Report on **NCK themadag "The sediment balance of the Wadden Sea"**,
Museum Boerhaave, Leiden, 10 October 2014

Organized by T. Gerkema (NIOZ, Texel) and H.M Schuttelaars (TU Delft)
Sponsored by ALW/NWO and NCK.

Summary of presentations:

T. Gerkema (NIOZ): Introduction

The overarching aim of this symposium is to look at the different elements of the Wadden Sea (outer deltas, basins etc) in connection to each other, exploring the balance with numerical or idealized models, and to identify related issues in coastal management.

The difficulties of determining the long-term (im)balance are discussed. Observationally, there are two methods. In the first, one examines the *process* by measuring the sediment fluxes through the inlets and across watersheds; in the second, one examines the *result* by measuring the changes in bathymetry. It has long been known that both have formidable obstacles (e.g. Van Straaten, 1975). For the first, these obstacles are the strong variability (in magnitude *and sign*!) on a wide range of timescales (tides, spring-neap cycle, seasonal, episodic storms...) and the limited spatial reach. For the second, the obstacle lies in the fact that erosion at one place is largely compensated by deposition elsewhere (movement of channels and islands); in the end, net effects are often too small to be measured reliably at timescales shorter than decades, especially on intertidal flats. This is illustrated by examples from Louters & Gerritsen (1994). Numerical or idealized models could in principle overcome these obstacles, but this hangs on a correct representation of erosion and deposition processes.

A final, more philosophical note is in praise of *erosion.* This word, also in metaphorical usage, has a distinctly negative flavour. However, the physical geographer (and novelist) W.F. Hermans once remarked: "*De aarde, zoals zij zich thans aan ons vertoont, zou niet denkbaar zijn zonder erosie. De mens, al in de meest primitieve beschavingsvorm een erosieve factor van groot gewicht, zou zonder erosie nooit zijn ontstaan. Het is heel wel mogelijk juist de erosie op te vatten als het voornaamste element dat een dynamische planeet als de aarde onderscheidt van een dood hemellichaam zoals, bij voorbeeld, de maan.*"

L.M.J.U. Van Straaten, *De sedimenthuishouding van de Waddenzee*, In: Symposium Waddenondezoek, Med. nr. 1 Werkgroep Waddengebied, 1975.
T. Louters & F. Gerritsen, *Het mysterie van de Wadden: hoe een getijdesysteem inspeelt op zeespiegelstijging*, report RIKZ-94.040, 1994. (online available at TU Delft repository)
W. F. Hermans, *Erosie*, Heijnis (Zaandijk), 1960 (citation from p. 10)

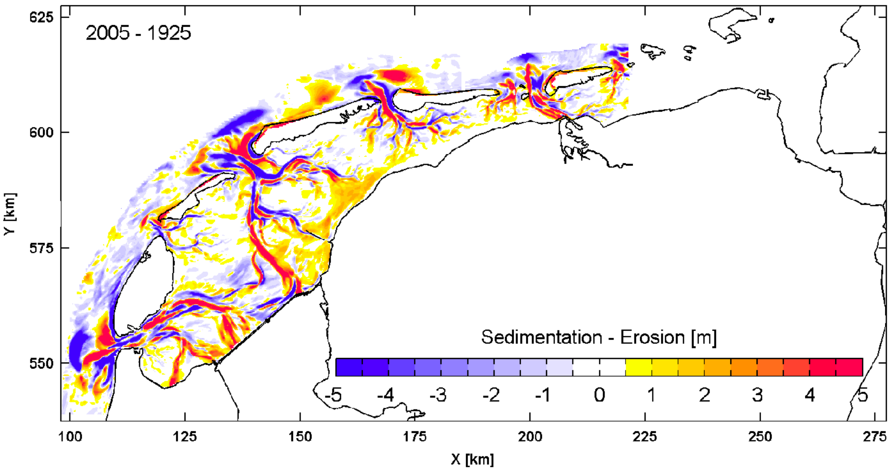
A.J.F. van der Spek (Deltares): Morphodynamic development and sediment budget of the Wadden Sea over the last century

The presentation starts with an overview of the geological background of the Wadden Sea. During the penultimate glacial period (Saalian), the Texel high was formed (*stuwwal*). Because of this 'high', the area became part of the Wadden Sea at a relatively late stage (e.g. Marsdiep was formed around 1200 AD) and this stamps, to the present day, the differences between the western and eastern parts of the Dutch Wadden Sea.

