Kustlijnzorg Project

Statistical modelling of the impact of nourishments on the beach and dune systems

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Abstract

A stochastic model has been developed, based on the historical trend analysis of long-term yearly-recorded Jarkus-data, in order to describe the long-term dynamics of Coastal State Indicators (e.g. MCL position). The model includes mathematical representations of the most relevant phenomena: long-term trend, influence of nearshore bar dynamics and impact of nourishments.

The stochastic model appears to be a useful tool to describe mathematically the impact of nourishments on the long-term trend of Coastal State Indicators, highlighting either a regressive (in time) behaviour of the transfer function representing the impact, that is consistent with the sawtooth concept, or a retentional or progressive (in time) behaviour of the transfer function (blocking mechanism in combination with longshore transport).

The description of the actual state of the system, or so-called Testing Coastline (TCL), would be performed with more insight on the structural developments, using the stochastic model. Moreover, its application would lead to an indication for the (expected) coastal state in the years T to T+10.

Finally, after defining the model parameters for a specific site, the model could be used as a predictive tool, to study the impact of nourishment design alternatives, and therefore support the optimal design of nourishments.

References

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Contents

1 Introduction

1.1 Context

The Dutch coastline along the SE part of the North Sea is about 350 km long. Commonly the Dutch coast is divided into three regions, *viz.* (1) the Delta coast in the south, (2) the Holland coast in the centre and (3) the Wadden coast in the north. The morphology of the Delta coast is dominated by tides. The morphology of the Holland coast between Hoek van Holland and Den Helder is typically a storm-dominated sandy coast. The Wadden coast is characterised by the presence of barrier islands and from a morphological viewpoint somehow comparable to the Delta coast. Some 15% of the coast consists of sea dykes and other man made sea barriers, 10% consists of beach flats along the tips of the northern Wadden islands and 75% consists of dune areas of varying widths, ranging from less than 100 meters to several kilometres. The primary function of the coast is to protect the low-lying hinterland from flooding. The sandy coast, however, represents important value to other functions as well: *e.g.* ecological value, drinking water supply, recreation, residential and industrial functions. Coastal erosion, dominant along half of the Dutch coast, is endangering these functions.

In order to stop any further structural recession of the coastline the Dutch government initiated the development of a new coastal policy, at the end of the 80's, the so-called "Dynamic Preservation of the Coastline" (Min V&W, 1990). The strategic objective was to guarantee a sustainable safety level and sustainable preservation of values and functions in the dune area. The specification of a set of operational aspects promoted an easy implementation. First of all the specification of a clear operational objective: the coastline will be maintained at its position in the year 1990.

An illustration of the elements involved in the decision mechanism of the "Dynamic Preservation" in order to achieve the strategic- and operational objectives is given in the following sections with reference to TAW (1995). The quantitative evaluation of their effectiveness is mainly based on the work by Roelse (2002).

Quantitative State Concept: the Momentary Coastline

The first element of the decision mechanism for coastline management is an objective assessment of the state of the system. For this purpose the concept of the Momentary Coastline (MCL) has been developed, defining the coastline position as a function of the volume of sand in the near shore zone. The calculation of the MCL (Figure 1.1) in any given cross-shore profile, is based on the area (or volume per unit length) of sand between two horizontal planes (Min V&W, 1991). The upper and lower boundaries are each located at a distance 'H' from the Mean Low Water Level (MLWL), where 'H' denotes the vertical difference between the dune foot and the mean low water level.

The actual calculation of the MCL is based on data from the Dutch yearly coastal monitoring program (JARKUS), which has been operational since 1963. JARKUS measures coastal depth profiles from the first dunes up to 1 km in a seaward direction, at alongshore intervals of 250 m.

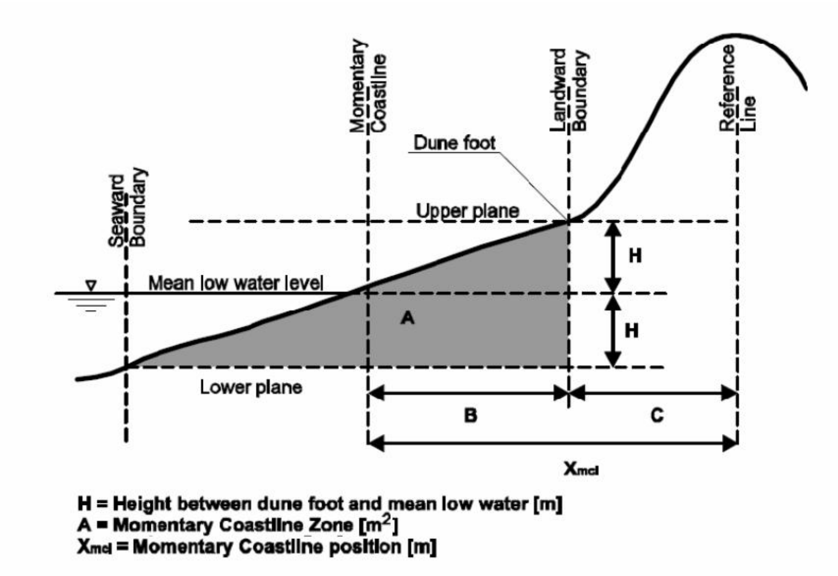

Figure 1.1 Calculation of the Momentary Coastline, MCL; source: Min V&W (1991).

Benchmarking Procedure

Next, a benchmarking procedure was developed, aimed at an objective assessment of erosion problems of a structural nature. For this purpose a predefined reference state needs to be described and compared with the observed (or predicted) system state. Basic building block of these state descriptions is the quantitative state concept: MCL.

The Basal Coastline

The operational objective to maintain the coastline at its 1990 position implies a reference state related to the 1990 coastline. As such the Basal Coastline (BCL) has been defined as the estimated position of the coastline on January 1st of 1990. The BCL position is derived from an extrapolation of the linear trend in positions of the 10 MCL-points during the years 1980 to 1989 (Figure 1.2). The choice for a 10 year linear trend extrapolation was inspired by the objective to counter structural, rather than incidental erosion.

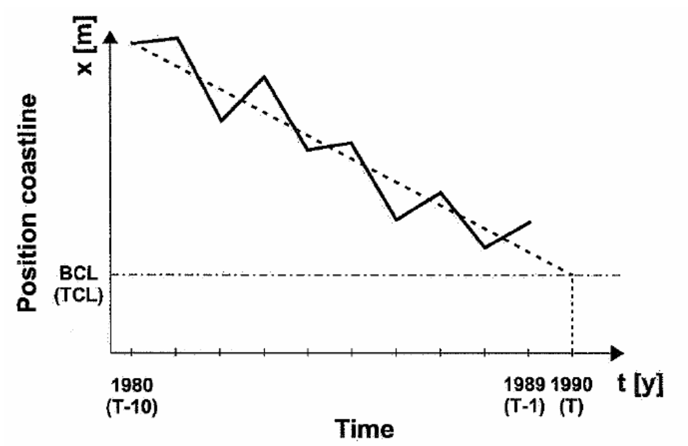

Figure 1.2 Procedure to define the Basal Coastline, BCL, and the Testing Coastline, TCL; source : van Koningsveld and Mulder (2004)

The Testing Coastline

Similarly, accounting for structural erosion, the description of the actual state of the system is based on a so-called Testing Coastline (TCL). The position of the TCL is determined, in a similar way as the BCL, by linearly extrapolating the trend of coastline positions (MCL) often previous years. Thus the position of the TCL in the year T can be determined by linearly extrapolating on the calculated MCL positions in the years (T-10) until (T-1) (Figure 1.2).

The state of the system can now be compared with the reference state, by comparing the TCL position with the BCL position. This comparison provides an indication for the (expected) coastal state in the year T. A TCL that moves landward of the BCL represents a signal to the responsible coastal authority to consider intervention.

Intervention Procedure: Sand Nourishment

The name "Dynamic Preservation", refers to the preferred approach to achieve the policy objectives. Dynamic Preservation implies the goal to make optimal use of natural processes. Consequently, the principal intervention procedure is sand nourishment.

Evaluation of the “Dynamic Preservation”

Since 1990, several evaluations, of single nourishment events (Roelse and Hillen, 1993) and the coastline policy as a whole (cf. Roelse, 1996, 2002; De Ruig, 1998), have been presented.

Considering the operational objective to preserve the coastline at its 1990 position, a quantitative evaluation leads to a clear conclusion: the "Dynamic Preservation" has been successful over the period of 1991-2000. With a yearly average of 6 Mm3 of sand nourishments over the last decade, Roelse (2002) states that there is no more coastal retreat and the number of transects exceeding the BCL is decreasing yearly.

With respect to the strategic objectives, viz. to guarantee a sustainable safety level and sustainable preservation of values and functions in the dune area, the lacking of explicit guidelines for benchmarking of effectiveness hampers an objective evaluation. However, evaluations of developments in safety levels and in values and functions of the dune area show positive indications (Roelse, 2002). To a lesser extent, the same accounts for sustainability.

Lescinski *et al.* (2008) provided a generic view of nourishment effectiveness, using a broad spectrum of analysis methods: long term, short term, individual and bulk. On the long term, the dynamic preservation policy appears effective not only at maintaining, but as well as increasing the beach volume along the Holland coast. Thus, the initial positive volume response in a sawtooth design can be observed. Moreover, in some cases, the erosional tail component to the sawtooth design was undetected.

To improve the effectiveness of nourishments, Lescinski *et al.* (2008) suggested that nourishments should be designed independently and not default to generic design assumptions. Such designs require at the desired locations an improvement of the system knowledge, in combination with a modelling procedure.

1.2 Objectives

The primary objective of this study is ***to improve the coastal system knowledge*** when nourishment procedures are applied, by describing the links between the beach system and the dune system. In particular, Lescinski *et al.* (2008) noted that a significant portion of sediment migrates to the dune line due to (1) landward feed of beach nourishments and (2) shoreward feed of sediment from reef-like behaviour of a shoreface nourishment. The impact of nourishments has therefore to be assessed by evaluating the respective behaviours of the beach and dune systems. Such an assessment would lead to ***a better understanding of the Aeolian transport patterns*** occurring when the coast is nourished.

Subsequently, by improving the system knowledge, the description of the actual state of the system, or so-called Testing Coastline (TCL), would be performed with more insight on the structural developments. This description leads to our second objective consisting on ***the development of a statistical model***, based on the historical trend analysis of long-term yearly-recorded Jarkus-data, to describe the long-term dynamics of Coastal State Indicators, and including a mathematical representation of the impact of nourishments. Moreover, such a model could be used as ***a predictive tool***, to study different nourishment design alternatives, and therefore support the optimal design of nourishments. Thus, design procedures could be adapted independently at the studied locations, and not based on former generic design assumptions.

Considering 43 years records of Jarkus data, a statistical model is proposed to describe the long-term behaviour of the Momentary Coastline (MCL), including mathematical representations of (1) the influence of nearshore bars, and of (2) the impact of nourishments. Paragraph 2 will present the methodology, including the description of the statistical model formulation, of the Coastal State Indicators used for the study, and of the selected sites. Paragraph 3 will discuss the results obtained for different types of sites (i.e. non-influenced by nourishments, weakly influenced and strongly influenced). Emphasize will be put on the evaluation of the impact of nourishments on both the beach and dune systems. Therefore the respective behaviours of the beach and dune systems will be linked.

The project has been followed by C. Brière and H.P.F. van den Boogaard. The review has been performed by B. Arens from Arens - Bureau Duinonderzoek.

2 Methodology

2.1 Statistical modelling

This paragraph presents a brief summary of the methodology that has been applied for the modelling of observed time series data of a coastal state indicator (CSI). Apart from the actual modelling and the identification of these models from observed data, it is outlined how uncertainties in the model parameters and model predictions can be derived. In more detail these issues are described in Appendix 6A, including the physical considerations and mathematical procedures that are involved.

Modelling of the CSI

The starting point in the approach is that the temporal evolution of CSI at a particular spatial position is described by a parameterised time series model of the form:

$$Z_t = \Phi\left(t|\vec{\Theta}\right) + V_t \tag{2.1}$$

For the meaning of the symbols in this equation, the following must be mentioned.

- The Z_t denotes the CSI as function of a (continuous) time *t*.
- The $\Phi\left(\cdot|\vec{\Theta}\right)$ is also a function of time and represents (a parameterised model for) the deterministic long(er) term temporal variations in the CSI.
- The $\vec{\Theta}$ are one or more uncertain parameters in the description of these “systematic” temporal variations. Estimates of these parameters must be obtained on the basis of measurements of the CSI.
- The V_t is a random noise that accounts for errors in the modelling of a CSI, and/or the errors in observations of the CSI. The V_t are particularly introduced to deal with the shorter term, non-systematic, and non-deterministic fluctuations.

As a result of all this, Equation 2.1 represents a *stochastic* time series model for the CSI.

An important issue in the modelling is that an accurate formulation of the model deterministic component $\Phi\left(\cdot|\vec{\Theta}\right)$ is derived. Preferably this formulation is based upon physical (system and process) knowledge, and/or is based on observed patterns in measured time series of a CSI. Such temporal patterns may represent important sub-processes of different time scales. Separate models can or must then be derived for the sub-processes and/or time scales. For the full model $\Phi\left(\cdot|\vec{\Theta}\right)$ this may lead to a superposition according to:

$$\Phi\left(\cdot|\vec{\Theta}\right) = \Phi_1\left(\cdot|\vec{\Theta}_1\right) + \Phi_2\left(\cdot|\vec{\Theta}_2\right) + \Phi_3\left(\cdot|\vec{\Theta}_3\right) + \cdots\cdots + \Phi_N\left(\cdot|\vec{\Theta}_N\right) \tag{2.2}$$

Both from a physical viewpoint, and from visual inspection of the presently available observed CSI time series, and from knowledge about human interferences in the coastal zone it was readily concluded that in the present case at least three sub-processes/sub-models must be taken into account:

- *Long term trends* in the CSI with gradual variations that extend over at least over one or more decades of years.
- *Cyclic or quasi-periodic variations* with periods in the range of 7 to 15 years.
- Effects of (beach, shore face, dune) *nourishments*. In time these nourishments have much the character of "irregular events". In fact, both the start, the duration, and the volumes of the several individual nourishments are mutually quite different. Depending on the scenario, nourishment can have an immediate effect on a CSI, or induce a gradually evolving change. The nourishment induces after-effects on a CSI that may extend over a few to many years.

