A "REFINED" APPROACH TO SEDIMENT BUDGETS. UNDERSTANDING THE SEDIMENT BUDGET OF THE WESTERN WADDEN SEA, THE NETHERLANDS.

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Abstract: The large influence of the Wadden Sea on the sediment budget of the Dutch coast is well known and seen as one of the reasons behind its structural erosion. Between 1933 and 2015, 367 million m^3 (mcm) of sediment was deposited in the Western Wadden Sea. Corrected for sand mining, dredging and dumping these volumes increase to 438 mcm. The largest changes occur in the basins of Texel Inlet and Vlie Inlet with increases in sediment volume of 272 mcm and 133 mcm respectively. Through the construction of a high-resolution sediment budget model we can estimate that the long-term accretional trend is 5.4 mcm/year. However, the present-day sediment import has reduced to 0.75 mcm/year. These significantly reduced import rates may have important implications for the future management of the Wadden Sea and its adjacent coastline.

Introducion

The Wadden Sea is a unique coastal wetland, consisting of an uninterrupted stretch of tidal flats and barrier islands that span a distance of nearly 500 km along the northern coast of the Netherlands and the North Sea coast of Germany and Denmark (Fig. 1). The large influence of the Wadden Sea on the sediment budget of the Dutch coast is well known and seen as one of the reasons behind its structural erosion. Among others, Stive et al. (1990) showed that the tidal flats in the Wadden Sea increase in height with sea-level rise. The sediments needed are delivered by the adjacent coastlines and result in structural coastal erosion. With the anticipated future changes in sea-levels, it is essential to better understand the sediment budget of the Wadden Sea for both the coastal erosion rates, but also the ability of the tidal flats to keep pace with sea-level rise.

Elias et al. (2012) concluded that the developments in the Wadden Sea are dominated by human interventions. Some of these interventions are evident such as the closures of the Zuiderzee (1932) and Lauwerszee (1969) that altered the basins dimensions and the hydrodynamic processes. Although these large-scale closures are the most noticable and drastic one-time interventions, an equally important change is that through time "fixed boundaries” formed around most of the Wadden Sea. Over the last century’s dykes, seawalls and shore-protection works were built to protect the hinterland, and to reclaim land. Although these protections sometimes failed in the past, nowadays dyke failure seldomly occurs and this basically means that the entire basin outline is fixed in place. Additionally, since 1990, the Wadden Island shorelines are stabilized with sand nourishments. This strategy keeps the islands dynamic, but their position remains more or less fixed as most of the coastline is not allowed to retreat behind its 1990 position. The realization that the natural hydrodynamic and morphodynamic processes now need to act within a fixed enclosure that bounds the Wadden Sea is an important constraint for the future management of the system. It also entails that processes that have occurred in the past, may not be representative for the future. As a result, a large uncertainty exists in predictions of the future morphodynamic state of the Wadden Sea. Assuming that the Western Wadden Sea needs to regain a similar morphodynamic configuration as the Eastern Wadden Sea (e.g. similar channel-flat configuration), it is estimated that another 900 million m^3 (mcm) to 1,500 mcm of sediment is needed and these volumes are likely to increase even further with (accelerated) sea-level rise (Elias et al., 2012). With such large numbers, it is essential to better understand the functioning of the Western Wadden Sea and its sediment budget. In this paper we present a new method of computing the sediment budget, that allows us to better estimate the present-day volume change rates. We summarize our findings in a conceptual sediment budget model for the Western Wadden Sea.

Fig. 1. An overview of the Dutch Wadden Sea. White lines indicate the partitioning of the individual tidal inlets and basins that form the Western Wadden Sea.

Understanding the morphodynamic changes in the Western Wadden Sea

Closure of the Zuiderzee

The Closure of the Zuiderzee, completed in 1932, is the largest single intervention ever constructed in the Wadden Sea. Preceding the closure, the Texel and Vlie tidal basins covered the southwestern part of the Wadden Sea and the former Zuiderzee (Fig. 2, left panel). In total, the basin covered a surface area of over 4000 km^2 with a basin length of 130 km. After the closure, the basin area was reduced substantially to an area of roughly 1500 km^2 (Fig. 2, right panel) and the length reduced to around 30 km.