A map illustrates what would have happened if sealevel-rise after the last glacial (Weichselian) had transgressed unhindered over the Pleistocene ground: the present-day western and northern provinces would have been largely non-existent. The fact that this did not happen is due to accumulation of Holocene sediment in the coastal zone. Sea-level rise not only caused flooding but also introduced a powerful agent for sediment transport: water waves and tidal currents. Their combined effect shaped the coastal zone, either as transgression or regression, depending on the rate of sea-level rise (creating room for sediment storage – the demand side) and availiblity of sediment (the supply side). In the earlier stages (around 5800 BP), the rate was so high that trangression dominated, but at later stages, when the rate of sea-level rise declined, barrier-island systems filled up, part of the coast (North and South Holland) became closed, and regression occurred. During the Middle Ages, the Wadden Sea extended westward (around the Texel high), mostly due to human activities (peat extraction, drainage etc), but also due to continuing sea-level rise, making the area susceptible for flooding and transgression.

In the present day, where does the sediment entering the Wadden Sea come from? Overall, it stems from erosion along the coast of Holland as well as from the sea-side of the islands. (This discussion refers to *sand*; for finer, suspended sediment, the main source comes from father south, the Channel. Overall, the Holocene sediment deposits in the Wadden Sea consist of about 80% sand and 20% silt, Beets & Van der Spek, 2000.)

In the past century, major human interferences were: the closure of the Zuiderzee (Afsluitdijk, 1932), the closure of Lauwerszee (1969), large sand nourishments along the Dutch coast (since 1990, order 10 million cubic meter per year). The first of these affected mainly the Marsdiep-Vlie basin, the second, the Friesche Zeegat. The intermediate inlet, Borndiep, has been relatively undisturbed. The closure of Zuiderzee enlarged the tidal range and tidal prism in the Marsdiep basin.



The bathymetric data from the *Vaklodingen* illustrates the main trends (see Figure). In the Marsdiep basin, an estimated accumulation of 4.6 million m³ per year occurred in the period 1935-1990 (mainly filling up the channels and gullies near the Afsluitdijk), which is reversed in the period 1990-2005 to an estimated loss of 1.3 million m³. During that last period, the Marsdiep and Eierlandse basins show a net loss, the more eastern basins a net gain. In distinguishing different basins, it should however be noted that their delineation is not fixed in time but is itself 'on the move'. For example, the Marsdiep basin has slowly extended itself eastward, at the detriment of the Vlie basin. The two, taken together, show a net gain in sediment in the period 1990-2005.

The effect of nourishments is most clearly visible in the balance along the coastline, which shows a decrease before 2001 but a stabilization since. Meanwhile, erosion at the outer deltas continues.

For the Wadden Sea as a whole, sediment accumulation has more or less kept pace with sea-level rise (2 mm/yr). The import depends on the supply from (shrinking) ebb-tidal deltas and bounding coast and barrier islands.

Outstanding questions are: 1) the identification of the mechanisms for import, and 2) how much 'demand' for sediment still exists in the relatively open western part of the Wadden Sea, with its low abundance of intertidal flats.

D.J. Beets & A.J.F. van der Spek, *The Holocene evolution of the barrier and the back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply.* Neth. J. Geosc. 79, 3-16, 2000.