For mathematical formulations of the sub-models $\Phi_n\left(\cdot\,|\vec{\Theta}_n\right)$ (and the involved uncertain parameters $\vec{\Theta}_n$) one is referred to Appendix 6A.

A model must be formulated for the random fluctuations V_t as well. In the present case this V_t is assumed to be a zero-mean Gaussian noise. In statistical sense such a random process is fully determined by its auto-covariance function $\Gamma_{s,t}$ defined by $\Gamma_{s,t} := \mathrm{E}\left[V_s \cdot V_t\right]$. From preliminary data analyses and modelling experiments it was concluded that in the present case it may well be assumed that V_t is a *white*, and *stationary* noise leading to $\Gamma_{s,t} = \sigma^2$ for $s = t$, and $\Gamma_{s,t} = 0$ for $s \neq t$. A priori the spread σ (or variance σ^2) of the noise V_t is usually not known. Together and simultaneously with the deterministic model parameters $\vec{\Theta}$, the spread σ must then be estimated from observed CSI-data.

Calibration of the CSI models

Estimates of the parameters ($\vec{\Theta}$ and σ) can be obtained through a calibration of the CSI-model. In this calibration the values of the parameters must be found for which the model fits best to an observed CSI time series $\left\{\hat{Z}_{t_k}\right\}_{k=1}^{K}$. The observation times t_k can be arbitrary distributed in time and need not to be on a regular temporal grid. It merely holds that the amount (i.e. quality and quantity) of data is large enough to obtain well defined estimates for the parameters.

Dealing with a stochastic model implies that a statistically consistent and well defined calibration procedure must be applied. Here a so called Maximum Likelihood approach is followed. This leads to a procedure where a function of the parameters, the so called minus log-likelihood function, must be minimised. This log-likelihood function is closely related to a least squares criterion. Due to non-linearities in the modelling, numerical techniques had to be used for the actual minimisation of the log-likelihood function. The result of the calibration is an optimal estimates $\hat{\Theta}$ and $\hat{\sigma}$ for the uncertain model parameters.

Uncertainties in the parameters and model-predictions

The stochastic formulation of the models, and the Maximum LikeliHood (MLH) based calibration procedure, has as an important advantage that also *uncertainties* in the (estimates $\hat{\Theta}$ and $\hat{\sigma}$ for the) parameters can be derived in a fully quantitative form. In standard MLH procedures it is assumed that the estimates $\hat{\Theta}$ and $\hat{\sigma}$ satisfy a Gaussian distribution, and from the log-likelihood function the spread in the $\hat{\Theta}$ and $\hat{\sigma}$ can be computed. From these spreads, and still assuming a Gaussian distribution, confidence intervals (e.g. 95%) can be constructed. These (symmetric) confidence intervals can be used for assessing the accuracy and (statistical) significance of the estimates for the parameters.

Theoretically the assumption of a Gaussian distribution of the parameters holds only in the asymptotic case that the amount of observed data is virtually infinite. In practice, and particularly in the present applications, data sets are limited, and Gaussian approximations of the distribution of the parameters can be less accurate or satisfactory.

In such cases so called *resampling techniques* provide an elegant and important alternative means for uncertainty assessment. When resampling, a large number of replicates is created from the original data set. In a replicate, an individual data point of the original set may be absent, or be present with a multiplicity larger/equal than one. For each replicate of the original data set the MLH-based calibration procedure is carried out. In the end this leads to an *ensemble* of parameter estimates. As a matter of the procedure this ensemble provides an *empirical probability distribution* of the parameters. From this distribution virtually any statistical and/or uncertainty measure can be computed, as for example the mean, spread, quantiles, and (skew) confidence intervals of arbitrary significance level (e.g. 95%).

The parameters identified for each replicate of the data set formally represent a candidate calibrated model. In this way also an ensemble of models is obtained, and for each input an ensemble of predictions can be derived as well. In its turn this ensemble represents a probability distribution of the model response to an input. On this basis uncertainties in model predictions can be computed as well. These uncertainties can again be represented in the form of a spread, or skew confidence intervals.

Confidence and prediction intervals

The confidence intervals described above provide a measure for the uncertainty in the estimate for the deterministic component $\Phi\left(\cdot\,|\vec{\Theta}\right)$ in the model. The uncertainty in the model will decrease when (in quantitative and qualitative sense) the amount of observed data increases. In the (theoretical) limit of an infinitely large data set a perfect estimate of $\Phi\left(\cdot\,|\vec{\Theta}\right)$ would be obtained. It most be noted, however, that even in that case new observations can not be predicted with negligible uncertainty. In fact, observations can still be affected by all kind of (observation) errors.

In the present stochastic model of Equation 2.1, these remaining errors are represented by the random noise V_t. According to this model, the uncertainty in a prediction Z_t of a new observation is then a superposition of the uncertainty in the deterministic

component, $\Phi\left(\cdot\,|\vec{\Theta}\right)$, and an uncertainty due to the random noise V_t. The noise V_t can never be predicted in strict sense, and after calibration merely its statistical properties are available, as for example its spread σ. By a proper combination of this spread and the identified uncertainty in $\Phi\left(\cdot\,|\vec{\Theta}\right)$, it is then possible, however, to compute so called *prediction* intervals for new observations Z_t. For a given significance level, 95%, the prediction interval specifies the range where a new observation can be expected with probability 0.95. In this way the prediction interval provides a measure for the accuracy with which a new observation can be predicted. As a matter of its definition such a prediction interval is always larger than the confidence interval that reflects the uncertainty in merely the deterministic model.
A main advantage of prediction over confidence intervals is that the former can directly be used to validate (in a statistically sound way) whether or not future measurements fit to the model, and thus verify the predictive skills of the model.

2.2 Dataset

The bathymetry of the Holland coast (Figure 2.1) is monitored on an annual basis and contained in the JARKUS data base of the Dutch Department of Public Works. The monitoring of this area started in 1963 in the southern part (km 99-km 118). From 1964 on, also the other part of the Holland coast (km 0-km 99) was included in the monitoring program.

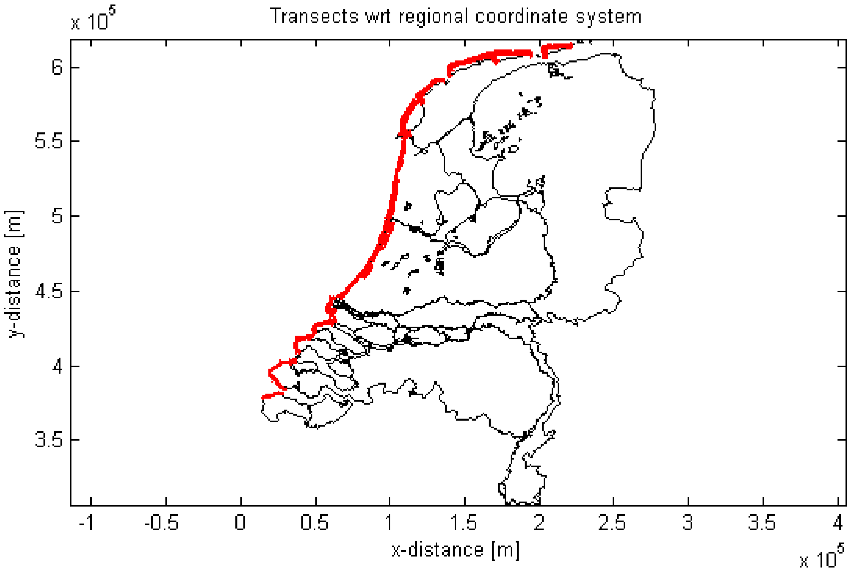

Figure 2.1 Location of Jarkus transects along the Dutch coast

The coastal profiles are measured from the fore dune to approximately 1 km seaward every 250 m alongshore. In areas with groins the alongshore spacing of profile sections ranges between 110 m and 310 m, because profiles are surveyed at locations in between the groins. The alongshore position of cross-shore survey lines is marked by a permanent base line of beach poles (RSP system). The cross-shore distance between consecutive depth measurements ranges from 10 m near the shoreline to 20 m offshore. The sub-aerial part of the profile data (down to the low water line) was initially gathered by levelling, but since 1977 photogrammetric methods and laseraltimetry are used. The sub-aqueous part of the data (up to the low water line at least) is gathered by sounding.

Profiles are usually surveyed between early April and late September. This implies that the time interval between two successive profile soundings at a particular location may vary between 0.5 and 1.5 year. Furthermore, it implies that the profile sampling has a seasonal bias. Little is known about seasonal changes in surf zone bathymetry along the Holland coast. Generally, spring and summer (April-September) are less stormy seasons than autumn and winter (Kroon, 1994). Nevertheless, Kroon (1994) observed hardly any seasonal differences in the mean profile shape and the width and height of the sweep zone, determined over a 17-year period near km 40. Furthermore, profiles surveyed during a more than average stormy spring may have characteristics of profiles during a less than average stormy winter. Therefore, it is expected that the biased sampling does not cause a strong bias in the shapes of the profiles. Moreover, the analysis of the profiles aims at describing morphological developments that exceed the level of seasonal changes. So, even with some seasonal bias present, long-term trends should become visible anyhow.

2.3 Definition of Coastal State Indicators

The objective of the data analysis is to aggregate the bathymetric data relevant for the description of the morphological features that change in time and space. In addition, these data should be compressed into only a few variables. This constraint is actually imposed to get an overview over the huge amount of data available along the cross-shore direction. The most compact way to summarise the above mentioned type of information is therefore in terms of sediment budgets and volumes. Moreover, a main characteristic of a nearshore profile is considered to be its “cross-shore position”. This information deals with the accretive or retreating nature of a coast. For example, along an accretive part of a coast the nearshore profile shifts seaward. Therefore, profile behaviour can be expressed in terms of change in cross-shore position of the profile. For that reason, the monitoring has been designed to give information about the indicators which can describe the state of the coast, based upon volume and position characteristics.

Beach system

The MCL -or Momentary CoastLine- represents the momentary horizontal position of the coastline, determined from the (so-called MCL) volume in a cross-shore profile between the dune foot (arbitrary positioned at NAP +3 m) at an elevation *H* above mean low water (mlw) and the depth contour at an equal depth *H* below mlw. The MCL volume and position are computed every year on the basis of annual surveys of bathymetry (named JARKUS for “JAaRlijkse KUStmetingen” or “Annual Coastal Surveys”) along cross-shore profiles with 250 m alongshore spacing. These two CSI give insight on the behaviour of the entire beach.

Upper part of the beach

A set of four Coastal State Indicators can been chosen to describe the upper part of the beach. The dune foot position and the shoreline position depend on the location of the NAP + 3 m- and NAP + 0 m- z-levels, respectively. The beach width is computed as the width between the dune foot position and the shoreline position, and is therefore correlated to these two CSI. Finally, the beach volume is defined as the amount of sand (per linear m) included between the NAP + 3 m- and NAP + 0 m- levels with the dune foot position and the shoreline position as landward and seaward boundaries, respectively.

Dune system

Volumes in the dunes are computed considering the boundary between the beach and the fore dunes at NAP + 3 m (dune foot position).

Aggregation of the information

Previous studies (e.g. Knoester, 1990) have shown that over alongshore distances the steepness of the nearshore profile varies, as well as the bar topography. Further, it has been shown that alongshore differences in trends in shoreline position exist. For a selected site (typically a coastal stretch of about 1 to 3 kms), large differences between cross-shore transects can be found. These differences are in particular due to coastal sand waves present along the coast, cusp, and bars or rip channels, etc …

Spatial aggregation by averaging the Coastal State Indicators values along the longshore direction has been therefore performed, as data aggregation enables to express the available information in a summary form. By filtering the short-spatial scale effects, the advantage of this procedure is moreover that predictability limits of statistical analysis can be overcome, as compression of information minimizes the noise in a time series.

Selection of Coastal State Indicators

In this study, only the representation of the long-term behaviours of the MCL positions and volumes and of the dune volumes will be performed, in order to describe the links between the beach and the dune systems.

2.4 Selection of sites

The Holland coast is an inlet-free, sandy, micro-tidal, wave-dominated coast of about 120 km length. This coastal stretch is bounded to the north by a tidal inlet (the Marsdiep) and to the south by 3 km long harbour moles of Rotterdam Harbour (Figure 2.2). The alongshore location of features, such as profile shape or grain size, will be given by the distance in kilometres from Den Helder, a town in the north of the area.

The mean wave height (H_{m0}) is about 1.2 m and the mean wave period (T_{m01}) is about 5 s (Roskam, 1988). Waves approach the coast mainly from southwesterly and north-northwesterly directions (Rijkswaterstaat, 1994). Analysis of the energy in the low-frequency part of the wave spectrum (0.03-0.10 Hz) indicates that about 5 to 10% of the time swell is present (Roskam, 1988). Alongshore differences in wave climate are small. In the north waves tend to be somewhat higher than in the south (about 0.2 m) (Roskam, 1988). The knowledge on alongshore differences in swell is rather limited. In the north the amount of swell related wave energy is larger than in the south (Stolk, 1989).