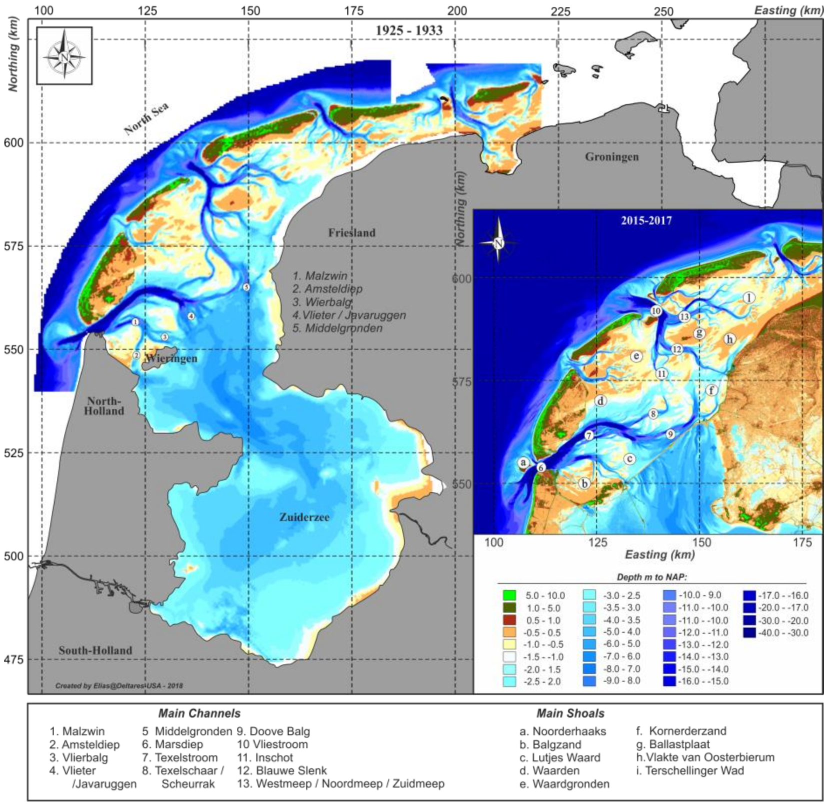

Fig. 2. Representative bathymetries for the Western Wadden Sea just before closure of the Zuiderzee (1926-1933), and the present-day configuration based on 2015-217 measurements.

The closure considerably altered the hydrodynamics and morphodynamics in the remaining, active part of the basin (Elias et al., 2003). The closure separated the back part of the basin (Zuiderzee) that was relatively shallow. Hence, the tidal characteristics changed from predominantly propagating to a more standing tidal wave, resulting in an increase of the tidal range and tidal prism through Marsdiep by approximately 26%. With these large changes in hydrodynamics and particularly in basin geometry pronounced changes in the morphology of the inlet have taken place. In the remaining active part of the basin the remaining shoal area was too small compared to the channel area, therefore, a morphologic adjustment of the basin was to be expected.

Sedimentation-Erosion Patterns

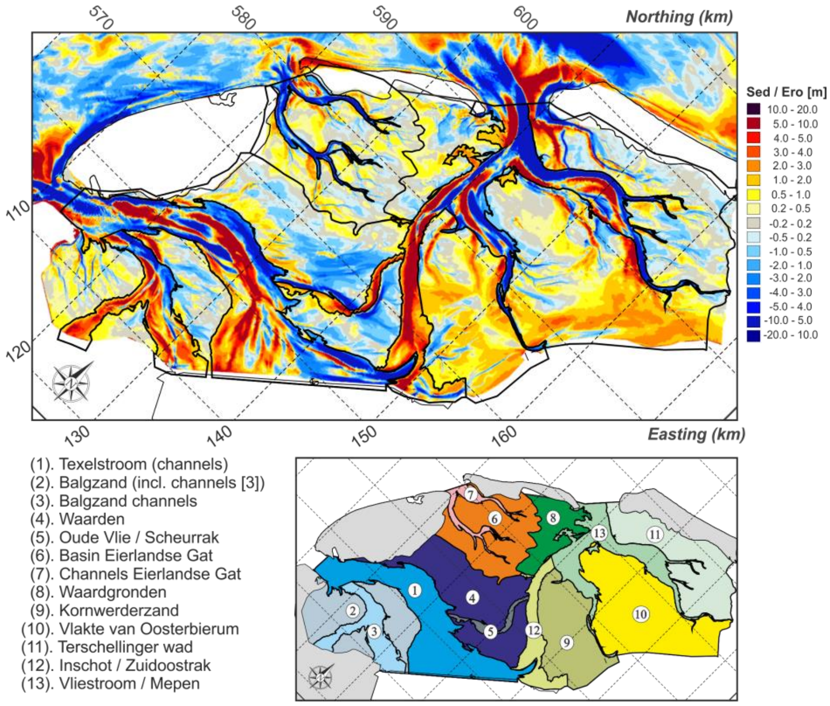

Fig. 3. Sedimentation-erosion of the Western Wadden Sea based on the bathymetries of 1933 and 2015. Warm (red-yellow) colors represent accretion and cold (blue) colors erosion. Polygons (black lines) show the subdivision in morphological units as used in the analysis.

