'Sand' Balance Approach

Assessing sediment budgets and transports using bathymetric data

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Title
'Sand' Balance Approach

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Summary

'Sharing good practices' is one of the objectives of the TIDE-project. In the Scheldt estuary there are good experiences in using the so-called 'sand balance approach', as an instrument for interpretation of the observations in bathymetry. The approach gives results (calculated sediment budgets) that have a direct relation with sediment management, being interventions that are relatively common in estuaries (like dredging and disposal). After an introduction and technical aspects is explained how it is used in estuarine management, with the Scheldt estuary as an example.

Disclaimer

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Contents

1 A sediment approach

1.1 Introduction

This document contributes to 'sharing good practices between the partners of the four TIDE-estuaries (Elbe, Humber, Scheldt, Weser), being one of the objectives of the TIDE-project. In the Scheldt estuary there are good experiences in using the so-called 'sand balance approach' as an instrument for interpretation of the observations in bathymetry. This approach uses data that are often reasonably well available (bathymetric data). Its outcomes (calculated sediment budgets) have a direct relation with sediment management and interventions that are relatively common in estuaries (like dredging and disposal). After an introduction and technical aspects is explained how it is used in estuarine management.

The 'sand balance approach' is in fact a volume balance, over a specified period and a specified area, of all sediments and objects (including even ship wrecks) that are in and on the water bed. It uses bathymetric measurements to calculate volumes (not mass). Sediments in the water column (and not observed by bathymetric measurements) are not included. In sandy environments (like for instance the Dutch and Flemish coasts) it is mainly changes in sand budgets that are calculated, hence the name 'sand balance'.[1]

1.2 Dynamic stability of estuaries and management issues

The physical behavior of an estuary covers hydrodynamics (governed by tide, geometry, river discharge and their mutual interactions) and morphodynamics (governed by hydrodynamics and sediment availability). We observe the trends in hydro- and morphodynamics in order to assess the physical behavior and compare this to policy objectives.

Policy objectives determine which states and developments of hydro- and morphodynamics are desired. Often the policy objectives include sustainable development of the estuary. For a tidal basin / estuary the sustainability of the physical behavior means a *dynamic* stability. This refers to a balance of hydro- and morphodynamical processes, on the various scales of time and space (see 1.3).

The assessment of a sediment balance provides information on status and trends in physical behavior and more precise, the sediment budgets. These budgets can be appropriate indicators for policy and management. Preservation of sediment budgets in itself may be a management objective[2]. Trends in sediment budgets can indicate whether short and/or long term physical behavior is changing[3]. The observed developments can be used to assess the scale and consequences of sediment management (dredging, disposal, sand mining, nourishments) as well as 'natural'[4] changes in bathymetry.

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1. *Usually we calculate budgets on the assumption that only sediment that can settle has to be taken in account. This and the name itself (sand balance approach) make it easy to neglect the role of fine sediments, which are stored in the water column. This may be true during normal flow, but they tend to settle in low dynamic areas like harbors.*
2. *For example, for the Dutch coast these budgets (comprising almost only sand) indicate the resilience for climate change and the Dutch coastal policy is based on the maintenance of sand budgets.*
3. *For example, in the Scheldt estuary, net budgets and transports are used to learn about the functioning of the multiple channel system (see chapter4).*
4. *Natural refers to 'sediment transports as result of water movement'. These have, of course, not just natural causes as all sorts of human interferences induce changes in hydrodynamics and hydrology.*

The morphological development of a basin is the result of (i) sediment demand, (ii) sediment availability and (iii) the ability to transport sediment. The net sediment transport (during a tidal cycle) of a tidal basin / estuary is governed by tidal asymmetry. When there are stronger currents during flood (ebb) we talk about flood (ebb) dominance. This means that there is more transport capacity in flood (ebb) direction. It may occur that an estuary has both areas of flood- and ebb-dominance, depending on the geometry on smaller scales. There is also a feedback mechanism as the tidal characteristics, including the occurrence of flood and ebb dominance, is depending on the morphology.