The mean tidal range is about 1.6 m. The alongshore variation in tidal range is small, ranging from 1.7 m near Scheveningen, through 1.55 m near Petten, to 1.4 m near Den Helder. Peak tidal current velocities generally do not exceed 1 m/s (Wiersma and Van Alphen, 1988). Density gradients occur due to discharge of fresh water from the River Rhine at the southern boundary of the study area. These gradients generate a cross-shore circulation with onshore directed bottom currents and offshore directed surface currents. The strength and frequency of occurrence of this circulation vary alongshore depending on the distance to the river mouth, the outflow regime of the River Rhine and the wind climate (Van Alphen *et al*., 1988).

Figure 2.2 Location of the studied sites

The slope of the shoreface varies gradually alongshore, with the flattest slopes of about 1:400 in the north and south. Towards the central part the shoreface slope steepens to about 1:160. However, near IJmuiden, the slope flattens to about 1:250 (Stolk, 1989). In the central part shoreface connected ridges occur. Slopes in the breaker zone vary from about 1:50 to 1:150. Nearshore bars are present along the larger part of the coast. The number of bars varies from 1 to 4.

The grain size of the sediment in the breaker zone is generally in the fine sand range. South of km 30, the grain size is in the 125-250 μm class, while northward the sediment tends to be somewhat coarser coming into the 250-500 μm class (Stolk, 1989). The sediment tends to fine seaward across the surf zone (Van Alphen, 1987).

Shoreline position studies reveal that the central part of this coast (km 38 to km 95) has been slightly accreting over the last 140 years, while the other parts have been eroding. The rate of shoreline progradation for the central part is estimated at 0.2 m/year. The rates of shoreline retreat for the southern and northern part are estimated at 0.3 m/year and 0.9 m/year respectively (Stolk, 1989). Sediment budget studies based on bathymetric data over the two decades reveal a similar pattern of erosion and accretion. The accretion rate for the central part is estimated at 0.45 million m^3/year and the erosion rates for the southern and northern part are estimated at 0.25 million m"/year and 0.20 million m^3/year, respectively (De Ruig and Louisse, 1991).

Human intervention in the development of this coast nearly dates back to the middle ages. The first seawall near Petten (km 20-26) was already built in the 16th century. The seawall had to be relocated more landward several times because of ongoing erosion north and south of the seawall (Stolk, 1989). Nowadays, the seawall is again a structure that protrudes into the sea. Groins were built along the eroding southern and northern parts of the coast from the late 18th century up to the early 20th century. Only the groins built in front of the Petten seawall were connected to a hard structure (Verhagen and Van Rossum, 1989). In the second half of the 19th century, harbour moles were constructed near Hoek van Holland (km 119), Scheveningen (km 102) and IJmuiden (km 55.5). These harbour moles were extended seaward in the late sixties and early seventies of the present century (Verhagen, 1989). Finally, in the last few decades beach and shoreface nourishments have been applied on several locations.

For this study, 6 sites have been selected (Figure 2.2), according to the following criteria:

- No nourishments have been applied:
  - Egmond-aan-Zee Coast3D (km 43-46)
  - Heemskerk (km 48.75-49.65)

- Only a few nourishments have been applied
  - Castricum-aan-Zee (km 46.50-48.50)
  - Noordwijk-aan-Zee (km 80.50-83.50)

- The coast has been intensively nourished
  - Zijpe (km 13.25-14.25)
  - Bergen-aan-Zee (km 32.25-34.25)

Moreover, the Egmond-aan-Zee Coast3D and Heemskerk sites have been selected assuming that the lee-influence of adjacent nourishments is weak. Finally, the choice avoided the selection of a site subject to the influence of the Marsdiep. The characteristics of the nourishments applied on the selected sites are summarized in Table 2.1.

Table 2.1 Characteristics of nourishments for the selected sites

Selected site	Starting date	Ending date	Starting RSP	Ending RSP	Amount per m (m^3)	type of nourishment
Castricum a. Zee	05/05	06/05	46.5	48.5	250	beach
Noordwijk a. Zee	01/98	04/98	80.5	83.5	422	shoreface
Noordwijk a. Zee	01/06	12/06	81.5	89	100	shoreface
Zijpe	09/76	09/76	12.975	13.75	441	dune
Zijpe	08/86	10/86	10.825	13.725	428	beach
Zijpe	04/87	09/87	13.755	18.1	390	beach
Zijpe	05/91	06/91	11	14	179	beach
Zijpe	05/96	06/96	12.2	14.1	241	beach
Zijpe	05/99	06/99	10	14	36	beach
Zijpe	06/01	10/01	11.08	14.01	512	shoreface
Zijpe	02/03	05/03	10	16	429	shoreface
Zijpe	06/03	07/03	11.1	13.75	165	beach
Zijpe	06/04	07/04	11.1	13.74	82	beach
Zijpe	01/06	12/06	10	17	229	shoreface
Bergen a. Zee	05/90	06/90	32.25	33.75	257	beach
Bergen a. Zee	05/90	06/90	32.25	33.75	40	stoss-side of dune
Bergen a. Zee	05/92	11/92	26.2	38.5	120	beach
Bergen a. Zee	06/94	06/94	32.9	33.5	168	beach
Bergen a. Zee	05/95	05/95	32.625	33.625	306	beach
Bergen a. Zee	06/98	06/98	31.05	33.5	144	beach
Bergen a. Zee	04/99	05/99	32.5	33.75	165	beach
Bergen a. Zee	04/00	08/00	32.25	34.25	497	shoreface
Bergen a. Zee	06/00	06/00	32.75	33.25	449	beach
Bergen a. Zee	08/05	09/05	31.5	36.2	319	shoreface
Bergen a. Zee	04/05	04/05	32.5	33.75	240	beach

3 Impact of nourishments

In the following sections, Coastal State Indicators are analysed in their aggregated form (see paragraph 2.3). The long-term behaviours of the Coastal State Indicators related to the Momentary Coastline area (i.e. MCL positions) and to the dune system (i.e. dune volumes) are successively investigated. To that end, different regression models are proposed for each Coastal State Indicators, and confidence and prediction intervals are evaluated. For each coastal stretch considered, model results enable to characterize/quantify:

- the morphological tendency (eroding/accretive)
- the coastal behaviour related to the dynamics of multiple bar systems
- the impact of nourishments (magnitude, delay of response, lifetime)
- the importance of the coastal variability – controlled by hydrodynamic forcing – (deterministic vs. stochastic)
- the links between the beach and dune system dynamics

3.1 Natural sites

Moderate rates of structural erosion or accretion only become apparent on larger time and space scales, because of the dominance of shorter scale oscillations caused by natural processes. In this chapter, our interest is typically into the scales intermediate to the short- term, event related, behaviour and the very long- term, structural trend of erosion or accretion associated with gradients in cross-shore and longshore directions over a coastal stretch.

These intermediate scales concern the temporal behaviour on decadal scales, leading to beachface amplitude oscillations of magnitudes comparable to those of the structural trend. The JARKUS data-set, comprising more than forty years of field observations of the duneface, beach and nearshore profile along the central Netherlands coast, has revealed typical properties of subaqueous bar morphodynamics on a decadal scale. Amongst the analyses is that of Wijnberg and Terwindt (1995) pointing towards the existence of four distinct morphodynamic regimes, each characterized by their own particular bar dynamics. A key aspect of the analysis is therefore to reproduce properly the effect of the costal bars migration on the behaviours of CSIs.

Egmond-aan-Zee Coast3D (km 43-46)

Egmond-aanZee Coast3D beach is located in the central part of the Noord Holland coast, and belongs to the LSCB-region III following the classification of Wijnberg and Terwindt (1995). In this area, the return period of a certain bar topography is estimated to be about 15 years.

The long- term behaviour of the MCL position is displayed in Figure 3.1 (top panel). The MCL position exhibits a progressive evolution over the last decades, at a rate of 0.12 m/year, to which a cyclic component with a period of the oscillation of 15 years has been added. It has been decided to fix the period of the oscillation, respect to Wijnberg and Terwindt’s evaluation, as the model showed unexpected long period for the cyclic component, when letting the parameter free, probably due to the presence of large values in years 1992 to 1994. When the coastal bar is generating on the shore, a large amount of sand is included in the computation of the MCL volume, resulting in large values every 15 years. It appeared however that the large amount of sand due to the presence of the coastal bar on the shore had a critical influence on the MCL volume, only for the period 1992-1994. Estimation of parameters is summarized in Table 3.1.

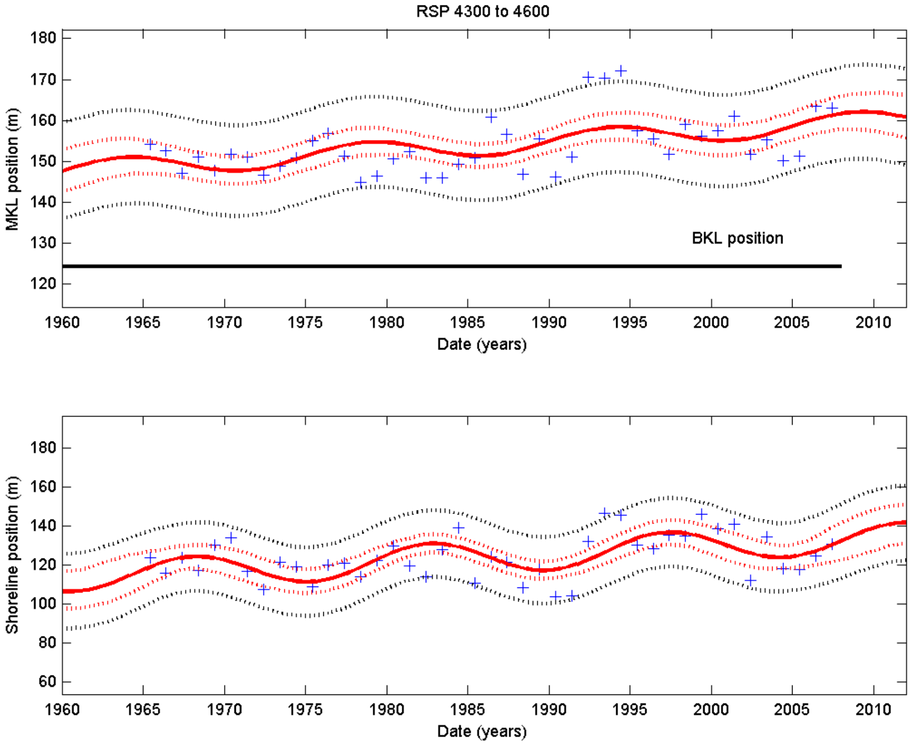

Figure 3.1 Long-term behaviours of CSIs at Egmond-aan-Zee: MCL position (m) is displayed on the top panel, where blue dots represent the observations, whereas, the solid red line, the dashed red lines and the dashed black lines represent the simulated mean trend, the boundaries of the 95% skew confidence interval, and the boundaries of the 95% skew prediction interval respectively. Similarly, long-term behaviour of the shoreline position is displayed on the bottom panel.

Table 3.1 MCL position (m), List of 95.00% confidence intervals for the parameters based on B-resampling of the model residuals.

Nr	Name of the uncertain model parameters	RSP estimate	RSP spread	Lower bound of skew confidence interval	Upper bound
1	alpha0 in Pol. Regres	153.9	0.8573	152.3	155.6
2	alpha1 in Pol. Regres	5.011	1.444	2.098	7.725
3	Period in Harm. Cmp	15.00	0	15.00	15.00
4	A[cos] in Harm. Cmp	1.920	1.224	-0.4364	4.351
5	B[sin] in Harm. Cmp	-1.641	1.235	-4.211	0.7741
6	Sigma_V	5.320	0.6196	4.036	6.519

Stive *et al*. (1996) showed that the evolution of the NAP +1 m z-level exhibits longshore and temporal oscillations. In particular, they noted that the linear trend of the NAP +1 m z-level shows a high longshore variability, but that the average over several kilometres is less than 1 m/year, while the accretional and erosional character is not very different from that over the last few hundred years. Standard deviations relative to the trend also show a high longshore variability, while the average over several kilometres is between 5 and 10 m. If, spatially, alternating accretional and erosional stretches of 2 to 3 km are observed alongshore; temporally, this longshore rhythmicity may be viewed as a “shoreline wave“ propagating towards the south with a propagation velocity of 150 to 200 m/year. Stive *et al.* (1996) evaluated the amplitude of the oscillation of about 20 m and its periodicity of about 15 years. In our case, we have defined the shoreline position arbitrarily at the NAP + 0 m z-level. The statistical model has been applied to the shoreline position datasets, using data collected between 1965 and 2008, and considering 5 free parameters (including the period and the amplitude of the oscillation). The long-term behaviour of the shoreline position is displayed on the bottom panel of Figure 3.1. The shoreline position exhibits a progressive evolution over the last decades, at a rate of 0.19 m/year. Confirming the analysis of Stive *et al.* (1996), an oscillation is found with amplitude of about 20 m and a periodicity of 14.7 years. In this case, the estimation for the lower and upper boundaries of the 95% skew confidence interval of the period of the oscillation (respectively 13.4 year and 16.7 year) shows the reliability of the estimation of uncertain model parameters.

The long-term trends of the dune foot position and of the dune volume have been obtained similarly (Figure 3.2). For both the dune foot position and the dune volume, long-term trends show progressive evolutions over the last decades, at rates of 0.1 m/year and of 2.6 m^3/m/year, for the dune foot position and for the dune volume, respectively. Cyclic components are found by the model, with periods of the oscillations consistent with previous results, i.e. of 16.2 years and 15.4 years, for the dune foot position and for the dune volume, respectively. The cyclic component found in the long-term behaviour of the dune volume is in good agreement (in a temporal point of view) with the one obtained for the dune foot position, as a landward shift of the dune foot position will necessarily induces a decrease of the dune volume.