The morphodynamic changes since closure are summarized in Fig. 3. The largest changes in the basin of Texel Inlet occurred along the closure dam. The closed-off channels (Malzwin, Vlieter and Middelgronden; see Fig. 2 for location) filled in as flow reduced to (near) zero. The main channel Texelstroom retained a stable position aligned with the coastal protection works along the southeastern side of Texel. The Doove Balg channel reoriented eastward along the closure dam, increasing in length and importance, and locally causing severe erosion. This long, large channel is a contributor to the large accretional area east of Doove Balg: the shoals Kornwerderzand and Vlakte van Oosterbierum along the Frisian coast. A large deposition is also observed in the former access channel Inschot-Zuidoostrak (see Fig. 3), that connected Vlie Inlet and the Zuiderzee, but is now closed off. The smaller Eierlandse Gat inlet only shows limited change in position of its main channels and shoals, but in general the channels have increased in depth while the shoals increased in height.

Data and Method

Available data

Basis of the present study is a series of bathymetric datasets, starting from 1925-1933. Data prior to 1985 were originally documented as analog charts, but were digitized in the nineties (see summary of data in de Kruif, 2001 and Elias, 2018). In total 6 maps can be reconstructed from these older datasets (Table 1). Since 1985, data is collected regularly using single-beam echo sounders and stored digitally. The ebb-tidal deltas and basins are measured in 3-year and 6-year intervals respectively. Following quality checking for measurement errors, data are combined with nearshore coastline measurements, interpolated to a 20x20 m grid, and stored digitally as 10x12.5 km blocks called "Vaklodingen". An additional 10 maps were created of which 6 maps have full coverage of coast, ebb-tidal delta and basin (Table 1).

Changes in survey techniques and instruments, and variations in correction and registration methods during the surveys over time make it difficult to estimate the exact accuracy of the maps. Wiegmann et al. (2005) and Perluka et al. (2006) estimate the vertical accuracy to range between 0.11-0.40 m. Estimates of volume corrections for dredging, dumping and sand mining, are based on the volumes presented in Rakhorst (1982), and Hoogervoorst (2005) and summarized in Table 2.

Table 1: Overview of bathymetric maps used to determine the sediment budget (cst = coast, etd = ebb-tidal delta).

year	**Texel Inlet**			**Eierlandse Gat**			**Vlie Inlet**		
	cst	**etd**	**basin**	**cst**	**etd**	**basin**	**cst**	**etd**	**basin**
1926	1925	1925	1933	1925	1930	1933	1926	1930	1933
1933	1925	1933	1933	1925	1930	1933	26/30	1933	1933
1950	-	1950	1951	-	-	1949	-	-	1951
1971	1971	1975	1972	1971	1971	1971	1972	1972	1972
1976	1971	1975	1977	1976	1976	1976	1976	1976	1978
1982	1980	1981	1982	-	1982	1982	82-88	1981	1982
1985	1987	1986	1985	1987	1987	1987	1988	1988	1988
1991	1991	1991	1991	1993	1993	1993	1992	1992	91/92/93
1994	1994	1994	-	1996	1996	-	1995	1995	-
1997	1997	1997	1997	1999	1999	1999	1998	1998	1998
2000	1999	1999	-	2000	2000	-	2000	2000	-
2003	2003	2001	2003	2002	2002	02-04	02/03	2002	02/03/04
2006	2005	2006	-	05/06	2006	-	2007	2007	-
2009	2009	2009	2009	2011	2011	2011	2010	2010	2010
2012	2012	2012	-	2014	2014	-	2013	2013	-
2015	2015	2015	2015	2017	2017	2017	2016	2016	2016

