A review of morphological studies and models relevant for the Wadden Sea

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This review presents brief summaries of a number of reports and mathematical models known to the author which may be relevant for short-term and long-term morphological developments of the Wadden Sea. It certainly is not a complete list of literature on this subject but it may guide other investigators working on this subject.

This work was done in the framework of the Delft Cluster Project Coasts 03.01.03.
1 Morphology

Morphology of the Wadden Sea, Impact of sand and shell borrowing (in Dutch).
W.D. Eysink, WL | Delft Hydraulics, Report R 1336 on literature study, May 1979

Content
The morphology of the Dutch Wadden Sea has been studied in an extensive literature survey covering 149 articles and reports of different disciplines (geology, archeology, history, biology, sedimentology, hydraulics, etc.). This has resulted in a rather complete description of the morphological mechanisms responsible for the shaping of the Wadden Sea. The report presents a lot of characteristic data and the first empirical relationship between the tidal prism and the volume of tidal basins. Based on this study it was concluded that sand borrowing ultimately will have an impact on the North Sea coast of the Wadden Sea area and that the impact of shell borrowing on the sediment transport in the Wadden Sea is negligible.

Comments
The report provides basic knowledge on the morphological processes in the Wadden Sea and estuaries. It also shows the existence of empirical morphological relationships that can be practical as engineering tools. The report is often used as a basis for other studies.

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Content
This report contains 149 brief summaries of the literature studied for Report R 1336.

Comments
The summaries show relevant parts of the original studies used in the literature study R 1336 by W.D. Eysink of WL | Delft Hydraulics.

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Nakdong estuary barrage and land reclamation, Morphological aspects.

Content
Study on the morphological impact of the Nakdong barrage.

Comment
General empirical relation for tidal inlet of a small estuary including the effect of the river discharge.

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Morphological response of tidal basins to changes.

Content
Presentation of empirical relationships for the Dutch Wadden Sea and the Delta area and the possibility to apply them in coastal engineering.

Comments
Empirical relations for channel cross section, depth and volume, for sand volume in outer deltas and for tidal flat area in the Dutch Wadden Sea.

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Morphological stability of inlets and channels of the western Wadden Sea.

Content
The report presents a number of empirical relationships for stable (in size) tidal channels and discusses the possibility of the use of empirical relationships, the “stability shear stress” approach, dimensionless parameters or numerical morphological modelling to solve the “stability equation” for a tidal channel. Further, forces causing channel migration are discussed and the possibilities of modelling morphological processes.

Comments
Many references and data.

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Simple morphological relationships for estuaries and tidal channels; Handy tools for engineering.

Content
Presentation of different empirical relationships. Discussion of the effect of waves and river discharge on channel profiles and of the effect of the shape of the tidal basin on the total channel volume and the relative channel area in a tidal basin.

Comment
Useful set of empirical relations for engineering with examples of application.

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Coastal Genesis Project, Some considerations on tidal inlets. A literature survey on hydrodynamic and morphodynamic characteristics of tidal inlets with special attention to “Het Friesche Zeegat”.

**Content**
Also in this report the interrelation between the different morphological units of the Wadden Sea is described based on the results of an extensive literature survey. It also discusses the possible impacts of human interference in the natural system and the applicability and restrictions in the validity of empirical relationships in literature.

**Comment**
General knowledge on tidal inlets and lagoon systems.

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**GEOPRO Project, Inventory Field Data Wadden Sea (in Dutch).**
A.W. van Kleef, Univ. of Utrecht, Institute of Geographical Research, Vakgroep Fysische Geografie, Report GEOPRO 1991.014 (Notitie AOFM-91.10.010, RWS-DGW)

**Content**
The report presents an overview of all historical field data of the Dutch Wadden Sea which are available in archives of RWS. This concerns discharge measurements (since 1948), soundings (1950-1985 in eastern part and 1930-1988 in western part), water level stations and records, station and records of wave measurements, position of rows with ripple measurements, map with median sediment diameter, historic maps, titles and brief summaries of some brief reports of the Meet- en Adviesdienst Hoorn (period 1952-1982) and a list of documents about the Wadden Sea.