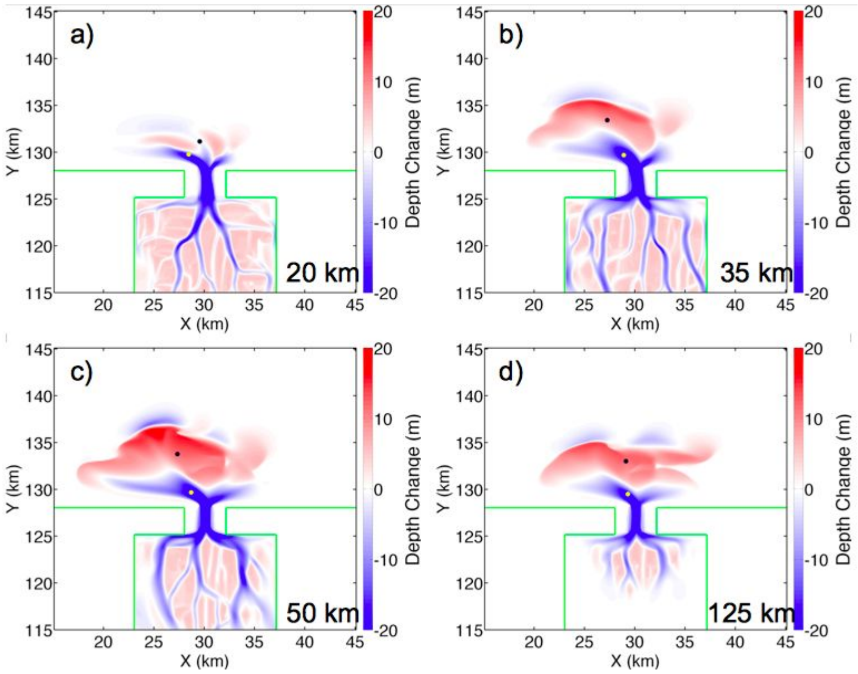
E.P.L Elias, A.J.F. van der Spek, Z.B. Wang & J. de Ronde, *Morphodynamic development and sediment budget of the Dutch Wadden Sea over the last century.* Neth. J. Geosc., 91, 293-310, 2012.

W. Ridderinkhof (IMAU, Utrecht Univ.): Influence of the back-barrier basin length on the geometry of ebb-tidal deltas.

In this presentation, the focus lies on the Marsdiep-Vlie basin, the area most affected by the closure of the Zuiderzee (1932). For example, the tidal range at Harlingen increased by about 50% (from 125 to 180 cm). Also, the tidal prism of the Marsdiep increased by about 30%. After the closure (1935-2005), in the Marsdiep-Vlie basin a decrease of the ebb-tidal delta volumes and a net sedimentation in the back-barrier basin has been observed. (The combined loss in the deltas is of the same magnitude as the combined gain in the basins.) Apart from the volumes, also the shape of the ebb-tidal deltas changed: asymmetry became more pronounced with the channels tilting leftward (i.e. opposed to littoral drift).

With the closure in 1932, the *length* of the back-barrier basin has changed. Hence, the research questions are: what is the effect of the length of a back-barrier basin on 1) the net sediment transport in a tidal inlet? 2) the sand volume and the asymmetry of an ebb-tidal delta? 3) Does this explain (part of) the changes in the Marsdiep and Vlie Inlets? Two techniques are used: an analytical model with an idealized inlet system and a numerical model using a similar set-up as an initial state. This idealized inlet system consists of one inlet that connects a sea to a rectangular back-barrier basin.

In the analytical model, tidal motion is induced by imposing a tide at sea. The model is an extension of that of Speer & Aubrey, 1985. Additionally, the basin length is varied, an inlet is added to the domain, and radiation damping and an asymmetric tidal forcing are considered. Due to nonlinear interactions, residual currents and higher harmonics (M4) are formed inside the inlet and basin. The resulting velocity at the mouth of the inlet is determined as a function of the basin length and the tidal-flat width and used to compute the local net sediment transport. For the latter, a simple transport formula: $Q_{tot}=\alpha\ u^3$ is used. The direction of the net sediment transport depends on the phase of the semidiurnal tidal (M2) velocity with respect to the M4 velocity, as well as on the relative magnitude of the seaward-directed residual current. If an M4-tide such as present at the North Sea is added to the imposed tide, the import of sediment is much enhanced for relatively short inlets (the state after closure). This is because the phase difference between the velocity components of the imposed M2- and M4-tides depends on the length of the back-barrier basin, despite the fact that the phase difference between the vertical components of the externally imposed M2 and M4-tides has a prescribed value.