Table 2: Overview of volumes of dredging, dumping and sand mining

Location	Period	Sand Mining	Shell Mining	Dredging	Dumping
Texel Inlet					
Marsdiep	1948-2002	-	-	-61.8	+62.7
Malzwin	1955-1981	-29.5	-	-21.1	+21.1
Boontjes	1960-1980	-3.6		-22.5	+22.5
Eierlandse Gat	1970-1976	-	-0.04	-9.0	
	1979-1985	-	-	-2.5	
	1985-1995	-	-	-3.9	
	1967-1980	-	-	-	
Vlie	1952-2002	-20.8	-	-	
	1976-1980	-		-	+0.006
	1970-1980	-	-0.5	-11.3	+11.3
	1930-1955	-	-	-	-
	Total	**-53.9**	**-0.50**	**-118.4**	**103.7**

Method

Construction of sediment budgets is a powerful method to analyses volume change and understand the sediment exchange between the various elements of a coastal cell. Sediment budgets for the Wadden Sea, such as presented in e.g., Elias et al. (2012), have been based on the classic approach of subdividing the Wadden Sea in individual tidal basins, following the tidal divides (see white lines in Fig. 1 for present-day estimates of the tidal divide locations). Applying such an approach on the present data-sets results in the volume change timeseries displayed in Fig. 4.

In essence, results similar to Elias et al. (2012) are obtained for the volume change of the total Western Wadden Sea. Differences are present in the volume changes of the individual inlets as we use the present-day (2015/2017) locations of the tidal divides to distinguish between the basins (see Fig. 1). Between 1933 and 2015, 367 million m^3 (mcm) of sediment was deposited in the Western Wadden Sea. Corrected for sand mining, dredging and dumping, this volume increases to 438 mcm. The largest changes occur in the basins of Texel Inlet and Vlie Inlet with increases in sediment volume of 272 mcm and 133 mcm respectively. The volume change in the basin of Eierlandse Gat Inlet is smaller and net erosional (-38 mcm). Most of the accretion occured in the period 1933-1975 (314 mcm). Larger accretional values during this time frame are expected as with the closure of the Zuiderzee, large tidal channels were cut off by the closure dam that rapidly filled in with sediments. Based on a linear trend analysis the sedimentation rate over the entire time frame 1933-2015 is estimated at 4.0 mcm/year.

Since 1975 we observe a decrease in the volume changes, but large fluctuations dominate the signal. Unrealistic large changes of 100 mcm accretion and sedimentation between subsequent measurements occur (Elias et al., 2012). Such fluctuations cannot be explained by normal inlet processes and common sense, and are likely related to measurement (in)accuracies.