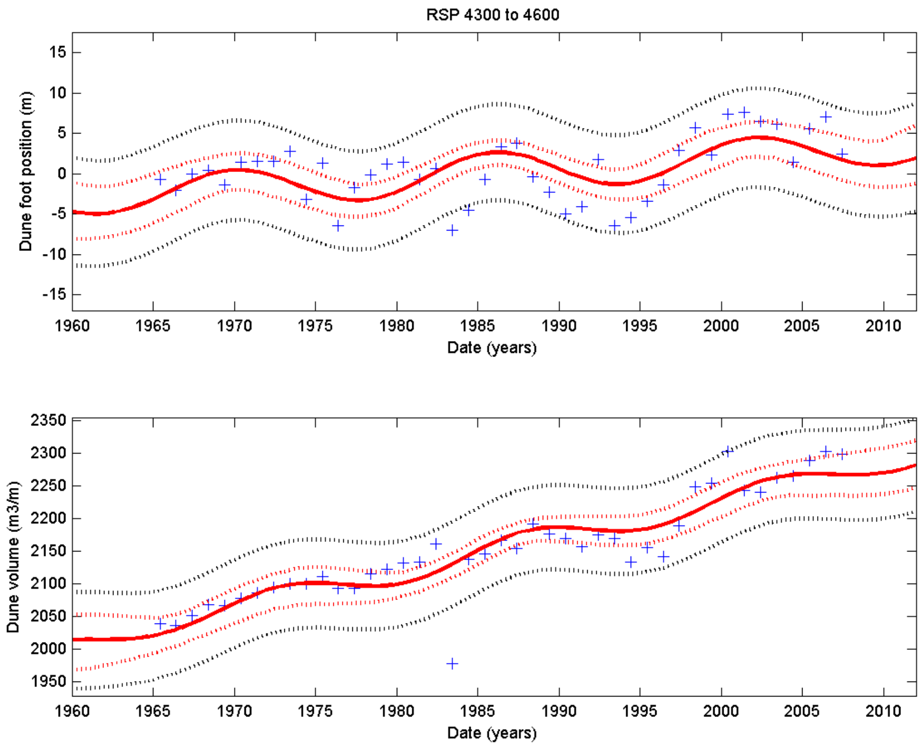

Figure 3.2 *Long-term behaviours of CSIs at Egmond-aan-Zee: Dune foot position (m) is displayed on the top panel, where blue dots represent the observations, whereas, the solid red line, the dashed red lines and the dashed black lines represent the simulated mean trend, the boundaries of the 95% skew confidence interval, and the boundaries of the 95% skew prediction interval respectively. The long-term behaviour of the dune volume is displayed on the bottom panel.*

Most interestingly is that the dune foot location tends to follow the shoreline position with a phase difference of about 3 to 4 years, and with less variations (Figure 3.1 bottom panel, and Figure 3.2 top panel). Assuming that the submerged profile influences the beach in modeling the shoreline shape, the dune foot will adapt its position to ensure the beach to reach an equilibrium profile (i.e. through the adaptation of its slope and its width). The oscillations in the long-term behaviour of the dune foot position are however less pronounced than for the shoreline position, as the NAP + 3 m z-level is anyhow less dynamic.

Heemskerk (km 48.75-49.65)

Hemskerk is located in the central part of the Noord Holland coast, and belongs to the LSCB-region III following the classification of Wijnberg and Terwindt (1995). In this area, the return period of a certain bar topography is estimated to be about 15 years.

The long- term behaviour of the MCL position is displayed in Figure 3.3 (top panel). The MCL position exhibits a regressive evolution over the last decades, at a rate of – 0.2 m/year. A cyclic component, representing the migratory bar behaviour, has been added, characterized by a calculated period of the oscillation of 12.8 years.

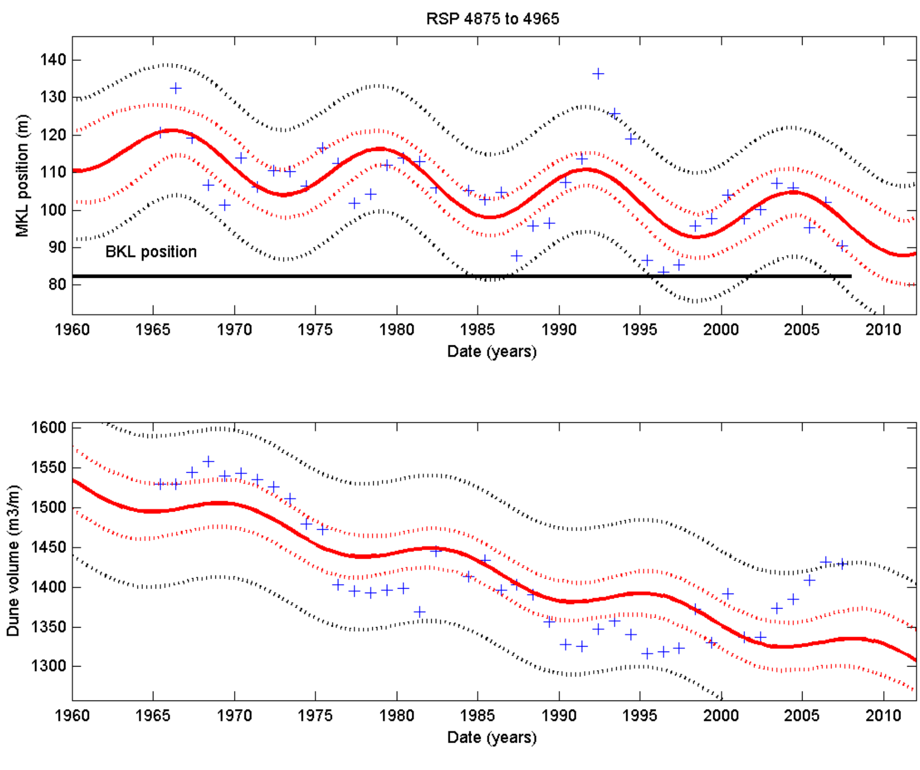

Figure 3.3 Long-term behaviours of CSIs at Egmond-aan-Zee: MCL position (m) is displayed on the top panel, where blue dots represent the observations, whereas, the solid red line, the dashed red lines and the dashed black lines represent the simulated mean trend, the boundaries of the 95% skew confidence interval, and the boundaries of the 95% skew prediction interval respectively. The long-term behaviour of the dune volume is displayed on the bottom panel.

The trend for the long-term evolution of the dune volume is displayed in Figure 3.3, bottom panel. Similarly to the long-term evolution of the MCL position, the long-term trend shows a regressive evolution of the dune volume over the last decades, at a rate of – 2.1 m^3/m/year. However, the model has been forced with a harmonic component, fixing the period of the oscillation at 13 years (to be consistent with the result obtained for the long- term behaviour of the MCL position), as the model showed unexpected value, when letting the parameter free, due to the increase of the dune volume since 2002 (probably related to nourishment procedures that took place in the surrounding, as done in Castricum, and not taken into account in the model).

The dune volume trend tends to follow the MCL position (or volume) with a phase difference of about 3 to 4 years (Figure 3.3). The submerged profile seems to influence the beach in modeling the shoreline shape; the dune foot will then adapt its position to ensure the beach to reach an equilibrium profile. The oscillations in the long-term behaviour of the dune volume tend to follow the oscillations in the long-term behaviour of the MCL position (or volume), with an adaptation time of about 3 to 4 years. However, the relation between the dune cycle and the shoreface/beach cycle needs to be examined in more details.

3.2 Weakly influenced sites

For the modelling of a time series of a CSI linear parameterised regression models are used. A cyclic component, representing the cyclic coastal bar behaviour occurring in a LSCB-region as defined by Wijnberg and Terwindt (1995), is added. The impact of nourishments is taken into account based on linear transfer functions, as described in the Appendix A.

Impact of beach nourishments - Castricum-aan-Zee (km 46.50-48.50)

Castricum-aan-Zee is located in the central part of the Noord Holland coast, and belongs to the LSCB-region III following the classification of Wijnberg and Terwindt (1995). In this area, the return period of a certain bar topography is estimated to be about 15 years.

The long- term behaviour of the MCL position is displayed in Figure 3.4 (top panel). The MCL position exhibits a regressive evolution over the last decades, at a rate of – 0.4 m/year. A cyclic component, representing the migratory bar behaviour, has been added, characterized by a calculated period of the oscillation of 11.3 years. Such parameter estimate is found when fixing the “initial guess” for P_1 to 13 years, whereas the model would calculate a period of the oscillation of 7.8 years if the “initial guess” for P_1 is fix to 10 years. That means that the model can find different minimums when minimizing the Minus Log-Likelihood function, depending on the initial choice of parameters. Such instability occurs as the amount of information (i.e. observation points) necessary for a statistical estimation of model parameters is too low, especially when considering the impact of nourishments (that adds 5 extra parameters per type of nourishments).

The impact of beach nourishment on the MCL position is represented via a transfer function displayed in the Figure 3.4, bottom panel. The maximum impact is found about 1.5 years after the application of the nourishment. The lifetime is estimated of about more than 10 years. Such a result can be hardly evaluated, as the intervention took place only 3 years ago, and no observations of the long-term behaviour of the MCL position, under the influence of nourishments, is available in Castricum-aan-Zee. Therefore, when a site is not or weakly influenced by nourishments, the model can be hardly used as a predictive tool describing the impact of nourishments. Only an expert judgment supporting the choice of representative transfer functions would enable to apply it for a selection of scenarii.

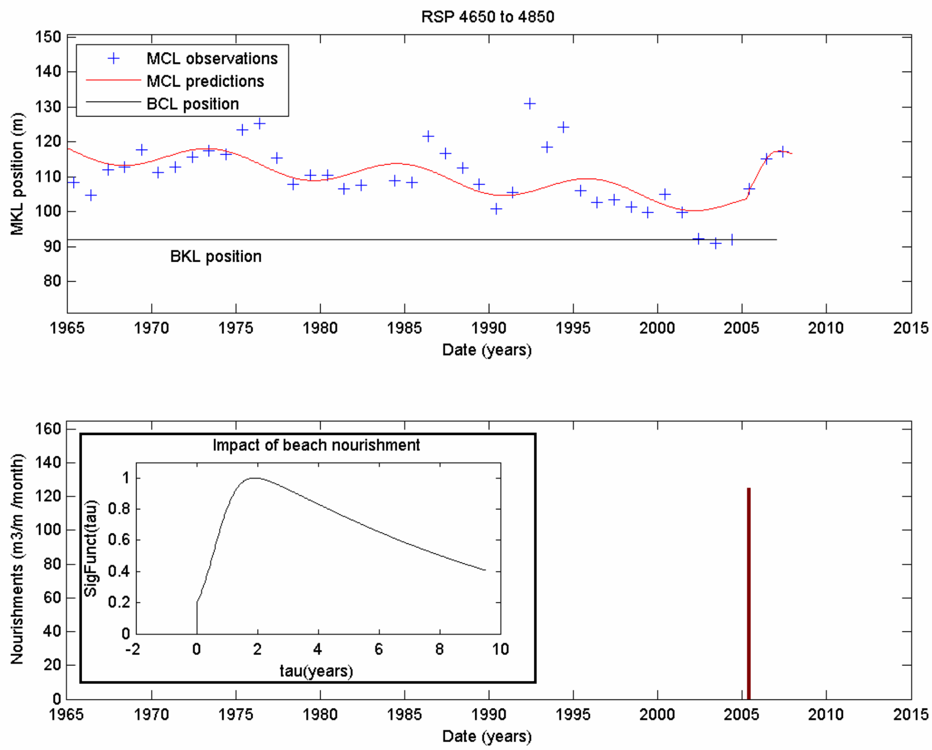

Figure 3.4 *(a) Long-term behaviour of the MCL position. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month) and normalised calculated function representing the impact of beach nourishment on the MCL position*

The trend for the long-term evolution of the dune volume is displayed in Figure 3.5, top panel. Differently to the long-term evolution of the MCL position, the long-term trend shows a progressive evolution of the dune volume over the last decades, at a rate of 0.73 m^3/m/year. When fixing the “initial guess” for the period of a cyclic component to 13 years, parameter estimate is of 13.5 years, which is consistent with the result found when describing the long-term behaviour of the MCL position. The dune volume tends to follow the MCL position (or volume) with a phase difference of about 3 to 4 years (Figure 3.4 and Figure 3.5). Similarly to the cases of Egmond-aan-Zee and of Hemskerk, the submerged profile seems to influence the beach in modeling the shoreline shape and the dune foot position. The oscillations in the long-term behaviour of the dune volume tend therefore to follow the oscillations in the long-term behaviour of the MCL position (or volume), with an adaptation time of about 3 to 4 years. However, the relation between the dune cycle and the shoreface/beach cycle needs to be examined in more details.

The impact of beach nourishment on the dune volume is represented via a transfer function displayed in the Figure 3.5, bottom panel. The maximum impact is found immediately after the application of the nourishment, as the dunes have been nourished themselves (up to NAP + 5 m). The lifetime is estimated to be about 3.5 years. Still, such result can be hardly evaluated, as the intervention took place only 3 years ago, and no observations of the long-term behaviour of the dune volume, under the influence of nourishments, is available in Castricum-aan-Zee. Moreover, the dataset appears quite noisy, leading to a delicate proper parameters estimate. The huge changes in the dune volume might be also related to measurement errors.