In the numerical model, changes in bathymetry are considered, as a result of the sediment transport (modeled with Van Rijn '93 formula). After 60 years, a channel system has formed with an outer delta, the size of which depends on the basin length (see Figure). So does the asymmetry of the delta, quantified as a leftward shift of the center of mass of the ebb-tidal delta. (At some point, lengthening the basin further has little effect, as the reflection of the tidal wave will be dampened by friction.) The effect of an M4 component such as present seaward of the Texel and Vlie Inlets causes sediment import for short basins, but export for long basins. This agrees with both the observations and with the results of the analytical model.

W. Ridderinkhof, H.E. de Swart, M. van der Vegt & P. Hoekstra, *Influence of the back-barrier basin length on the geometry of ebb-tidal deltas.* Ocean Dyn. 64, 1333-1348, 2014.

W. Ridderinkhof, H.E. de Swart, M. van der Vegt, N.C. Alebregtse & P. Hoekstra, *Geometry of tidal inlet systems: A key factor for the net sediment transport in tidal inlets.* J. Geophys. Res. Oceans, 119, doi:10.1002/2014JC010226

J. Hofstede (MELUR, Schleswig-Holstein): The Wadden Sea – out of hydro-morphological steady state!

Under the assumption that – sooner or later – the Wadden Sea will leave its present hydro-morphological steady state due to accelerating SLR, some hypotheses are presented on the timing and localization of expected changes:

- Increasing tidal range may delay the tipping point from steady to unsteady state;
- Basins with larger MTR (mean tidal range) may leave steady state later than basins with lower MTR;
- Drowning of inter-tidal flats may generally start from the sea and continue in a landward direction;
- Smaller sub-basins in the inner parts of the basin may leave steady state later than the more central and seaward parts of the tidal basin.

The assumption is that MLSR (mean sea-level rise) is accompanied by a rise in MTR (mean tidal range). This is illustrated by a long time series from three German tidal gauges (Norderney, Cuxhaven, Husum) showing a mean rise in MTR of about 20 cm in the past century, which is similar to the mean sea-level rise over the same period. Observations suggest that – over the last century – mean low-water level hardly changed, while the mean high-water grows over-proportionally, so that the MTR effectively grows at a similar rate as the mean sea-level itself. Model investigations on future changes in MTR in relation to MSL are in line with these observations.

One well-known steady state in Wadden Sea tidal systems is a strong linear relation between the cross-sectional area of a tidal inlet versus the tidal prism. Also, a clear relation is seen between PV (sub-tidal channel volume) and P (tidal prism). Empirically, a logarithmic relation is found in PV/(PV+P) against basin area. The logarithmic behaviour means that small basins undergo relatively strong changes in PV/(PV+P) and hence in morphologic adjustments. Finally, empirical data suggests that the mean height of tidal flats (measured with respect to mean high water) is rather independent of the mean tidal range.

Hofstede, J.L.A. (in prep.) *Theoretical considerations on how Wadden Sea tidal basins may react to accelerated sea level rise*. Zeitschrift für Geomorphologie / Annals of geomorphology. DOI: 10.1127/zfg/2014/0163