A reliable 'sand' balance requires monitoring results. The budgets are determined out of bathymetric data for predefined areas and periods. This gives insight in the development of the areas and in the relative importance of the various sediment sources and losses, resulting in deposition and erosion. The 'sand balance approach' is used to describe the system and understand development, but not for predicting effects of interventions of natural developments (e.g. future rates of Sea Level Rise).

1.3 Large and small scales of space and time

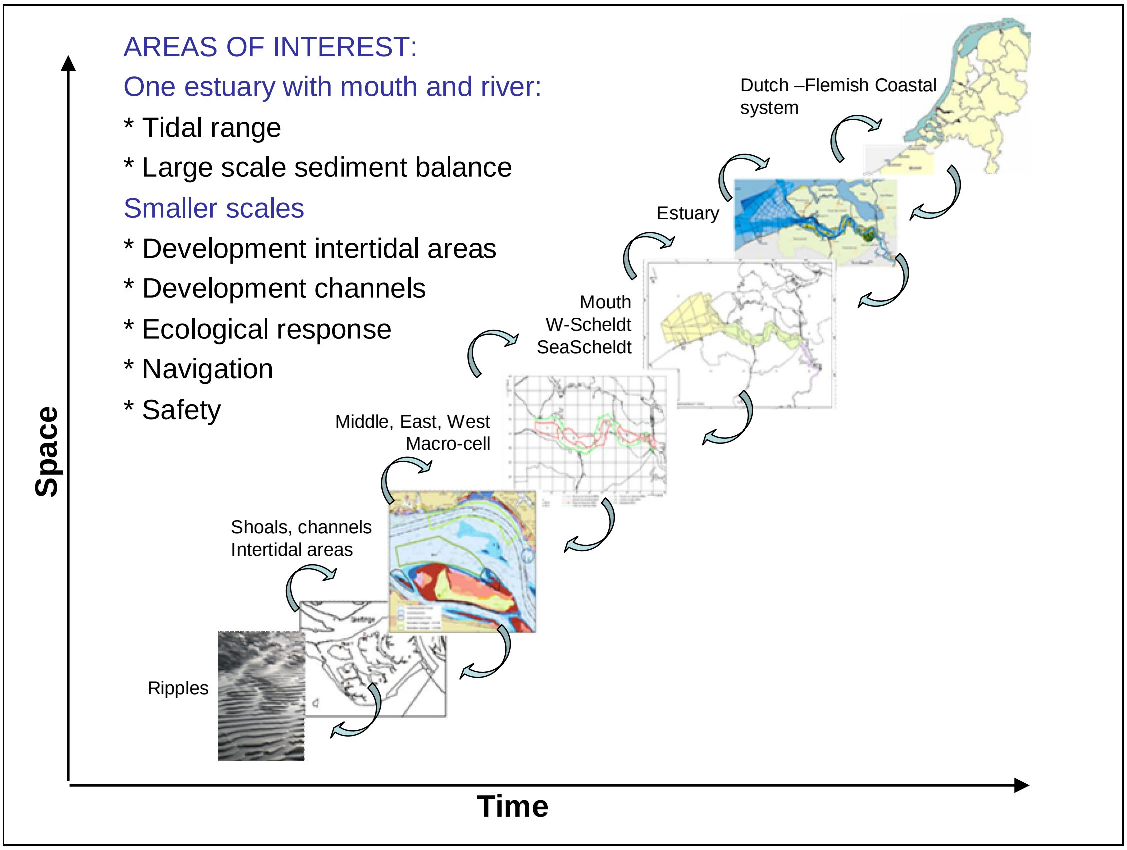

Figure 1: Scales of time and space in an estuary (illustrated using the Scheldt)

Figure 1 shows areas of interest, morphological elements and associated scales (time, space) for the Scheldt estuary. Large-scale issues like tidal range and sediment balance cannot be translated straightforward to individual smaller areas. Observed trends in sediment budgets differ often between groups of channels and shoals (called macro cells, a concept that is explained in section 4.2). Such differences between scales of time and space make assessments more complex.

