SEDIMENT IMPORT BY TIDAL INLETS
SEDBOX -model for tidal inlets Marsdiep and Vlie, Wadden sea, The Netherlands
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1 Physical processes of sandy tidal inlet systems

1.1 Introduction

This study focusses on the sediment balance of three large-scale tidal inlets (Marsdiep, Vlie and Borndiep) of the Dutch Wadden Sea based on the analysis of measured volume data (Chapter 2) and the use of a sediment box model for tidal inlets (SEDBOX-model; Chapter 3).
This latter model is a simple mass balance model for tidal inlets, which can be used to simulate the exchange of sediments between the morphological elements of a tidal inlet system.
A sand-dominated tidal inlet system consists of various different sedimentary subsystems being the shoreface, the barrier island, inlets and deltas, back-barrier basin and the mainland, see **Figure 1.1**.
Barrier islands-Lagoon coasts comprise approximately 15% of the total coastline of the world. Barrier islands protect low-lying coastal plains and back-barrier basins against storms. Classic examples are the sandy Atlantic and Gulf coasts of the U.S.A., where barrier islands are found along more than 60% of the coastline. Similar barrier islands can be found along the south-east coast of India. Examples of barrier islands in Europe are the Frisian Islands and Wadden Sea coasts along the North Sea.

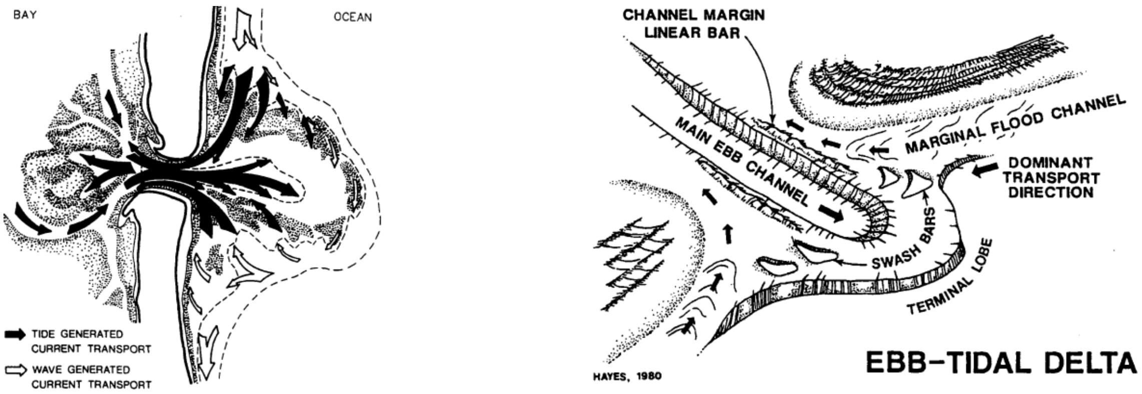

Figure 1.1 *Tidal inlet system*

1.2 Hydrodynamics

The morphology of inlets is mainly influenced by the tide-induced and wave-induced processes and the basin geometry. The wave field does not directly affect the inlet channel.
As long as the basin length is small compared to the tidal wave length, the water level inside and outside the basin will rise and fall more or less simultaneously and the hydraulic gradients along the inlet will be relatively small. Because the tidal wave propagates in shallow water and through the tidal inlet, the wave will be deformed (shoaling) and higher harmonics are generated. Changes in amplitude and phase of the tidal components in the inlet and in the back-barrier basin will result in asymmetry of the tidal wave with significant differences of the duration of the falling and rising tidal stages.
The deformation of the tidal wave will also affect the peak flood and ebb velocities in the inlet channel and the associated transport rates. Generally, the flood period of the tidal cycle in the inlet channel is characterized by a relatively high current velocity of short duration, whereas the ebb period has a relatively low velocity of longer duration. Thus, the inlet channel generally is flood-dominated (peak flood velocity > peak ebb velocity) in meso-tidal conditions. The channels in the outer delta may be flood- or ebb-dominated depending on the channel size, location and direction in relation to tidal wave parameters. Residual currents are important for the net transport directions, particularly for fine sediments.
Shoaling and breaking of wind-generated waves at the outer edge of the ebb delta will result in wave-induced oblique currents enhancing the flood tidal currents and retarding the ebb currents. Wave penetration through the inlet depends on the inlet geometry and the strength of the tidal currents. The maximum wave height in the inlet is of the order of 1 to 2 m during storms.

1.3 Sediment transport

The Sediment transport patterns due to waves and currents are:

- generation of littoral drift along the adjacent coasts;
- supply of sediment to the inlet by wave and tide-induced forces via the flood channels; sediment is also supplied over the delta by onshore-directed shoaling waves;
- import of sediment through the inlet by the currents and by-pass of sediments along the delta edge and across the delta by wave- and tide-induced currents (mainly in downdrift direction);
- deposition of imported sediments on the flats and in the channels of the flood-tidal delta.

The net import of sediment by the back-barrier basin is caused by the following mechanisms:

- tidal asymmetry and distortion; the peak flood velocities are relatively large over a shorter duration, whereas the peak ebb velocities are relatively small over a longer duration resulting in a net landward transport due to the non-linear relationship between velocity and transport;
- reduction of wave energy in the direction of the tidal inlet; the sediment transport capacity decreases for decreasing wave energy; the transport capacity on the seaward side is larger than that on the landward side of the inlet for the same flow velocity;
- presence of a small overdepth of the channels of the basin, because the water depths are lagging behind with respect to sea level rise;

- fine particles show a settling-lag behaviour; a fine particle needs some time to reach the bottom after the flow velocity has reduced below the critical flow velocity; after each tidal cycle it is deposited more inland until it is deposited at a location where the flow velocity is too small to erode the particle;
- silt and clay particles show a scour-lag behaviour; these particles have a larger critical flow velocity for erosion than for deposition; after each tidal cycle the particle will be deposited more inland until the flow velocity is too small to erode the particle.

The inlet acts as a blockade for the littoral drift. The alongshore wave-induced currents generated along the updrift coast are blocked by the in- and outgoing channel currents. Net import of sediment by the back-barrier basin will result in erosion of adjacent shorelines/beaches and a reduction of the sediment volume of the outer delta. The bed material composition of the bed surface generally shows distinct patterns: coarser sediments in the inlet channel, less coarse materials in the interior flood channels and fine sediments in the shoal areas of the flood delta. This distribution suggests that a sorting process is taking place as the sediments are transported landward; the coarser sediment and shell fragments are deposited as the flood velocity slows down and the finer material is carried to the shoal areas at further distance from the inlet. The bed materials of the bars and shoals of the ebb-tidal delta are relatively coarse, because the finer sediments are winnowed by wave action and carried away to the back-barrier basin by the tidal currents, where they are deposited.

2 Analysis of three tidal inlet systems of western Wadden Sea: Marsdiep, Vlie and Borndiep basins

2.1 Description of Marsdiep,Vlie and Borndiep tidal basins of Wadden sea

2.1.1 Basin and tidal characteristics

The geographic situation of the Marsdiep, the Vlie and the Borndiep basins of the dutch Wadden sea is shown in **Figure 2.1.1**. Sediment volume data are available for the period after closure of the Zuiderzee in 1932. The basic data for the situation around the year 2000 (Van Geer 2007; Arcadis, 2010) are given in **Table 2.1.1A**.

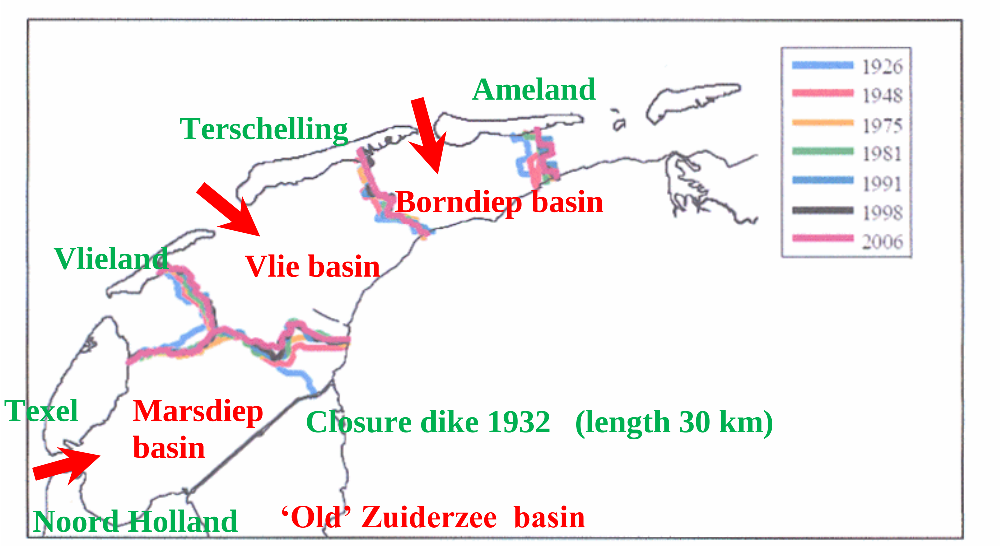

Figure 2.1.1 *Plan view of tidal basins with tidal divines of Dutch Wadden sea*

Parameter	Marsdiep	Vlie	Borndiep
H= mean tidal range (m)	1.5 - 1.7	1.8 -2.0	2.0
B= width of inlet below MSL (m)	3000	7000	3500
$A_{cross-section}$= area of cross-section below MSL (m^2)	50000	78000	35000
A_{basin} = surface area of total tidal basin at level of MHW (m^2)	710 10^6	660 10^6	275 10^6
A_{flats} = surface area of inner tidal flats at level of MLW (m^2)	130 10^6	335 10^6	160 10^6
$A_{channels}$ = surface area of inner tidal channels (m^2)	580 10^6	325 10^6	115 10^6
$A_{outerbasin}$ = surface area of outer basin (m^2)	150 10^6	150 10^6	80 10^6
$A_{ebbdelta}$= surface area of outer ebb delta (m^2)	80 10^6	80 10^6	40 10^6
$A_{outerchannels}$= surface are of outer channels and coast (m^2)	70 10^6	70 10^6	40 10^6

Table 2.1.1A *Basic data (year 2000) of tidal basins Marsdiep and Vlie, Wadden Sea, The Netherlands*

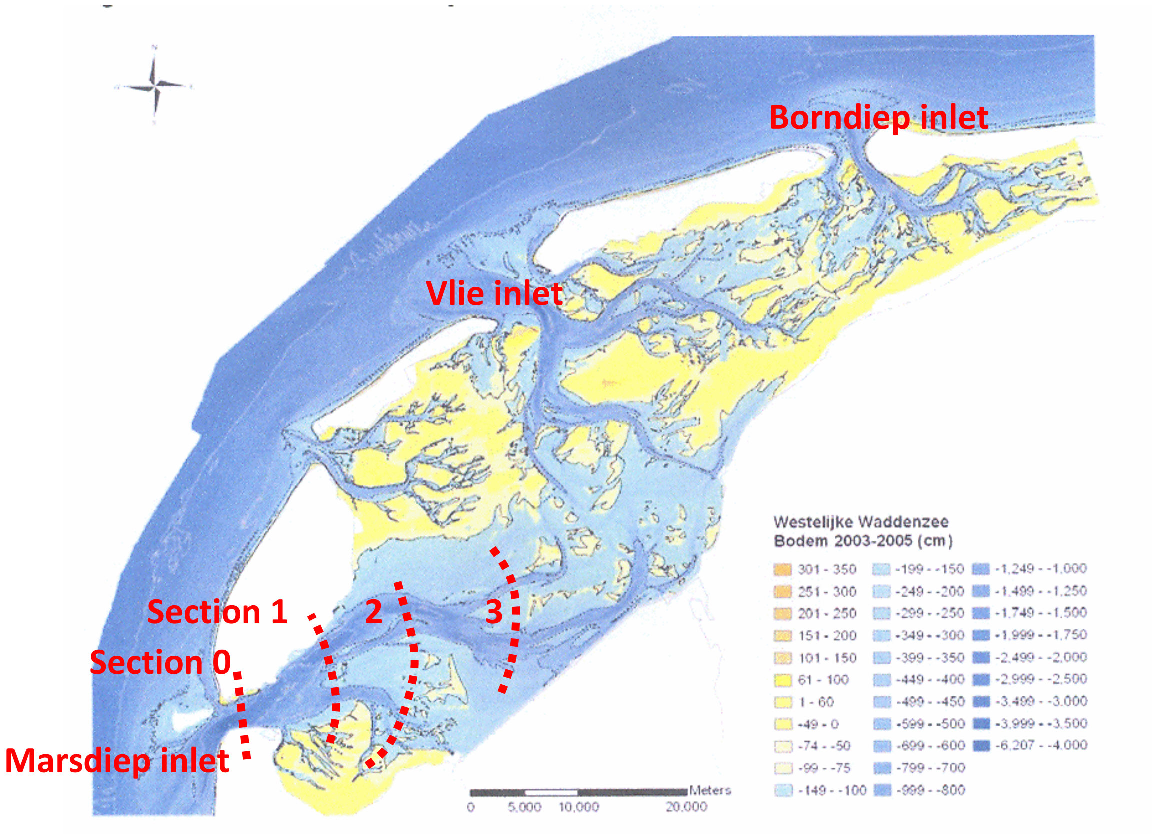

Figure 2.1.2 *Tidal channels in Marsdiep en Vlie 2004*

Before closure the tidal range (Den Helder) of the Marsdiep inlet was about 1.1 m, which increased to about 1.35 m shortly after closure. The tidal prism of the Marsdiep basin showed an increase by about 25% after closure (Battjes 1961 and **Table 2.2.1**). The present tidal prism of the Marsdiep basin is about 1000 10^6 m^3. The tidal prism of the Vlie basin was fairly constant after 1933. The present tidal prism of the Vlie basin also is about 1000 10^6 m^3. The wet cross-section (below MSL) of both inlets is of the order 50,000 to 80,000 m^2. In the past between 1933 and 2000 the tidal prism of the Marsdiep basin was fairly constant at a value of about 1000 10^6 m^3 despite a significant sedimentation of about 200 10^6 m^3 in the basin.

The tidal range at Den Helder was approximately constant at 1.35 m between 1933 and 1982 (Rijkswaterstaat 1985). The tidal range at Harlingen at the end of the basin increased slightly from 1.76 m in 1933 to about 1.86 m at 1982, see **Table 2.1.1B.** The increase of HW was larger than the increase of LW.

The tidal propagation in the inner basins of the Wadden sea is influenced by three basic mechanisms: shoaling (funnelling) due to the decrease of the total cross-sectional area of the main channels in landward direction; tidal damping due to bottom friction and tidal reflection due to basin geometry.
The cross-sectional area of the main channels (see **Figure 2.1.2**) of the Marsdiep basin can be roughly described by: $A = A_o e^{-\beta x}$ with A_o= area cross-section at throat $\cong$ 50000 m^2, β=1/L, L= converging length scale $\cong$ 20 km, yielding β=0.00005. Other measured values for the Marsdiep basin (see **Figure 2.1.2**) are: A_1= 35000 m^2 at 10 km from throat, A_2= 25000 m^2 at 15 km from throat, A_3= 15000 m^2 at 25 km from the inlet throat. The area of these sections can be described by an exponential function with L$\cong$ 20 km.
Assuming linear friction in a funnel-type basin (Van Rijn 2011), the tidal range as function of distance from the inlet can be described by: $H=H_o e^{-(-0.5\beta+\mu)x}$ with H_o= tidal range at inlet, β=1/L, μ= friction coefficient.
The tidal range in the basin will be approximately constant for $\beta/2\mu \cong 1$.
Tidal amplification (increase of tidal range) will occur for $\beta/2\mu > 1$.
Tidal damping (decrease of tidal range) will occur for $\beta/2\mu < 1$.
The friction coefficient is roughly μ =2 10^{-5} for a channel depth of h=10 m, μ =2.2 10^{-5} for h=5 m and μ =3.5 10^{-5} for h=3 m. The β-value is about 5 10^{-5}. Thus: $\beta/2\mu \cong 1.25$ for h=10 m, $\beta/2\mu \cong 1.1$ for h= 5 m and $\beta/2\mu \cong$ 0.7 for h= 3 m . Hence, tidal amplication is dominant for channel depths larger than about 5 m. Tidal damping will be dominant for very small channel depths (<3 m).
The values of **Table 2.1.1B** show that the tidal range in the Marsdiep basin increases slightly in landward direction (tidal amplification), both in 1933 and in 1982. Based on this, it is concluded that the tidal funnelling effect is dominant over the bottom friction effect. Futhermore, the tidal amplication in 1982 is somewhat larger (about 5%) than in 1933 which can be explained by the observed sedimentation in the channels (channel volume reduction of about 4% between 1933 and 1997). Most likely, the parameter $\beta/2\mu$ is somewhat larger for 1982 than for 1933.
Similar effects will be valid for the Vlie basin where continuous sedimention of the flats and channels takes place also.

Tidal parameters	**Den Helder**		**Harlingen**	
	1933	**1982**	**1933**	**1982**
HW (to NAP)	+0.48 m	+0.56 m	+0.77 m	+0.93 m
LW (to NAP)	-0.85 m	-0.81 m	-0.99 m	-0.93 m
Tidal range	1.33 m	1.37 m	1.76 m	1.86 m

Table 2.1.1B *Tidal parameters of Marsdiep basin*

The volume data of the flats, channels and outer delta of the Marsdiep and Vlie basins are given in **Tables 2.1.2, 2.1.3** and **2.1.4**. The volume data of the channels and flats include the effects of sand mining (about 50 10^6 m^3 in Marsdiep basin en about 30 10^6 m^3 in Vlie basin in the period 1933 to 1997/1998).
The sediment volume of the outer basin includes the ebb delta and the coastal zone between the -20 m NAP and the 0 m NAP line. The proper definition of the outer delta volume in absolute values involves the definition of the original seabottom without presence of the outer delta (inlet). The original seabottom can be estimated from the adjacent seabottoms on both sides of the inlet. The volumes of the outer deltas of Marsdiep and Vlie have been estimated by Deltares 1992, 1995a, 2012, Elias 2006 and Elias et al. 2012. The values given in **Table 2.1.4** have been estimated (by the present author) from the available data and the bathymetry of the year 2000 (see **Figures 2.2.2** and **2.2.4**). The volume losses of the outer deltas plus adjacent coasts are respectively: 4 million m^3/year for Marsdiep and 2.2 million m^3/per year for Vlie. The volumes in 1933 and in 1975 have been obtained by using the annual volume losses given in **Table 2.1.4**.
The total erosion of the outer basins can be roughly subdivided in coastal erosion (25% to 35%) and ebb delta erosion (75% to 65%). The annual coastal erosion volumes in the outer basins are respectively: about 1 million m^3/year for Marsdiep and 0.4 million m^3/year for Vlie (see Table 2.1.4).