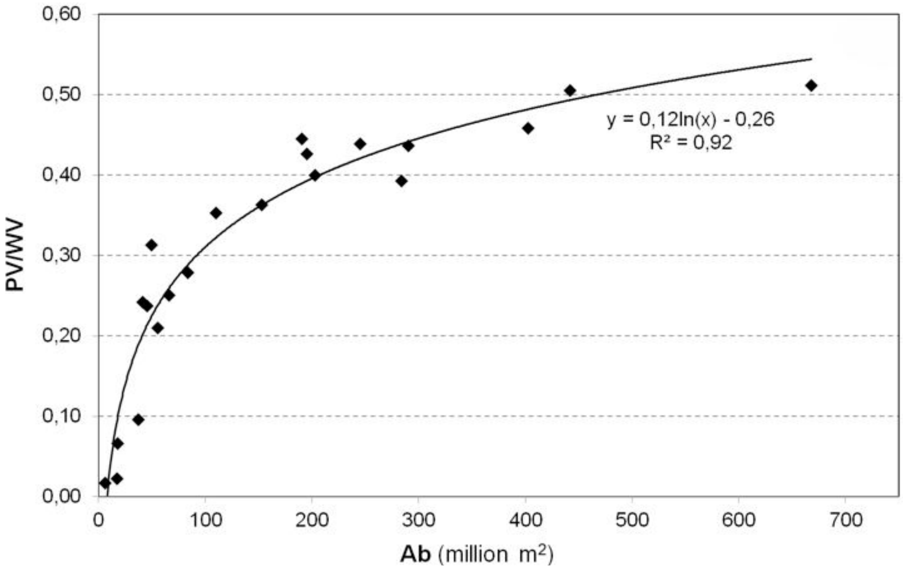


Figure: The proportion of sub-tidal channel volume (PV) to total water volume (WV = PV + P) in relation to basin size (Ab in million m2) for 21 tidal basins in the Wadden Sea.

M.G. Sassi (NIOZ, Texel): Assessing the sedimentary balance of the Dutch Wadden Sea: modeling the balance or balancing the model?

The presentation starts with an overview of the ZKO/BMBF `PACE' project, involving NIOZ, Deltares and IOW Warnemünde, HZG and Danish partners. The goal of the project is to set up a numerical model for the entire Wadden Sea, with realistic boundary conditions and forcing, for both hydrodynamics and transport of suspended sediment. Some focal areas will be studied in detail, one of which is the western Dutch Wadden Sea (this presentation). For this purpose, the GETM/GOTM/FABM model is used. We focus on the years 2009-2011.

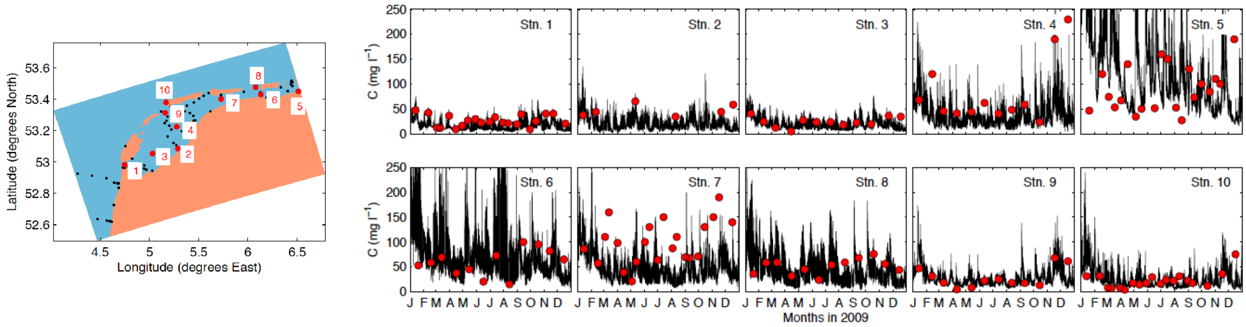
The model domain extends eastward to Rotummerplaat (where a 'wall' is placed on the watershed). In the horizontal, the resolution is 200m (but runs for testing parameter sensitivities are at 500m), in the vertical 10 or 30 layers are used (terrain following sigma layers). Sea-level elevations (tides and wind set-up) are derived from larger-scale models and are imposed at the open boundaries, the same for temperature and salinity. Atmospheric forcing is imposed at the free surface, and freshwater discharges are based on measured records.

A few examples are shown to demonstrate the accuracy of the model for the hydrodynamics (Duran-Matute et al., 2014, Sassi et al., 2015a). Two features come out clearly from the model. First, the importance of the watershed south of Terschelling: its long-term mean residual flow is of similar magnitude as the one for the Marsdiep, even though its tidal prism is 30 times smaller! Second, those residuals are not steady, but they fluctuate strongly depending on the wind. This episodic character underlines the importance of long time-series to get a reliable mean value.