The use of mathematical models to estimate the sediment balance out of hydrodynamic processes is developing, but still too limited to give reliable results in complex and dynamic systems like estuaries. Results of a ‘sand balance approach’ are, on the other hand, of importance in improving and judging numerical tools. It is one of the requirements of morphological modeling that they reproduce the development of sediment budgets sufficiently.

2 Determination of sediment budgets

2.1 Procedure and data

The sand (sediment) balance is a relatively simple procedure. The budget is determined as a mass balance (in practice: volumes) of sediment that is in/on the waterbed. The time rate of change of the volume of sediment in a compartment is simply the difference between two measurements, which, by definition, must be equal to the result of human interventions and 'natural' transport of sediment. Calculations are done relative to a constant reference plane.

$\Delta V_{transport} = \Delta V_{tot} - \Delta V_i$

* $\Delta V_{transport}$: The calculated difference between transports into and out of the area during the period. A positive value suggests sedimentation, a negative one suggests erosion.
* ΔV_{tot}: the changes in volume, based on measurements
* ΔV_i: the changes in volume as result of human interventions

The results of this procedure, if presented with their variation in time and space, give a relatively detailed image on evolutions and trends in morphological behaviour.

The approach requires data on:

- Variation of bathymetry in time, based on field measurements;
- Dredging activities, specified in space and time and dredged amounts;
- Disposal activities, also specified in space and time and amounts; preferably including the relative content of sediments that will suspend (like silt/clay);
- Possible other interventions that influence the sediment balance, like nourishments and sand mining (but both can be regarded as special variations on dredging and disposal). It also comprises interventions in geometry like embankments and removal of wrecks, as these have impact on the measured bathymetric and hence the calculated volumes.

2.2 Schematization and synchronization

The approach requires a schematization, in areas for which the determination of sediment budgets is needed. These schematizations must be made on morphological considerations, and not on, for instance, administrative grounds or on aspects of data-collection. Schematizations should represent the presence of shoals and channels and their development in time. The latter gives an extra complication with the requirement that the coordinates of the areas do not change. A changing schematization makes an interpretation in terms of sediment budget no longer possible. This means that the calculations of sediment budgets on smaller scales can get difficult or even impossible, when morphological elements like channels and shoals change too much in position[5]. Changes in surface-area must be taken in account when conclusions are drawn on average depth or height of morphological elements out of the sediment budgets.

2.3 Uncertainties

The processes of measurements and synchronization / interpolation introduce all kind of uncertainties on the outcome. The approach uses, for example, data from different sources. These data can vary, in time intervals, in methods of interpolation of data and in used measurement techniques. The importance of the study-results for policy and management requires good insight in all these uncertainties. This is not easy as one has to deal with:

5. *Alternative may be to look at changes in hypsometric curves of areas and to derive volume-changes out of these.*

- A lack of insight into the accuracy of the measurements;
- Lack of spatial resolution: usually very little data is available to derive transport between smaller morphological elements, for instance between shoals and neighboring channels;
- Methods and techniques have developed during the years, also and especially in the processing following the measurements: there are many human factors left that can introduce errors;
- The processing and analysis of data, especially from older surveys, can be very labor-intensive

As illustration:
A small change in bed level over a wide shelf area is, for example, equivalent to a large supply or loss of sediment (10 mm erosion over an area of 10x10km2 is equivalent to 1 million m3 of sediment). Only long-running survey programs can deduce such slight but systematic changes of bed levels.
Tectonic processes also have implications on the sediment balance, being either natural processes (on geological timescales) or the result of human activities (e.g. gas mining near the Dutch Wadden Sea). These are effects in the same order of magnitude.