Years		Volume flats above MLW (m³)	Area of flats (m²)	Height of flats above MLW (m)	Volume Channels below MLW (m³)	Area Channels (m²)	Depth Channels below MLW (m)	Tidal prism (m³)
1933	0	$42.6\ 10^6$	$131.1\ 10^6$	0.33	$2370\ 10^6$	$558\ 10^6$	4.25	$1018\ 10^6$
1951	18	$36.6\ 10^6$	$109.8\ 10^6$	0.33	$2262\ 10^6$	$579\ 10^6$	3.91	$1020\ 10^6$
1965	32	$33.9\ 10^6$	$97.0\ 10^6$	0.35	$2258\ 10^6$	$592\ 10^6$	3.82	$1019\ 10^6$
1972	39	$48.5\ 10^6$	$111.8\ 10^6$	0.43	$2224\ 10^6$	$577\ 10^6$	3.86	$1003\ 10^6$
1977	44	$42.9\ 10^6$	$115.3\ 10^6$	0.37	$2226\ 10^6$	$573\ 10^6$	3.88	$1007\ 10^6$
1982	49	$32.7\ 10^6$	$107.3\ 10^6$	0.30	$2275\ 10^6$	$581\ 10^6$	3.91	$1016\ 10^6$
1988	55	$39.6\ 10^6$	$106.3\ 10^6$	0.37	$2278\ 10^6$	$582\ 10^6$	3.91	$1008\ 10^6$
1991	58	$39.3\ 10^6$	$110.0\ 10^6$	0.36	$2254\ 10^6$	$579\ 10^6$	3.89	$1008\ 10^6$
1997	64	$35.9\ 10^6$	$98.9\ 10^6$	0.36	$2270\ 10^6$	$590\ 10^6$	3.85	$1010\ 10^6$

Table 2.1.2 *Volume data of tidal basin Marsdiep (Wadden Sea); Appendix G of Van Geer (2007)*

Years		Volume flats above MLW (m³)	Area of flats (m²)	Height of flats above MLW (m)	Volume channels below MLW (m³)	Area Channels (m²)	Depth Channels below MLW (m)	Tidal prism (m³)
1933	0	$105\ 10^6$	$216\ 10^6$	0.49	$1273\ 10^6$	$468\ 10^6$	2.72	$1080\ 10^6$
1951	18	$131\ 10^6$	$236\ 10^6$	0.56	$1227\ 10^6$	$446\ 10^6$	2.75	$1080\ 10^6$
1965	32	$118\ 10^6$	$238\ 10^6$	0.50	$1240\ 10^6$	$446\ 10^6$	2.78	$1120\ 10^6$
1972	39	$139\ 10^6$	$274\ 10^6$	0.51	$1214\ 10^6$	$406\ 10^6$	2.99	$1100\ 10^6$
1977	44	$145\ 10^6$	$323\ 10^6$	0.45	$1194\ 10^6$	$360\ 10^6$	3.32	$1110\ 10^6$
1982	49	$131\ 10^6$	$297\ 10^6$	0.44	$1234\ 10^6$	$380\ 10^6$	3.25	$1120\ 10^6$
1988	55	$153\ 10^6$	$307\ 10^6$	0.50	$1164\ 10^6$	$353\ 10^6$	3.30	$1080\ 10^6$
1992	59	$172\ 10^6$	$334\ 10^6$	0.51	$1139\ 10^6$	$323\ 10^6$	3.52	$1060\ 10^6$
1998	65	$179\ 10^6$	$335\ 10^6$	0.53	$1116\ 10^6$	$322\ 10^6$	3.47	$1060\ 10^6$

Table 2.1.3 *Volume data of tidal basins Vlie (Wadden Sea); Appendix G of Van Geer (2007)*

Outer basin	Marsdiep		Vlie	
	Ebbdelta+coast	Ebbdelta	Ebbdelta + coast	Ebbdelta
Area outer delta and basin (km²)	80; 150		80; 150	
Sedimentvolume year 2000 (m³)	$380\ 10^6$	$450\ 10^6$	$320\ 10^6$	$350\ 10^6$
Sedimentvolume year 1975 (m³)	$480\ 10^6$	$525\ 10^6$	$375\ 10^6$	$400\ 10^6$
Sedimentvolume year 1933 (m³)	$650\ 10^6$	$650\ 10^6$	$470\ 10^6$	$470\ 10^6$
Total sediment loss (erosion m³) in period 1933-2000	$270\ 10^6$ ($4\ 10^6$ m³/yr)	$200\ 10^6$ ($3\ 10^6$ m³/yr)	$150\ 10^6$ ($2.2\ 10^6$ m³/yr)	$120\ 10^6$ ($1.8\ 10^6$ m³/yr)

(Outer basin is defined between -20 m NAP and 0 m NAP in cross-shore direction)

Table 2.1.4 *Volume data of outer delta plus adjacent coasts of Marsdiep and Vlie (Wadden Sea)*

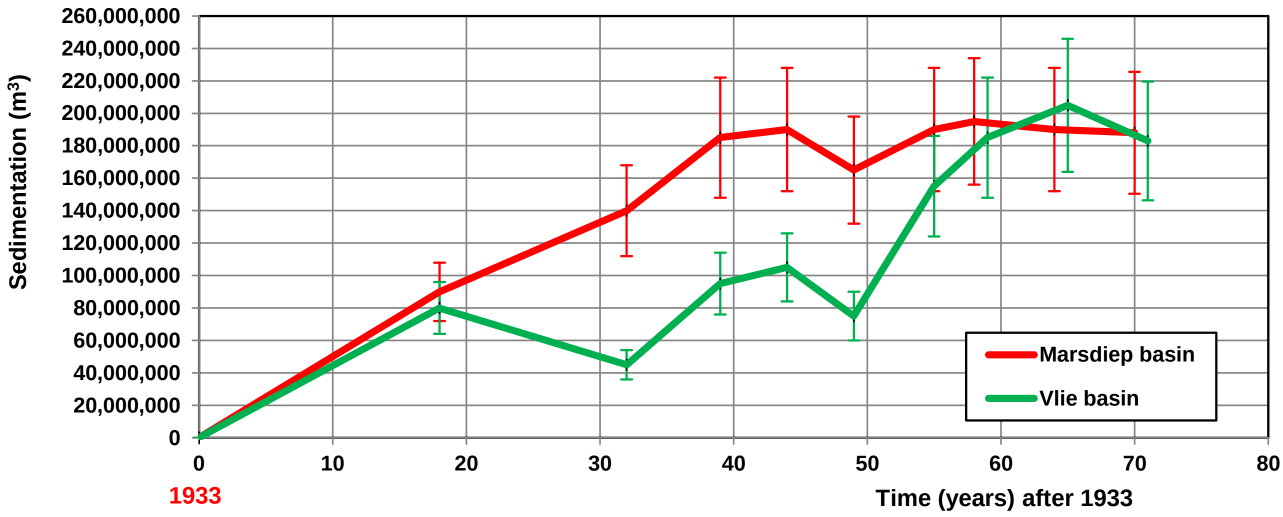

Figure 2.1.3 *Sedimentation of Marsdiep and Vlie basins according to Rijkwaterstaat (2005)*

Rijkswaterstaat (2005) has compared the bathymetries (below +1 m NAP) of 1933 and 2003, see **Figure 2.1.3** and **Table 2.1.5**. The volume data of Rijkswaterstaat are based on the fixed NAP-level and are reasonably accurate as it only involves the comparison of two bathymetries in a constant basin area. The inaccuracy of this volume data is largely determined by the total inaccuracy of the bathymetry data, which is of the order ± 0.1 m resulting in an inaccuray of ± 20% of the volume data obtained by substraction of bathymetries.
The annual deposition volumes vary in the range of 2 to 4 10^6 m^3/year for Marsdiep basin and 2.5 to 3.5 10^6 m^3/year for Vlie basin:

Van Geer (2007) has determined the deposition and erosion volumes of the flats and channels with respect to the plane of Mean Low Water (MLW), see **Table 2.1.6**. This requires the division of the total basin area in subcompartments and the determination of the MLW-level in each subcompartment, which easily leads to additional errors.
The deposition volumes of the flats and channels of Van Geer can be converted to a fixed datum of 1933 by using the sea level rise effect as follows (see **Figure 2.1.4**):

$$V_{deposition,channels} = V_{channels,sea\ level\ rise} + (V_{channels,1933} - V_{channels,1997}) = A_{channels}\ \Delta s + (V_{channels,1933} - V_{channels,1997})$$

$$V_{deposition,flats} = V_{flats,sea\ level\ rise} + (V_{flats,1997} - V_{flats,1933}) = A_{flats}\ \Delta s + (V_{flats,1997} - V_{flats,1933})$$

with: V= volume, A= area and Δs = sea level rise over 64 years = 0,002x64 =0,128 m.

Herein, a constant area of the channels and flats is used (see **Table 2.1.6**), but these values also vary in time due variation of MLW. Furthermore, the variationof MLW also depends on long term tidal variations. These effects will also introduce small errors.

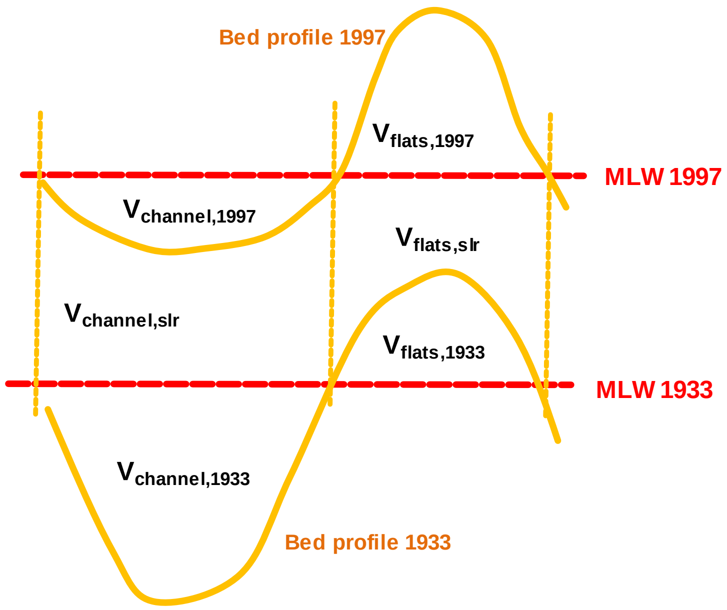

Figure 2.1.4 *Volume change due to shift of MLW level (same bottom profile)*

Basin	**Deposition volumes with respect to NAP**	**Sand mining volumes**	**Total true deposition**
Marsdiep	190 10^6 m^3	50 10^6 m^3	240 10^6 m^3
Vlie	185 10^6 m^3	30 10^6 m^3	215 10^6 m^3
Total deposition	375 10^6 m^3	80 10^6 m^3	455 10^6 m^3

Table 2.1.5 *Measured deposition volumes of Rijkswaterstaat (2005); period 1933 to 1998*

Basin	**Deposition/Erosion volumes with respect to MLW**	**Sea level rise volume**	**Sand mining volumes**	**Total true deposition with respect to 1933**
Marsdiep flats (area 125 km^2)	-7 10^6 m^3	16 10^6 m^3	50 10^6 m^3	233 10^6 m^3
Marsdiep channels (area 575 km^2)	100 10^6 m^3	74 10^6 m^3		
Vlie flats (area 275 km^2)	74 10^6 m^3	36 10^6 m^3	30 10^6 m^3	349 10^6 m^3
Vlie channels (area 400 km^2)	157 10^6 m^3	52 10^6 m^3		
Total	324 10^6 m^3	178 10^6 m^3	80 10^6 m^3	582 10^6 m^3

Table 2.1.6 *Measured deposition volumes of Van Geer (2007); period 1933 to 1998*

2.1.2 Volume data of Marsdiep basin

Based on the data of Tables 2.1.5 and 2.1.6, the observed deposition volume plus the sand mining volume is about 240 million m^3 over a period of 64 years or 3.8 $\pm$ 20% million m^3/year or 5.4 $\pm$ 20% mm/year. The observed deposition volume without the sand mining volume about 3 million m^3/year.

The morphological changes of the flats of the Marsdiep basin over period 1933 to 1997 with respect to MLW (see **Tables 2.1.2** and **2.1.7**) are:

- annual decrease of the volume of the flats of about -0.11 million m^3/year in period 1933 to 1997; annual sand mining at the flats is estimated to be about 0.13 million m^3/year; total annual change of volume of the flats is almost zero (constant volume);
- mean height of the flats is 0.36 ± 0.06 m; variations between 0.30 and 0.43 m over 64 years;
- maximum increase of flat height of 17 mm/year (4%) in the period 1965 to 1972;
- maximum decrease of flat height of -14 mm/year (4%) in the period 1977 to 1982;
- mean area of flats is 115 km^2 over period 1933 to 1997; variations between 97 and 130 km^2;
- maximum increase of flat area of +2 km^2/year (2%) in the period 1965 to 1972;
- maximum decrease of flat area -1.2 km^2/year (1%) in the period 1933 to 1951.

Thus, the annual changes of the flats are of the order of 1% to 4% per year. The data of **Table 2.1.2** shows a rather constant value of the surface area of the flats of about 115 km^2 (±15%) between 1933 and 1997.
The average deposition rates in mm/year (last column of **Table 2.1.7**) are artificial rates which are obtained as the ratio of the deposition volume between 1933 and 1997 and the area involved. This latter area is assumed to be constant (125 km^2) over the period considered. The mean flat height increases from 0.33 m to 0.36 m over 64 years. Thus, the real deposition rate of the flats is 0.5 mm/year. The channel depth decreases from 4.25 m to 3.85 m or a deposition rate of 6.3 mm/year.

Deposition and sand mining	**Marsdiep: 700 km²** (mean value of 1933 to 2000) Flats: 125 km² Channels: 575 km²	
Sedimentation 1933-1997	Flats: - 7 10^6 m^3 or -0.11 10^6 m^3/year Channels: +100 10^6 m^3 or 1.55 10^6 m^3/year	-0.9 mm/year 2.7 mm/year
Sand mining 1933-1997	50 10^6 m^3 or 0.80 10^6 m^3/year	1.1 mm/year

Table 2.1.7 *Sedimentation and dredging volumes in Marsdiep based on data of Van Geer 2007*

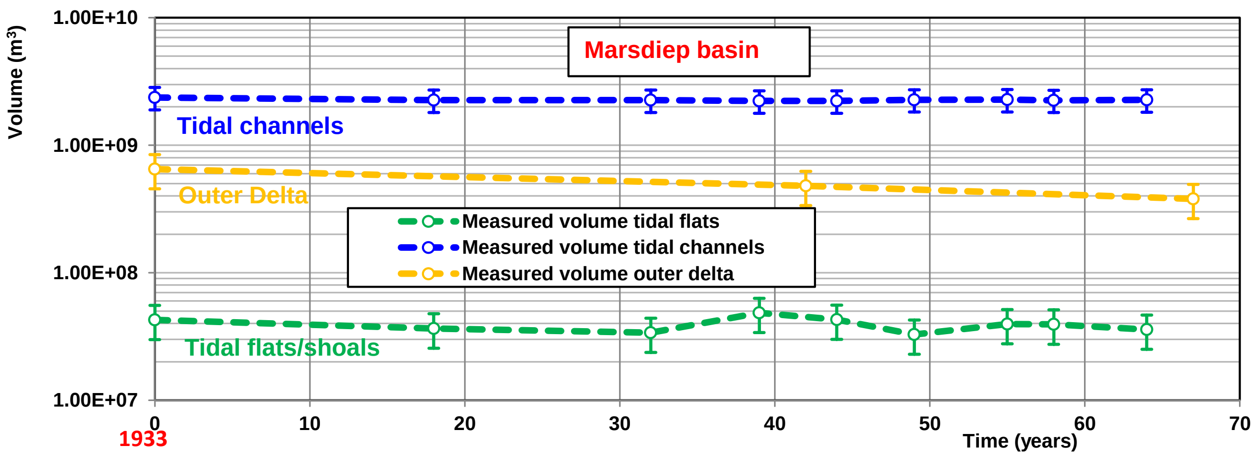

Figure 2.1.5 *Measured volume data of Marsdiep basin 1933 to 1997*

Figure 2.1.5 shows the volume data of the flats (to MLW) and channels (to MLW) of the inner basin and the volume data of the outer delta of the Marsdiep basin. The computed equilibrium volume based on Equations 3.11 to 3.13 are also shown. The inaccuracy of the volumes is of the order of 20% to 30%. The following characteristics are given:

- decrease of the outer delta volume of about 200 million m^3 over 70 years or about 3 million m^3/year;
- almost no change of the area and volume of the flats;
- gradual decrease (sediment deposition) of the volume of the tidal channels of about 100 million m^3 over 64 years or about 1.5 million m^3/year.

The annual deposition rate (5.4 $\pm$ 20% mm/year) of the Marsdiep basin is larger than the annual sea level rise of about 2 mm/year during the period 1933 to 2000.

2.1.3 Volume data of Vlie basin

Based on the data of **Tables 2.1.3** and **2.1.6**, the observed deposition volume plus the sand mining volume is about 215 to 350 million m^3 (280 $\pm$ 30%) over a period of 65 years or 4.3 $\pm$ 30% million m^3/year or 6.4 $\pm$ 30% mm/year. The observed deposition volume without the sand mining volume is 3,8 million m^3/year. It is noted that the deposition volumes based on Van Geer (2007) are larger than those of Rijkswaterstaat (2005).

The morphological changes of the flats of the Vlie basin with respect to MLW (see **Table 2.1.3** and **2.1.8**) are:

- annual increase of the volume of the flats of about 1.13 million m^3/year in period 1933 to 1998; annual sand mining at the flats is estimated to be about 0.17 million m^3/year; true increase of volume of the flats is about 1.3 million m^3/year;
- mean flat height of 0.5 m; flat height varies between 0.44 and 0.56 m (0.5$\pm$0.05; 10% variation);
- maximum increase of flat height of 10 mm/year (2%) in the period 1982 to 1988;
- maximum decrease of flat height of -12 mm/year (2%) in the period 1972 to 1977;
- increase of area of flats from 215 to 335 km^2 or 1.85 km^2/year; mean area of flats is 275 km^2;
- maximum increase of flat area of +12 km^2/year (4%) in the period 1972 to 1977;
- maximum decrease of flat area of -5 km^2/year (2%) in the period 1977 to 1982.

Thus, the annual changes of the flats are of the order of 1% to 4% per year. The data of **Table 2.1.3** shows a gradual, but consistent increase of the surface area of the flats from about 215 to 335 km^2 (increase of 55%) between 1933 and 1998 or 1.85 km^2/year.
The average deposition rates in mm/year (last column of **Table 2.1.8**) are artificial rates which are obtained as the ratio of the deposition volume between 1933 and 1998 and the area involved. This latter area is assumed to be constant (275 km^2) over the period considered. The mean flat height increases from 0.49 m to 0.53 m over 65 years or 0.6 mm/year. Thus, the real vertical growth rate of the flats is 0.6 mm/year.
The mean flat height is not a very good indicator to identify the overall growth rate of the flats. Actually, the surface area of the flats shows the largest growth rates. The flat height increases marginally; the flat surface area increases significantly.
The channel depth increases from 2.72 m to 3.47 m over 65 years or a real erosion rate of -11.5 mm/year.
The channel depth increases significantly (erosion), but the channel area decreases even more. Hence the channels become smaller, but deeper. Overall, the channels show deposition of about 157 10^6 m^3 over 65 years or 2.4 10^6 m^3/year (**Table 2.1.8**).

Deposition and sand mining	**Vlie: 675 km²** (mean value of 1933 to 1998) Flats: 275 km² Channels: 400 km²	
Sedimentation 1933-1998	Flats: + 74 10^6 m³ or 1.13 10^6 m³/year Channels: +157 10^6 m³ or 2.42 10^6 m³/year	4.1 mm/year 6.1 mm/year
Sand mining 1933-1998	30 10^6 m³ or 0.45 10^6 m³/year	0.7 mm/year

Table 2.1.8 *Sedimentation and dredging volumes in Vlie basin based on the data of Van Geer (2007)*

Figure 2.1.6 shows the volume data of the flats (to MLW) and channels (to MLW) of the inner Vlie basin and the volume of the outer delta of the Vlie basin. The inaccuracy of the volumes is of the order of 30%. The volumes of the flats maybe somewhat too large. Therefore, only lower error bars are shown. The computed equilibrium volumes based on Equations 3.11 to 3.13 are also shown.