For the transport of suspended sediment, three classes are used, defined by their settling velocities (w_s): 0.125, 1 and 2 mm/s. Erosion is modelled by a zero-order PK rsuspension model (single-layer): $E=M_0(\tau/\tau_c-1)^{1.5}$ and deposition by $D=w_sC$ (with concentration C). At the open boundaries the depth-mean C is prescribed. The initial state is given by a bed layer thickness of 1 mm and a uniform concentration of 10 mg/l. Spin-up takes 6 months.

The sensitivity to the two key parameters is tested by running the model for τ_c = 0.05, 0.25, 0.5 Pa, and M_0 = 0.005, 0.025, 0.05 gr/m^{2}s. This already produces 9 possible combinations. Furthermore, any of these can be picked for any of the three sediment classes, yielding a total of 9^3=729 possibilities. This unwieldy number of results is presented in condensed form. For the transport of suspended sediment in the Marsdiep (year 2009), the median of all realizations varies in time (because of wind effects), and this variation is of similiar magnitude as the changes brought about by different parameter realizations (interquartile range).

Applying the same parameter setting to each class gives nine possible realizations. The mean annual sediment flux through the Marsdiep appears to vary not only in magnitude for the different realizations, but also in *direction.*This demonstrates the extreme sensitivity to the parameter setting. It is particularly large for the mean annual transports across the watershed.



For one parameter realization (τ_c = 0.5 Pa, and M_0 = 0.005 gr/m^{2}s, applied to all three classes), a comparison with SPM concentrations RWS-MWTL data from 2009 is made for 10 stations (see Figure, red dots indicating measurements). The model values show a good correspondence, although the model's temporal variability is larger and more erratic at the landward ends of the channels at Lauwers and Zoutkamperlaag (stations 5 and 6) than the data. For the western Dutch Wadden Sea, the model shows a long-term net eastward flux across the watershed as large as the one in Marsdiep.

M. Duran-Matute, T. Gerkema, G.J. de Boer, J.J. Nauw & U. Gräwe (2014): *Residual circulation and freshwater transport in the Dutch Wadden Sea: a numerical modelling study*, Ocean Sci., 10, 611-632.

M.G. Sassi, T. Gerkema, M. Duran-Matute & J.J. Nauw (2015a): *Residual water transport in the Marsdiep tidal inlet inferred from observations and a numerical model.* J. Mar. Res., *subm.*

M.G. Sassi, M. Duran-Matute, T. van Kessel. & T. Gerkema, (2015b): *Variability of residual fluxes of suspended sediment in a multiple tidal-inlet system: the Dutch Wadden Sea.* Ocean Dyn., *subm.*

T. van Kessel (Deltares): Suspended sediment exchange North Sea – Wadden Sea: effect on sediment balance

The presentation starts with the water balance. The Dutch Wadden-Sea basin in the model (eastward end at

Rottumerplaat) covers an area of about 2000 km^2 at high water and 840 km^2 at low water. The combined tidal prism of all inlets is 3.1 billion m^3. The average freshwater discharge at Afsluitdijk is 450 m^3/s. The typical residence time lies between 1 and 10 days. Rainfall (840 mm/year) exceeds evaporation (560 mm/year). Modelling the hydrodynamics involves tides, wind effects (set-up and waves), salinity (freshwater discharge) and temperature.

Sediment transport involves movement by the water, movement in the water (i.e. settling, for mud affected by flocculation), deposition and erosion (additional factors for mud: consolidation, bio-turbation).

The mystery of the Wadden Sea is that although there is a net export of water through the inlets and a large tidal exchange with the North Sea, a net fine sediment import and sedimentation is observed in the Wadden Sea. This import goes against the gradient, as SPM levels in the Wadden Sea exceed those in the North Sea.