3 Sediment budgets at different scales of space and time

Methodology
Coastal and estuarine systems can be studied as interrelated units. For coasts, one can specify littoral cells, which are linked by various transfer processes that operate over different spatial and temporal scales. The units or cells are identified according to morphological and process information and defined as relatively self-contained units within which sediment circulates. Cell and sub-cell boundaries can be defined consistently by identification of discontinuities in rate or direction of sediment transport.
These boundaries can be a ‘total’ barrier for sediment transport, resulting in independent morphological cells over a timescale of decades. Examples of this are barriers to longshore sediment transport, represented by e.g. deep inlets with strong currents, major artificial man-made structures or deep navigation channels that are maintained over long periods.

Less strict barriers are also used as boundaries, varying from shallow inlets to so-called ‘transient partial boundaries’ like spits, sand banks and short breakwaters. For the identification of units in estuaries we may need go one step further and make use of the hydrodynamic conditions (see example of the Scheldt in 4.2).

Interpretation for various scales, in relation to policy and management
The state and development of sediment budgets can differ on various scales of time and space[6], as well as their meaning for policy and management. It may, for example, be that a total sediment budget shows a constant status and/or trend, while at the same time the distribution of the sediment over smaller morphological elements shows significant changes, which may be related to undesired developments.

An important parameter for the evaluation of long term developments can be the total sediment budget and the ability for a system to adapt to sea level rise. On smaller scales the state and trends in sediment budgets may be used to assess stability and development of smaller morphological units: main channels, secondary channels, shoals and intertidal areas (see also chapter 4).

For all scales holds: observations must be compared with historical trends and evaluated in the light of policy-objectives. The Scheldt case elaborates this. The focus in this estuary is both (i) on the budgets of smaller units, in light of the preservation of the multiple channel system (as elaboration of ‘dynamic stability’ and (ii) on large-scale developments in budgets, in light of ‘long term safety and keeping up with sea level rise’.

6. *See figure 1 for an explanation of scales of time and space*

4 Sediment balances for the Scheldt Estuary

4.1 General

The Scheldt estuary can, in terms of morphodynamics, be distinguished in:

- The estuary in Flanders: the Upper Sea Scheldt (stretching from Gent to Rupelmonde, not included in figure 2) and the Lower Sea Scheldt (up to the border)
- The estuary in the Netherlands: Western Scheldt (from the border to the mouth , usually the line between Vlissingen and Breskens is used within sediment budget calculations)
- The mouth, stretching North and South along the coastline, usually the towns of Zeebrugge and Westkapelle are used for boundaries.

This distinction reflects the different morphological characteristics: a one-channel system (Flanders), a two(multiple) channel system (Netherlands) and the mouth. First some aspects of schematization of the Western Scheldt are discussed (4.2), before results of a 'sand balance study' are shown as an example (4.3).