The following characteristics are given:

- decrease of the outer delta volume of about 120 million m³ over 70 years or about 1.8 million m³/year;
- gradual increase of the volume of the flats of about 74 million m³ over 65 years or about 1.1 million m³/year;
- gradual decrease (sediment deposition) of the volume of the tidal channels of about 157 million m³ over 65 years or about 2.1 million m³/year.

The annual deposition rate (6.4 mm/year) of the Vlie basin is much larger than the annual sea level rise of about 2 mm/year during the period 1933 to 2000.

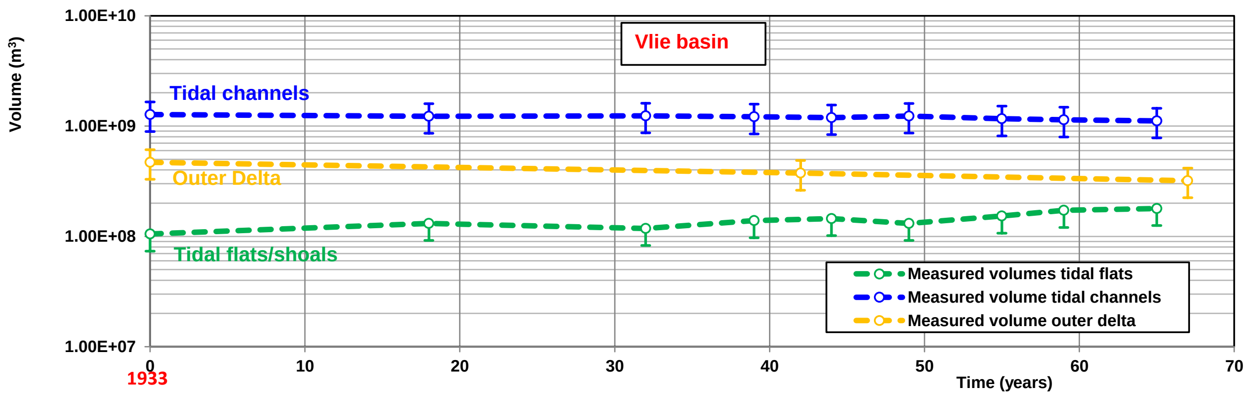

Figure 2.1.6 *Measured volume data of Vlie basin 1933 to 1998*

2.1.4 Volume data of Borndiep basin

Table 2.1.9 shows the deposition and erosion volumes of the tidal flats and the tidal channels with respect to mean low water (MLW) based on Van Geer (2007).

The morphodynamic development of the flats of the Borndiep basin in the period of 1926 to 1999 with respect to MLW can be summarized, as (see **Table 2.1.9**):

- annual increase of volume of flats of 0.28 miljoen m³/year; estimated annual sand mining volume of 0.12 million m³/year; total increase of volume of flats of 0.4 million m³/year;

- average increase of flats of 0.6 m; the height of the flats above MLW varies between 0.55 and 0.65 m (0.6±0.05 m; 10% variation);
- increase of surface area from 150 to 170 km^2 or 0.27 km^2 per year; average surface area is 160 km^2;
- maximum increase of flat height of 5 mm/year (1%) in the period 1993 to 1999;
- maximum decrease of flat height of -5.6 mm/year (1%) in the period 1950 to 1967;
- maximum increase of surface area of 3 km^2/year (2%) in the period 1984 to 1989;
- maximum decrease of surface area of -2 km^2/year (1%) in the period 1978 to 1984.

Year		Volume flats above MLW (m^3)	Area of flats (m^2)	Height flat above MLW (m)	Volume channels below MLW (m^3)	Area of channels (m^2)	Depth channels below MLW (m)	Tidal prism (m^3)
1926	0	83.5 10^6	148.4 10^6	0.563	314 10^6	127 10^6	2.47	508 10^6
1950	24	98.8 10^6	152.2 10^6	0.649	337 10^6	124 10^6	2.72	496 10^6
1967	31	86.6 10^6	156.8 10^6	0.552	322 10^6	120 10^6	2.68	509 10^6
1973	37	97.8 10^6	159.5 10^6	0.613	330 10^6	117 10^6	2.82	497 10^6
1978	42	97.8 10^6	159.5 10^6	0.613	330 10^6	117 10^6	2.82	497 10^6
1984	48	84.0 10^6	148.4 10^6	0.567	321 10^6	129 10^6	2.49	512 10^6
1989	63	94.1 10^6	163.6 10^6	0.575	323 10^6	113 10^6	2.85	501 10^6
1993	67	96.3 10^6	169.0 10^6	0.569	316 10^6	108 10^6	2.93	499 10^6
1999	73	104.2 10^6	171.4 10^6	0.608	305 10^6	106 10^6	2.88	491 10^6

Table 2.1.9 *Volume data of Borndiep basin (Wadden sea); Appendix G of Van Geer (2007)*

Table 2.1.10 presents the total deposition volumes for the period 1926 to 1999. The estimated annual sand mining/dredging volume is about 1 miljoen m^3/year for Marsdiep and 0.5 million m^3/year for Vlie. The sand mining volume for Borndiep in the period 1950 to 2000 is estimated to be 0.3 million m^3/year.
The total deposition in Borndiep basin in the period 1926 to 1999 is estimated to be about 100 million m^3 or 1.35 million m^3/year or about 5 mm/year with respect to 1926. This latter value is much larger than the sea level rise of 2 mm/year in that period. So, the deposition relative to MLW is about 3 mm/year. The flats and channels have about the same deposition of about 2 mm/year with respect to MLW, see **Table 2.1.11**. Sand mining/dredging corresponds to about 0.8 mm/year.
The vertical growth of the flats is about 0.4 mm/year between 1926 and 1999 (**Table 2.1.9**).

Basin	Deposition/erosion with respect to MLW	Sea level rise volume	Sand mining volume	Total
Borndiep flats (area 160 km^2)	21 10^6 m^3	24 10^6 m^3	17 10^6 m^3	100 10^6 m^3
Borndiep channels (area 115 km^2)	21 10^6 m^3	17 10^6 m^3		

Tabel 2.1.10 *Measured deposition volumes of Van Geer (2007); period 1926 to 1999*

Deposition and sand mining	Borndiep: **275 km^2** (mean value of 1926 to 1999) Flats: 160 km^2 Channels: 115 km^2	
Deposition 1933-1998	Flats: 21 10^6 m^3 or 0.28 10^6 m^3/year Channels: 21 10^6 m^3 or 0.28 10^6 m^3/year	1.8 mm/year 2.4 mm/year
Sand mining 1933-1998	17 10^6 m^3 of 0.23 10^6 m^3/year	0.8 mm/year

Table 2.1.11 *Deposition and sand dredging volumes in Borndiep basin based on data of Van Geer (2007)*

Deltares (1992) has estimated the sand volumes of the outer ebb delta of the Borndiep basin, see **Table 2.1.12**. The sand volumes show a significant increase up to 1958 followed by a significant decrease to 121 million m^3 in 1999, see also **Figure 2.1.7**. There is a slight volume increase over the total period between 1926 and 1999.

Year		Sandvolume outer delta (m^3)
1926	0	114 10^6
1934	24	145 10^6
1958	31	164 10^6
1966	37	146 10^6
1974	42	129 10^6
1976	48	141 10^6
1982	63	121 10^6

Tabel 2.1.12 *Volume data of outer ebb delta of Borndiep basin based on Deltares (1992)*

Figure 2.1.7 shows the development of the volumes of the flats and channels of the inner basin and the ebb delta volume of the outer basin (inaccuracy of 30%). The computed 'equilibrium' volumes are also shown. This yields:

- almost constant volume of the outer ebb delta of 120 million m^3 over 73 years;
- slight increase of volume of flats of 21 million m^3 over 73 years or 0.28 million m^3/year;
- slight decrease of volume of channels (deposition) of 21 million m^3 over 73 years or 0.28 million m^3/year; channel cross-sections decrease and channel depths increase;
- volumes of flats and channels are close to 'equilibrium' values; volume of outer ebb delta is far below (factor of 3) the 'equilibrium' value.

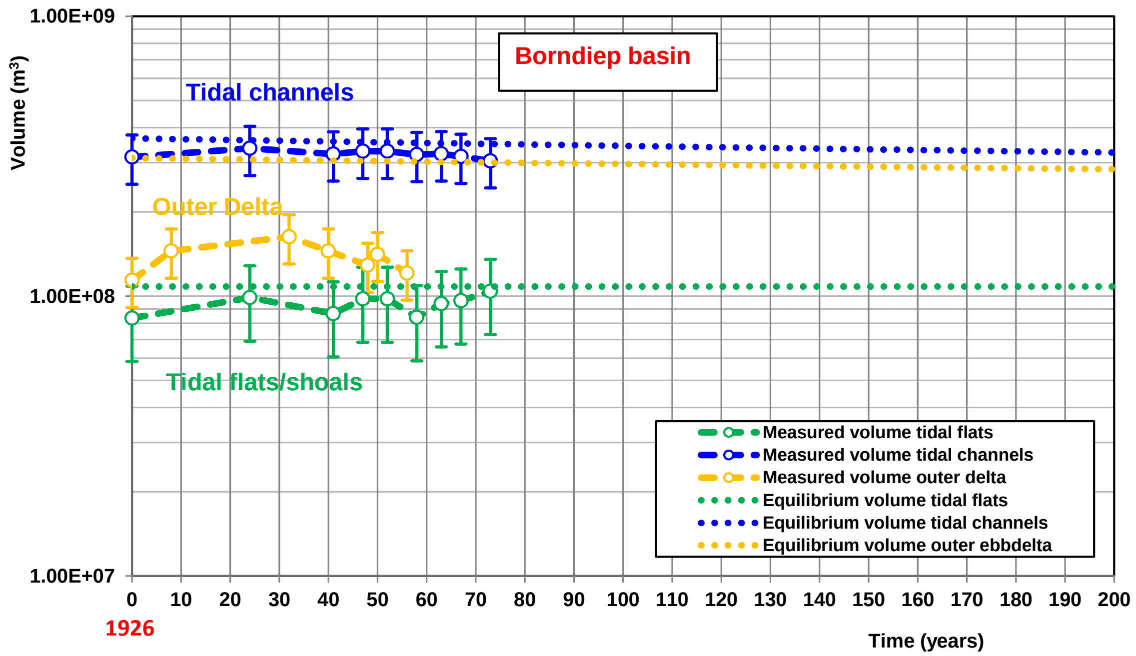

Figure 2.1.7 *Observed volume data of Borndiep basin 1926 to 1999*

2.2 Net sand transport trough inlets

2.2.1 Marsdiep inlet

The historical development of the throat (Marsdiep) of the Texel inlet was studied by many researchers (Battjes 1961, Sha 1989, Elias 2006). **Table 2.2.1** shows the flood and ebb volumes over time based on measured data of Rijkwaterstaat. The flood volume before the closure of the Zuiderzee in 1932 is estimated to be about 700 10^6 m^3 (Lorentz, 1926). The average flood volume after 1932 is about 900 10^6 m^3, which means an increase of about 30%. Before closure the tidal wave in the Texel basin and the Zuiderzee basin with a total area of about 4000 km^2 was a damped propagating tidal wave with relatively low values of the tidal range (order of 0.2 to 0.7 m) in the Zuiderzee and large phase differences between the inlet and the southern boundary. After closure the area reduced to about 700 km^2 and tidal wave changed into a more reflecting type of wave with an almost simultaneous rise and fall of the water surface over the entire basin. Furthermore the tidal range inside the basin increased considerably to about 1.8 m, see **Table 2.2.1**. These changes resulted in a significant increase (30%) of the flood volume through the Marsdiep inlet. The area of the cross-section remained approximately constant at a value of about 52000 $\pm$ 3000 m^2 over the period 1900 to 2000.

Table 2.2.1 also shows that the ebb volume through the Marsdiep is, on average, slightly larger (10%) than the flood volume. The difference amounts to about 100 10^6 m^3 per tide, which can be partly explained by the input of the fresh water volume into the Marsdiep basin coming from the IJsselmeer basin behind the closure dike. The IJssel river discharges into the IJsselmeer basin with a mean discharge of about 300 m^3/s and peak values up to 2000 m^3/s. Including the input of rainfall, the mean water input will be of the order of 1000 m^3/s, which yields a maximum volume of about 45 10^6 m^3 over a tidal cycle of 12 hours. This volume is discharged into the Wadden Sea at low tide (about 3 to 4 hours) when the Wadden Sea level is below the IJsselmeer level of -0.2 m NAP in the summer. Hence, about 50% of the difference between the ebb and flood volumes through the Marsdiep inlet can be explained by fresh water discharge into the Wadden Sea through the closure dike. According to Battjes (1961), there is no net flow from the Vlie basin to the Marsdiep basin, which is confirmed by the measured values of the flood and ebb volumes through the Vlie throat (see **Table 2.2.2**) which are almost equal. According to Battjes (1961), the ebb volume of the through the Marsdiep inlet is overestimated most probably due to errors in the vertical distribution of the flow velocity profiles (limited number of measuring points over large water depth up to 30 m).

Tidal phase	Before 1932 Lorentz 1926	1939 Battjes 1961	1951 Battjes 1961	1958 Battjes 1961	1971 RWS 1982	1997 RWS 1998
Area cross-section (m^2) Marsdiep	50000 to 55000	49000	50000	52000	54000	54000
Tidal range (m)	1.2 (inlet) 0.2 (Urk) 0.4 (A'Dam)	1.4 (inlet) 1.8 (Harlingen)				
Flood (m^3)	700 10^6	860 10^6	890 10^6	920 10^6	950 10^6	800 10^6
Ebb (m^3)	-	910 10^6	1000 10^6	1010 10^6	1000 10^6	1100 10^6

Table 2.2.1 *Measured flood and ebb volume for mean tide of Marsdiep inlet*

Figure 2.2.1 shows measured water level and flow velocities in the Marsdiep inlet before and shortly after the closure of the Zuiderzee basin in 1932 (Battjes, 1961). It is noted that the measured velocities before 1932 represent the flow velocity at a few metres below the water surface, wheras those in 1938 represent depth-averaged velocities. The water level variations before and after closure are very similar; high water is slightly higher and low water is slightly lower. However, the flow velocity variation has changed significantly. Before closure the flow velocity distribution is rather symmetric, whereas it is asymmetric

after closure. The ratio of the peak flood and peak ebb velocities after closure is about 1.25. In 1971 the flow velocity distribution in the throat (Station 6, Figure 2.2.3B) is very similar to that shortly after closure and the ratio of the peak flood and ebb velocities is still about 1.25. This change of the velocity distribution has had a major impact on the erosion of the outer delta, which has reduced in volume from about 650 10^6 m^3 in 1932 to about 450 10^6 m^3 in 2000 or a decrease of about 3 million m^3 per year. A larger velocity asymmetry leads to more net erosion of the outer delta and adjacent coasts (less sediment is coming back). This volume reduction is opposite to the equilibrium relationship of Walton and Adams (1976), see Equation (3.13). According to this relationship, the outer delta volume should increase if the tidal prism (flood volume) increases. The tidal prism of the Marsdiep inlet has increased from about 700 10^6 m^3 to about 900 10^6 m^3 (before and after closure in 1932), which is an increase of almost 30%. However, the measured volume of the outer delta shows a significant decrease of about 30%. Based on this, it is concluded that the equilibrium relationship of Watson and Adams is not valid for the Marsdiep inlet, as there is no unique relationship between the delta volume and the tidal prism. Basically, this relationship should include a parameter expressing the asymmetry of the horizontal tide. The increase of the tidal velocity asymmetry leads to an increase of the net import capacity of the inlet. More import of sand will lead to erosion of the outer delta and the adjacent coasts.
The net import of sand through the Marsdiep (**Figures 2.2.2** and **2.2.3A**) inlet was computed earlier by Van Rijn (Deltares 1995a) based on measured tidal velocities through the cross-section of the Marsdiep-channel for the springtide of 29/30 March 1971 (Rijkwaterstaat 1982). On that date flow velocities have been measured simultaneously in 8 stations (Rijkswaterstaat, 1982). The horizontal tide is asymmetric with maximum flood velocities of about 1.8 m/s and maximum ebb velocities of 1.6 m/s, see **Figure 2.2.3B**. The TRANSPOR-model (Van Rijn, 1993) was used to compute the sand transport rates. Assuming d_{50} = 0.0003 m, d_{90} = 0.0005 m, k_s = 0.05 m, Temperature = 15°c and Salinity = 30 promille, the sand transport rates were computed, see **Figure 2.2.3C**.
The net import can be computed as: $T_{sand,inner\ basin} = (1/\rho_{bulk})\ N_{tide} \sum^m (\sum^n (q_s+q_b)\ \Delta t)\ \Delta b$
with: q_b, q_s= bed and suspended sand transport (kg/s/m), ρ_{bulk}= dry bulk density of sand (1650 kg/m^3), Δt= time step trough the tidal cycle, Δb= width of subsection, n= number of time steps over tidal cycle, m= number of subsections over width of inlet, N_{tide}= number of tides during one year.

Integration over the width of the cross-section and over the flood and ebb phases of the tide yields:

- transport during (spring) flood phase of 6 hours = 21.000 m^3;
- transport during (spring) ebb phase of 6 hours = 13.000 m^3.

The transport rates during springtide are approximately 30% larger than those during mean tidal conditions based on the nonlinear relationship between sand transport and flow velocity, giving (730 tides per year):

- yearly-integrated flood transport = 0.7 x 21.000 x 730 = 10.7 10^6 m^3/year;
- yearly-integrated ebb transport= 0.7 x 13.000 x 730 = 6.6 10^6 m^3/year.

Based on these results, the net yearly-integrated sand transport through the Marsdiep channel is of the order of 4 million m^3/year for mean tidal conditions. The computed net transport rate of 4 million m^3 per year should be considered with care because the representative sediment sizes in the cross-section of the Marsdiep-channel are not known in sufficient detail. A median diameter of 300 μm was assumed but the values in the deeper parts of the cross-section may be somewhat coarser (500 μm) leading to smaller transport rates.
A realistic estimate of the net yearly-integrated sand transport rate through the Marsdiep-channel will be about 4±1 million m^3/year. Similar values are reported by Deltares 1995 and Elias 2006.