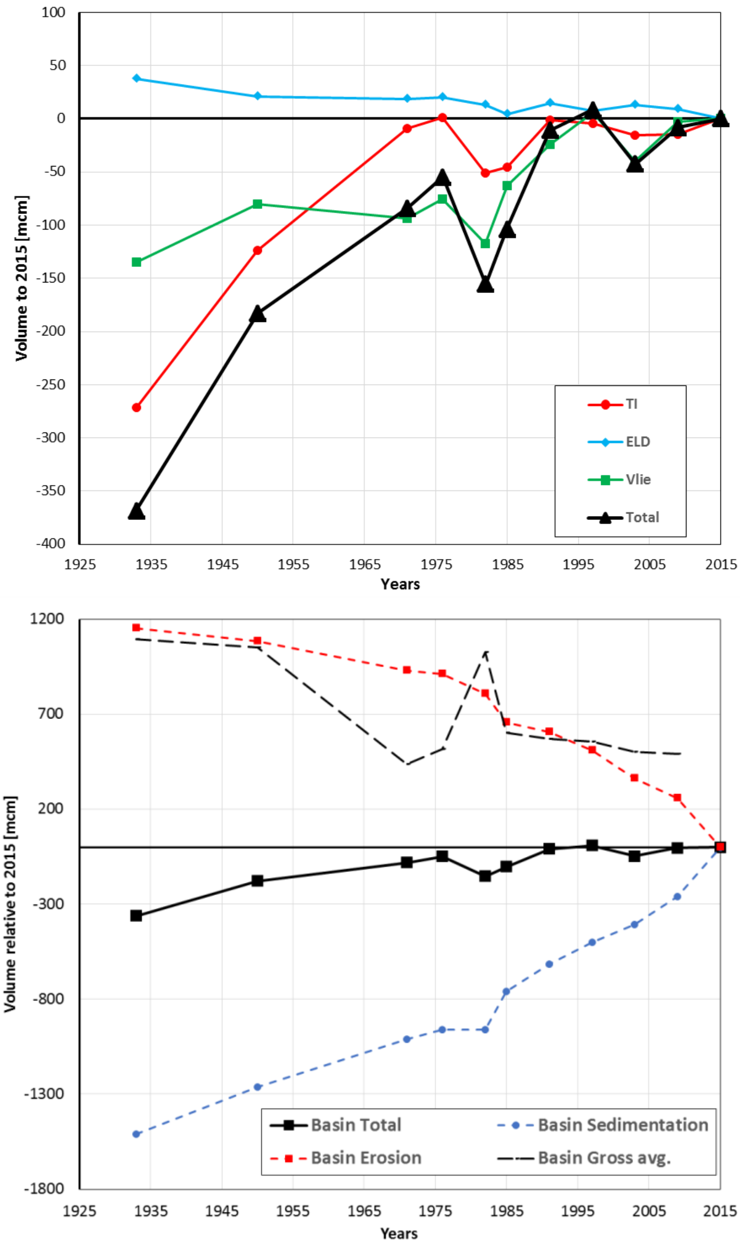

Fig. 4 top panel. Sedimentation erosion (1933-2015) for the 3 basins (Texel Inlet = TI; Eierlandse Gat inlet= ELD, Vlie inlet = Vlie) that form the Western Wadden Sea, see Fig. 1 for locations. Bottom panel: Net and gross volume changes for the Western Wadden Sea as a whole.

The surface area of each individual area is several hundreds of km^2 and small errors in surface area or height can result in large volume changes. Although the long-term trend of decreasing sediment deposition is clear, the fluctuations make estimates of the future sediment changes in the basin difficult and inaccurate. Such estimates are however essential for understanding the development and from that, sustainable management of the system.

A “refined” method of computing the sediment budget was applied to obtain representative estimates of the present-day sediment volume change rates. This revised method consists of the following steps:

1. Create a series of coherent bathymetric maps (as summarized in Table 1). Each map is visually inspected and obvious data outliers are corrected or excluded from the analysis.
2. Determine periods with coherent and representative sedimentation-erosion patterns. In the Western Wadden Sea the maps of 1933–2015 provide a representative pattern. For each sedimentation-erosional area polygons are defined (Fig. 3).
3. For each polygon, compile time-series of volume change and determine trend lines for long-term, medium-term and present-state behavior d (Fig. 5 and Table 2).
4. Summarize the results in a conceptual sediment-budget model of the Western Wadden Sea (Fig. 6).

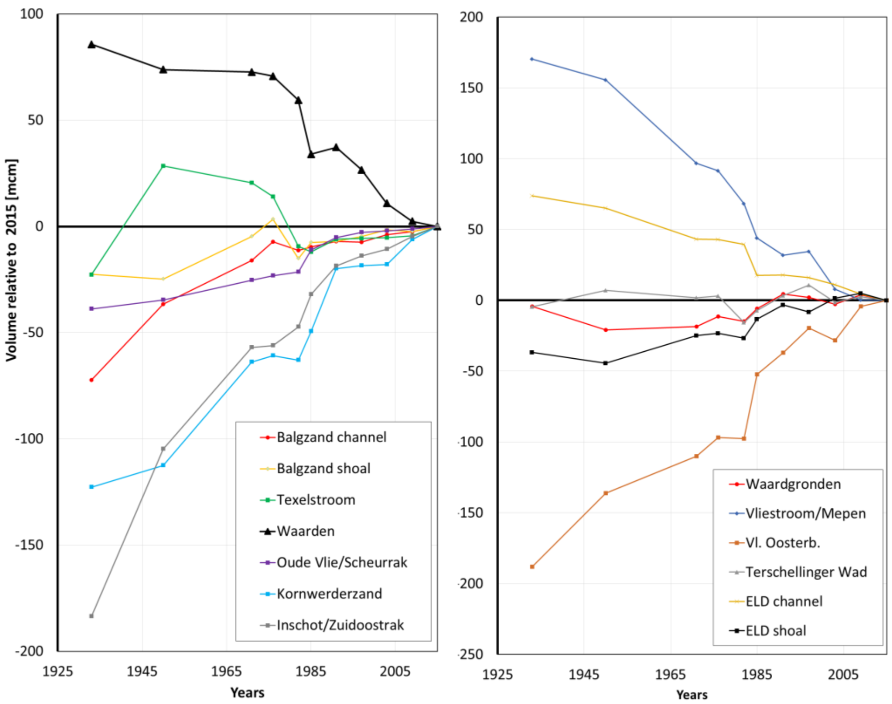

Fig. 5. Time-series of volume changes for the 13 polygons displayed in Fig. 3.