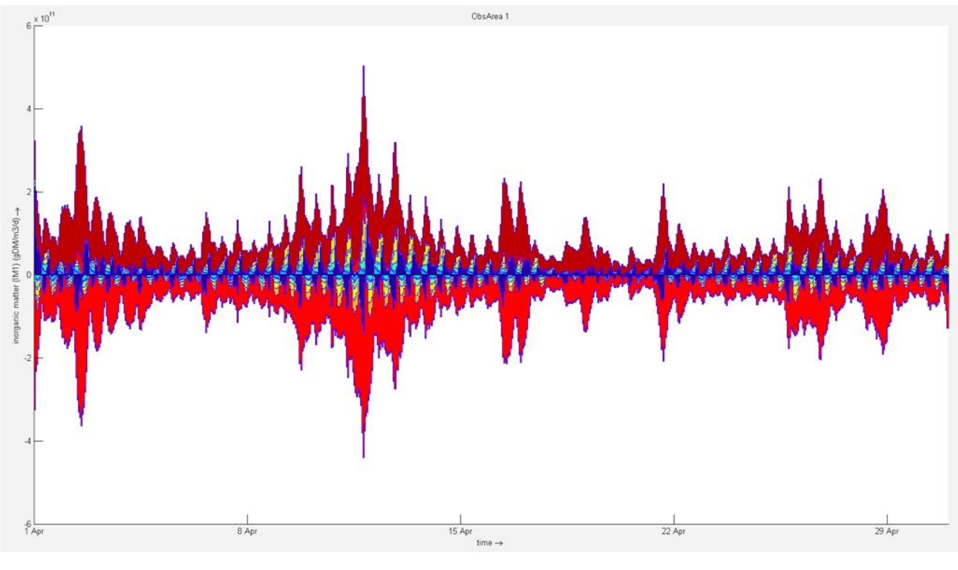
Various mechanisms for this have been proposed in the literature: tidal asymmetry, settling and scour lag, water level effects – i.e. mean depth variations at high and low water – tidal straining, estuarine circulation, and wave effects. Note that these mechanisms act quite differently on sand (high w_s) than on mud (low w_s).

Since the sediment enters via the inlets, it might seem natural to focus on those spots. But this doesn't take into account the *mud devil*! For sand, settling is fast, and mechanisms for net transport are at work *locally* (unless taking into account long-term morphological change at tidal-basin scale affecting the hydrodynamics within the inlets). For mud, on the other hand, larger distances are covered within a tidal period (order 10 km), because of slow settling, and the fate of the sediment is not (only) determined by local processes in the inlet but by global factors, notably by *sinks and sources away from the inlet.* In other words, for the same hydrodynamics, vastly different SPM levels and mud balances are possible (cf. previous talk and parameter sensitivities!). The 'external' sinks and sources are often poorly known and are highly dependent on local forcing and sediment properties, biotic factors etc. Modelling all this is a challenge and requires calibration.

Modelling and measuring are complementary: the weakness of one is the strength of the other. Measurements tell us the 'reality' but have poor spatial and temporal coverage, and is expensive to do. Models are cheap, provide data anywhere and anytime, but approaches reality only to some extent.

The best way forward lies in combining the methods, exploiting their strengths. Hence one needs 1) local observation to establish concentration levels and sediment properties, to be used for model calibration/validation; 2) one uses a numerical model to determine groass fluxes and temporal variability at time-scales from tides to seasons (incl. storms); 3) use global observations (Vaklodingen, Lidar, SIBES etc) to determine bed levels and composition, and their long-term net changes, hence net fluxes.

A preliminary sketch of the balance (per year) is given: the net effect of import and export is 2.1 Mt (import), the net effect of deposition and erosion is 1.6 Mt (deposition), finally there is an inflow via freshwater (0.56 Mt).



The variability (even within a month) is shown to be very large (see Figure), underlining the episodic character of the transports. Hence the concept of a `net mud balance' has only meaning for long time scales (years, decades).

van Kessel, T. (2015): Set-up and application of SPM model for the Dutch Wadden Sea. Deltares report 1209473-000-ZKS-0015, Delft, The Netherlands.