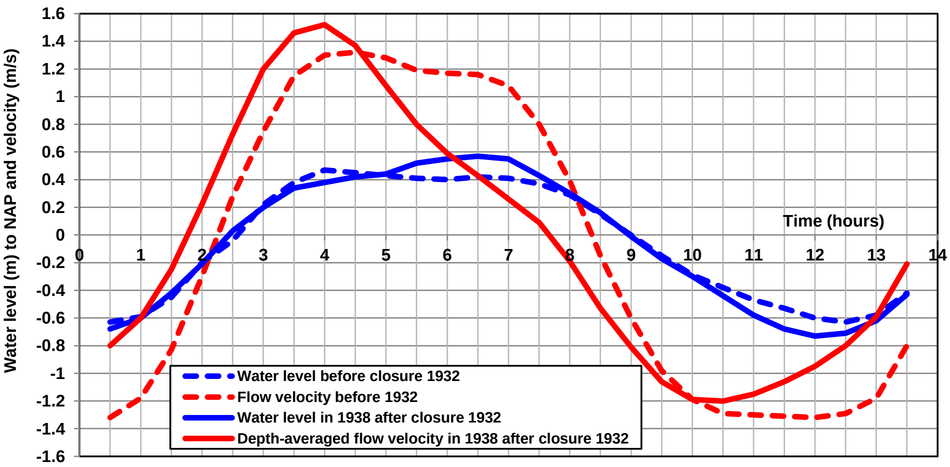

Figure 2.2.1 *Measured water levels and flow velocities before and after closure (1932), Marsdiep inlet*

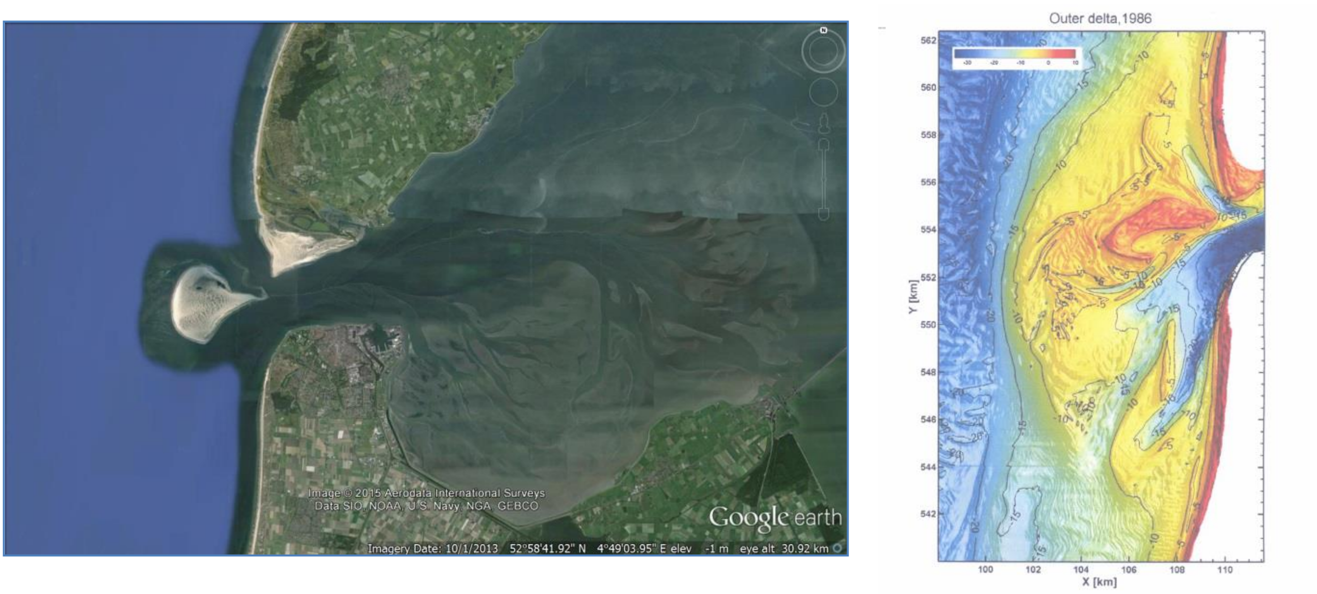

Figure 2.2.2 *Marsdiep inlet, Wadden Sea*

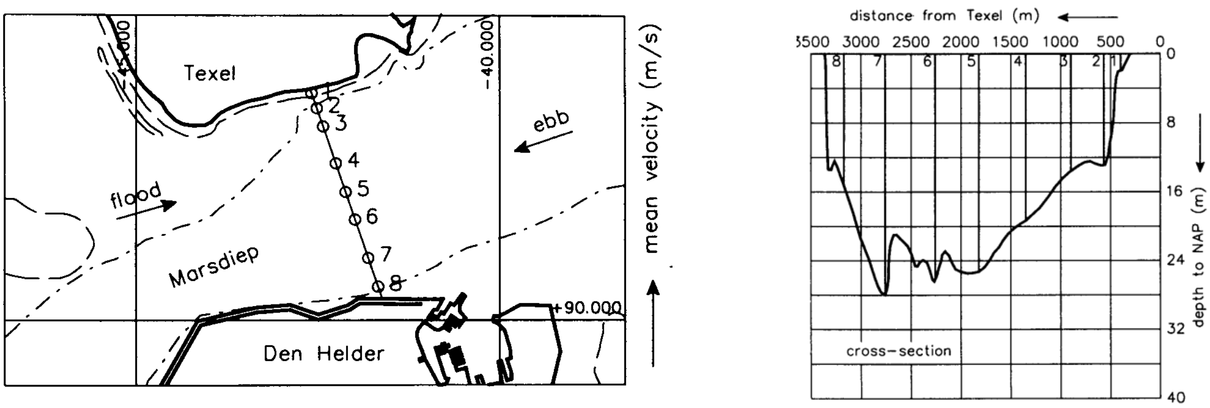

Figure 2.2.3A *Plan view and cross-section Marsdiep 1971*

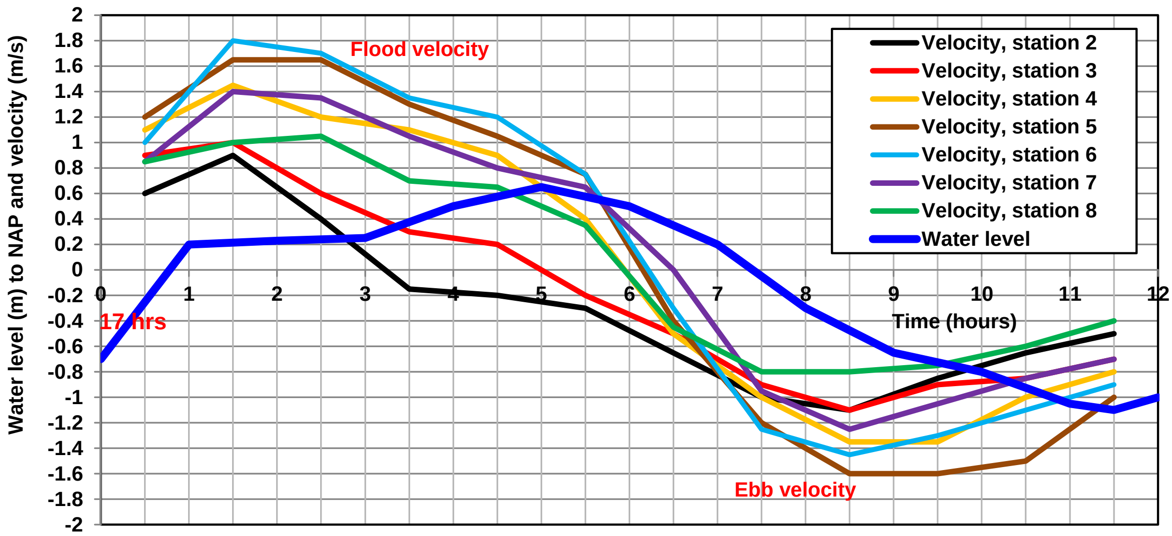

Figure 2.2.3B *Measured water level and velocity, springtide 29/30 March 1971, Marsdiep channel*

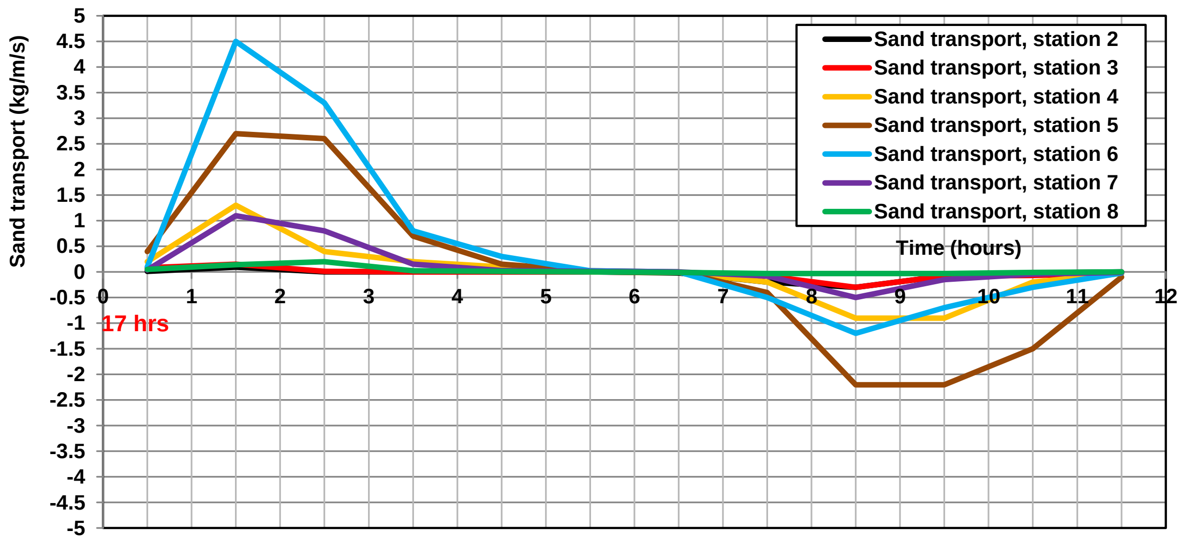

Figure 2.2.3C *Computed sand transport rates, springtide 29/30 March 1971, Marsdiep channel*

2.2.2 Vlie inlet

The width of the Vlie inlet (**Figure 2.2.4**) is about 7 km, which is much wider than the Marsdiep inlet (about 3 km). The Vlie inlet consists of a central main ebb channel and two smaller flood channels along the island tips. The ebb-tidal delta extends 10 km seaward and roughly 10 to 15 km along the Vlieland and Terschelling coasts. An almost linear erosion trend with erosion rates of 2 million m^3/year over 65 years dominated the Vlie ebb delta between 1933 and 2003 (Deltares, 2012). The present volume of the outer delta of the Vlie is of the order of 350 10^6 m^3. In the period 1933 to 2003 the shoal area (roughly bounded by the -15 m contour) of the outer delta decreased from 140 km^2 to 112 km^2. The seaward edge of the outer delta has moved landward.

During the last decades the pattern of channels and shoals of the outer delta is quite stable with the main channel Vliestroom in the middle of the inlet and smaller channels along the island tips.

The net import of sand through the Vlie inlet can be estimated from measured data of Rijkswaterstaat (1978).

Rijkwaterstaat (1978) has carried out extensive flow and sediment transport measurements in the Vlie inlet between the islands of Vlieland and Terschelling during April and June of 1976. The measurements were performed in all three sandy channels (see **Figure 2.2.4 left**):

- Zuiderstortemelk (south channel A bordering island of Vlieland);
- Stortemelk (middle channel B);
- Boomkensdiep (north channel C bordering island of Terschelling).

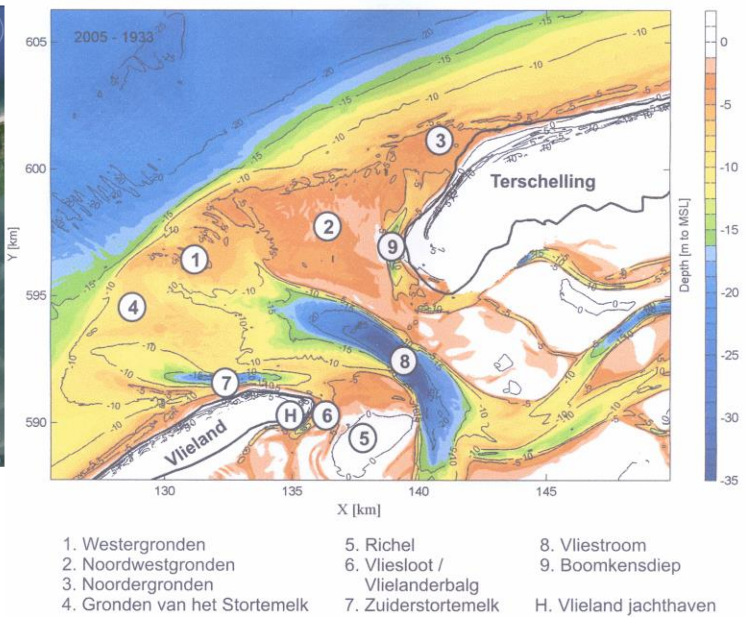

Figure 2.2.4 *Vlie inlet, Wadden Sea*

The bed of the channels consists of sand in the range of 0.2 to 0.4 mm. Mud is only present at the flats and shoals inside the basin. **Figure 2.2.5** shows the cross-sections of the three main channels. The total area below NAP is about 78000 m^2.

Flow measurements in three stations (one station in the middle of each channel) have been done in the period 6 to 14 April 1976. Flow and sediment transport measurements in 14 stations across the inlet have been carried out in the period 14 to 18 june 1976 (springtide). The suspended sediment transport measurements consisted of taking water samples at three points in the water column (0.5 m above local bottom, at 1/3h and at 2/3h, h= local water depth). The concentrations of sand (> 50 μm) and fines (< 50 μm) were determined by filtration.

Figure 2.2.6 shows the depth-averaged flow velocities and the tidal water levels as function of time in three stations (one station in each channel). The spring tidal range is about 2.2 m. The peak tidal velocities in the south and north channel are about 1.4 m/s during flood and about 0.9 m/s during ebb flow. Both channels are flood-dominated channels. The peak tidal velocities in the middle channel are about 1.25 m/s during flood and about 1.3 m/s during ebb flow. Hence, the middle channel is a slightly ebb-dominated channel. The peak flood flow (horizontal tide) is about 2 hours earlier than maximum high water.

The water volumes entering and leaving the basin through the inlet based on the measured data are shown in **Table 2.2.2**. The total inflow and outflow volumes through the inlet during springtide are about 1250 to 1300 10^6 m^3 (1050 to 1100 10^6 m^3 during mean tide). The flood and ebb volumes are about equal (difference < 3%), which means that there is almost no net flow across the tidal divines inside the basin. All water entering the basin through the throat of the inlet, also leaves the basin through the throat. It can be clearly seen (**Table 2.2.2**) that the middle channel is slightly ebb-dominated and that both side channels are flood-dominated channels.

The measured sediment transport data are given in **Table 2.2.3**. The data show that the middle channel also is ebb-dominated for sand transport.
The net sand transport through the inlet is about 41 10^6 kg during the flood phase and about 33 10^6 kg during the ebb phase of springtide, which means a net sand import of 8 10^6 kg during springtide. The net sand import during mean tide is about 70% of that during springtide due to the nonlinearity of the sand transport-flow velocity relationship, yielding a net import of about 5.5 10^6 kg or 3500 m^3 during one mean tidal cycle, using a bulk density of 1600 kg/m^3 for sand.
The net annual sand import is 730 x 3500 m^3= 2.5 $\pm$ 0.5 $10^6 m^3$/year (based on 730 tidal cycles per year).
The inflow of sand during the flood tides is about 0.7x(41 10^6/1600)x730 = 13 10^6 m^3/year.
The outflow of sand during the ebb tides is about 0.7x(33 10^6/1600)x730 = 10.5 10^6 m^3/year.
Thus, the net sand import is about 10% of the gross value of 23.5 10^6 m^3/year.
In reality, the net import of sand will be somewhat larger as the suspended sand transport in the lower 0.5 m of the water column and the bed load transport were not measured.

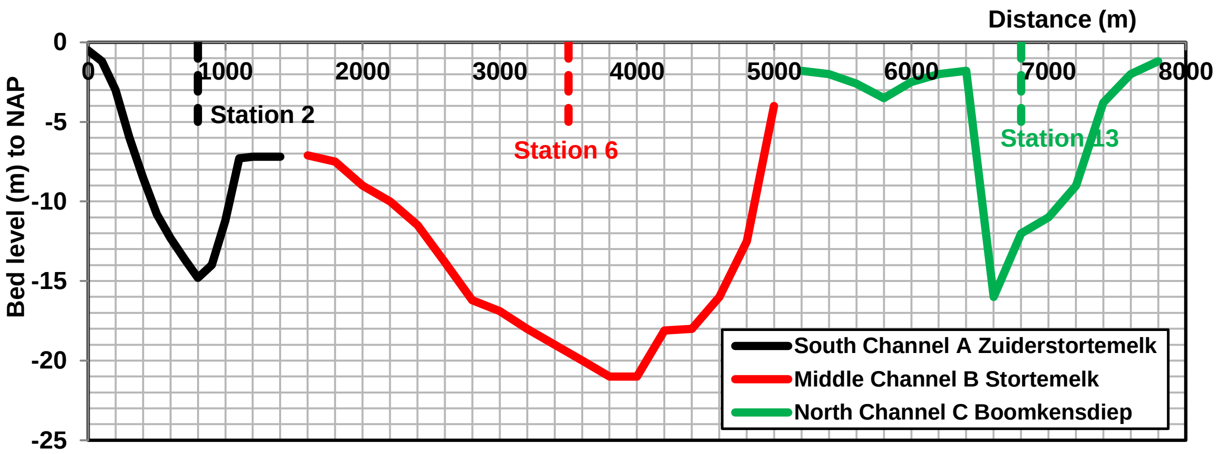

Figure 2.2.5 *Cross-sections of Vlie inlet, Wadden Sea, The Netherlands*

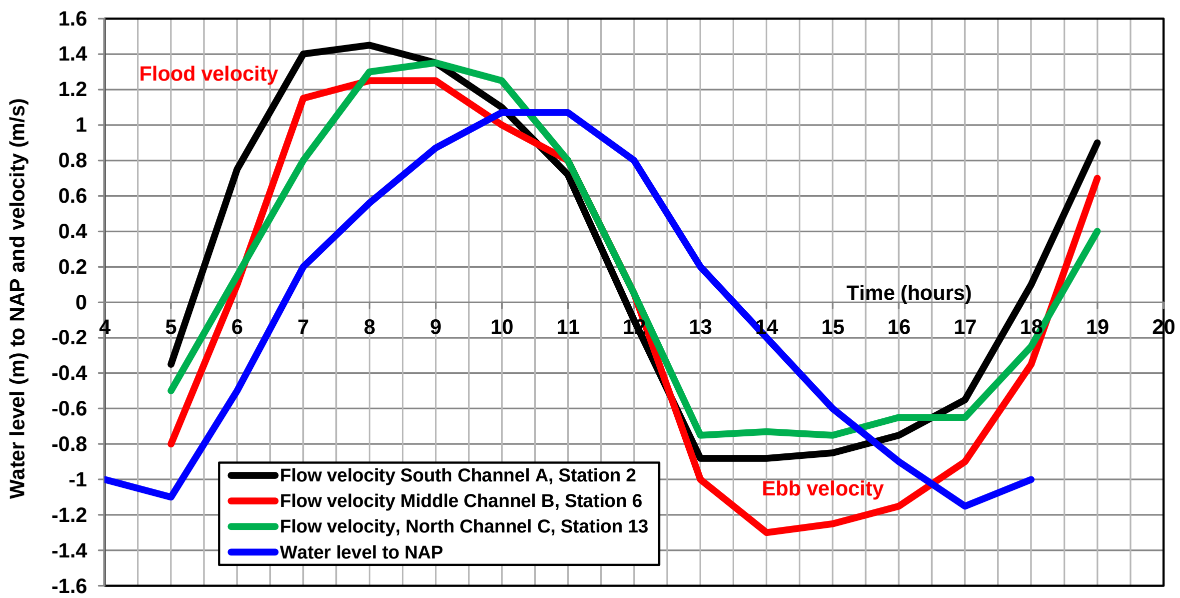

Figure 2.2.6 *Measured water levels and flow velocities during springtide in June 1976, Vlie inlet*