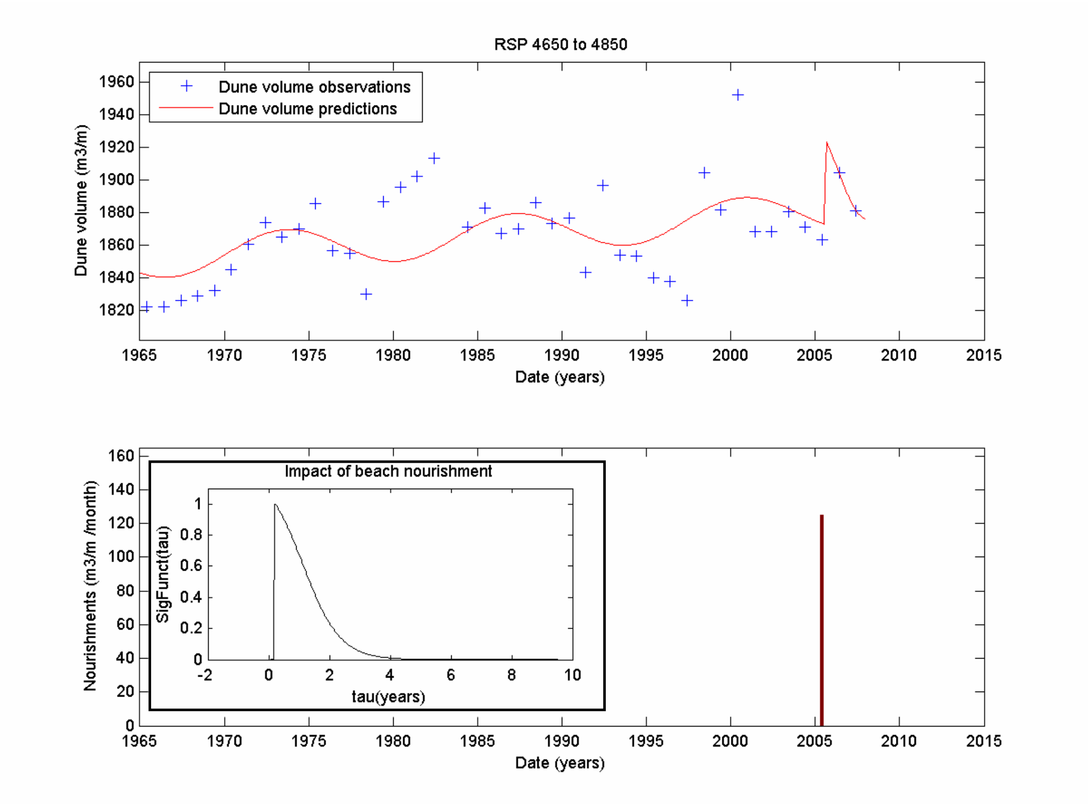

Figure 3.5 *(a) Long-term behaviour of the Dune volume. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month) and normalised calculated function representing the impact of beach nourishment on the dune volume*

Impact of shoreface nourishments - Noordwijk-aan-Zee (km 80.50-83.50)

Noordwijk-aan-Zee is located in the northern part of the Zuid Holland coast, and belongs to the LSCB-region IV following the classification of Wijnberg and Terwindt (1995). In this area, the return period of a certain bar topography is estimated to be about 4 years.

The long- term behaviour of the MCL position is displayed in Figure 3.6 (top panel). The MCL position exhibits a stable evolution over the last decades, at a rate of 0.14 m/year. A cyclic component, representing the migratory bar behaviour, has been added, characterized by a calculated period of the oscillation of 4.8 years (in agreement with the literature, Wijnberg and Terwindt, 1995). Over the coastal stretch defined from Beach Pole RSP 80.50 to Beach Pole RSP 83.50, two shoreface nourishments were applied at Noordwijk. Accretion (in terms of MCL position) is noticed after the application of the nourishment (Figure 3.6). Following Lescinski *et al.* (2008), the observed volume conservation is associated to a lateral diffusion in combination with the net drift, which likely transported sediment north from the 1999 Katwijk nourishment. Besides, north of the area was nourished in late 2002 (not taken into account by the model), effectively blocking the net longshore drift. This blocking mechanism, in combination with the net longshore transport, results in the observed volume conservation. This behaviour is properly represented by the model, as the transfer function representing the impact of a shoreface nourishment on the MCL position (Figure 3.6, bottom panel) exhibits an asymptotic behaviour 1 year after the intervention.

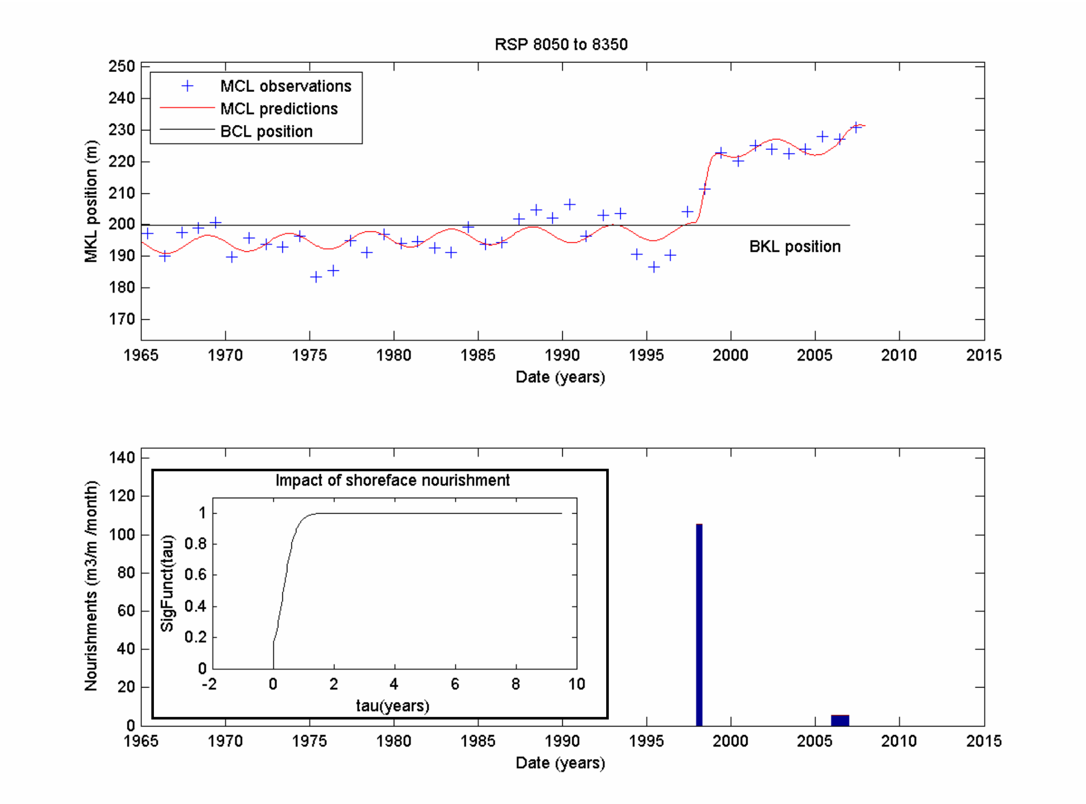

Figure 3.6 *(a) Long-term behaviour of the MCL position. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month) and normalised calculated function representing the impact of shoreface nourishment on the MCL position*

The trend for the long-term evolution of the dune volume is displayed in Figure 3.7, top panel. The long-term behaviour of the dune volume exhibits also a progressive evolution over the last decades, at a rate of 4.1 m^3/m/year. Parameter estimate for the period of the cyclic component is 5.2 years, which is consistent with the result found when describing the long-term behaviour of the MCL position and with the literature (Wijnberg and Terwindt, 1995). The dune volume tends to follow the MCL position (or volume) with a phase difference of about 1 year (Figure 3.6 and Figure 3.7). However, a visual inspection does not approve totally such an evaluation. The relation between the dune cycle and the shoreface/beach cycle needs to be examined in more details.

The impact of the shoreface nourishment on the dune volume is represented via a transfer function displayed in the Figure 3.7, bottom panel. The transfer function looks similar to the one found when describing the impact of shoreface nourishment on the MCL position (Figure 3.6). The maximum impact is found immediately after the application of the nourishment, which seems not physically consistent, as the maximum impact is expected occurring with a delay respect to the application of the nourishment. The transfer function exhibits then an asymptotic behaviour after the intervention. The asymptotic regime is physically consistent, respect to the blocking mechanism, in combination with the net longshore transported sediment, described previously.

Still, result of the analysis can be hardly evaluated, as the site is weakly nourished, and observations of the long-term behaviour of the dune volume, under the influence of nourishments, might contain a significant stochastic part, leading to a delicate proper parameters estimate.

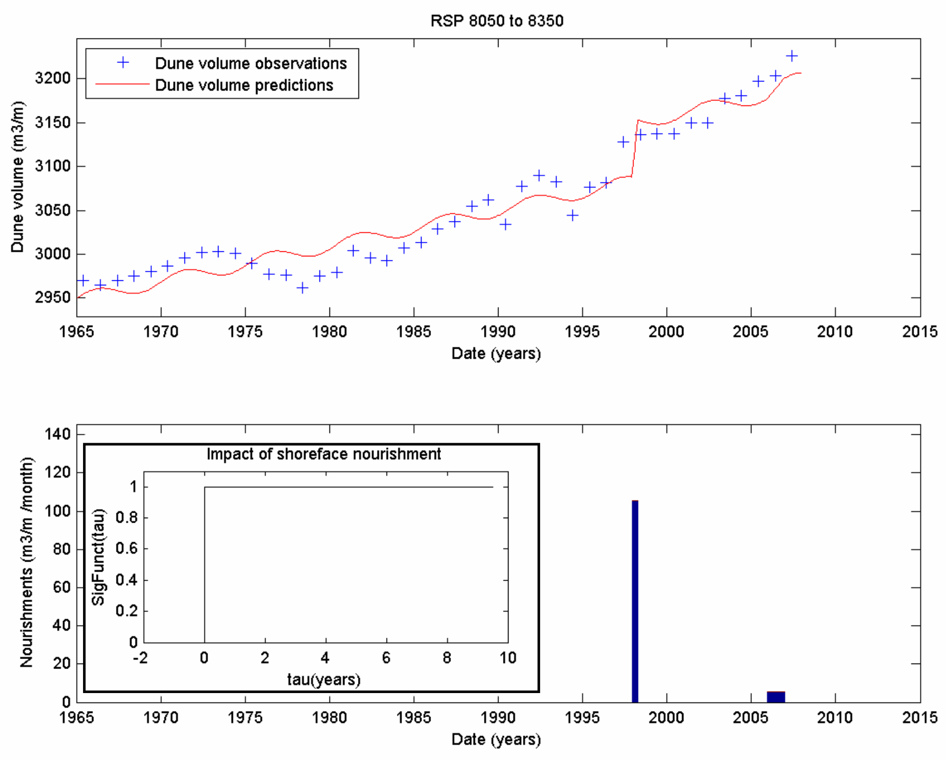

Figure 3.7 *(a) Long-term behaviour of the dune volume. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month) and normalised calculated function representing the impact of shoreface nourishment on the dune volume.*

3.3 Strongly influenced sites

The impact of nourishments is taken into account based on linear transfer functions, as described in the Appendix A. When different types of nourishments are applied at the same location, the corresponding transfer functions are evaluated, by estimation of 5 parameters per type of nourishment.

Zijpe (km 13.25-14.25)

Zijpe is located in the northern part of the Noord Holland coast, and belongs to the LSCB-region II following the classification of Wijnberg and Terwindt (1995). In this area, the return period of a certain bar topography is estimated to be about 15 years.

Over the coastal stretch defined from Beach Pole RSP 13.25 to Beach Pole RSP 14.25, dune, beach and shoreface nourishments were applied at Zijpe. In order to limit the number of free parameters that should be estimated, only beach and shoreface nourishments are considered when investigating the long-term behaviour of the MCL position.

The long- term behaviour of the MCL position is displayed in Figure 3.8. The MCL position exhibits a slightly regressive evolution until 1987, at a rate of – 0.1 m/year. A cyclic component, representing the migratory bar behaviour, has been added, characterized by a calculated period of the oscillation of 14.9 years (in agreement with the literature, Wijnberg and Terwindt, 1995).

Accretion (in terms of MCL position) is noticed after the application of the nourishments (Figure 3.8), and the positive impacts are gradually disappearing after a couple of years. The model reproduces properly these phenomenon, as the transfer functions representing the impacts of a beach and a shoreface nourishments on the MCL position (Figure 3.9) exhibit the following behaviours: (1) in case of a beach nourishment, the maximum impact is found about 0.5 to 1 year after the application of the nourishment, and the lifetime is estimated to be about 7 to 8 years; (2) in case of a shoreface nourishment, the maximum impact is delayed, occurring about 5 years after the application of the nourishment, and the lifetime is estimated to be about 8 to 9 years.

