJmuiden	-17.74	6.71
Hook van Holland	-19.82	6.55

Table 4: the present sand nourishment costs: parameters triangle distribution function

The present	Parameter A – most optimistic cost estimation	Parameter B– most realistic cost estimation	Parameter C – most pessimistic cost estimation	Average μ_K	Standard deviation σ
Constant costs	55	280	505	280	92
Variable costs	66	75	84	75	4

The average and the standard deviation are determined as follows:

$$\mu_K(K) = \frac{A + B + C}{3} \quad : 1$$

$$\sigma^2{}_K(K) = \frac{1}{18} \cdot \left(A^2 + B^2 + C^2 - A \cdot B - A \cdot C - B \cdot C\right) \quad : 2$$

Table 5: the future sand nourishment costs: parameters triangle distribution function

The future	Parameter A – most optimistic cost estimation	Parameter B– most realistic cost estimation	Parameter C – most pessimistic cost estimation	Average μ_K	Standard deviation σ
Constant costs	1106	5628	10150	5628	1846
Variable costs	1327	1508	1688	1508	74