Channel	Water volume (m^3) during springtide June 1976	
	Flood	**Ebb**
South Channel A Zuiderstortemelk	238 10^6	112 10^6
Middel Channel B Stortemelk	794 10^6	965 10^6
North Channel C Boomkensdiep	254 10^6	167 10^6
Total	**1286 10^6 m^3** (≅1100 10^6 m^3 at mean tide)	**1244 10^6 m^3** (≅1050 10^6 m^3 at mean tide)

Table 2.2.2 *Water volumes entering and leaving through the Vlie inlet, Wadden Sea*

Channel	Effective width of channel (m)	Mass of sand > 50 μm (kg) during springtide		Mass of fines < 50 μm (kg) during springtide	
		Flood	**Ebb**	**Flood**	**Ebb**
South Channel A Zuiderstortemelk	1000	17 10^6 (17000 kg/m)	4 10^6 (4000 kg/m)	1 10^6 (1000 kg/m)	6 10^6 (6000 kg/m)
Middle Channel B Stortemelk	3000	15 10^6 (5000 kg/m)	24 10^6 (8000 kg/m)	30 10^6 (10000 kg/m)	36 10^6 (12000 kg/m)
North Channel C Boomkensdiep	1000	9 10^6 (9000 kg/m)	5 10^6 (5000 kg/m)	9 10^6 (9000 kg/m)	8 10^6 (8000 kg/m)
Total		41 10^6 kg	33 10^6 kg	40 10^6 kg	50 10^6 kg

(values between brackest are masses per unit width)

Table 2.2.3 *Sediment mass entering and leaving through the Vlie inlet during springtide, Wadden Sea*

The transport data of the fines < 50 μm shows that the ebb transport is larger than the flood transport (export of fines!), which is not in line with analysis results of bathymetry data giving relatively large sedimentation values of fines in the Vlie basin. The gross transport value of fines is about 90 10^6 kg for springtide, which is equivalent to an annual value of 0.7x730x90 10^6/1000 = 45 10^6 ton per year.
The flood-averaged and cross-section averaged concentration of fines can be determined as the ratio of the mass of fines during flood and the flood volume, yielding a value of 40 10^6/1286 10^6= 0.3 kg/m^3 or 30 mg/l, which is a realistic value. Similarly, the ebb-averaged and cross-section averaged concentration of fines is about 40 mg/l. The concentration of fines during conditions with maximum flow will be about 50 to 100 mg/l. As the measured concentrations are small, errors may easily occur during the filtration, drying and weighing procedure. Furthermore, the sediment transport measurements were only done in 6 stations across the wide inlet of 7 km. This may be the reason for small errors in the transport values of the fines.
Herein, it assumed that there is a net import of fines (< 50 μm) in the Vlie basin of the order of 1% of the gross value of 45 10^6 ton/year, yielding about 0.45 10^6 ton/year or about 1 10^6 m^3/year using a bulk density of 0.45 ton/m^3.
Figure 2.2.7 shows concentrations of fines in the Vlie basin just outside the entrance of the harbour of Harlingen (Deltares 2013), which are in the range of 30 to 150 mg/l over a period of 10 years between 1986 and 1996. Dankers et al. (2009) also report a variation range of 30 tot 150 mg/l for the entire Wadden Sea.
A large part of the fines is present in the bed between the pores of the sand particles or concentrated in thin mud layers. The percentage of fines/mud in the bed increases in landward direction and is largest near the coasts of the mainland.

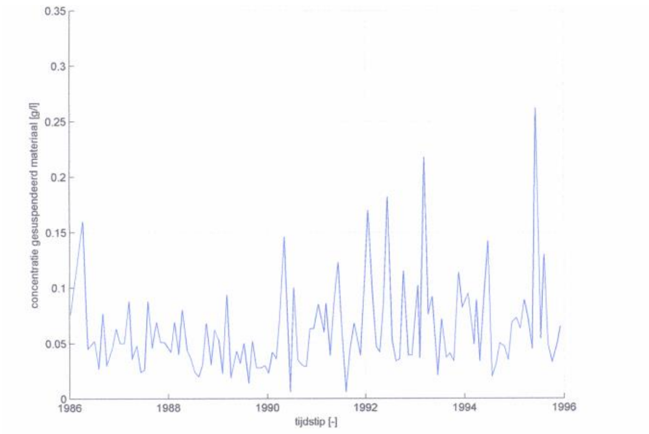

Figure 2.2.7 *Concentration of fines just outside harbour entrance of Harlingen, Wadden Sea*

2.3 Sand balance of outer basins Marsdiep and Vlie

2.3.1 Sand supply from adjacent coasts

The outer basin of the tidal inlet Marsdiep is situated between between the coast of North-Holland and the island of Texel. The outer basin of the tidal inlet Vlie is situated between the islands of Vlieland and Terschelling. Both outer basins have an alongshore length scale of 15 to 20 km.
To better understand the supply of sand from the coasts on both sides of the inlets to the outer basins, available coastal data is summarized in **Table 2.3.1** (Deltares 1995a,b). The coastline changes represent long term average values. Erosion dominates on both sides of the Marsdiep inlet despite regular sand nourishments. The coasts on both sides of the Vlie inlet are rather stable. The associated coastal erosion volumes ($V_{erosion}$) can be quantified by the expression: $V_{erosion} = \Delta y_{erosion}\, h_{profile}\, L_{section}$,
with $\Delta y_{erosion}$= coastline changes (m/year), $h_{profile}$ = profile height above the -8 m depth contour (m) and $L_{section}$= section length (m).

Areas on both sides of inlets	**Coastline change - erosion + accretion (m/year)**	**Sand erosion volume (m³/year)**	**Sand nourish ment (m³/y)**	**Estimated longshore sand transport in zone above -8 m NAP (m³/year)**	**Estimated longshore sand transport in zone between -8 m NAP and -20 m NAP (m³/year)**
Noord-Holland 1860-1990 (L=25km; h_p=20m)	-1	0.5 10^6	0.5 10^6	+0.2 to 0.5 10^6 northgoing	+0.5 to 1.0 10^6 northgoing
Texel middle section 1978-1990 (L=15km; h_p=20 m)	-5	1.5 10^6	1.0 10^6	south: -0.3 10^6 north: +0.5 10^6	south: +0.5 10^6 north: +1.0 10^6
Vlieland-middle section 1978-1990 (L=10km; h_p=20 m)	-1 west +1 east	-0.1 10^6 to 0.1 10^6	0	west: -0.2 10^6 east: +0.5 10^6	west: +0.4 10^6 east: +1.0 10^6
Terschelling-middle section 1978-1990 (L=15km; h_p=20 m)	+1 to +2	0	0.2 10^6	west: -0.1 10^6 east: +0.6 10^6	west: +0.5 10^6 east: +1.2 10^6

+ direction north to -east; - opposite direction
L= section length, h_p= profile height above -8 m depth line, distance to inlet = 5 km
Table 2.3.1 *Coastal data of North-Holland, Texel, Vlieland and Terschelling (based on Deltares 1995a,b)*

The maximum coastal erosion volume is about 1.5 million m^3/year for the middle section of Texel. This section was intensively nourished to compensate volume losses due to erosion. The erosion volumes at the middle sections of the islands of Vlieland and Terschelling are minor to nil (1978 to 1990).

The last column of **Table 2.3.1** shows the annual longshore transport rates of sand in the surf zone above the -8 m depth line at the updrift and downdrift boundaries of the coastal sections. These values are in line with earlier estimates (Deltares 1995a,b). Given the dominant influence of the waves from south-west directions, the net annual longshore sand transport along the coast of North-Holland is to the north with a maximum value of about 0.5 million m^3/year near the Marsdiep inlet. The net annual longshore transport along the islands of Texel, Vlieland and Terschelling is of the order of 0.5 million m^3/year and is directed to the north-east given the orientation of these islands. These values do occur at the most downwave boundaries of the middle sections at these islands; these boundaries are assumed to be 5 km away from the inlets. The net longshore transport at the upwave boundaries is assumed to be opposite to that at the downwave boundaries, which is caused by the wave shielding effect of the outer delta. Only low waves smaller than about 2 to 3 m can pass the shoals of the outer delta area. This effect is largest at the island of Texel (opposite longshore transport of 0.3 million m^3/year) and somewhat less at the islands of Vlieland and Terschelling (0.1 to 0.2 million m^3/year) because the upwave boundaries of these island are much more exposed to the milder waves from the sector north-east. Based on this, the net annual longshore transport values in the surf zone on both sides of the inlets are directed towards the inlet.

The estimated net longshore transport in the surf zone at both boundaries of the middle Texel section is estimated to be about 0.8 million m^3/year, which is in reasonable agreement with the observed erosion volume of about 1.5 million m^3/year. The estimated net annual longshore transport values at the islands of Vlieland and Terschelling are much larger than the observed erosion volumes, which are quite small. This is an indication that these islands are to a large extent supplied with sand carried by the dominant tidal flood currents coming from the downdrift side of the outer deltas. The flood currents on the updrift side also deliver sand to the outer deltas. It is assumed that the downdrift transport of sand by the flood currents is about 50% of the updrift transport due to wave shielding effect.

The net tide-related sand transport in the shorefacre zone between -8 m and -20 m NAP at the updrift sides of the inlets is estimated to be about 1 million m^3/year.
The net annual sand transport from the south towards the outer delta can be estimated by:

$$T_{sand,outerdelta} = b_{eff}\, \Delta t_{eff}\, N_{tide}\, q_{sand}/\rho_{bulk},$$

with b_{eff} = effective cross-shore width of outer delta (≅ 5000 m), Δt_{eff} = effective tidal period with sand transport (≅ 2 hours flood = 7200 s), N_{tide}= number tides per year (730), q_{sand}= sand transport at peak tidal flow with waves superimposed (in kg/s/m) and ρ_{bulk} = dry bulk density of sand (1600 kg/m^3).

A tidal flood current of 0.4 to 0.5 m/s to the north at a depth of 15 m with waves of 2 m over a sand bed of 200 tot 300 μm generates a sand transport rate of about $q_{sand} \cong 0.05$ kg/s/m, see **Figure 2.3.1**.
This yields: $T_{sand,outerdelta}$= 0.75 million m^3.
Hence, a net sand transport of about 0.5 to 1 million m^3 per year into the outer basin from the shoreface zone (between -8 m and -20 m NAP) is a realistic value.
The net annual sand transport rate leaving the basin at the northern boundary is assumed to be about 50% to 70% of that entering the basin at the southern boundary, because the northern boundary is partly sheltered from the waves by the presence of the ebb delta shoals, see **Figure 2.2.2 right**.

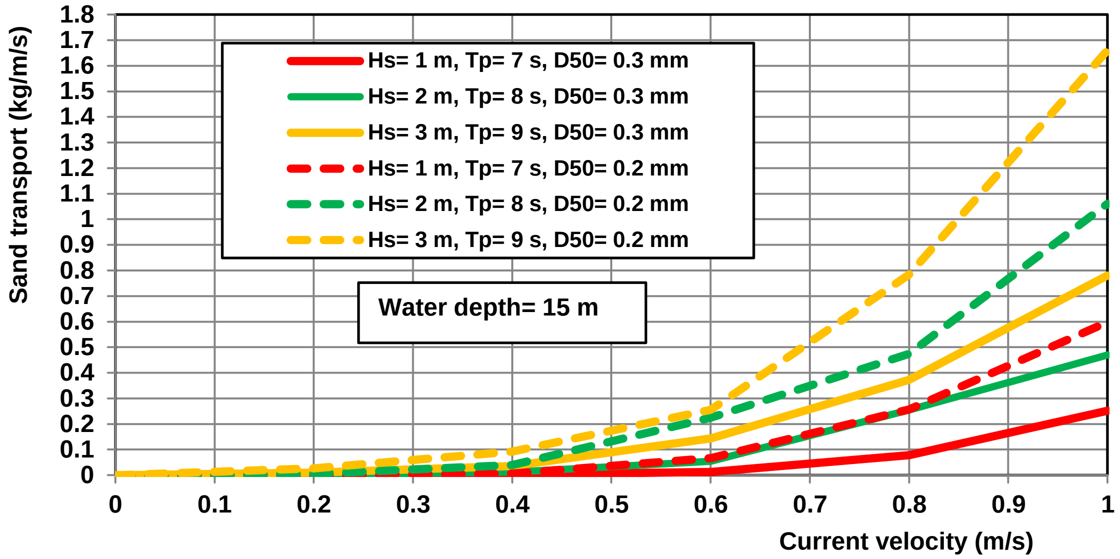

Figure 2.3.1 *Sand transport as function of current velocity and wave height, h= 15 m, D_{50}=0.2; 0.3 mm*

Figure 2.3.2 *Sand balance outer basin Marsdiep (sand transport values in million m^3 per year)*

2.3.2 Sand balance for outer basin Marsdiep

The sand balance of the Marsdiep outer basin is estimated to be (see **Figure 2.3.2**):
Throat: -3.8 million m^3/year out of outer basin
South; surf zone -8/+3 m: +0.3 million m^3/year into outer basin (Deltares 1995b)
South; shoreface zone -20/-8 m: +1.0 million m^3/year into outer basin (Deltares 1995b)
North; surf zone -8/+3 m: +0.2 million m^3/year into outer basin
North; shoreface zone -20/-8 m: -0.7 million m^3/year out of outer basin
Net cross-shore transport across -20 m: 0 (Deltares 1995a)
Total erosion of outer delta incl. coast: -3.0 million m^3/year
The supply of sand from the adjacent coasts to the outer basin is about 0.8 million m^3/year.

The total erosion volume includes the sand nourishment volumes which have been intensified after 1990.
The sediment balance of the Marsdiep outer basin yields a total erosion volume (coast+ebbdelta) of about 3 million m^3/year, which is considerably smaller than the total erosion volume given by Elias et al. (2012). They give a total erosion volume (mostly sand) of about 375 10^6/70= 5.3 million m^3/year between 1935 and 2005. This latter value is much larger than the sedimentation volume (sand+fines) observed in the inner Marsdiep basin: 240 10^6/65 = 3.5 million m^3/year, see Table 2.1.5. Assuming a percentage of fines of about 25%, the sedimentation volume of the sand fraction of the inner Marsdiep basin is about 2.6 million m^3/year. This latter value is about 50% of the erosion volume of the outer basin given by Elias et al. (2012), The relatively large values given by them may partly be caused by relatively large area of the outer basin studied by Elias et al.

2.3.3 Sand balance for outer basin Vlie

The sand balance of the Vlie outer basin is estimated to be (see **Figure 2.3.3**):

Throat:	-2.8 million m^3/year out of outer basin
South; surf zone -8/+3 m:	+0.5 million m^3/year into outer basin
South; shoreface zone -20/-8 m:	+1.0 million m^3/year into outer basin
North; surf zone -8/+3 m:	+0.1 million m^3/year into outer basin
North; shoreface zone -20/-8 m:	-0.7 million m^3/year out of outer basin
Net cross-shore transport across -20 m:	0 (Deltares 1995a)
Total erosion of outer delta incl. coast	-1.9 million m^3/year

The supply of sand from the adjacent coasts to the outer basin is about 0.9 million m^3/year.

The total erosion volume includes the sand nourishment volumes which have been intensified after 1990.
The sediment balance of the Vlie outer basin yields a total erosion volume (coast+ebbdelta) of about 1.9 million m^3/year, which is in good agrement with the erosion value of 146 10^6/70= 2.1 million m^3/year given by Elias et al. (2012).

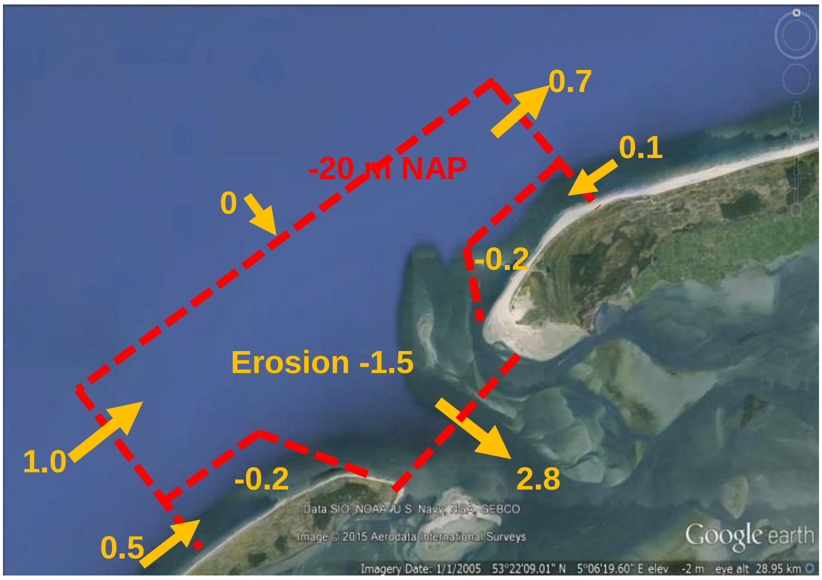

Figure 2.3.3 *Sand balance outer basin Vlie (sand transport values in million m^3 per year)*

3 Schematization of tidal inlet system and application of SEDBOX-model

3.1 System schematization

A tidal inlet system can be subdivided in the following basic elements (see Figure 3.1.1):

- inlet throat;
- outer basin with adjacent coasts and offshore ebbdelta;
- Inner basin with tidal flats and channels.

A small harbour basin may be present in the inner basin and is therefore separately modelled.
The tidal inlet system is in a dynamic equilibrium if the volume of sediments entering the inner basin over the tidal cycle is about the same as the volume of sediments leaving the inner basin. In that case the wet cross-section of the throat and the inner channels are in dynamic equilibrium with the tidal water volumes passing the cross-sections of the throat and channels. The volume of sediments accumulated in the ebbdelta and in the tidal flats will be more or less constant in the dynamic equilibrium situation. Empirical relationship are proposed in the Literature, which describe these 'equilibrium' volumes and cross-sections as function of the tidal prism.