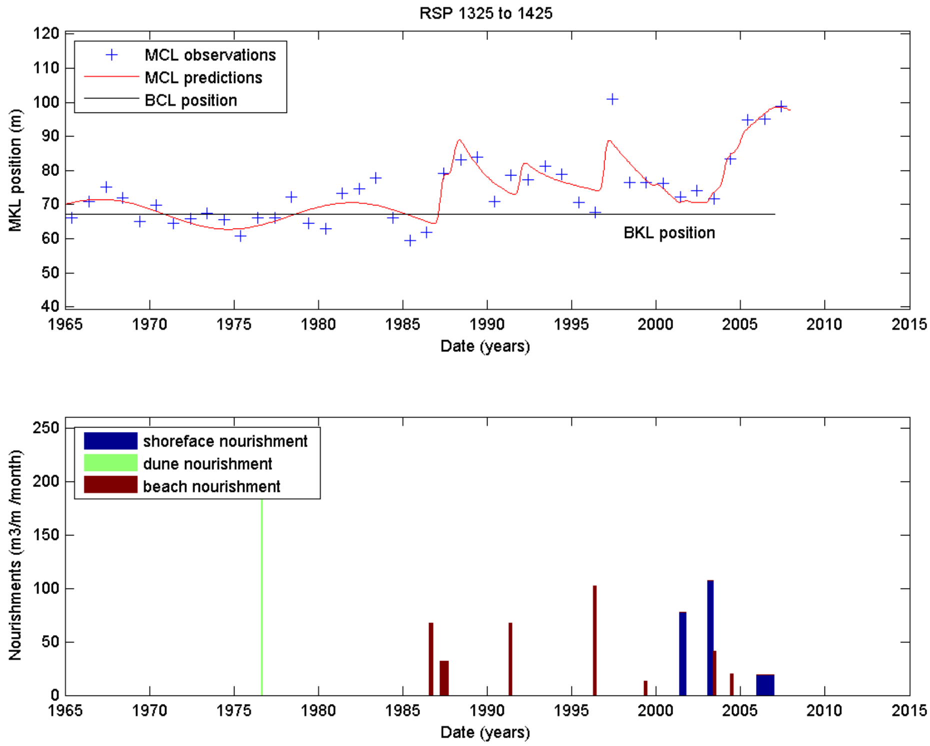

Figure 3.8 *(a) Long-term behaviour of the MCL position. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month).*

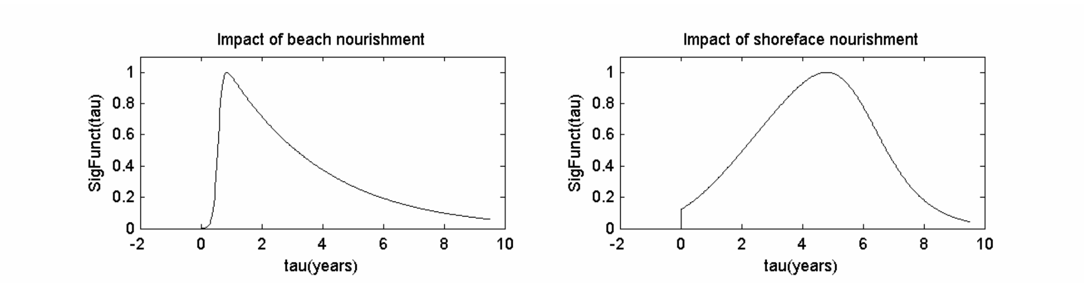

Figure 3.9 *Normalised calculated transfer functions representing (a) the impact of a beach nourishment on the MCL position, and (b) the impact of a shoreface nourishment on the MCL position.*

The long- term behaviour of the dune volume has been also studied, however resulting in some unrealistic model parameter estimates. The analysis can be hardly performed due to a highly noisy dataset (e.g. in 1972, a trend break is found in the dune volume, probably associated to human interventions).

Bergen-aan-Zee (km 32.25-34.25)

Bergen-aan-Zee is located in the central part of the Noord Holland coast, and belongs to the LSCB-region III following the classification of Wijnberg and Terwindt (1995). In this area, the return period of a certain bar topography is estimated to be about 15 years. From Beach Pole RSP 32.25 to Beach Pole RSP 34.25, beach and shoreface nourishments have been applied since 1990. Both types of nourishments are considered when investigating the long-term behaviours of the MCL position, and of the dune volume.

The long- term behaviour of the MCL position is displayed in Figure 3.10. The MCL position exhibits a regressive evolution until 1990, at a rate of – 0.4 m/year. A cyclic component, representing the migratory bar behaviour, has been added, characterized by a calculated period of the oscillation of 9.5 years, that is lower than the expected 15 years- value. A growth of the MCL volume (or position) is observed after the application of nourishments that can be associated to a blocking mechanism, in combination with the net longshore transport. The volume growth is properly reproduced by the model, through two transfer functions representing respectively the impact of the beach and shoreface nourishments on the MCL position (Figure 3.11). In case of beach nourishment, the first impact is found immediately after the application of the nourishment, and a gradual seaward migration of the MCL position is then obtained. Such shape of the transfer function is associated to a blocking mechanism, in combination with the net longshore transport, occurring on the beach system; sand is then transferred to the dune system. In case of shoreface nourishment, the maximum impact is obtained immediately after the application of the nourishment, and the function exhibits then an asymptotic behaviour.

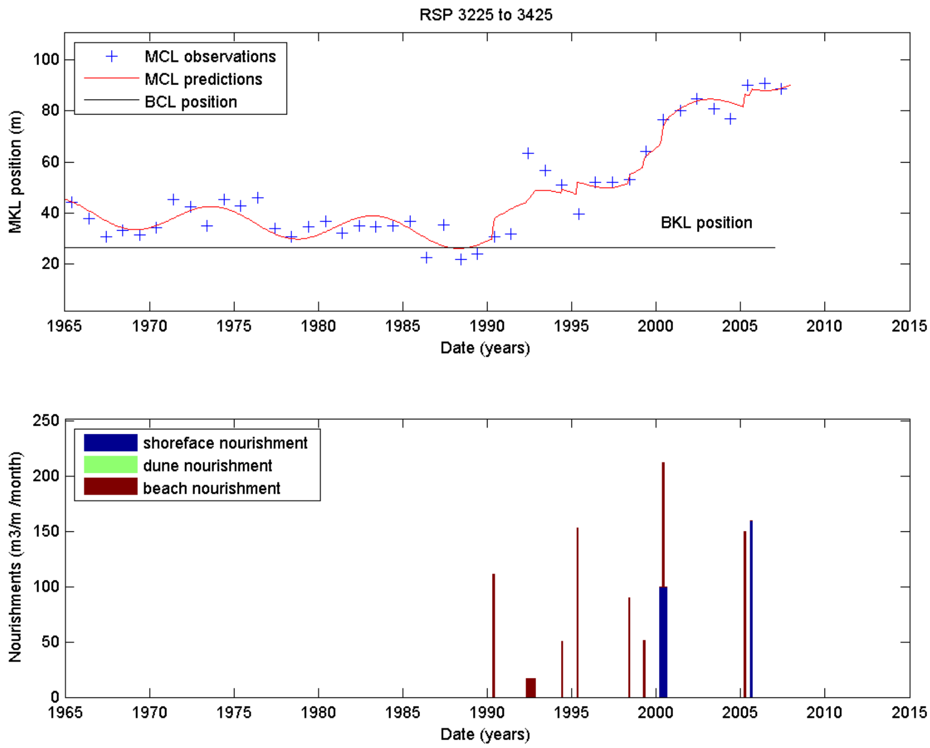

Figure 3.10 (a) Long-term behaviour of the MCL position. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month).

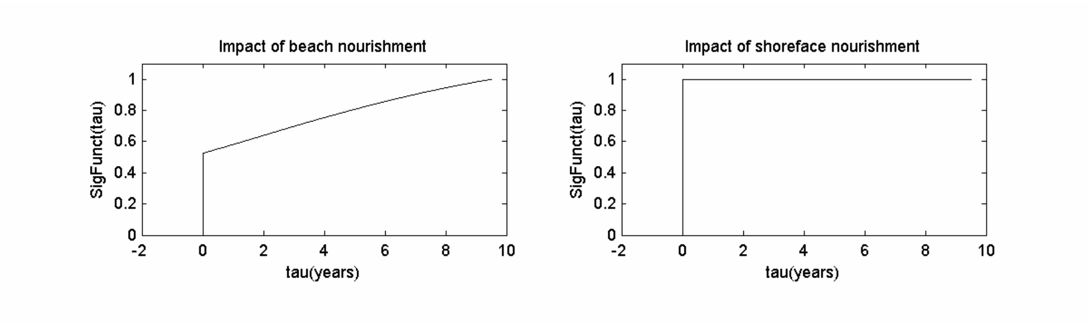

Figure 3.11 Normalised calculated transfer functions representing (a) the impact of a beach nourishment on the MCL position, and (b) the impact of a shoreface nourishment on the MCL position.

The long- term behaviour of the dune volume is displayed in Figure 3.12, showing a regressive evolution of the dune volume until 1990, at a rate of –- 6.87 m^3/m/year. A cyclic component, representing the migratory bar behaviour, has been added, characterized by a calculated period of the oscillation of 8.5 years. After the application of both the beach and shoreface nourishments, a growth of the dune volume is observed. The volume growth is reproduced by the model, through the two transfer functions representing respectively the impact of the beach and shoreface nourishments on the dune volume (Figure 3.13). Such a result can be hardly evaluated, as the site is, with respect to the dune volume, highly disturbed. Moreover, there is probably also a leak in the dunes, since part of the inland transported sand has been removed from the system (e.g. because of burial of roads …).

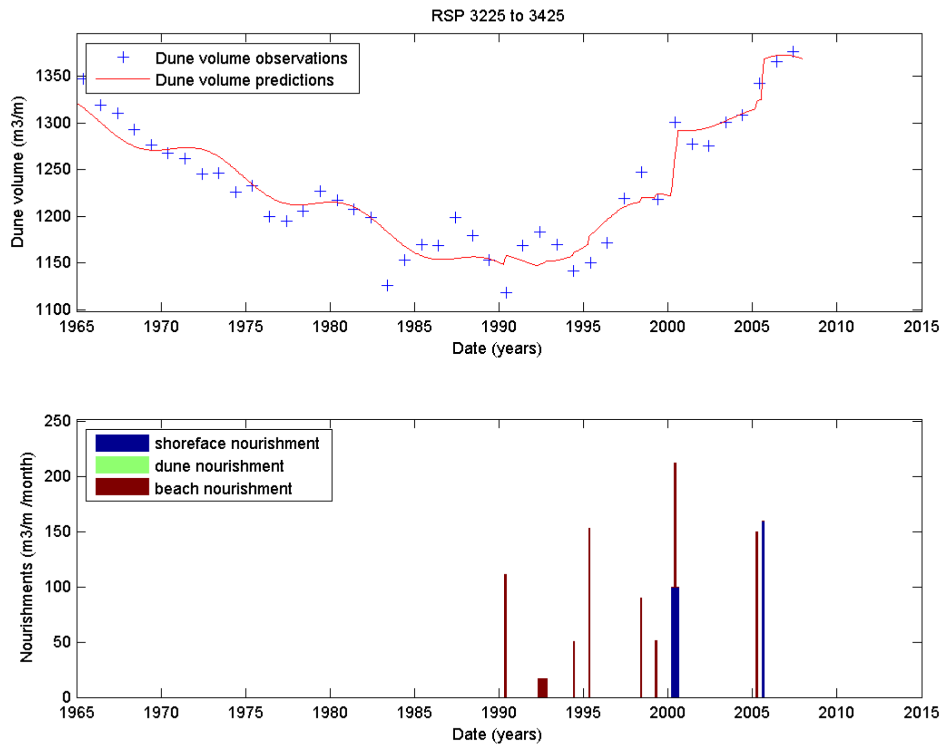

Figure 3.12 (a) Long-term behaviour of the dune volume. Blue dots represent the observations, whereas the solid red line represents the simulated mean trend. (b) Nourishment (m^3/m/month).

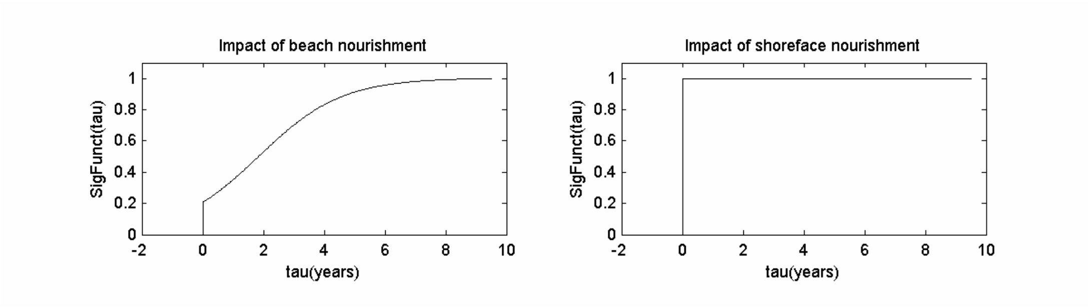

Figure 3.13 Normalised calculated transfer functions representing (a) the impact of a beach nourishment on the dune volume, and (b) the impact of a shoreface nourishment on the dune volume.

4 Discussion

4.1 Literature-based system knowledge

Based on the results of a literature study (Duin *et al.*, 2004), the following effects are expected to occur as a consequence of the placement of the shoreface nourishment (Figure 4.1).

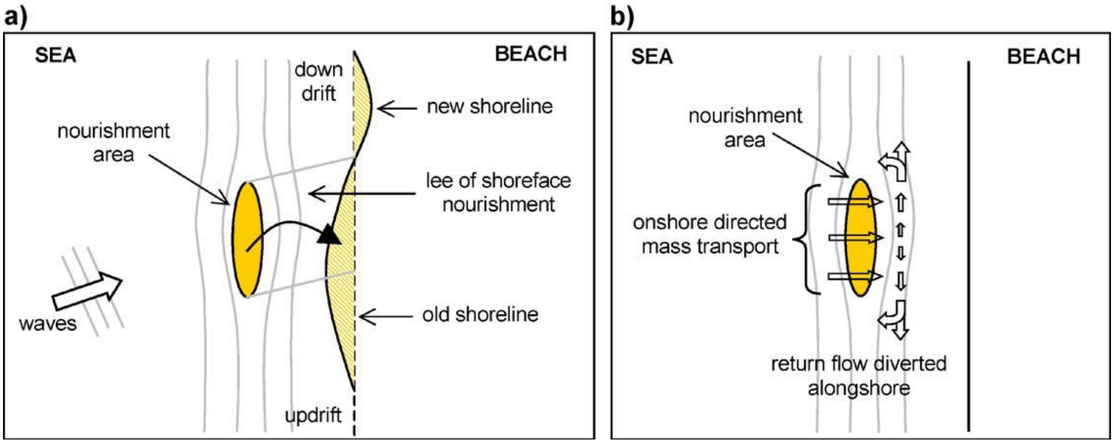

Figure 4.1 Effects expected to occur as a consequence of the placement of a shoreface nourishment (from Duin et al., 2004)

(1) longshore effect: large waves break at the shoreface nourishment causing a calmer wave climate behind the shoreface nourishment area (wave filter) and a reduction of the longshore current and, hence, the transport capacity. The shoreface nourishment acts as a blockade, resulting in:

- a decrease of the longshore transport;
- updrift sedimentation;
- downdrift erosion.