Table 3. An overview of computed trend values in the Western Wadden Sea

Area	**Long-term trend (1933-2015)**	**Medium term trend (1974-2015)**	**Present day trend**	**Present day Period**
Texelstroom	*-0.08*	*-0.08**	*0.09*	*1991 - 2015*
Balgzand shoal	*0.28*	*0.27***	*0.27*	*1991- 2015*
Balgzand channel	*0.77*	*0.31***	*0.31*	*1991 - 2015*
Waarden	*-1.15*	*-1.81*	*-1.64*	*1991 - 2015*
Oude Vlie	*0.55*	*0.55**	*0.22*	*1991 - 2015*
Eierland shoals	*0.60*	*0.75****	*0.75*	*1950 - 2015*
Eierland channels	*-0.96*	*-1.02*	*-1.08*	*2000 - 2015*
Waardgronden	*-0.21*	*0.44****	*0.11*	*1985 - 2015*
Kornwerderzand	*1.63*	*1.63*	*0.87*	*1991 - 2015*
Vl. van Oosterb.	*2.71*	*2.66*	*1.49*	*1991 - 2015*
Terschellinger Wad	*0.03*	*0.11*	*-0.11*	*1971 - 2015*
Vliesloot	*2.11*	*1.62*	*0.78*	*1991 - 2015*
West-/Oostmeep	*-2.35*	*-2.37*	*-2.13*	*1991 - 2015*
Totaal	***3.93***	***3.04***	***-0.08***	

* trend based on 1933-2015, ** trend based on 1991-2015, *** trend based on 1951-2015

Results and Analysis

A key element in the analysis presented here is the use of areas that display coherent morphodynamic behavior. If coherent behavior occurs over a certain time-frame, data outliers can easily be identified and excluded from the analysis. An additional advantage from this method is that trend lines are now available for the sub-elements in the basin. In addition to the large-scale behavior we can also describe the morphological trends for the individual channels and shoals. Note that our analysis was performed for each individual sedimentation-erosion area (see Elias, 2018), but for the results presented in this paper we regrouped areas to larger elements to create a manageable number of polygons (see Fig. 3). Estimates of the long-term (historic) trends are derived from the linear trend line over the period 1933-2015. The medium-term trends are based on periods starting between 1950-1971 to 2015. The medium-term trend eliminates the two oldest, potentially most inaccurate measurements from the analysis. A large difference between the long- and medium-term trends is an indication of (1) measurement inaccuracy or (2) large influence of the initial channel infilling due to the closure dam. By analysis of these differences, we can better assess whether the long-term trends are reasonable or not.

The short-term or present-day trends are based on time-frames starting between 1991-2003 till 2015. Instead of just using a fixed interval with possibly controversial starting points, we plot the whole array of trend lines starting from 2015 and increasing in length towards 1933. We take the longest trendline that still has good correspondence with the short-term trend. In general, trend lines starting around 1997-2003 provide a representative estimate of the present-day behavior. Our motivation behind this method is that the various elements in the Wadden Sea likely respond differently to the effects of closure. In some areas the response is near instantaneous, while other areas show a gradual decrease or ongoing linear trend.

In total 40 polygons (Texel inlet 17, Eierlandse Gat 9 and Vlie 17) were defined based on the sedimentation-erosion patterns. For each of the polygons the timeseries of volume changes and the trends were determined. We grouped the 40 polygons into 13 coherent areas (see Fig. 3). The resulting time-series are shown in Fig. 5 and trend values are presented in Table 3. With the exception of Texelstroom and Waarden, the polygons in the basin of Texel Inlet show an accretional trend. The relatively large volume fluctuations observed in the Texelstroom time-series are somewhat misleading. In this polygon, the net change is small compared to the gross-changes that are an order of magnitude larger. As a result, minor fluctuations in the erosion or deposition can already lead to distinct net volume fluctuations, even though the overall behavior of the channel does not change drastically. The recent changes show a small accretional trend. A larger deposition directly after closure seems logical due to the infilling of the blocked off channels near the closure dam (Fig. 3). Temporarily, erosion started to dominate as Doove Balg realigned with the closure dam and extended eastward. Continuous erosion is observed on the shoal area Waarden as both the main channel Texelstroom, and the shoal deposits migrate eastward. The latter is likely a result of the prevailing wind and wave directions. The present-day erosional value of -1.64 mcm/year for Waarden exceeds the long-term average value of -1.15 mcm/year. The use of higher resolution polygons allows us to clearly identify the 1985 map as an outlier (this map is also identified as an outlier in the other timeseries).