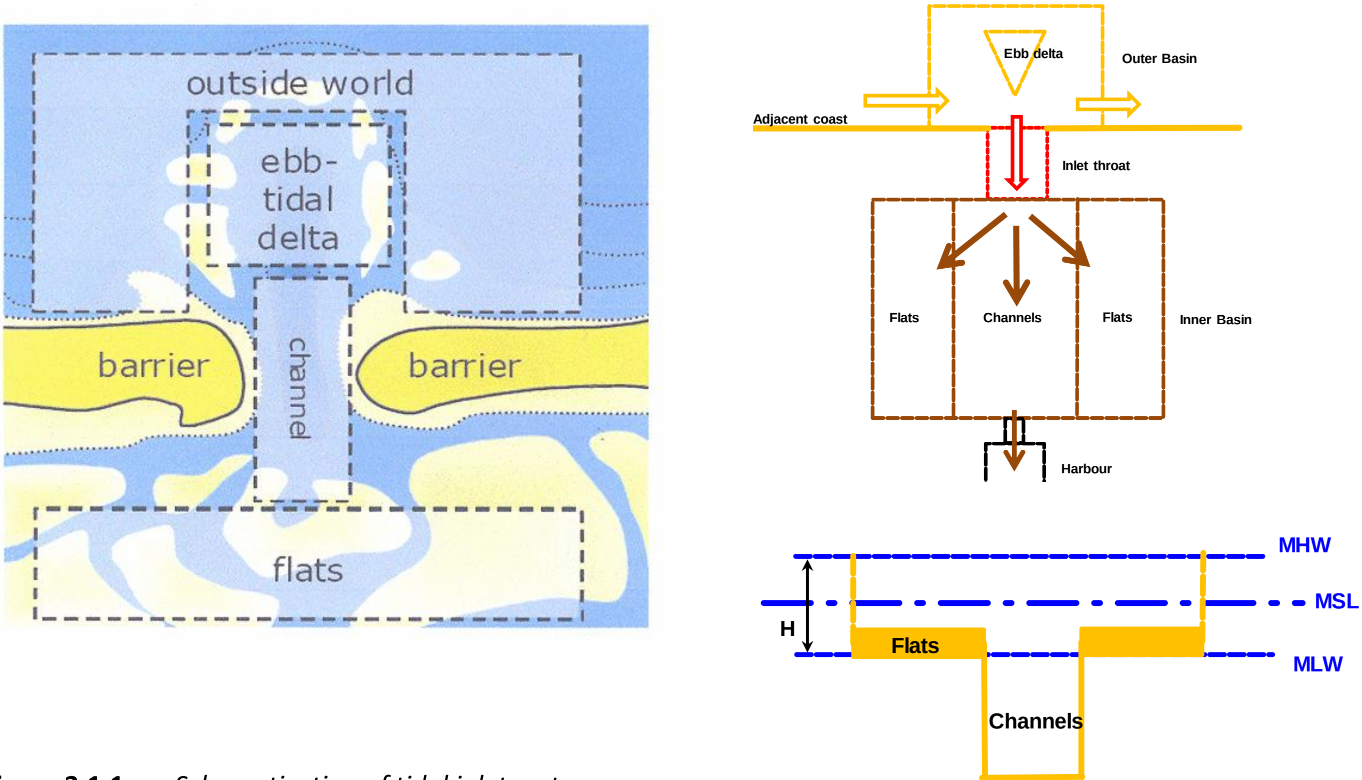

Figure 3.1.1 *Schematization of tidal inlet system*

3.2 Model equations

It is assumed that:

- no mud can be deposited in the outer ebb delta due to the exposure to waves;
- sediment volume of the flats decreases due to sea level rise because MLW will be higher;
- sediment volume of flats increases due to increase of tidal range because MLW will be lower;
- water volume of tidal channels increases due to sea level rise because MLW will be higher;

- water volume of tidal channels decreases due to increase of tidal range because MLW will be lower;
- sediment volume of outer ebb delta is defined as the volume of sediment above the plane through the coastal profiles of the adjacent coasts outside the outer basin;
- sediment volume of outer ebb delta decreases due to sea level rise because the level of MSL will shift upwards and the adjacent coastal profiles outside the outer basin will also shift upwards with sea level rise;
- erosion of the ebb delta is reduced if the mean thickness of the ebb delta is smaller than 2 times the minimum thickness (input value of about 2 m); if the ebb delta becomes gradually smaller, the channels of the ebb delta will become wider and larger resulting in a reduction of the current velocities and thus to less erosion; the erosion is larger for a higher thickness of the ebb delta than for a lower thickness value: the mean thickness values of the Marsdiep and Vlie basins are in the range of 5 to 6 m in 1933; the erosion of the coast will increase if the erosion of the outer delta is reduced;
- sand and mud import through inlet throat is distributed (e-coefficients) over flats, channels and harbour; mud (silt+lutum) is defined as the fraction smaller than 63 μm;
- net import capacity of sand through the throat of the inlet will be approximately constant in time and is not influenced by internal and external effects (mining, sea level rise); only the division between flats and channels is influenced by these effects; this is a very conservative and safe assumption;
- net import capacity of the outer basin (sediment supply to the outer basin) is assumed to be constant in time; the net import is reduced slightly using a reduction coeficient ($r = V_{w,channel}/P$ if $V_{w,channel} < P$); the reduction is only applied if the channel volume of the inner basin is smaller than the tidal prism volume (the channels are then so small that the ebb currents can erode more sediments resulting in a larger ebb transport component); no reduction is applied if $r > 1$; examples: $r_{vlie\ basin}$= 1.1 in 1933 and $r_{marsdiep}$= 2.1 in 1933.

The net import of sand is the difference of two large quantities; the flood and ebb transport components. The flood transport through the throat mostly consists of sand eroded from the tidal channels just seaward of the the throat, where the flood velocities are gradually accelerating towards the throat. Similarly, the ebb transport through the throat mostly consists of sand eroded from the tidal channels just landward of the throat, where the ebb velocities are gradually accelerating towards the throat. The eroded sand is resupplied by sand from further away in the system.
The net import of sand will increase if the ebb velocities become smaller due to an overdepth of the channels just landward of the throat. An overdepth of these channels may be the result of dredging activities or due to the subsidence of the bed surface due to mining activities (gas, water or salt in deeper soil layers). Generally, these activities are planned further away from the throat and thus it will take time (decades) before the disturbing effects of dredging/mining can influence the depth of the main channels just landward of the throat.
The assumption of an approximately constant import of sand limits the prediction horizon of the model to about 30 years in the case of significant dredging and mining at the far end of the inner basin.
Dredging of sand from the channels of the inner basin will lead to less deposition on the flats. Similarly, dredging from the flats of the inner basin will lead to less deposition in the channels.
The import of fines (smaller than 63 μm) through the throat largely depends on the supply from outside regions. Fine sediments are almost absent in the bed of the throat and the adjacent main channels.
Most fine sediments are present in the tidal flats and in the smaller channels at the end of the basin.
Dredging of fines from the flats of the inner basin will immediately lead to a reduction of the ebb transport component and hence to an increase of the net import of fines.
Sea level rise and soil subsidence due to dredging and mining will generally lead to a slight increase of the tidal prism and asymmetry and thus to a slight increase of the net sand import through the the inlet.

The time development of volumes of the subsystems are desribed by:

$$V_{s,flats} = V_{s,flats,t=o} + e_{flats}\ r\ T_{sand,i} + e_{flats}\ T_{fines,i} - A_{flats}\ \Delta s/1000 + A_{flats}\ 0.5\ \Delta H + V_{ex} \quad (3.1)$$

$$V_{s,ebbdelta} = V_{s,ebbdelta,t=o} - e_{ebbdelta}\ r\ T_{sand,i} + T_{sand,ob} - A_{ebbdelta}\ \Delta s/1000 + V_{ex} \quad (3.2)$$

$$V_{w,channels} = V_{s,channels,t=o} - e_{channels}\ r\ T_{sand,I} - e_{channels}\ T_{fines,i} + A_{channels}\ \Delta s/1000 - A_{channels}\ 0.5\ \Delta H - V_{ex} \quad (3.3)$$

$$V_{w,harbour} = V_{s,harbour,t=o} - e_{harbour}\ r\ T_{sand,i} - e_{harbour}\ T_{fines,i} + A_{harbout}\ \Delta s/1000 - A_{harbour}\ 0.5\ \Delta H - V_{ex} \quad (3.4)$$

$$\Delta V_{e,coast} = (1 - e_{ebbdelta})\ r\ T_{sand,i} - A_{coast}\ \Delta s/1000 \quad (3.5)$$

with:

$V_{s,flats}$ = sediment volume of tidal flats (sand and mud) between mean low water (MLW) and mean high water (MHW);
$V_{s,ebbdelta}$ = sediment volume of outer ebbdelta (sand) below mean sea level (MSL) with layer thickness δ;
$V_{w,channels}$ = water volume of tidal channels of inner basin below MLW;
$V_{w,harbour}$ = water volume of tidal harbour channels of inner basin below MLW;
V_{exl} = sediment volume due to external dredging/mining (negative in m^3/year) or dumping (positive);
$\Delta V_{e,coast}$ = erosion volume of coast inside outer basin (to be compensated by nourishment);
A_{basin} = surface area of total tidal basin at level of MHW ($A_{basin}= A_{flats}+A_{channels}+A_{harbour}$);
A_{flats} = surface area of inner tidal flats at level of MLW;
$A_{channels}$ = surface area of inner tidal channels;
$A_{harbour}$ = surface area of inner harbour basin;
$A_{ebbdelta}$ = surface area of ebb delta;
$A_{outerbasin}$ = surface area of outer basin;
A_{coast} = surface area of coastal zone;
P = tidal prism;
$T_{sand,i}$ = net transport of sand (> 63 μm) trough tidal inlet throat (inputvalue in m^3/year; import +)
$T_{fines,i}$ = net transport of fines (< 63 μm) trough tidal inlet throat (inputvalue in m^3/year; import +)
$T_{sand,ob}$ = net transport of sand (> 63 μm) to outer basin (inputvalue in m^3/year)
H = tidal range (m);
ΔH = change of tidal range (m/year; + increase; - decrease);
Δs = sea level rise (mm/year);
e = exchange coefficient ($e_{flats}+e_{channels}+e_{harbour}$ = 1),
r = coefficient related to ratio channel volume of inner basin and tidal prism volume.

The coefficients are described by:

$$e_{flats} = \gamma_1\ (V_{w,flats}/V_{total}) \quad (3.6)$$

$$e_{harbour} = (V_{w,harbour}/V_{total}) \quad (3.7)$$

$$e_{channels} = 1 - e_{flats} - e_{harbours} \quad (3.8)$$

$$e_{ebbdelta} = \text{minimum}\ (1-\gamma_2,\ 0.5\ \delta_{ebbdelta}/\delta_{ebbdelta,minimum}) \quad (3.9)$$

$$r = V_{w,channels}/P \qquad \text{if } V_{w,channels}/P \leq 1 \quad (3.10a)$$

$$r = 0.5 V_{w,channels}/P \qquad \text{if } V_{w,channels}/P \geq 1 \quad (3.10b)$$

$$r = 1 \qquad \text{if } 1< V_{w,channels}/P >1 \quad (3.10c)$$

with:

γ_1 = calibration coefficient for flats (input value, range 0.5 to 2);
γ_2 = calibration coefficient for coast (input value, range 0.25 to 0.35);
$\delta_{ebbdelta}$ = $V_{s,ebbdelta}/A_{ebbdelta}$ = thickness of ebb delta;
$\delta_{ebbdelta,minimum}$ = minimum thickness of ebb delta (inputvalue $\cong$ 2 m);
$V_{w,flats}$ = A_{flats} H - $V_{s,flats}$ = maximum water volume above inner tidal flats;
$V_{w,channels,max}$ = $V_{w,channels} + A_{channels}$ H = maximum water volume of inner tidal channels;
$V_{w,harbour,max}$ = $V_{w,harbour} + A_{harbour}$ H = maximum water volume of inner tidal harbour;
V_{total} = $V_{w,flats} + V_{w,channels,max} + V_{w,harbour,max}$

Equation (3.6) determines how much sediment from the net sediment import is carried onto the flats.
Equation (3.9) determines how much sand is eroded from the outer ebb delta and from the adjacent coast and roughly varies between 0.5 and 0.75. If the mean thickness of the outer delta becomes smaller than about 2 m, more sand is eroded from the coast and less sand is eroded from the ebbdelta.
Equation (3.10) yields that the net import of sand slightly increases if the channel volume of the inner basin becomes larger than two times the tidal prism (situation with relatively deep channels) and slightly decreases if the channel volume becomes smaller than the tidal prism (situation with relatively shallow channels).

The equilibrium volumes are described by:

$$V_{s,flats,\ equilibrium} = d_{flats,eq}\ A_{flats,eq} = \alpha_f\ A_{flats,eq}\ H = (0.42 - 0.24\ 10^{-9} A_{basin})(1-0.000025\ A_{basin}^{0.5})\ A_{basin}\ H \quad (3.11)$$
$$V_{w,channels,equilibrium} = \alpha_c\ P^{1.57} \quad (3.12)$$
$$V_{s,ebbdelta,equilibrium} = \alpha_d\ P^{1.23} \quad (3.13)$$

$$P = A_{basin}\ H - V_{s,flats} \quad (3.14)$$

with:

P = tidal prism of inner basin;
$A_{flats,eq}$ = $(1-0.000025\ A_{basin}^{0.5})\ A_{basin}$ = equilibrium area of flats for Wadden Sea basin (based on Renger and Partenscky 1974, 1980);
α_f = $d_{flats,eq}/H = (0.41 - 0.24\ 10^{-9} A_{basin})$ = relative flat height in the range of 0.2 to 0.4 for Wadden Sea basin (based on Deltares 1992);
α_c = calibration coefficient (≅ 0.0000087 for Wadden Sea basin based on Renger and Partenscky 1974, 1980; ≅ 0.000016 for the Wadden Sea based on Deltares 1992);
α_d = calibration coefficient (≅ 0.0055 for exposed deltas to 0.0085 for sheltered deltas based on Walton and Adams, 1976; ≅ 0.0066 for Wadden Sea based on Eysink 1990; Equation (3.13) is questionable as the sediment volume of the ebb delta also depends on the asymmetry of the tidal velocities in the inlet (see also Ridderinkhof et al. 2014).

The basic input values of the model are:

1. volumes (m^3) of the flats, channels, harbour, basin at initial time (t=0);
2. surface areas (m^2) of flats, channels, harbour, outer ebbdelta, outer channels (assumed to be constant);
3. external volumes (dredging/mining or dumping volume) as function of time;
4. minimum thickness of outer ebb delta (≅ 2 m);
5. tidal range (m) and sea level rise (mm/year) as function of time;
6. net transport rates of sand and fines through the inlet (in m^3/year);
7. net sand transport rate to outer basin (in m^3/year from adjacent coasts);
8. calibration coefficient to modify the sediment exchange with the tidal flats;
9. calibration coefficient to subdivide the total erosion volume of the outer basin over the ebbdelta and the coasts adjacent to the the inlet.

The parameters for the Marsdiep and Vlie basins are given in **Table 3.2.1**.
It is noted that the SEDBOX-model can only be used for future predictions if it is shown that the observed volume changes in the past can be explained by a constant import of sediment through the inlet and that the net import of sediment remains approximately constant in the future situation.

Parameter	Marsdiep	Vlie
H= mean tidal range (m)	1.5 - 1.7	1.8 - 2.0
B= width of inlet below MSL (m)	3000	7000
$A_{cross\text{-}section}$= area of cross-section below MSL at inlet throat (m^2)	50000	78000
A_{basin} = surface area of total tidal basin at level of MHW (m^2); mean value over 1933 to 2000	700 10^6	675 10^6
A_{flats} = surface area of inner tidal flats at level of MLW (m^2) mean value over 1933 to 2000	125 10^6	275 10^6
$A_{channels}$ = surface area of inner tidal channels (m^2) mean value over 1933 to 2000	575 10^6	400 10^6
$A_{outerbasin}$ = surface area of outer basin + channels + coast (m^2)	150 10^6	150 10^6
$A_{ebbdelta}$= surface area of outer ebb delta (m^2)	80 10^6	80 10^6
A_{coast} = surface area of coastal zone (m^2)	20 10^6	20 10^6
$V_{s,flats,t=0}$ = sediment volume (m^3) of tidal flats (sand and mud) between mean low water (MLW) and mean high water (MHW) at t=0 (1933)	42.6 10^6	105 10^6
$V_{w,channels,t=0}$= water volume (m^3) of tidal channels of inner basin below MLW at t=0	2370 10^6	1270 10^6
$V_{s,ebbdelta,t=0}$ = sediment volume (m^3) of outer delta at t=0 (1933)	650 10^6	470 10^6
$\delta_{minimum}$ = minimum thickness of ebbdelta	2	2
$T_{sand,i}$= net transport of sand over tidal cycle trough tidal inlet throat (in m^3/year; import +)	3.8 10^6	2.8 10^6
$T_{fines,i}$= net transport of fines (<63 μm) over tidal cycle trough tidal inlet throat (in m^3/year; import +)	0.8 10^6	0.6$10^6$
$T_{sand,ob}$= net transport of sand over tidal cycle from coasts to outer basin (in m^3/year)	0.8 10^6	0.9 10^6
$\alpha_{channel}$ = coefficient equilibrium volume channel	0.0000087	0.0000087
α_{delta} = coefficient equilibrium volume outer delta	0.0066	0.0066
γ_1 = calibration coefficient sediment for tidal flats (-)	**1.2**	**1.8**
γ_2 = calibration coefficient sediment for coast of outer basin (-)	**0.25**	**0.15**

Table 3.2.1 *Basic data of tidal basins Marsdiep and Vlie, Wadden Sea*

3.3 Measured and computed sediment volumes Marsdiep basin

3.3.1 Basic data

The basic data of the SEDBOX-model for the present siutation (Van Geer 2007) are given in **Table 3.2.1**.
The γ_1-coefficient has been used to get the best agreement with measured volume data of the flats and channels of the inner basin. The γ_2-coefficient has been used to get the best agreement with measured coastal erosion volumes (outer basin).
The net sand transport values passing the throat of both inlets are taken from the sand balance results (see **Section 2.3**) and are **not** calibrated. These values are assumed to be constant over the period (1932 to 2000) after closure of the Zuiderzee. The net import value of fines is set to 20% of the net sand transport import for the Marsdiep basin and to 30% for the Vlie basin (based on Arcadis 2010). These values are also constant over time.
As the volume data of the flats and channels include the effect of dredging, the dredging volumes are not explicitly modelled.

3.3.2 Situation between 1933 and 2000

Figure 3.3.1 shows the measured and computed volumes of the Marsdiep basin as function of time between 1933 and 2000; sea level rise is 2 mm/year. In 1932 the Zuiderzee basin was closed by a closure dike. It can be seen that the measured sediment volume of the tidal flats and the measured water volume of the tidal channels of the Marsdiep basin are fairly constant between 1933 and 2000.
The net sand transport through the inlet is set to 3.8 million m^3/year.
The net transport of fines (< 50 μm) through the inlet is set to 0.8 million m^3/year (about 20% of sand transport).
The net import of sand into the outer basin from the North Sea coast is set to 0.8 million m^3 per year
The behaviour of the measured volume of the flats, channels and outer delta between 1933 and 2000 can be represented fairly well by the SEDBOX-model using the data given in **Table 3.2.1** and sea level rise of 2 mm per year. The volumes of the flats are somewhat overestimated.
The subdivision of the net sediment transport through the inlet over the flats and channels is related to the water volumes above the flats and channels. As the flats only cover about 20% of the total Marsdiep basin, only 5% of the net sediment import is deposited on the flats of the Marsdiep basin. This percentage increases slowly in time to about 6% in 2100. Most sedimentation takes place in the channels reducing the water volume in the channels.

The *computed* volumes of the flats increase from 42.6 10^6 to 43.9 10^6 m^3 between 1933 and 2000 or an annual deposition of about 0.019 10^6 m^3/year. The *measured* value is -0.11 10^6 m^3/year (erosion!).
The *computed* volumes of the channels decrease from 2370 10^6 to 2145 10^6 m^3 between 1933 and 2000 or an annual deposition of about 3.35 10^6 m^3/year. The *measured* deposition is 1.6 10^6 m^3/year.