**Comment**
Good guide to trace historical data of the Dutch Wadden Sea of RWS.

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**GEOPRO Project, Available sediment data of the Dutch Wadden Sea (Part I).**

**Content**
The report presents an extensive literature survey on the sedimentology of the Dutch Wadden Sea. The results are describes in relation with the geology, morphology and hydrography of the Wadden Sea inclusive effects of land reclamation areas and the exploitation of sand and shells.

**Comments**
The report contains a lot of geological and sedimentological data and sources/archives of those data.
Coastal Genesis, Equilibrium relations in the ebb tidal delta, inlet and backbarrier area of the Frisian inlet system,

Contents
Study on empirical relationships for the cross section of a tidal channel and the adaptation of the channels to the new conditions after closure of the Lauwers Sea.

Comments
Discussion of different relationships and a lot of field data of the Frisian Inlet system.

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ISOS*2 Project, Impact of sea level rise on the morphology of the Wadden Sea in the scope of its ecological function.
• Phase 1-Inventory of available data and literature and recommendations on aspects to be studied.
• Phase 2-Investigations on empirical morphological relations.
• Phase 2-Investigations on empirical morphological relations, Data reports ISOS*2.
  Part 1: Results, Calculations and Methods Phase 2,
  Part 2: Selected data of the Dutch Wadden Sea,
  E.J. Biegel, Univ. of Utrecht, Inst. for marine and atmospheric research, November 1992
• Phase 3-Proposed set-up of a dynamic morphological model for Wadden Sea basins and estuaries based on empirical relations.
• Phase 4- General considerations on hydraulic conditions, sediment transports, sand balance, bed composition and impact of sea level rise on tidal flats.

Content
This study focusses on the existence of empirical relationships between morphological units (such as tidal inlet and local channel profile, basin volume, sand volume of outer delta, height of tidal flats) and characteristic hydraulic parameters in the Wadden Sea based on data in literature and field data from the Dutch Wadden Sea (Phases 1, 2 and partly 4). The purpose was to look for the possibility to develop a concept for the development of mathematical models with a stable computational scheme for long-term morphological developments. Proposals for such schemes have been presented in the Phase 3 report. The Phase 4 report gives a more general description of the morphology of the Wadden Sea and additional empirical relations for the tidal flats in particular.

Comments
Discussion and development of many empirical relationships in Phase 2 report. Basis for long-term morphological models MORRES, ESTMORF and ASMITA in the Phase 3 report.

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Dutch “slufter”, Tentative inventory of abiotic parameters (in Dutch). 

**Content**
In the scope of maintenance and improvement of existing slufter or salt dune valleys there is a need for better knowledge on the morphological characteristics of slufter. This study was a start to find such characteristic relations.

**Comment**
Information on slufter (Slufter on Texel and Zwin in Zeeland), salt dune valleys and salt marshes. Unfortunately, the follow-up study on systematic rules was not executed.

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**Effects of future sea-level rise and subsidence on the Wadden Sea tidal system; Sediment dynamics and biology; What do(n’t) we know?**

**Content**
Contributions of different institutes on different disciplines such as geology, morphology, subsidence, hydrodynamics, biology and modeling.

**Comments**
General information on state of the art.

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**Study on the arrangement of the eastern part of the Western Scheldt, Analysis of the physical system (in Dutch).**

**Content**
Extensive literature survey on the morphology of the Western Scheldt estuary considering geology, geography, hydrography, morphology, sedimentology, impact of dredging and a conceptual model based on empirical relations.

**Comment**
The report presents a lot of data on the Western Scheldt estuary and valuable analyses of processes and impact of men, which also can be of great value for the understanding of processes in the Wadden Sea.
Channel migration in outer deltas (in Dutch)

Content
Extensive literature survey on the causes of channel migration in outer deltas. The report describes the processes at work and presents extensive quantitative analyses of the relative importance of the different processes and a number of empirical relations.

Comment
The report presents basic knowledge on channel migration and a number of suggestions for mathematical modelling of this process.

Channels in estuaries, 1-D modelling of parallel channels (in Dutch)

Content
Extensive literature survey on the behaviour of channels in estuaries. The report describes the processes at work and presents extensive quantitative analyses of the relative importance of the different processes and a number of empirical relations.