The largest sedimentation rates are observed in the shoal area Kornwerderzand and the channel Inschot-Zuidoostrak. This former main connection between Zuiderzee and Vlie inlet, completely filled in with sediments after it was closed off and abandoned. Sedimentation values significantly reduced from 2.11 mcm/year to 0.78 mcm/year for the present-day. A similar large reduction in accretion rate was also observed on the adjacent Kornwerderzand shoal from 1.63 to 0.87 mcm/year. Smaller but continuous sedimentation rates are observed on the Balgzand shoal (0.27 mcm/year). The Eierlandse Gat inlet shows a contracting behavior between the channel and shoal areas. The channels show a significant continuous erosion of -0.96 to -1.08 mcm/year, while the shoals increased in volume by 0.6 to 0.75 mcm/year.

In Vlie inlet, a similar behavior of large, continuous erosion of the remaining main channels (-2.35 to -2.13 mcm/year), and large-scale accretion on the main shoal area Vlakte van Oosterbierum exists. The accretion rate of this shoal reduced from 2.71 mcm/year for the long-term average, to 1.49 mcm/year for the present day. Smaller volume changes are observed along the tidal divide (Terschellinger Wad), for the present-day we estimate a small net erosion of -0.11 mcm/year as the channels extend eastward.

Discussion

The results of the trend analysis are summarized in Figure 6, in the form of sediment budget models describing the historic (1933-2015) and present-day changes (respectively top and bottom). To construct the sediment budget model we need to provide estimates of the exchange between the basins (green arrows in Figure 6). In the historic sediment-budget model, we estimate that 0.5 mcm/year of sediment is transported eastward over the Terschellinger Wad. Based on the sedimentation rates observed on Vlakte van Oosterbierum, the sediment transport from the basin of Texel Inlet to the Vlie basin is estimated at 1.5 mcm/year. Sediment exchange with the Eierlandse Gat basin is zero due to the well-developed shallow shoals that remain stable in position. With these estimates, and taking into account sediment loss or gain through sand mining, dredging and dumping, an average sediment import rate through the inlets of 5.4 mcm/year is found. Most of the sediments, 4.4 mcm/year are supplied through Texel Inlet. Sediment import through Vlie inlet averages 1.2 mcm/year, while in Eierlandse Gat inlet a small net export of -0.2 mcm/year occurs. In reality these rates are likely somewhat higher as we did not account for any addition volume losses caused by subsidence or compaction. The observed rates in the inlet compare well with the observed losses from the adjacent ebb-tidal deltas (Elias, 2018).

The present-day changes show a significantly reduced sediment import. Based on the observed basin changes only small imports of 0.25 and 0.01 mcm/year would remain at Texel Inlet and Vlie Inlet. Sediment export rates at Eierlandse Gat are slightly increased to -0.33 mcm/year. Applying similar assumptions as in the historic budget, but with a slightly decreased sediment exchange between Texel and Vlie Inlet (1.0 mcm/year), a sediment import rate of 1.25 mcm/year is computed at Texel Inlet. Both Eierlandse Gat and Vlie Inlet now show a sediment export of 0.3 and 0.5 mcm/year respectively.

The observed decrease of sediment import into the basin can be interpreted as a positive outcome for the coastal sediment budget, as this entails that the sediment losses from the open-sea coast to the Wadden Sea have reduced. However, for the basin the reduced import rate may pose a concern. Using the concept of Stive et al. (1990), we assume that, given sufficient sediment supply, the tidal flats in the Wadden Sea grow with similar rate as the sea-level rise. With an historic sediment import of 5.0 mcm/year and a flats surface area of the 750 km^2, theoretically a sea-level rise of around 7 mm could be accommodated. Following this reasoning, with the present-day predicted sediment export the Wadden Sea tidal flats would not be maintained. It is questionable if this is actually the case. In Figure 4 (bottom panel) we provide an overview of the net and gross volume changes wherein gross changes are defined as the total erosion or sedimentation volume. The net changes show the decreasing net volume changes, hence decreasing net import rates. However, these net changes are a result from an order of magnitude larger gross sediment transports. If we look at the gross averaged rates, computed as the average of the absolute values of sedimentation and erosion, then we observe that the gross transports only show a minor reduction over the past decades. This indicates that still large amounts of sediment are moved around in the basin (hence sufficient transport capacity), but the availability of potential sedimentation space (= locations where energy levels are low enough to allow for net sedimentation, small water depths, low current velocities) may limit the amount of accretion that actually takes place. As a result, only limited accretion occurs and one may consider the basin to be in an equilibrium state on the decadal time-scales. This equilibrium state is governed by a relative deep basin with limited inter-tidal and supra-tidal shoal area. A distinct shift in basin morphology (formation of a system similar to the eastern Wadden-Sea) can only occur through formation of potential sedimentation space. It is questionable if sufficient sediments are available to accommodate such change naturally.