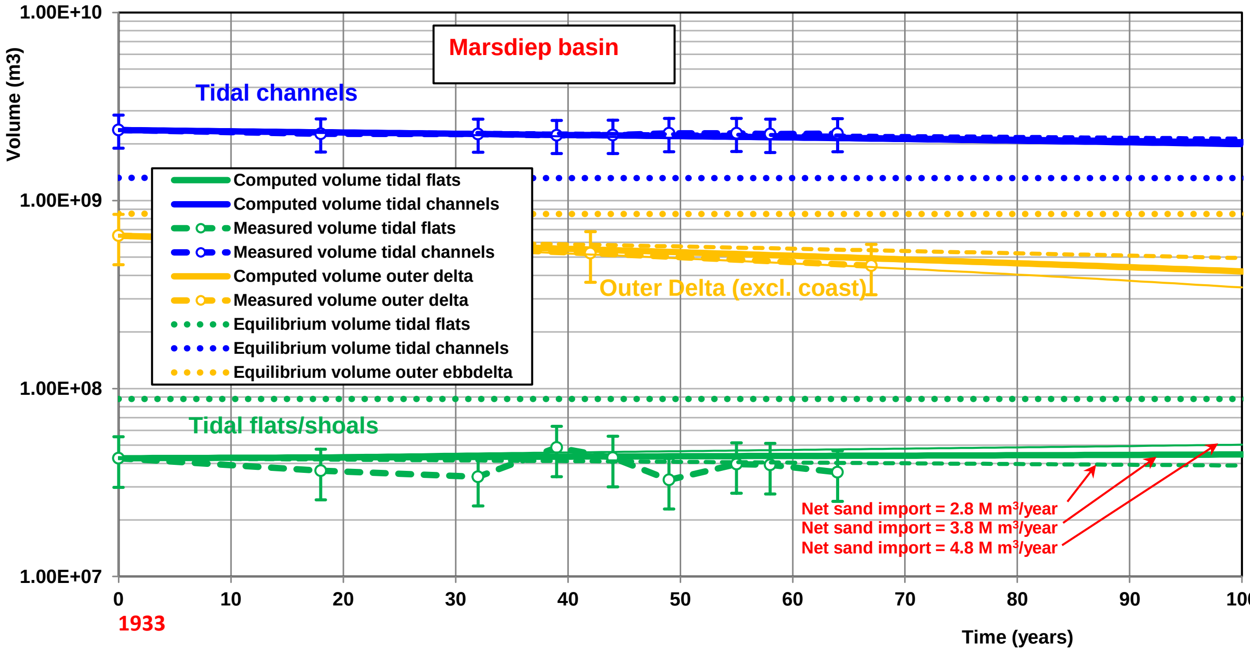

Figure 3.3.1 *Measured and computed volume data for Marsdiep basin; sea level rise= 2 mm/year*

The computed volumes of the flats and the channels inside the basin show a trend towards their equilibrium values. The equilibrium values have not been calibrated. Compared to the equilibrium value, the volume of the flats inside the basin is much too small. The volume of the channels is too large. The equilibrium volumes of the outer delta are much too large, as the computed and measured volumes of the outer delta move away from the equilibrium values (see also **Section 2.2.1**). It should be realized that the 'true' equilibrium volumes of the Marsdiep are unknown. The equilibrium values are represented by empirical relationships (Equations 3.11, 3.12 and 3.13) which are based on the behaviour of various other basins with an inaccuracy of the order of ±50%.

The net import of sand into the outer basin from the North Sea coast is assumed to be 0.8 million m^3 per year, see **Section 2.3.2**. This volume of sand is supplied (import of sand into the outer basin) by tidal currents in combination with waves from the sea bed of the North Sea. The sand transport values at the nothern side of the outer basin are smaller than those at the southern side, which is caused by the wave shielding effect of the delta.

Figure 3.3.1 also shows the effect of smaller and larger sand import values trough the inlet (3.8 ± 1 million m^3/year). The flats grow more for a larger sand import of 4.8 million m^3/year and less for a smaller sand import of 2.8 million m^3/year. Compared to the measured volume data of the flats, a net sand import of 2.8 million m^3/year also is a very realistic estimate. However, the decease of the outer delta volume is less well simulated. Using a net sand import of 4.8 million m^3/year, the erosion of the outer delta is more severe.
The computed annual deposition volumes of the flats in the Marsdiep basin for the period 1933 to 2000 are given in **Table 3.3.1**. Measured values are also shown. The deposition is largest for a sea level rise of 1.7 mm/year. The computed values are within the variation range of the measured values.
It is concluded that the measured volume development of the flats, channels and outer delta of the Marsdiep basin over the period 1933 to 2000 can be reasonably well simulated using a constant net import of sediment.

Basin	**Measured deposition 1933 to 2000**	**Computed annual Sedimentation 1933-2000**	
		sea level rise 1.7 mm/year	**sea level rise 2 mm/year**
Annual change of volume of flats in Marsdiep basin	0 to 0.5 10^6 m^3/year	0.055 10^6 m^3/year	0.019 10^6 m^3/year
Annual change of volume of flats in Vlie basin	1 to 1.4 10^6 m^3/year	0.55 10^6 m^3/year	0.48 10^6 m^3/year

Table 3.3.1 *Annual changes of volume of flats in Marsdiep and Vlie basins between 1933 and 2000*

3.3.3 Future situation with increasing sea level rise

In Section 3.3.2 it has been shown that a constant import of sediment through the inlet throat can very well explain the observed volume changes over a period of about 70 years in the past (1933 to 2000). The SEDBOX-model can only be used for future predictions (over about 50 years or so) if the net import of sediment through the inlet remains fairly constant during this period. This strongly depends on the future tidal conditions in the Marsdiep basin. The tidal range and the tidal prism should remain fairly constant.
Based on the tidal analysis given in **Section 2.1.1**, it is assumed tha the tidal range and tidal prism will remain fairly constant in the near future (coming 50 years) with limited sea level rise up to 5 mm/year.

Four scenarios of future sea level rise have been used to compute the volumes of the flats, channels and outer delta:

A. constant value of 1.7 mm per year between 1933 and 2100;
B. constant value of 2 mm per year between 1933 and 2100;
C. constant value of 2 mm/year between 1933 and 2020 and 3 mm/year between 2020 and 2100;
D. constant value of 2 mm/year between 1933 and 2020 and 4 mm/year between 2020 and 2100.

The sea level rise values of these scenarios are quite moderate and are of the same order of magnitude as the annual sedimentation rates in the present situation. Hence, the reduction of the channel depths of the Marsdiep basin will be similar as that in the present situation and thus the tidal characteristics will not change much. Based on this, it is assumed that the SEDBOX-model can also be used for future predictions with moderate sea level rise values up to 4 mm/year.

Scenario B with sea level rise of 2 mm/year yields a gradually increasing volume of the flats and a gradually decreasing volume of the channels, see **Figure 3.3.2**.

Scenario A leads to somewhat larger deposition rates at the flats, see **Table 3.3.2**.

Scenario C leads to an increase of the volume of the flats up to 2020, but the volume of the flats slightly decreases after 2020. The volumes of the channels and the outer delta are mot much affected.

Scenarion D leads to a significant loss of the volume of the flats after 2020 (gradual drowning of the flats). In 2100 the volume of the flats is about 40% smaller than that in 2020. The volumes of the channels and the outer delta are not so much affected.

The computed annual volume changes of the flats in the Marsdiep basin for the period 2020 to 2100 are given in **Table 3.3.2**. Deposition changes to erosion for a sea level rise larger than 3 mm/year.

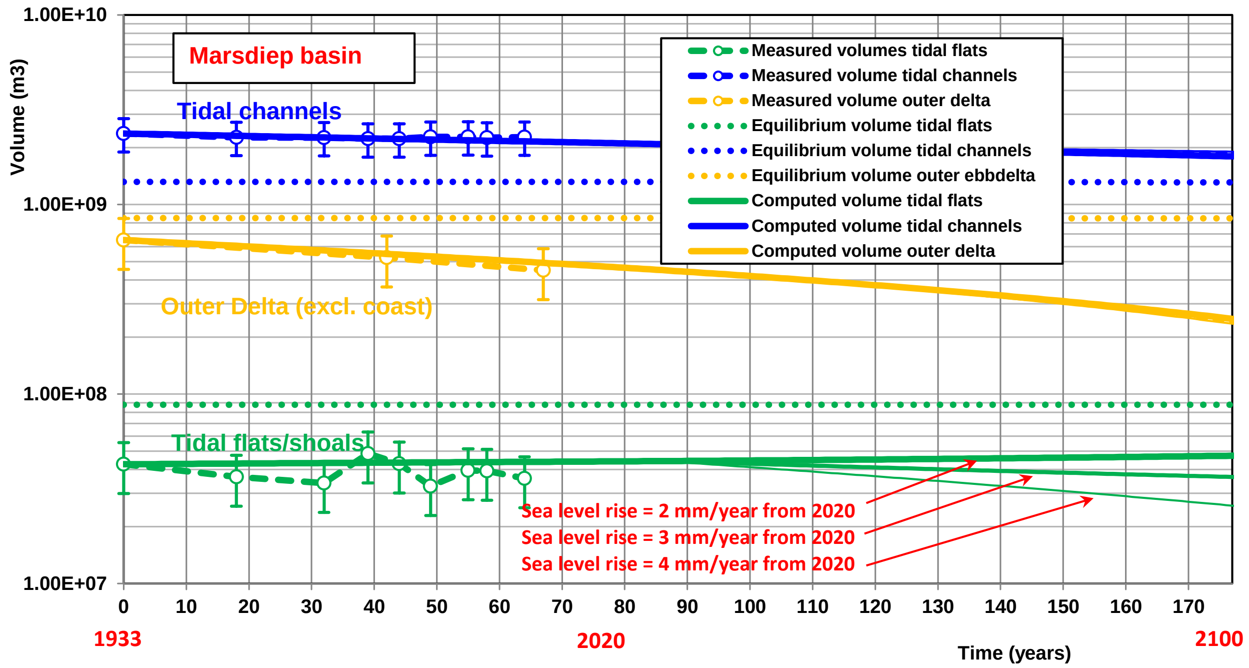

Figure 3.3.2 *Measured and computed volume data of Marsdiep basin; sand import=3.8 millions m³/year*

Basin	Computed annual Sedimentation + or Erosion - (in m³/year); 2020-2100			
	Scenario A sea level rise 1,7 mm/year 1933-2100	Scenario B 2 mm/year 1933-2100	Scenario C 3 mm/year after 2020	Scenario D 4 mm/year after 2020
Annual change of volume of flats in Marsdiep basin	0.063 10^6 m^3/year (deposition)	0.032 10^6 m^3/year (deposition)	-0.088 10^6 m^3/year (erosion)	-0.21 10^6 m^3/year (erosion)
Annual change of volume of flats in Vlie basin	0.48 10^6 m^3/year (deposition)	0.41 10^6 m^3/year (deposition)	0.15 10^6 m^3/year (deposition)	-0.09 10^6 m^3/year (erosion)

Table 3.3.2 *Computed annual volume changes of flats in Marsdiep and Vlie basins; 2020 to 2100*

Figure 3.3.3 shows the coastal erosion volume inside the outer basin (Marsdiep). The coasts on both sides of the inlet will be much more exposed to wave attack when the outer ebb delta has become so small that waves can penetrate more easily towards the coast. The annual coastal erosion volume strongly depends on the net sand transport rate through the inlet (export for outer basin) and on the minimum value of the thickness of the ebbdelta. This latter values is set to 2 m (input value). If this parameter is set to 0, no additional coastal erosion will occur. In that case the erosion of the ebb delta will be more severe.
Most of the coastal erosion will occur on the updrift side of the inlet (coast of North-Holland, which is defended by many groins).
If the net sand transport through the inlet is assumed to be 3.8 million m^3/year, the coastal erosion volume is about 1 million m^3/year up to 2100 after which it increases to about 1.6 million m^3/year in 2133. The increase of sea level rise (3 mm/year or 4 mm/year after 2020) does not have much effect on this.
If the net sand transport through the inlet is assumed to be 4.8 million m^3/year (large value), the coastal erosion is about 1.2 million m^3/year up to 2070 after which it increases 3 million m^3/year in 2133 due to reduction of the ebb delta volume and hence increased wave attack on the coast.

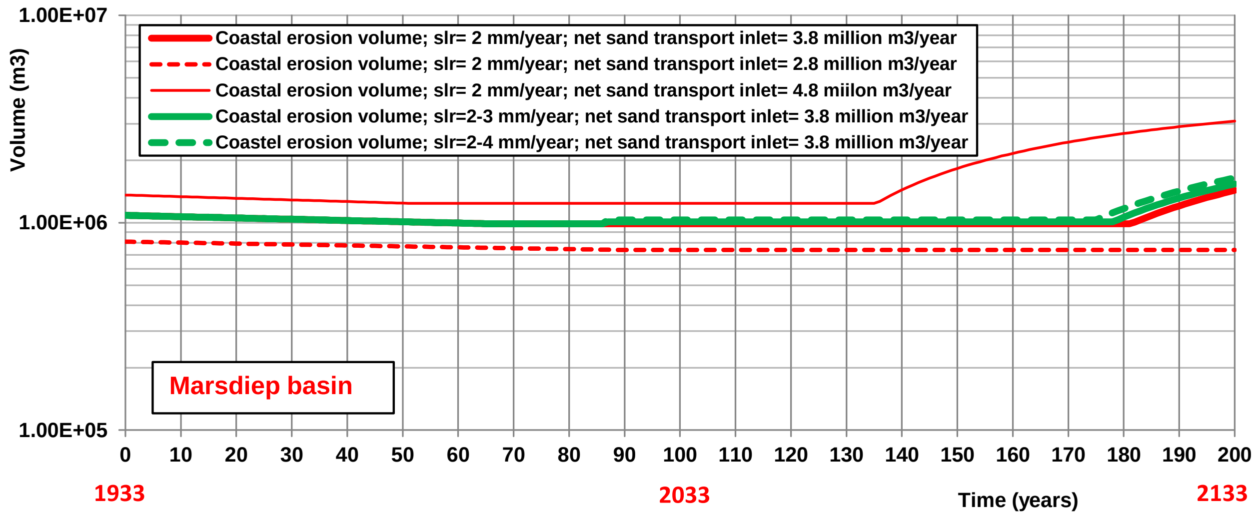

Figure 3.3.3 *Computed coastal erosion volume for Marsdiep basin*

3.4 Measured and computed sediment volumes Vlie basin

3.4.1 Situation between 1933 and 2000

The input data are shown in **Table 3.2.1**. Sea level rise is set to 2 mm/year.
The net sand transport through the inlet is set to 2.8 million m^3/year.
The net transport of fines (< 50 μm) through the inlet is set to 0.6 million m^3/year (about 20% of sand transport).
The net import of sand into the outer basin from the North Sea coast is set to 0.9 million m^3 per year

Figure 3.4.1 shows the measured and computed volumes of the Vlie basin as function of time (over 100 years from 1933).
The measured sediment volumes of the tidal flats show an increasing trend (deposition) between 1933 and 2000. Similarly, the measured volumes of the tidal channels show a decreasing trend (deposition) in the same period.

The measured sediment volumes of the outer delta show a gradual decrease from 470 10^6 m^3 to 350 10^6 m^3 or a decrease of about 2 million m^3 per year, see **Table 2.1.4** (Elias, 2006).

It is noted that the measured volumes of the flats of the Vlie basin are based on the data of Van Geer (2007, see **Table 2.1.3**). The measured volumes of the flats shown in **Figure 3.4.1** may be somewhat too large (30%). The volume data of Rijkswaterstaat (2005) suggests smaller deposition volumes for the Vlie basin (see **Tables 2.1.5** and **2.1.6**). Therefore, only lower error bars are shown for the flats in Figure 3.4.1.

The behaviour of the volumes of the flats, channels and outer delta between 1933 and 2000 can be represented fairly well by the SEDBOX-model using the data given in **Table 3.2.1** and sea level rise of 2 mm per year. The volumes of the flats are underestimated by the model, particularly after 1983.

The subdivision of the net sediment transport through the inlet over the flats and channels is related to the water volumes above the flats and channels. As the flats cover about 40% of the total Vie basin, about 30% of the net sediment import is deposited on the flats of the Vlie basin. This percentage decreases slowly in time to about 28% in 2100.

The *computed* volumes of the flats increase from 105 10^6 to 137 10^6 m^3 between 1933 and 2000 or an annual deposition of about 0.48 10^6 m^3/year. The *measured* value is 1.15 10^6 m^3/year.
The *computed* volumes of the channels decrease from 1270 10^6 to 1168 10^6 m^3 between 1933 and 2000 or an annual deposition of about 1.52 10^6 m^3/year. The *measured* deposition is 2.4 10^6 m^3/year.

Sea level rise of 2 mm per year yields a volume of about 1.4 10^6 m^3 per year. The computed volumes of the flats increase by about 0.48 10^6 m^3 per year. The computed volumes of the channels decrease by about 1.52 10^6 m^3 per year. The sum of the sea level rise volume, the deposition volumes of the flats and the channels is about (0.48+1.52+1.4) 10^6 m^3, which is equal to the total net sediment import of 3.4 10^6 m^3 (sand+mud) per year through the throat.

The computed volumes of the tidal flats move away from the 'equlibrium' value, which is an indication that the 'true' equilibrium volume is much larger. Similarly, the computed volumes of the tidal channel move away from the equilibrium values, which most likely are much too large.

The net import of sand into the outer basin from the North Sea coast is assumed to be 0.9 million m^3 per year. This volume of sand is supplied (import of sand into the outer basin) by tidal currents in combination with waves from the sea bed of the North Sea.

Figure 3.4.1 also shows the effect of smaller and larger sand import values trough the throat (2.8 $\pm$ 1 million m^3/year). The flats grow more for a larger sand import of 3.8 million m^3/year and less for a smaller sand import of 1.8 million m^3/year. Compared to the measured data, a net sand import of 3.8 million m^3/year also is a very realistic estimate. However, the decease of the outer delta volume is less well simulated (too large decrease).

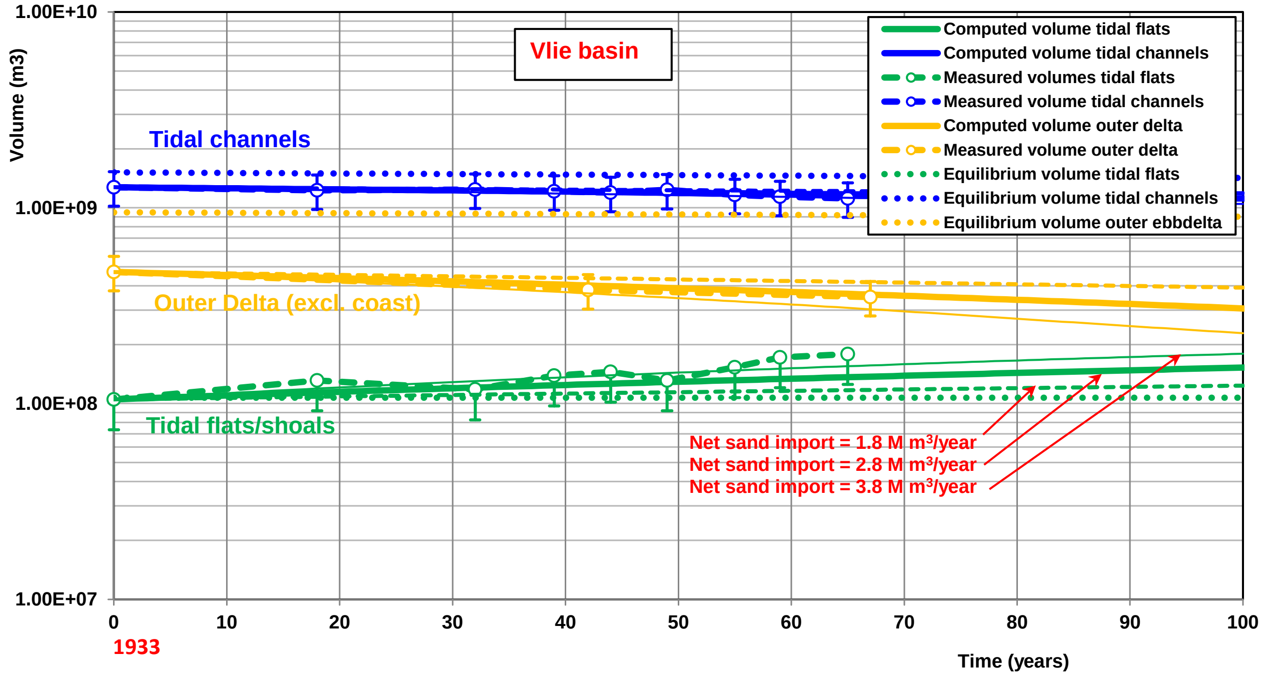

Figure 3.4.1 *Measured and computed volume data for Vlie basin; sea level rise= 2 mm/year*

The computed annual deposition volumes of the flats in the Vlie basin for the period 1933 to 2000 are given in **Table 3.3.1**. Measured values are also shown. The computed deposition is largest for a sea level rise of 1.7 mm/year. The computed values are somewhat smaller than the measured values (factor 2).