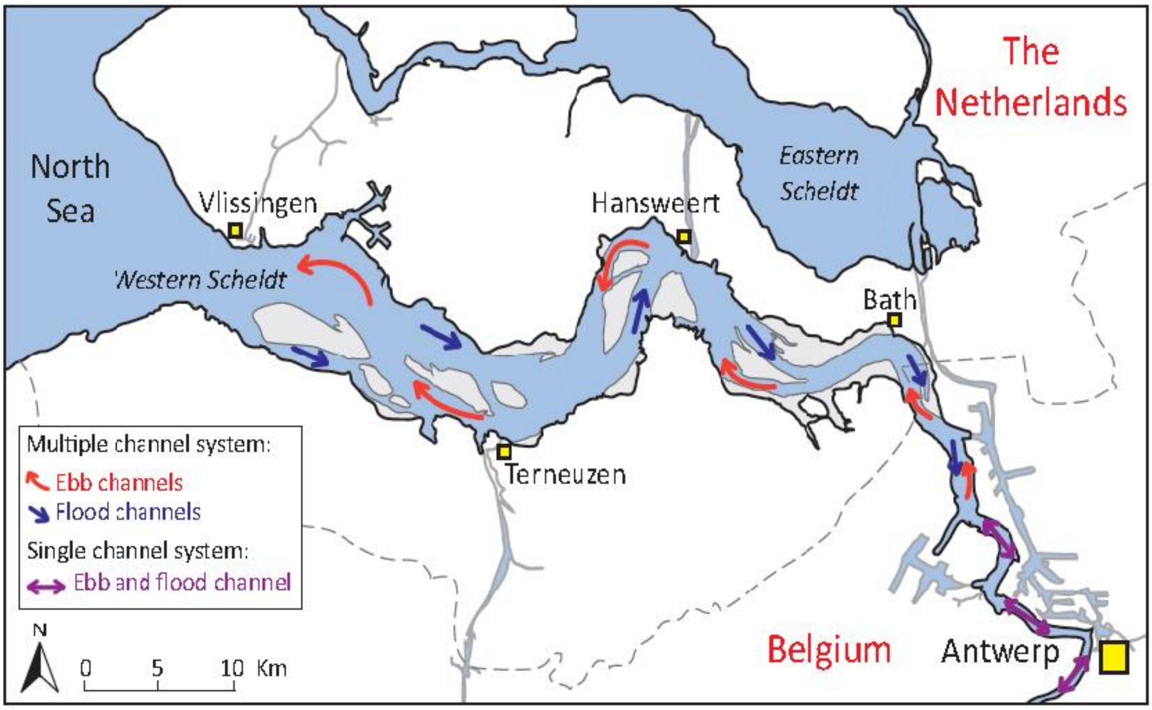

Figure 2: The Scheldt estuary with ebb and flood channels, up to Antwerp. The estuary continues, as the upper Sea Scheldt, until the city of Gent

4.2 History and development-objectives of the Western Scheldt

The multiple channel system of the Western Scheldt shows ebb and flood channels with large intertidal flats in between. Numerous stable and/or migrating 'connecting channels' intersect these intertidal flats. The ebb and flood channels join at highly dynamic, shallow areas (including the sills, where a lot of dredging works needs to be done). In this way the channels form six rather distinct topographic units with strong interaction between its morphologic elements (e.g. Van Veen, 1950) and very large gross water and sediment transport rates through their branches. These units are the so-called macro-cells (see Figure 3). This schematization, in a chain of morphological cells, proved to be a useful tool.

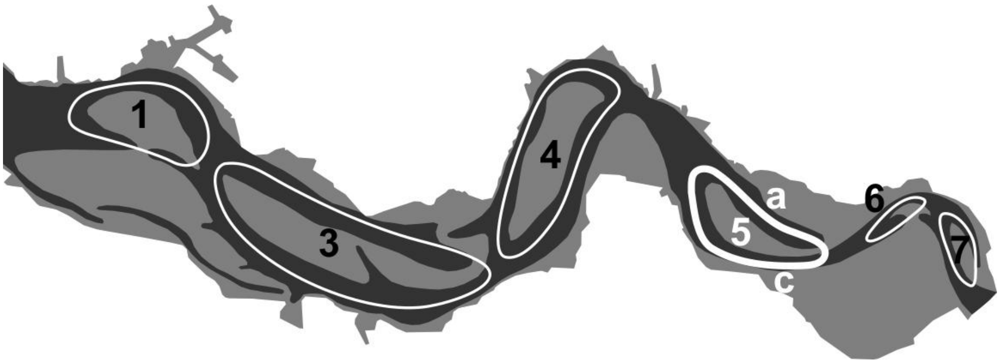

Figure 3 morphological schematization of the Western Scheldt multiple channel system in a chain of cells

The multiple channel system was able to develop itself as a remainder of a period when the estuary was much larger. Centuries ago the channels had to feed and drain large tidal basins along the estuary. A major part of these basins were cut off the estuary by embankments, when they were transformed into polders (usually after a period of sedimentation). The channels lost in that way part of their original function. An accepted hypothesis is that the multiple channel system did not disappear as it became self-preserving, due to the large gross sediment transport rates through the channels and the overall asymmetry of the system (Winterwerp, 2001). The asymmetry results in significant residual transports circulating through the cells, in the flood or ebb direction of the branches.