In contrast to the Western Wadden Sea, sufficient, abundant, potential sedimentation space is present in the Eastern Wadden Sea. This may explain why local subsidence due to gas extraction is not clearly visible as these depressions are instantaneously filled in with sediments.

Conclusions

The long-term sediment budget of the Western Wadden Sea is derived using high-resolution sediment volume changes of constituent areas. The volume changes of individual, coherent, sedimentation-erosion areas allow us to determine detailed trends and reduce measuring error and uncertainty. The individual timeseries are used to accurately determine estimates for the long-term, medium-term and present-day sediment volume change rates. Based on the results of a simple sediment budget model we derived a value of 5.4 mcm/year sediment import into the Western Wadden Sea over the 1933-2015 time-frame. This sediment import has reduced to 0.75 mcm/year for the present-day trends.

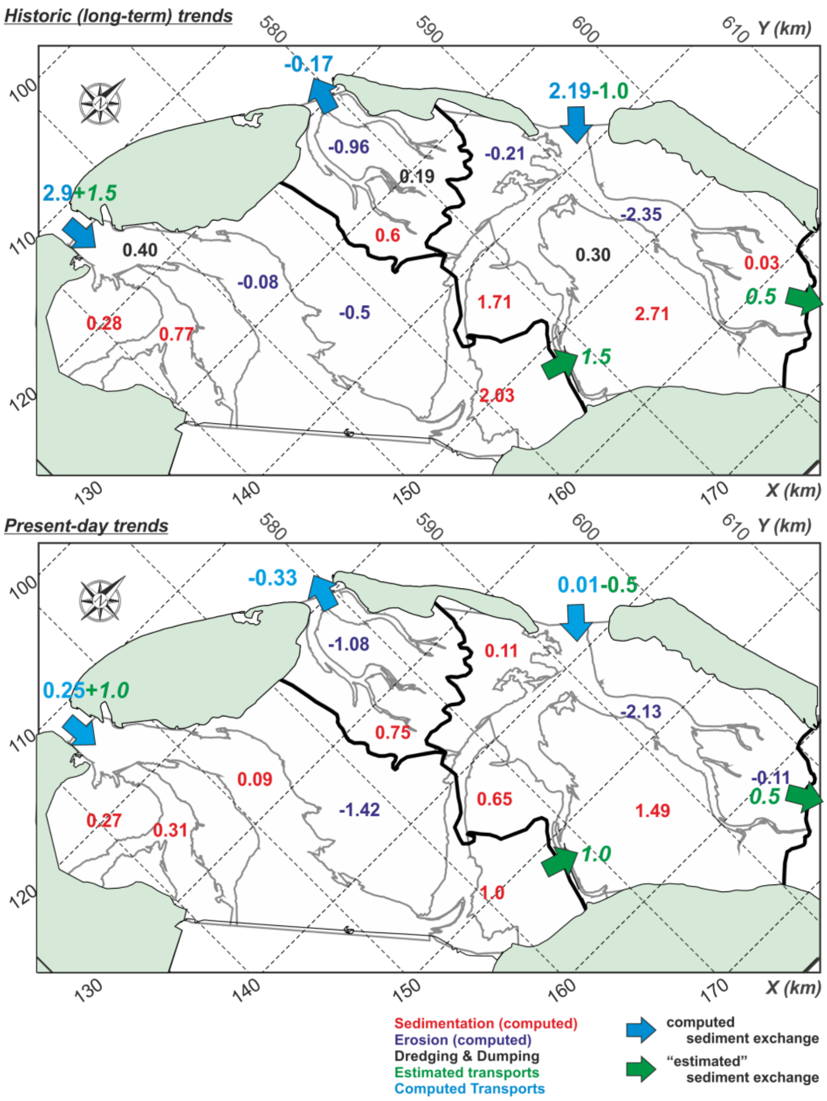

Fig. 6. Conceptual sediment budget model based on the long-term, 1933-2015 trends (top) and present-day trends (bottom). Green values are estimates of the sediment exchange between the basin and added as additional term in the computed inlet transports.

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