P.C. Roos (Twente Univ.): Observations of barrier island length explained using an exploratory model of multiple inlet systems

In this presentation, results from an exploratory, idealized model are shown that accounts for the interaction between inlets/basins. Empirical data suggest a connection between barrier-island length and tidal amplitude: larger tidal amplitudes corresponding with smaller islands and also with shorter inlet spacing. Also, inlet spacing decreases with increasing basin width. How can these characteristics be explained, as well as the stability of such multiple-inlet systems?

The model builds on the seminal paper by Escoffier. It considers the sand balance in one inlet, with a competition between wave-driven import and tide-driven export. For a given tidal-current amplitude, two equilbria exist with different cross-sectional areas, a stable and an unstable one. This model was later extended to double or triple inlet systems (Van de Kreeke, 1990, and later work).

Here the model is extended to an arbitrary number of inlets and takes into account spatial variations in water motion over the basin. The results fit into Hayes' classification system (stronger tides, more inlets *vs.* weak tides, few inlets).

An exploratory model like this helps to understand the possible changes in the multiple-inlet configuration brought about by external factors, such as basin reduction, dredging activities, sea-level rise or storm-induced breaches. It stresses the interaction between basins and hence the need for an integral approach.

F.F. Escoffier, *The stability of tidal inlets*, Shore and Beach, VIII, 114-115, 1940.
P.C. Roos, H.M. Schuttelaars & R.L. Brouwer, *Observations of barrier island length explained using an exploratory morphoduynamic model,* Geophys. Res. Lett. 40, 1-6, doi:10.1002/grl.50843, 2013.

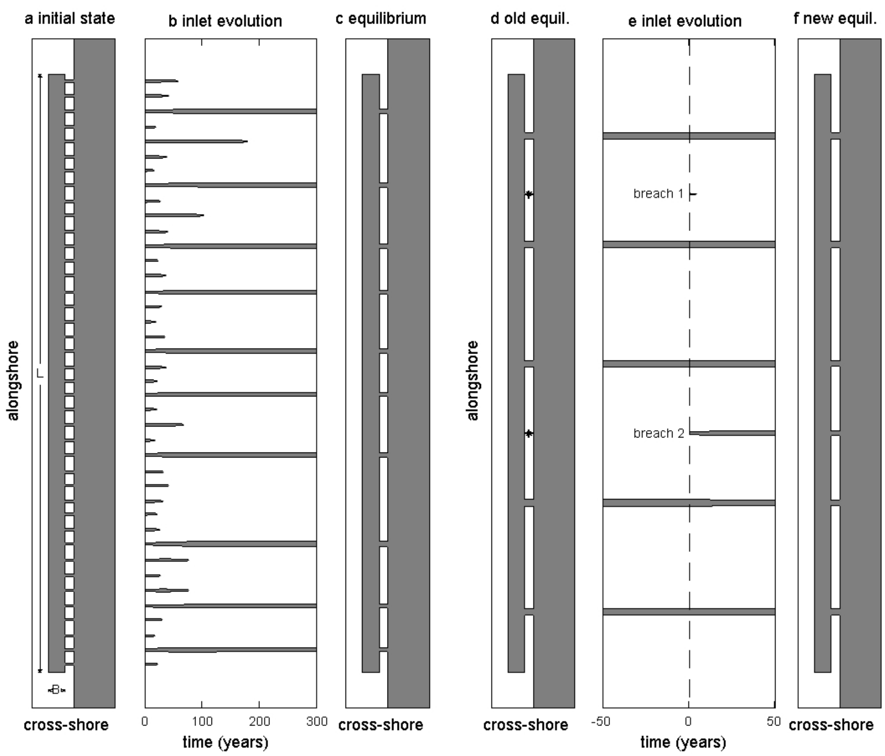


Figure: Two examples of model simulations carried out with the idealised multiple inlet model. Left: starting from (a) a large number of inlets, (b) gradual evolution towards (c) an equilibrium with multiple inlets open. Right: starting from (d) an equilibrium with two storm-induced breaches at t=0, (e) gradual evolution, during which one of the breaches is closed, towards (f) a new equilibrium state in which the other is still open. N.B. panels (b) and (d) are time stacks of the inlet width over time, the other panels are top views of the initial and final situation.