Comment
The report presents basic knowledge on channel behaviour and a number of suggestions for mathematical modelling.

Dynamics and sedimentary development of the Dutch Wadden Sea with emphasis on the Frisian Inlet, A study of the barrier islands, ebb-tidal deltas, inlets and drainage basins.
A.P. Oost, Univ. of Utrecht, Fac. of Earth Science, Publ. No. 126 (Thesis).

Content
Extensive general description of historical developments and morphological processes in the Dutch Wadden Sea and the Frisian Inlet system in particular.

Comment
A lot of historical data and information on bed forms.

The morphodynamics of the Wadden Sea on different space and time scales (in Dutch).

Content
General description of the morphology of the Wadden Sea. The different units of the system are classified on different hierarchic levels with different times of response.

Comment
Also this report presents a general description of the morphology of the Wadden Sea and a number of empirical relationships for characteristic morphological units derived from literature.
The riddle of the sands. A tidal system’s answer to a rising sea level (English version). Het mysterie van de Wadden. Hoe een getijdesysteem inspeelt op zeespeigelstijging (Dutch version).

Content
This report is a final publication based on the results of the ISOS studies of which ISOS*2 concerned the morphological part. The report gives a clear picture of the genesis and the morphology of the Wadden Sea. It also describes the possible effects of increased sea level rise and human interference (like closure works, sand mining and bottom subsidence due to gas mining) on the morphology and ecology of the area.

Comment
A good report for the general understanding of the system of the Wadden Sea.

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2 Morphological (impact) studies


Content
The report presents a brief description of the history of coastal development of the Dutch coast and the impact of human interference particularly in the past 100 to 150 years. Further, it describes two conceptual models, i.e. one for a uniform coast and one for tidal inlets and estuaries. Based on these models and historic data an attempt was made to predict the development of the North Sea coast for the next 100 years.

Comment
Conceptual model for a uniform coast and first version of a conceptual model (MORRES) for estuaries and lagoons describing the sand demand of a tidal basin system due to human interference under conditions with constant sea level rise.

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Morphological and ecological effects of sea level rise: An evaluation for the western Wadden Sea.

Content
Publication of a study on the building of the ISOS model for the Netherlands to support decision-making in the context of sea level rise. Part of the paper describes the principle of time lagging in the response of the bottom of the Wadden Sea and the effect on the tidal flat area. Another part describes the possible impact on the ecosystem.

Comment
Principle of sea bed response in the Wadden Sea in case of (sudden) change in sea level rise as included in the present version of MORRES.

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Coastal defence Eierland (Texel), Hydraulic morphological impact study, Phase I (in Dutch).

Content
Preliminary study on the erosion problem of the northwestern coast of the island of Texel and investigations on possible coastal defence structures with emphasis on a solution with a long groyne.

Comment
Application of UNIBEST.LT and CL, DUROS and DUROSTA, TRISULA and SCOUR.
Evaluation seaward coastal defence, Texel-Eierland groyne (in Dutch).

**Content**
The report describes the historical development of the northeastern coast of Texel and the actual development of the coast and the seabed after construction of a long groyne.

**Comment**
Comparison between prediction and reality.

Evaluation of seaward coastal defence (in Dutch)

**Content**
Description of the actual developments around recent coastal defence works in The Netherlands, i.e.:
- Texel-Eierland
- North-East Vlieland
- West-Ameland
Further, potential locations for seaward coastal defence are discussed.

**Comment**
Comparison between prediction and reality.

Gas extraction at East-Ameland, impact of bottom subsidence (in Dutch)

**Content**
The report presents a prediction of hydraulic, morphological, ecological and economic impacts in the Wadden Sea and on Ameland caused by bottom subsidence expected due to gas extraction.

**Comment**
Application of a coastline model to predict the long-term development of the North Sea coast without and with bottom subsidence.
Monitoring impacts of bottom subsidence at East-Ameland, Evaluation after 13 years of gas extraction (in Dutch)

Content
The report describes the impacts of bottom subsidence after 13 years of gas extraction. Until now hardly any effects could be found which actually are caused by bottom subsidence. Most of the changes are caused by the strong dynamic behaviour of the area.