The multiple channel system is, taking the previous in mind, regarded to be in some sort of dynamic equilibrium, on a timescale of decades. On larger timescales geologists describe the stage of the Western Scheldt as one that is somewhere in between “a one channel system with bordering flats” and “a drowned estuary with no intertidal flats”[7]. These possible ‘endpoints’ of the morphologic development do not fit within the policy objectives, neither of the Netherlands nor Flanders. The countries both made ‘conservation of the multi-channel system’ as an important policy objective. This is thought to serve the long term goals for safety, accessibility and system integrity (both non-biotics and ecology) in the best way. Present management aims hence at a balanced combination of dredging, disposal and sand mining, to preserve the physical characteristics of the multiple channel system.

A basic hypothesis for management aimed at ‘conservation of the multiple channel system’ is that the objective can be broken down to smaller scales. This implies that the objective is met if the cell structure of all macro cells is preserved. The stability of the entire multiple channel system is hence studied by analyzing the stability of the individual. Preservation of the large circulating sediment transport capacity through the branches and the overall asymmetry is assumed crucial. The asymmetry between the ebb and flood channel (producing net water level differences over the intertidal flat) is also important, as it is thought to be the driving force for the (re)generation of the ‘connecting channels’ (Swinkels, 2009).

Sediment balances of macro cells (and of smaller morphological units) help to assess whether the development and stability of channels and intertidal flats is at stake. The example of critical thresholds for disposal below illustrates how this can help to evaluate sediment management, without knowing the exact system-functioning.

7. *On the geological timescale the sediment availability and demand (most important the one as result of sea level rise) will determine if and how fast the estuary develops towards one of these two ‘endpoints’*

Example: critical thresholds for disposal in a secondary channel
There is a threshold on the amount of dredged material for a secondary channel[8] to receive yearly. Above this threshold a channel system in equilibrium will probably become unstable and degenerate. This is a process that occurs at large timescales: decades to centuries. Such long time scales have the risk that only after a long time, when it may be too late, the negative impact (of a disposal strategy) is known. A concept based on transport capacity and autonomous evolution of the macro-cell helps to assess the approximate magnitude of the disposal capacity.
An indicative theoretical level of 5% to 10% of the transport capacity is available as an engineering rule, for a first indication of the disposal capacity in systems like the macro cells of the Scheldt estuary. With additional data and verification for a given location and estuary a more detailed evaluation or design of disposal strategies will be possible (see e.g. Wang and Winterwerp, 2001; Jeuken and Wang, 2010).

4.3 Results / observations for the Scheldt estuary

For the Scheldt estuary, various reports are available based on the 'sand balance approach'. The most extensive is the report by Haecon (2006, in Dutch), being the first one covering both the Dutch and the Flemish part of the estuary. As an example for the description of the approach, some figures of this study are presented below.