(2) cross-shore effect: large waves break at the seaward side of the shoreface nourishment; remaining shoaling waves generate onshore transport due to wave asymmetry over the nourishment area; the smaller waves in the leeside generate less stirring of the sediment and the wave-induced return flow (cross-shore currents) reduces. This results in:

- an increase of the onshore sediment transport;
- a reduction of the offshore sediment transport.

4.2 Study-based system knowledge

The statistical model has been applied to 6 sites, selected depending on the occurrence of nourishments. Both the long-term trends of the MCL position (or volume) and of the dune volume have been described. In general, multiple patterns were consistently observed throughout the analysis:

- A cyclic component, characterized by typical properties of subaqueous bar morphodynamics, is present in the long-term trend of the selected CSIs (both

MCL position and dune volume), showing that the beach system can be seen as a transferring zone between the subaquaous system and the dune system.

- In the long-term trends of the MCL position and of the dune volume, a phase difference of about 3 to 4 years is obtained for the sites located in the LSCB-region III, following the classification of Wijnberg and Terwindt (1995), where the return period of a certain bar topography is estimated to be about 15 years.
- In the long-term trends of the MCL position and of the dune volume, a phase difference of about 1 year is obtained at Noordwijk-aan-Zee (in LSCB-region IV, following the classification of Wijnberg and Terwindt, 1995), where the return period of a certain bar topography is estimated to be about 4 years.

- Lateral diffusion of nourishments to directly adjacent areas is assumed, as for example in Hemskerk, (consistent with van Duin *et al.* (2004) and Grunnet and Ruessink (2005)).
- The impacts of nourishments can be described as two types:
  a) either with a regressive behaviour in time (consistent with the sawtooth concept, e.g. Castricum-aan-Zee, Zijpe)
  b) or with a retentional or progressive behaviour in time (e.g. Noorwijk-aan-Zee, Bergen-aan-Zee)

- A blocking mechanism of longshore net transport is assumed to explain volume conservation or even a potential accretion.
- Such accretion appearing after the nourishment and post initial blocking phase (e.g. Bergen-aan-Zee) is consistent with van Duin *et al.* (2004) and Grunnet and Ruessink (2005).
- Nourishments sometimes result in accretion multiple years after (~5 years) the application (e.g. Zijpe).

4.3 Limitations on the application of the statistical model

The application of the statistical model to 6 different sites enabled to highlight some limitations on its use:

- The impact of nourishment on the long-term behaviour of a CSI can be hardly represented when the site is not nourished or weakly nourished, as the definition of a transfer function representing the impact requires a statistically significant amount of information.
- The model parameters estimate appears to be highly dependent on the “initial guess”. A proper application of the statistical model requires therefore system knowledge.
- Model development is a necessity in order to represent more properly e.g. the confidence interval of parameter estimates, the shape of transfer functions, and to make it operational for predictions of the impact of nourishment alternatives.

5 Conclusions

Considering 43 years records of Jarkus data, a statistical model has been proposed to describe the long-term behaviours of the Momentary Coastline (MCL) and of the dune volume, including mathematical representations of (1) the influence of nearshore bars, and of (2) the impact of nourishments.

The statistical model has been applied to 6 different sites (i.e. non-influenced by nourishments, weakly influenced, and strongly influenced). Emphasize has been put on the evaluation of the impact of nourishments on both the beach and dune systems.

5.1 Linking beach and dune dynamics

A cyclic component, representing the typical properties of subaqueous bar morphodynamics, has been calculated when describing the long-term behaviours of the selected CSIs (both MCL position and dune volume, for the 6 selected sites). The calculated periods of the oscillations are, in general, in good agreement with the analysis of Wijnberg and Terwindt (1995).

The long-term trends of the MCL position and of the dune volume exhibit a phase difference of about 3 to 4 years for the sites located in the LSCB-region III (following the classification of Wijnberg and Terwindt, 1995), where the return period of a certain bar topography is estimated to be about 15 years.

On the other hand, the long-term trends of the MCL position and of the dune volume exhibit a phase difference of about 1 year at Noordwijk-aan-Zee (in the LSCB-region IV, following the classification of Wijnberg and Terdwindt, 1995), where the return period of a certain bar topography is estimated to be about 4 years.

5.2 Applicability of the statistical model

The statistical model appears to be a useful tool to describe mathematically the impact of nourishments on the long-term trend of CSIs, highlighting either a regressive (in time) behaviour of the transfer function representing the impact, that is consistent with the sawtooth concept, or a retentional or progressive (in time) behaviour of the transfer function.

The description of the actual state of the system, or so-called Testing Coastline (TCL), would be performed with more insight on the structural developments, if using the statistical model. In that case, its application would lead to an indication for the (expected) coastal state in the years T to T+10.

5.3 Recommendations

A phase difference of about 1 year to 3-4 years has been noticed when comparing the long-term behaviours of the MCL position and of the dune volume. The relation between the dune cycle and the shoreface/beach cycle needs however to be examined in more details.

It is recommended to test the predictive capacity of the statistical model, by applying it to several locations and for different design scenarii. In case of good results, the data-driven model would be a useful tool to support decision on nourishment design, by providing indications for the (expected) coastal state in the next decade.

A systematic evaluation of the long-term behaviours of CSIs (especially the MCL volume and position) along all the transects of the Holland Coast is also recommended. In this case, inputs in the nourishment characteristics would be optimised, and system knowledge would support the definition/calculation of the transfer functions representing the impact of nourishments. The model parameters estimate on one specific transect would certainly contribute to a better evaluation of the model parameters for adjacent transects, leading to a clear picture of the impact of the nourishment procedures on the coastal system, over the overall Holland Coast.

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A Statistical model: model formulation and uncertainty assessment

Description of the stochastic model for Coastal State Indicator time series

In continuous time, the mathematical formulation of the model reads:

$$Z_t = \Phi\left(t \mid \vec{\Theta} \right) + V_t \tag{A.1}$$

Z_t represents the model prediction of a Coastal State Indicator at a time *t*. The model prediction is built up of two components, $\Phi\left(\cdot \mid \vec{\Theta} \right)$ and V_t.

$\Phi\left(\cdot \mid \vec{\Theta} \right)$ is a parameterised function of time, representing the deterministic, long term "systematic" variations in the temporal evolution of a Coastal State Indicator. These systematic variations may consist of trends in the series, and/or seasonal or even longer term cyclic behaviour.

$\vec{\Theta} := \left(\Theta_1, \Theta_2, \Theta_3, \cdots\cdot, \Theta_N \right)$ in Equation A.1 denotes a set of (uncertain) model parameters that are used in the mathematical description of the long term trends or formulation of cyclic components.

V_t is a zero mean random noise, representing the uncertainties in the modelling of the Coastal State Indicator and/or the uncertainties in the observations. In the present case it is assumed that V_t is a Gaussian white noise. For each time *t* the noise V_t is a Gaussian random variable, and V_s and V_t are independent for times *s* and *t* when $s \neq t$. The spread of V_t is denoted by σ_V and is assumed to be independent of time, so that V_t is actually a stationary noise. The spread σ_V is not known beforehand and is considered as an uncertain model parameter as well. The value of σ_V must thus be estimated from observed data, just as the parameters $\vec{\Theta}$ in the deterministic part of the model.

Models for the deterministic long term variations

A visual inspection of plots of the time series of the several (aggregated, Jarkus based yearly samples) Coastal State Indicator over the period 1965 to 2007 suggests a temporal evolution that often contains a long term, gradually increasing (or decreasing) trend. In the present case such long term trends are described by a polynomial function of time *t*, leading to:

$$\Phi\left(t \mid \vec{\Theta} \right) = \alpha_0 + \alpha_1 \cdot t + \alpha_2 \cdot t^2 + \cdots\cdot + \alpha_N \cdot t^N \tag{A.2a}$$

with the model parameters $\vec{\Theta}$ then consisting of:

$$\vec{\Theta} := (\alpha_0, \alpha_1, \alpha_2, \cdots, \alpha_N) \tag{A.2b}$$

For the (maximal) order *N* of the polynomial a proper guess must be made. On one hand the value of *N* should be large enough to represent sufficiently accurate the shape of a trend. On the other hand, however, *N* must be small compared to the number of data points to prevent overfitting of the model. In the present case, when dealing with 43 yearly Jarkus samples, preliminary experiments showed that the order of the polynomial should be restricted to *N*=1 (linear trend in time).

In many cases the visual inspection of the Coastal State Indicator time series also suggested the presence of a cyclic component, potentially representing the cyclic coastal bar behaviour occurring in a LSCB-region defined as an area in which the coastal profiles exhibit similar large scale developments (Wijnberg and Terwindt, 1995). In these LSCB-regions, large-scale profile developments were considered to be a combination of horizontal shifting of the profile in cross-shore direction and changing of the shape of the profile, exhibiting more or less a similar long-term behaviour of the coastal bars in each LSCB-region. Such a component was modelled by a harmonic time series. This harmonic function was added to the polynomial function described above, leading to the following extension of the model:

$$\Phi\left(t \mid \vec{\Theta}\right) = \alpha_0 + \alpha_1 \cdot t + \alpha_2 \cdot t^2 + \cdots + \alpha_N \cdot t^N + A_1 \cdot \cos\left(\tfrac{2\cdot\pi}{P_1} \cdot t\right) + B_1 \cdot \sin\left(\tfrac{2\cdot\pi}{P_1} \cdot t\right) \tag{A.3a}$$

More generally, more than one harmonic component may be present, or necessary to represent or approximate a period function, so that Equation A.3a can be generalised to:

$$\Phi\left(t \mid \vec{\Theta}\right) = \alpha_0 + \alpha_1 \cdot t + \alpha_2 \cdot t^2 + \cdots + \alpha_N \cdot t^N + \sum_{\ell=1}^{L}\left(A_\ell \cdot \cos\left(\tfrac{2\cdot\pi}{P_\ell} \cdot t\right) + B_\ell \cdot \sin\left(\tfrac{2\cdot\pi}{P_\ell} \cdot t\right) \right) \tag{A.3b}$$

In that case the vector of model parameters $\vec{\Theta}$ consists of:

$$\vec{\Theta} := (\alpha_0, \alpha_1, \alpha_2, \cdots, \alpha_N \; ; P_1, A_1, B_1, P_2, A_2, B_2, \cdots, P_L, A_L, B_L) \tag{A.3c}$$

Parameter P_ℓ denotes the period (here in years) of the $\ell - th$ harmonic component, while A_ℓ and B_ℓ denote the amplitudes of the cosine and sine functions. Although 2 free parameters (for the amplitude) are involved in the harmonic component, a linear form with respect to A_ℓ and B_ℓ of the expression provides advantages in the estimation of the parameters.

The period P_ℓ of the $\ell - th$ cyclic component is considered as an unknown model parameter and the derivation of a best estimate of this period is a part of the calibration procedure.

For every harmonic/cyclic component three unknown model parameters are involved. To avoid overfitting, the number *L* of harmonic components that is included in the model must be limited. In most of the present applications, *L* was restricted to *L=1*.

Representation of the impact of nourishments

In the present case the effect of a (beach, shore face, or dune) nourishment on a CSI is described by a linear transfer function $h(\cdot)$. The idea is that an incremental nourishment $U(s)$ during a small time interval $(s, s+\Delta s)$ leads to a change of the CSI for times $t > s$, and that this change is of size $h(t-s)\cdot U(s)\cdot \Delta s$ at time *t*. In this way the (after)effect is proportional to the amount of nourished sand (i.e. $U(s)\cdot\Delta s$), but also depends on the elapsed time $\tau = t - s$ (through a time depending scaling factor $h(\tau)$). The total effect of a series of incremental nourishments is assumed to be the superposition of the individual effects. In continuous time ($(\Delta s \to ds)$ this then leads to the following linear model for the total effect on the CSI of a continuous time series $U(\cdot)$ of nourishments:

$$\begin{aligned}\Phi(t) &= \int h(t-s)\cdot U(s)\cdot ds \\ &= \int h(\tau)\cdot U(t-\tau)\cdot d\tau\end{aligned} \tag{A.4}$$

In this formulation the function $U(\cdot)$ actually represents a nourishment *density*, and must be expressed as a volume (e.g. in m^3) of sand that is released per unit of time. In other cases when nourishments are concentrated in coastal transects, a representation of $U(\cdot)$ as a volume per unit of length and per unit of time will probably be better suited.

The transfer function $h(\cdot)$ can depend on (and will in general be different for) the *type* of (beach, shore face, or dune) nourishment that is carried out. In fact, when all these types are present in a nourishment scenario we may have specific transfer functions $h_B(\cdot)$ for beach nourishments $U_B(\cdot)$, and other specific functions $h_S(\cdot)$ for shore face nourishments $U_S(\cdot)$, and also other functions $h_D(\cdot)$ for dune nourishments $U_D(\cdot)$. The total effect of nourishments of different type is again assumed to be linear superposition of the individual effects leading to the following generalisation of Equation A.4:

$$\Phi(t) = \int h_B(t-s)\cdot U_B(s)\cdot ds + \int h_S(t-s)\cdot U_S(s)\cdot ds + \int h_D(t-s)\cdot U_D(s)\cdot ds \tag{A.5}$$

Components for the modelling of long term variations and cyclic components in the CSI have been omitted in the right hand side of this equation, but can readily be included.