Comment
Comparison between prediction and reality.

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Bottom subsidence due to gas extraction in the Wadden Sea, Effects on sand demand and tidal flats according to computations with the morphological response model MORRES (in Dutch).
In: Effects of bottom subsidence due to gas extraction in the Wadden Sea (in Dutch).

Content
Study on the additional sand demand and loss of tidal flat area of the Dutch Wadden Sea due to gas extraction.

Comment
Application of MORRES.

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Integral Bottom Subsidence Study Wadden Sea, Geomorphology and Infrastructure (in Dutch).
Effects of bottom subsidence due to gas extraction at the Wadden Sea, Morphological, Infrastructure and economical aspects.

Content
The impact of the total subsidence of all gas fields affecting the Dutch Wadden Sea was studied. Important aspects where the impacts on the tidal flat areas (reduction of level and area as a boundary condition for bird life in this natural reserve) and on the North Sea coasts of the islands. These impacts were studied for the Frisian tidal inlet with the models ESTMORF, ASMITA and MORRES. Further MORRES was used to extrapolate the ESTMORF and ASMITA results to the other tidal basins.

Comment
Application of ESTMORF, ASMITA and MORRES.
3 Morphological models

A model of the morphological behaviour and stability of channels and flats in tidal basins.

Content
The report presents a brief description of the general features of a tidal inlet with an overview of empirical relationships that have been derived. Further, it presents an analytical model analyses of the sedimentation history in a prismatic tidal channel which shows that the cross sections in the channel gradually will adapt to the local tidal flow volumes in agreement with the empirical relationship for a channel cross section. This situation actually corresponds with a situation without a tide averaged longitudinal sediment transport gradient. Without tidal flats the net sediment influx remains and the channel ultimately will completely silt up. The effect of channel geometry on the tidal propagation in the channel was investigated with a 1D numerical tidal model (WENDY) for a number of schematized situations. It appears that the tidal flats cause a distortion of the tide which results in a situation where the net sediment influx reduces and an equilibrium can be reached. Finally, a 1D tidal basin model was built in which the morphological steering parameters are based on empirical equilibrium relationships selected from literature.

Comment
This model was a first step to the development of ESTMORF. A weak point is that the adaptation process in the model is determined by a constant characteristic time scale which has to be adopted. Also the equilibrium ratio for tidal flat area is prescribed based on a relationship which is not generally applicable.

MORRES (MORphological RESponse model for tidal basins)

Model description
MORRES is a sediment balance model of a tidal basin system of the Wadden Sea consisting of an outer delta, a tidal inlet and a basin. The volumes of all units are related to the tidal prism in the throat of the tidal inlet described by empirical relationships. The model can handle two types of disturbances in the dynamic equilibrium of the system, i.e. sudden changes due to human interference and gradual changes due to a discontinuity in relative sea level rise by global heating or bottom subsidence. The model presents the time history of the sand demand of the system and the adaptation rate to the new equilibrium situation. Besides, it presents the time history of the change in tidal flat area (not described in the ISOS-Phase 3 report). That information should be regarded as tentative information.

Comments
Two models are available at WL | Delft Hydraulics, i.e. a model in BASIC which also has been implemented in a LOTUS version for the Dutch Wadden Sea (of August 1993) presented to RWS-DGW. The latter includes hypsometric curves of all tidal basins of the Dutch Wadden Sea which are used in the computations. The model is suitable to get a quick impression of possible impacts of changes in the system.
Morphodynamics of estuaries, A literature survey.

Content
The report presents an overview of physical processes in estuaries and the way nature responds to human interference, of empirical relationships that have or can be used in numerical modelling and of recently achieved progress in morphological modelling.

Comment
This study was made in the scope of the DYNASTAR project, which ultimately resulted in the development of ESTMORF.

ESTMORF (ESTuarium MORFologie).

Model description
ESTMORF is a numerical model for long-term morphological developments due to a disturbance in an estuary or tidal basin, which initially was in a state of dynamic equilibrium. The model computes the tidal motion in a 1D-network schematisation of the outer delta-tidal basin system. The morphological response to a change in the system is computed with a morphological module in which changes in the sediment transport relative to the equilibrium situation are determined by parameters based on empirical equilibrium relations. So, basically, it is a sediment transport model in which the chain of reactions induced by a local disturbance is properly simulated until a new equilibrium is reached.