It is concluded that the measured volume development in the Vlie basin over the period 1933 to 2000 can be reasonably well simulated using a constant net import of sand and fines.

3.4.2 Future situation with increasing sea level rise

Four scenarios of future sea level rise have been used to compute the volumes of the flats, channels and outer delta:

A. constant value of 1,7 mm per year between 1933 and 2100;
B. constant value of 2 mm per year between 1933 and 2100;
C. constant value of 2 mm/year between 1933 and 2020 and 3 mm/year between 2020 and 2100;
D. constant value of 2 mm/year between 1933 and 2020 and 4 mm/year between 2020 and 2100.

Scenario B yields a gradually increasing volumes of the flats and gradually decreasing volumes of the channels, see **Figure 3.4.2**.
Scenario A yields somewhat larger deposition rates than that of scenario B, see **Table 3.3.2**.
Scenario C also leads to a smaller increase of the volumes of the flats up to 2100. The volumes of the channels and the outer delta are mot much affected.
Scenarion D leads to a small loss of the volumes of the flats after 2020, but the volumes of the flats in 2100 still are much larger than in 1933.
The volumes of the channels and the outer delta are only slightly affected.

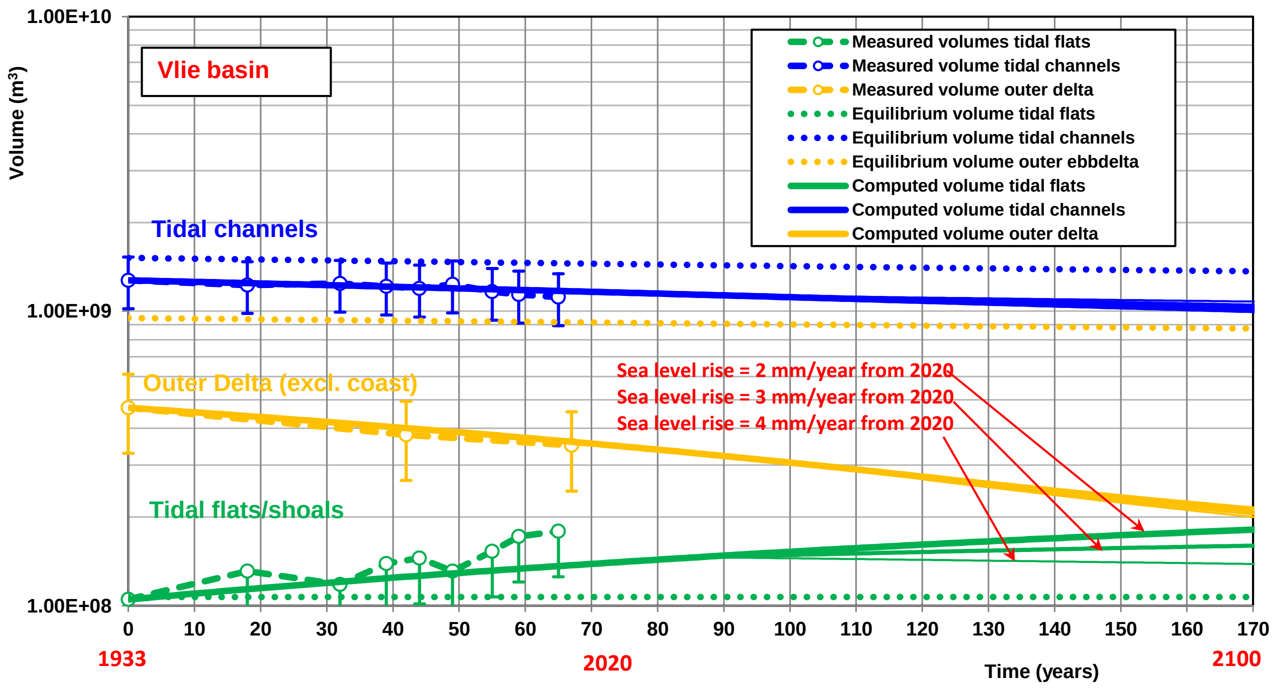

Figure 3.4.2 *Measured and computed volumes of Vlie basin, net sand import = 2.8 million m³/year*

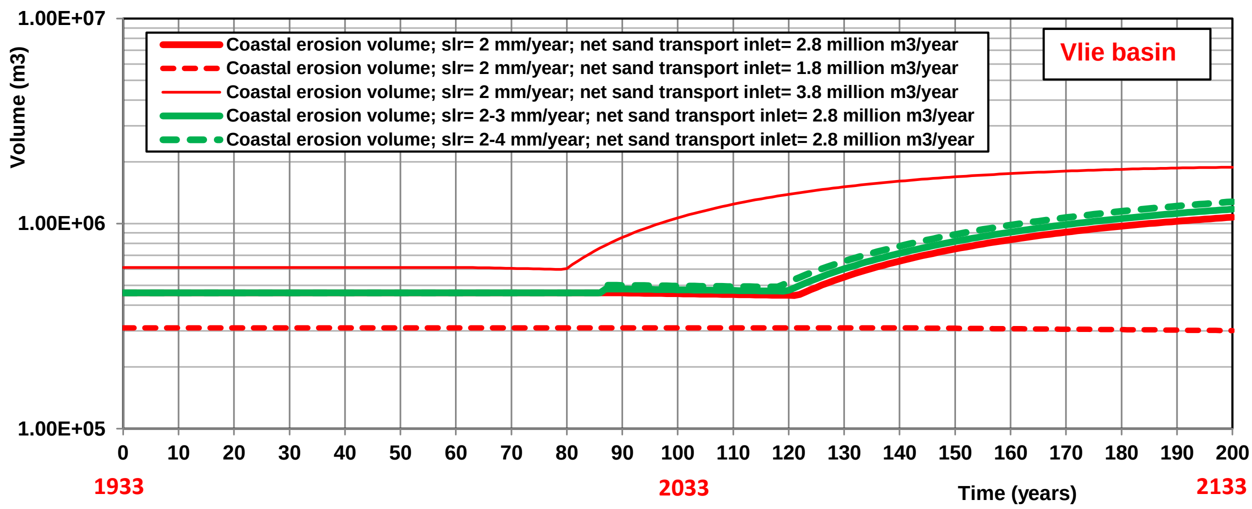

Figure 3.4.3 *Computed coastal erosion volume for Vlie basin*

The computed annual volume changes of the flats in the Vlie basin for the period 2020 to 2100 are given in **Table 3.3.2**. Deposition changes to erosion for a sea level rise larger than 3.5 mm/year.
It can be concluded that the Vlie basin can much better follow the effecs of a significant increase of sea level rise than the Marsdiep basin.

Figure 3.4.3 shows the coastal erosion volume inside the outer basin (Vlie). The coasts on both sides of the inlet will be much more exposed to wave attack when the outer ebb delta has become so small that waves can penetrate more easily towards the coast. The annual coastal erosion volume strongly depends on the net sand transport rate through the inlet (export for outer basin) and on the minimum value of the thickness of the outer ebb delta. This latter parameter is set to 2 m (input value). Most of this erosion will occur on the updrift side of the inlet (northern tip of Terschelling, which is defended by many groins).

If the net sand transport through the inlet is assumed to be 2.8 million m^3/year, the coastal erosion volume is about 0.45 million m^3/year up to 2050 after which it increases to about 1 million m^3/year in 2133 due to reduction of the ebb delta volume and hence increased wave attack on the coast. The increase of sea level rise (3 mm/year or 4 mm/year after 2020) does not have much effect on this.
If the net sand transport through the inlet is assumed to be 3.8 million m^3/year (large value), the coastal erosion volume increases to about 1.9 million m^3/year in 2133.

3.5 Measured and computed sediment volumes Borndiep basin

The calibrated SEDBOX-model has been used to simulate the volume development of the flats and channels of the Borndiep basin. **Table 3.5.1** shows the input data used.

The net sand import through the inlet is set to 1.2 million m^3/year (constant in time, see also Deltares 1995).

The net mud import (< 63 μm) through the inlet is set to 0.4 million m^3/year (about 30% of net sand import; constant in time).

The net sand transport from the coast to the outer ebb delta is set to 0.8 million m^3/year (constant in time).

Parameter	**Borndiep**
H= mean tidal range (m)	2
B= width of inlet below NAP (m)	3500
$A_{cross-section}$= cross-section of throat below NAP (m^2)	35000
A_{basin} = surface area of tidal basin at level of MLW (m^2); mean value over 1933 to 2000	275 10^6
A_{flats} = surface area of flats at level of MLW (m^2) mean value over 1933 to 2000	160 10^6
$A_{channels}$ = surface area of tidal channels (m^2)	115 10^6
$A_{outerbasin}$ = surface area of outer basin + channels + coast (m^2)	80 10^6
$A_{ebbdelta}$= surface area of outer ebb delta (m^2)	40 10^6
A_{coast}= surface area of coastal zone (m^2)	20 10^6
$V_{s,flats,t=0}$ = sediment volume (m^3) of flats between MLW and MHW at t=0 (1933)	83.5 10^6
$V_{w,channels,t=0}$= water volume (m^3) of channels below MLW at t=0	314 10^6
$V_{s,ebbdelta,t=0}$ = sediment volume (m^3) of outer ebb delta at t=0 (1933)	114 10^6
$\delta_{minimum}$ = minimum layer thickness of outer ebb delta (m)	2
$T_{sand,i}$= net sand transport through inlet (in m^3/year; import +)	1.2 10^6
$T_{fines,i}$= net mud transport through inlet (in m^3/year; import +)	0.4 10^6
$T_{sand,ob}$= net sand transport from coast to outer basin (in m^3/year)	0.8 10^6
$\alpha_{channel}$ = coefficient equilibrium volume of channels	0.0000087
α_{delta} = coefficient equilibrium volume of outer delta	0.0066
γ_1 = calibration coefficient sediment for tidal flats (-)	**1.5**
γ_2 = calibration coefficient sediment for coast of outer basin (-)	**0.15**

Tabel 3.5.1 *Input data of Borndiep basin*

Figure 3.5.1 shows the measured and computed volumes of the Borndiep basin over 200 years from 1926. The measured and computed volumes of the flats show an increase over time (deposition). The measured and computed channel volumes decrease over time (deposition). The decrease of the measured channel volumes is somewhat overpredicted.
The computed volumes of the outer delta show a slight increase from 114 10^6 m^3 to 141 10^6 m^3 over 200 jaar or a slight increase of 0.14 million m^3 per year in agreement with the slight increase of the measured values over the period 1926 to 1999.

The behaviour of the volume development of the flats and channels of the Borndiep basin can be simulated with reasonable agreement using a constant net import of sand and mud through the inlet and a sea level rise of 2 mm/year.

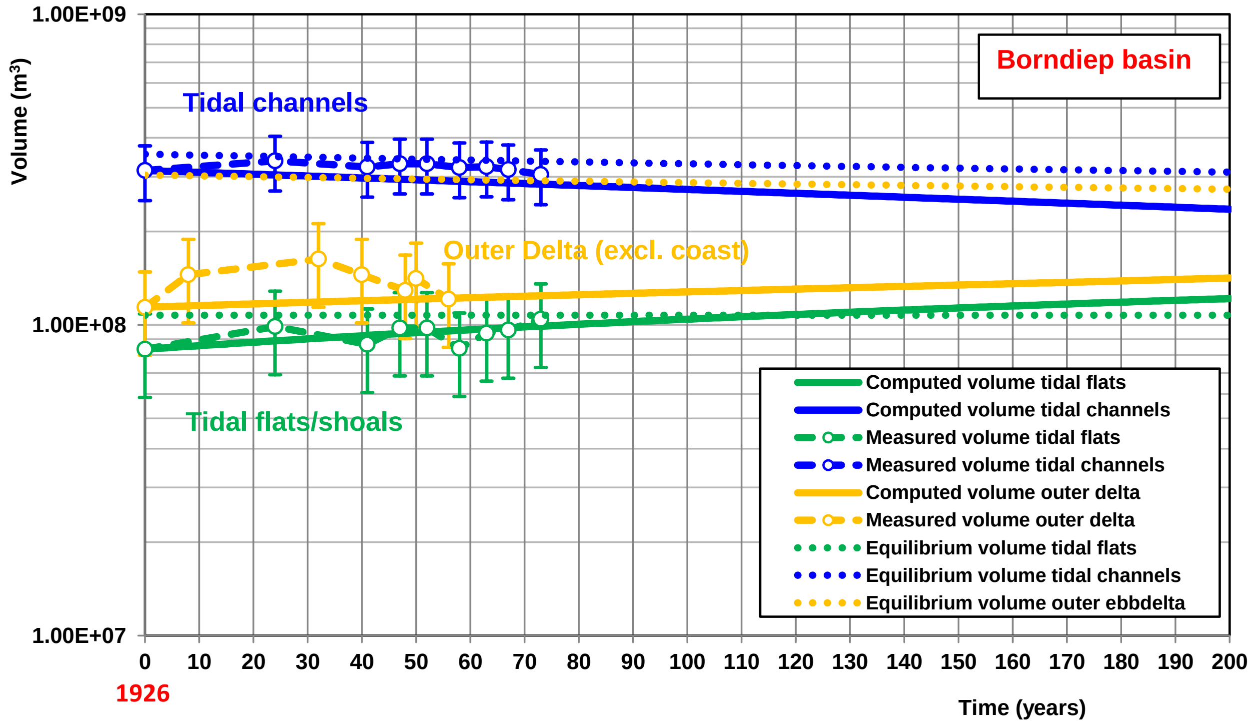

Figure 3.5.1 *Measured and computed volumes of flats and channels of Borndiep basin; Sea level rise = 2 mm/year*

4 Overall evaluation

The sand balances of the Marsdiep, Vlie and Borndiep basins of the western dutch Wadden Sea have been studied using measured volume data and model simulations for the period (1933 and 2000) after closure of the Zuiderzee.
As an overall check of all results, the measured and computed volumes over the period 1933 to 2000 for the Marsdiep and Vlie basins are summarized and compared.

Table 2.1.5 shows the measured deposition volumes of Rijkswaterstaat (2005). These volumes are obtained by comparing the bathymetries (below +1 m NAP) of 1933 and 2003. The 'true' total deposition can be obtained by adding the sand mining volume in the period 1933 to 2000. This results in a 'true' total deposition volume of about 455 10^6 m^3 for both basins consisting of sand (>63 μm) and fines (<63 μm).

Table 2.1.6 shows the measured deposition volumes of Van Geer (2007). These volumes are obtained by determing the volumes of the flats with respect to mean low water MLW. Similarly, the volumes of the channels with respect to MLW have been determined. As the level of MLW gradually increases due to sea level rise, the sea level rise volume above the flats and channels between MLW in 1933 and 2000 must be added to the deposition volumes. The sand mining volumes must also be added to the volumes of Van Geer (2007). The 'true' total deposition volume of sand and fines is 582 10^6 m^3 for both basins with respect to the datum of 1933. This latter value is somewhat larger (30%) than that of Table 2.1.5. The volumes of the Marsdiep basin (total 240 10^6 m^3) of **Table 2.1.5** in good agreement with that (total 233 10^6 m^3) of Table 2.1.6. The volumes of the Vlie basin (total 349 10^6 m^3) of **Table 2.1.6** are about 50% larger than that (total 215 10^6 m^3) of **Table 2.1.5**.

Table 4.1 shows the erosion volumes in the outer basin and coastal zone seawards of the Marsdiep and Vlie inlets, which amounts to a total volume of 420 10^6 m^3 (only sand). The long term average coastline recession around the Marsdiep inlet is assumed to be in the range of 1 to 4 m/year (see Appendix A). The long term average coastline recession around the Vlie inlet is assumed to be about 1 m/year (see Appendix A).
The erosion volume of 420 10^6 m^3 is somewhat smaller (about 10%) than the total deposition volume of 455 10^6 m^3 of the inner basins (**Table 2.1.5**).

Table 4.2 shows the computed sediment transport volumes through the Marsdiep and Vlie inlets during the period 1933 to 2000, yielding a total volume (of sand and fines) of about 550 10^6 m^3. This latter value is about 20% larger than that (455 10^6 m^3) of **Table 2.1.5**.

Basin	**Erosion volumes with respect to NAP**
Marsdiep ebbdelta	200 10^6 m^3
Vlie ebbdelta	120 10^6 m^3
Coastline recession of 4 m at north side of Marsdiep inlet and 1 m at south side of Marsdiep inlet over 67 years (20 km, profile height=20 m)	70 10^6 m^3
Coastline recession of 1 m on both sides of Vlie inlet over 67 years (20 km, profile height=20 m)	30 10^6 m^3
Total	420 10^6 m^3

Table 4.1 *Measured erosion losses (only sand) in coastal zone seaward of inlets Marsdiepe and Vlie; period 1933 to 2000*

Basin	**Net sand transport through inlet**	**Net transport of fines through inlet**
Marsdiep during 67 years (sand: 3.8 10^6 m^3/year) (fines: 0.8 10^6 m^3/year)	255 10^6 m^3	54 10^6 m^3
Vlie during 67 years (sand: 2.8 10^6 m^3/year) (fines: 0.8 10^6 m^3/year)	188 10^6 m^3	54 10^6 m^3
Total	443 10^6 m^3	108 10^6 m^3
	551 10^6 m^3	

Table 4.2 *Computed sediment transport through inlets Marsdiep and Vlie; period 1933 to 2000*

All values (sand and fines) of **Tables 2.1.5, 2.1.6** and **4.2** are within the range of 455 tot 582 10^6 m^3 (520 ± 60 10^6 m^3) or within a variation range of about 15%, which is a very reasonable result. The total volume of **Table 4.1** is somewhat smaller (420 10^6 m^3) as it only concerns the sand fraction. Based on this, it may be concluded that the deposition volume of fines (<63 μm) for the two basins Marsdiep and Vlie is of the order of 100 10^6 m^3 (20% of the total).

The measured deposition volumes of the inner basins Marsdiep and Vlie can be fairly well simulated by the SEDBOX-model using constant sediment transport rates through the inlets, which have been determined independently without calibration.
It should be realized that the flats and channels are modelled as two large-scale volumes with sedimention or erosion. In reality the flats and channels consist of many individual flats and channels, of which some may show sedimentation while others may show erosion.
On the long term with relatively large sea level increase (5 to 10 mm/year) the import of sand may grow somewhat as the inner channels will become deeper resulting in less flow resistance and larger flow velocities and thus a larger tidal prism.

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