The transfer functions $h(\cdot)$ must be identified from observed time series of the nourishments $U(\cdot)$ and the CSI series Z_t. In practice the amount of Z_t-observations is usually limited, and for reasonable estimates (after a model calibration) for the transfer functions, suitable low dimensional *parameterisations* $h(\cdot|\vec{\Theta}_h)$ of the $h(\cdot)$ will have to be formulated. In the present case two sigmoid functions are used for this parameterisation of the transfer functions $h(\cdot)$ and in a formula this reads:

$$h(\tau|\vec{\Theta}_h) = c \cdot S(\tau|\mu_1,\lambda_1) \cdot S(\tau|\mu_2,\lambda_2) \tag{A.6}$$

$S(\cdot)$ corresponds to a sigmoid function defined by:

$$S(\tau|\mu,\lambda) := \frac{\exp\left(\frac{\tau-\mu}{\lambda}\right)}{1 + \exp\left(\frac{\tau-\mu}{\lambda}\right)} \tag{A.7}$$

This sigmoid function includes two parameters, a *shift* parameter μ and a *shape* parameter λ, For $\lambda > 0$ the function $S(\cdot)$ *increases* monotonically from 0 at $\tau \downarrow -\infty$ to 1 for $\tau \uparrow \infty$, while for $\lambda < 0$ the function $S(\cdot)$ *decreases* monotonically from 1 at $\tau \downarrow -\infty$ to 0 for $\tau \uparrow \infty$. The steepness in this increase or decrease is determined by the absolute value of λ. The shift parameter μ represents the argument τ for which $S(\tau|\mu,\lambda) = \frac{1}{2}$. In particular it holds that the curve of $S(\cdot)$ is symmetric in the point $(\mu,\frac{1}{2})$.
The $h(\cdot)$ of Equation A.6 is actually the product of two such sigmoid functions $S(\cdot)$, and this product is multiplied by a scale factor *c* to control the maximum value of the total profile. In this way the parameterisation $h(\cdot|\vec{\Theta}_h)$ of $h(\cdot)$ involves 5 parameters $\vec{\Theta}_h$. In fact: $\vec{\Theta}_h := (\ \mu_1,\lambda_1;\mu_2,\lambda_2;c\ )$.

A main advantage of the formulation of Equation A.6 is that it can deal with a wide variety of (for practice realistic) $h(\cdot)$ profiles. This is illustrated in Figure A.1 where the function $h(\cdot|\vec{\Theta}_h)$ is plotted for some variations of the shape and shift parameters $(\mu_1,\lambda_1;\mu_2,\lambda_2)$ (*c=1* in all six subplots). In this sense the present parameterisation tends to be highly generic, and thus suited for the modelling of the impact of nourishments on a CSI.

It was mentioned before that different types of nourishments may have different impacts on a CSI. This means that for each type of nourishment a separate parameterisation $h(\cdot|\vec{\Theta}_h)$ will have to be used. While one particular $h(\cdot|\vec{\Theta}_h)$ involves 5 parameters (or less when some of $(\mu_1,\lambda_1;\mu_2,\lambda_2;c\ )$ can be fixed) the total number of $\vec{\Theta}_h$-parameters can thus become a multiple.

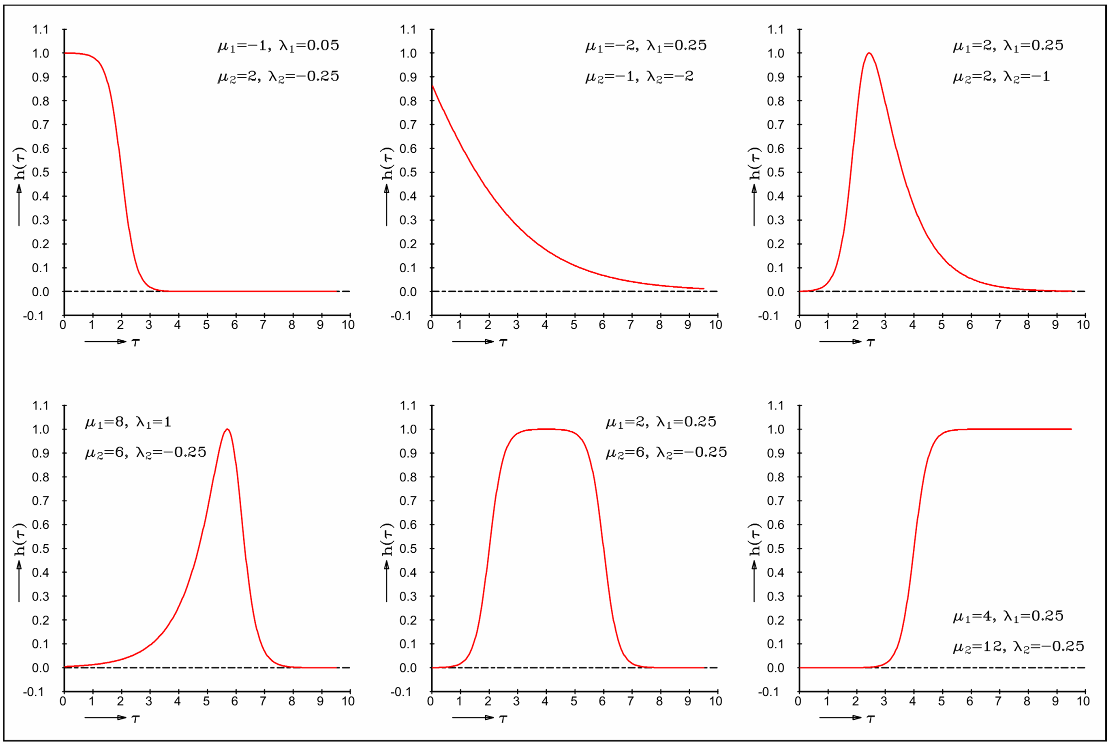

Figure A.1 Plots of parameterised transfer functions $h(\cdot|\vec{\Theta}_h)$ *of Equation A.6 for six variations of the parameter vector* $\vec{\Theta}_h := \left(\mu_1, \lambda_1 ; \mu_2, \lambda_2 ; c\right)$. *In all case c=1.*

Calibration of the CSI models

For the calibration of the model of Equation A.1, a set of CSI observations $\left\{ t_k, \hat{Z}_{t_k} \right\}_{k=1}^{K}$ is used, where t_k and $\hat{Z}_{t_k}$ denote the time and CSI value of the k^{th} measurement, and the parameters $\vec{\Theta}$ are identified such that in an “appropriate sense” the model predictions agree optimally with the targets $\left\{ \hat{Z}_{t_k} \right\}_{k=1}^{K}$. In the present case, the calibration procedure follows closely the approach described by Van den Boogaard *et al*. (2006).

For a set of Coastal State Indicator “observations” $\left\{ t_k, \hat{Z}_{t_k} \right\}_{k=1}^{K}$, the model of Equation A.1 “reduces” to a set of *K* stochastic equations:

$$\hat{Z}_{t_k} = \Phi\left(t_k \mid \vec{\Theta} \right) + V_{t_k} \tag{A.8a}$$

Fully equivalently, Equation A.8a can be interpreted as a set of *K* observations for the noise V_t according to:

$$\hat{V}_{t_k} = \hat{Z}_{t_k} - \Phi\left(t_k \mid \vec{\Theta} \right) \tag{A.8b}$$

It is assumed that V_t is a zero mean Gaussian white random process. Therefore the *K* "observations" $\hat{V}_{t_k}$ should satisfy a *K*-variant zero mean Gaussian probability density distribution $f_K(\cdot)$ with a $K \times K$ auto-covariance matrix Γ with entries $\Gamma_{k,k} = \sigma_V^2$ and $\Gamma_{k,\ell} = 0$ for $k \neq \ell$. On this basis, a Maximum Likelihood criterion (Kendall and Stuart, 1961) can be applied to derive an estimate for the parameters $\vec{\Theta}$. In fact, this estimate $\hat{\Theta}$ is the value of $\vec{\Theta}$ that minimises the minus Log-Likelihood function $J(\Theta) := -\ell n\left(f_K\left(\hat{V}_{t_1}, \hat{V}_{t_2}, \cdots, \hat{V}_{t_K}\right)\right)$. In the present case this function $J(\cdot)$ is:

$$J(\Theta) = \tfrac{1}{2} \cdot K \cdot \ell n\left(2 \cdot \pi \cdot \sigma_V^2\right) \; + \; \tfrac{1}{2} \cdot \sum_{k=1}^{K} \left(\frac{\hat{Z}_{t_k} \; - \; \Phi\left(t_k \,|\, \vec{\Theta}\right)}{\sigma_V^2} \right)^2 \qquad \text{(A.9)}$$

Due to the non-linear dependence of $\Phi\left(\cdot \,|\, \vec{\Theta}\right)$ on $\vec{\Theta}$ the cost function of Equation A.9 cannot be minimised analytically. In the present applications a Quasi-Newton gradient descent technique (see e.g. Press *et al*., 1986) was applied for the minimisation of the minus LogLikelihood function.

Analytical covariance matrix and spreads for the estimates of the model parameters

Apart from the estimate for $\hat{\Theta}$, the Maximum Likelihood (MLH) formalism also provides an estimate for its covariance matrix $\Gamma^{(\Theta)}$. This covariance matrix is the inverse H^{-1} of the Hessian matrix *H* of the minus Log Likelihood function evaluated at its minimum. The Hessian matrix is the matrix of second order derivatives and thus the entries of H are $H_{n,m} := \left.\frac{\partial^2 J}{\partial \Theta_n \, \partial \Theta_m}\right|_{\Theta = \hat{\Theta}}$. From a so determined $\Gamma^{(\Theta)} := H^{-1}$ the spreads and correlation coefficients of the estimate $\hat{\Theta}$ can be computed which provide a quantitative measure for the uncertainties in $\hat{\Theta}$.

Uncertainty assessment by means of resampling

It was noted above that the spread of the estimates $\hat{\Theta}$ can be evaluated through the Hessian of the Minus Log Likelihood function. However, this recipe is theoretically valid under the asymptotic condition of a sufficiently large data set of observations. For small data sets, skewness properties can be highly important in the representation of the uncertainties, especially when constructing non-symmetric (skew) confidence and/or prediction intervals.

Resampling techniques may then serve as an attractive alternative method for uncertainty assessment, as resampling creates a large ensemble of data sets, each of which is replicated from the original data sample. For each resample the actual statistic $\hat{\Theta}$ is recomputed. The resampling techniques applied in this study are the JackKnife and Bootstrap techniques (see e.g. Efron and Tibshirani, 1993).

Confidence intervals for model outputs

The set $\left\{\hat{\Theta}^{(\ell)}\right\}_{\ell=1}^{L}$ of parameter estimates found in a resampling based calibration procedure forms a convenient foundation for a quantitative and statistically well based assessment of confidence and prediction intervals for model outcomes.

Thus, Coastal State Indicators are predicted by the calibrated model for some time *t*, which can be quite general and is not necessarily restricted to the observation times $\left\{ t_k \right\}_{k=1}^{K}$ of the data $\left\{ \hat{Z}_{t_k} \right\}_{k=1}^{K}$ used in the model calibration. In particular the time *t* can now also refer to times out of the range covered by the $\left\{ t_k \right\}_{k=1}^{K}$ and for such times the model is actually used for extrapolation, or forecasting.

Actually, through the set of resamples $\left\{\hat{\Theta}^{(\ell)}\right\}_{\ell=1}^{L}$ an ensemble of *L* (deterministic) models $\Phi\left(\cdot \mid \hat{\Theta}^{(\ell)}\right)$ is available. In fact, for any time *t* this provides *L* estimates $\left\{ \Phi\left(t \mid \hat{\Theta}^{(\ell)}\right) \right\}_{\ell=1}^{L}$ for the “output” of the deterministic part of the model. This ensemble $\left\{ \Phi\left(t \mid \hat{\Theta}^{(\ell)}\right) \right\}_{\ell=1}^{L}$ can conveniently be used for the construction of spreads or (*skew*) confidence intervals. A so constructed skew 95% (or other confidence level γ) confidence interval $\left[\Phi_{2.5\%}(t), \Phi_{97.5\%}(t)\right]$ represents the uncertainty in the output of the deterministic part of the model. Therefore this confidence interval reflects the uncertainty in the identified long term systematic variations in the Coastal State Indicator, such as trends and/or cyclic components. In the construction of the confidence interval $\left[\Phi_{2.5\%}(t), \Phi_{97.5\%}(t)\right]$ no effects of the short term random variations (“the noise in model and observations) have yet been included.

Prediction intervals

Prediction intervals (of some confidence level γ , e.g. $\gamma = 95\%$) are a means to quantify the accuracy with which such an observation Z_t can be predicted. In the construction of prediction intervals the uncertainty in both the calibrated model $\Phi\left(t \mid \hat{\Theta}\right)$ (represented by e.g. a confidence interval) and spread of the observation noise V_t (here assumed to be a zero mean white Gaussian random process) must appropriately be accounted.

For the 95% prediction interval $\left[Z_{2.5\%}(t),\ Z_{97.5\%}(t)\right]$, the cumulative distribution function $F_{Z_t}(\cdot)$ of Z_t is computed from the resampled models $\Phi\left(t \mid \hat{\Theta}^{(\ell)}\right)$ and corresponding resampled spreads $\hat{\sigma}_V^{(\ell)}$ of the noise V_t. The lower bound $Z_{2.5\%}(t)$ of the 95% (skew) prediction interval is then the *z* that satisfies $F_{Z_t}(z) = 0.025$ (i.e. the 2.5% quantile of the distribution) while similarly the upper bound corresponds to the 97.5% quantile.

For the interpretation of the 95% prediction interval $\left[Z_{2.5\%}(t),\, Z_{97.5\%}(t)\right]$, on the average 95% of the available observations $\hat{Z}_{t_k}$ are expected to be within the prediction interval.