Comment
The model has a stable computational scheme and is capable to show the impact on the system in great detail. The model is not capable of simulating natural changes such as channel migration (the channels are fixed).

ASMITA (Aggregated Scale Morphological Interaction of Tidal basin and Adjacent coast).

Model description
The model is a mix of the MORRES an ESTMORF models. It basically schematises the situation around a tidal basin into three main units, i.e. the seacoast, the outer delta and the tidal basin. The basin is subdivided into a flat area and a channel area each with a fixed area; the depth is variable. Also the outer delta has a fixed area with variable depth. The coast can be subdivided in sections, where each section consists of an area representing the foreshore (with constant depth and variable width) and a seaward sea area (with a constant width and variable depth). The flow conditions in the tidal basin are characterised by the tidal prism in the inlet. The sediment transport is described as tidal volume times a characteristic suspended sediment concentration. In case the equilibrium situation is disturbed locally the sediment transport capacity will change resulting in a change in sediment exchange between the different unit resulting in a chain of sedimentation and erosion reactions until new
equilibrium is reached. The change in local transport capacity is related to the relative disturbance from the empirical equilibrium relationship for the morphological unit.

**Comment**
ASMITA is meant to predict the impact of changes in a tidal basin on the seacoast adjacent to the tidal inlet. A brief description of the model is presented in the report on Geomorphology and Infrastructure of the Integral Study on Bottom Subsidence Wadden Sea, NAM, December 1998.

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**DELFT3D-MOR.**

**Model description**
DELFT3D is a numerical package based on the finite difference method. It is capable of 3D (multi layer flow) or 2DH modelling of tidal flow (FLOW module) and, among others, sediment transport (sand or silt) and morphological changes (either SED or MOR module). This is the standard package of WL | Delft Hydraulics for short-term morphological problems. The package also includes a Rapid Assessment Module (RAM) for medium to long-term morphological developments with the 2DH mode.

**Comment**
State of the art model tidal areas exclusive coastline development. Developments to include the functionalities of coastline models (coastal erosion/accretion and dune erosion) in DELFT3D are in progress.

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**UNIBEST (UNIform Beach Sediment Transport model).**
WL | Delft Hydraulics.

**Model description**
UNIBEST is a model package for studies of sandy coasts with more or less uniform beach profiles. UNIBEST.LT computes the littoral drift along the coast for a given wave climate at deep water and can generate a relation between the net littoral drift and different coastline orientations around the actual orientation. This serves as a boundary condition for coastline computations with the UNIBEST.CL module. This module is based on the one-line theory and is based on a curvi-linear grid. With this model the impacts of structures (harbours, groynes, and detached breakwaters) on the coast and mitigating measures to stop coastal erosion can be investigated.
The UNIBEST.CT module can be used to compute cross-shore transports and dune erosion during storms.

**Comments**
State of the art package for coastal studies.

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A Fuzzy Expert System to assess the effects of climate change on the ecosystem of the Wadden Sea.

Content
The report describes the possibilities of determining the impact of climate change on the Wadden Sea ecosystem by an expert system based on the fuzzy set theory.

Comment
Application of new methods.

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Area models of coastal morphology

Content
This report describes the latest developments to improve the coastal area model DELFT3D.MOR in the scope of the MAST project. The report shows results on validation of the model against measured developments at various locations along the Dutch coast, results on attempts to improve the landward boundary conditions to include the behaviour of the dry beach and dunes, and to improve the capability of 3D computations. All these developments are still in an experimental stage but show good possibilities.

Comments
All these developments are still in an experimental stage but show good possibilities for the near future.

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Modelling of secondary flow and 3D sediment transport in the Western Scheldt (in Dutch).

Content
The report presents the results of quasi-3D computations. The effect of lateral secondary flow on sediment transport and bar formation near Hansweert has been tested as well as the possibility of improving the present formulation for longitudinal secondary flow. Results have been compared with field data and results of 3D computations.

Comment
Research on improvement of the DELFT3D package.