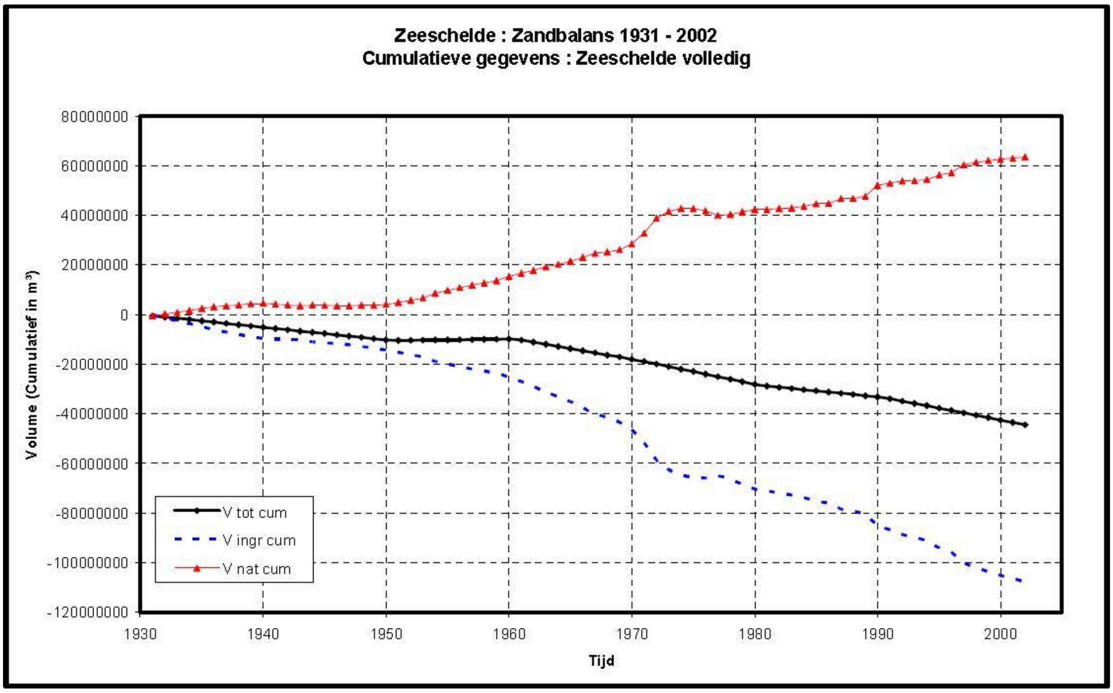

Figure 4: 'Sand' balance approach for Sea Scheldt

Figures 4 and 5 show typical results of a 'sand' balance study. The blue dashed lines represent the sum of all human interventions. The black lines represent the measured volumes. Adding measured volumes and human interventions results in a *calculated* net volume change which is, assumed to be the result of transport (the red line, with triangles).
For the Sea Scheldt (figure 4) is assumed that there is no net transport over its upstream boundaries. For the Western Scheldt (figure 5) there is net transport upstream, towards the

8. *The primary channel is the main channel and can be either the flood or ebb channel. The secondary channel is the other. In the Western Scheldt the ebb channel is the primary channel, except in macro cell 4.*

Sea Scheldt. This can be derived from figure 4 (red line) and is shown (with a green line) in figure 5. This volume is needed to derive the net transport between Western Scheldt and the mouth of the estuary.

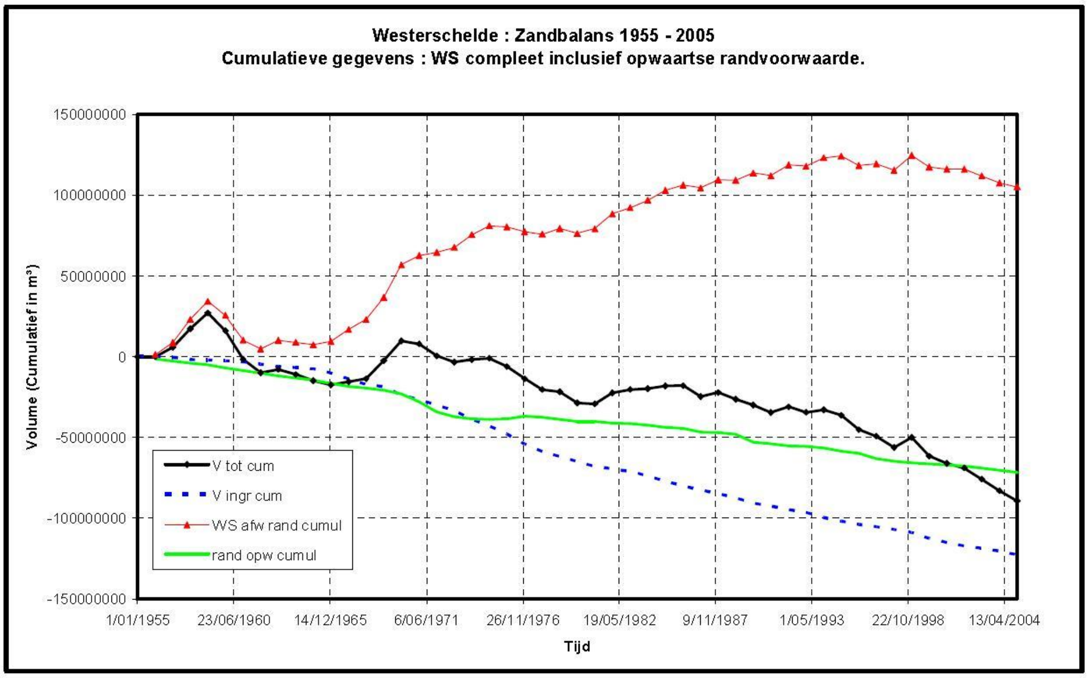

Figure 5: 'Sand' balance approach for Western Scheldt

Examples of lessons that can be learned from figures 4 and 5:

- The sediment volumes of both Sea Scheldt and Western Scheldt have decreased, more or less continuous, over the last decades
- This loss of sediment in the estuary is less than the net result of human interventions
- There has been a long term trend of import of sediment from West (the mouth) to East (the Sea Scheldt).
- There may be a change in trend of import from the mouth to the Western Scheldt, occurring around the first half of the 1990's.

Such lessons are based on trends. Sudden changes between years (like e.g in figure 5 before 1970) can easily be the result of uncertainties as described in 2.3. These should regarded with care.

Please note that,

(i) the sediment transport also reacts on the 18,6 year-period of the tide[9];

(ii) the uncertainty in the calculation of the net transport between Western Scheldt and the mouth is also depending on the uncertainty in the sediment balance of the Sea Scheldt.

9. *The time-lag is, for the Scheldt estuary, approximately 4-5 years (theoretically, but cannot be observed in recent years, probably due to the dominance of all human interventions)*

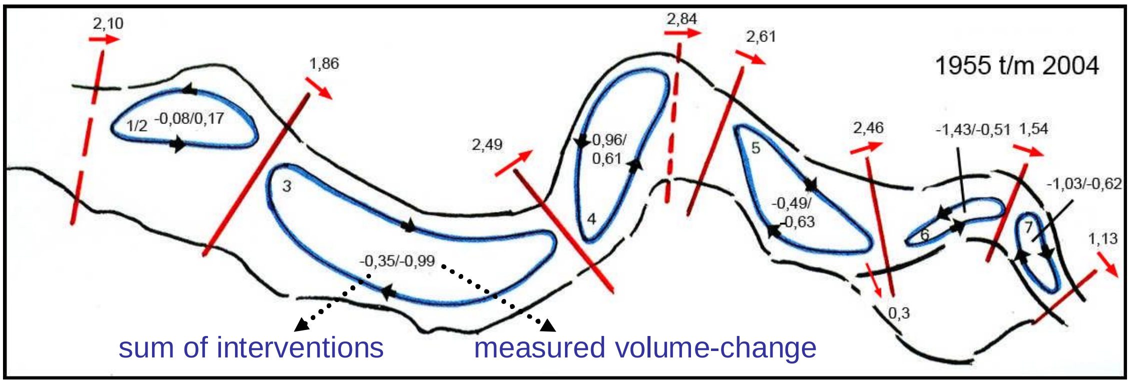

Figure 6: Calculated yearly transports between macro-cells, based on 'sand' balance of Western Scheldt

Figure 6 is an example of information of a 'sand' balance study for smaller areas. It shows a longitudinal distribution of the net transports, between macro-cells, averaged over 50 years. In this period, the net transport has been upstream (red arrows). The figure includes the sum of interventions, observations and calculated net transports with neighboring macro-cells. Some macro-cells show more export to the macro-cell upstream than they receive as import from the macro-cell downstream. These cells have sediment budgets that decreased more than the sum of all human interventions. Figures 4 and 5 already showed the magnitude of these interventions and their effect on the large-scale balance.

There is no full discussion in this document on the value and interpretation of the results and conclusions of Haecon (2006) for the management of the Scheldt estuary. This would require extensive information, on available system knowledge, developments in policy and management, uncertainties, as well as the evaluation of recent monitoring data.

5 Contribution to TIDE-objectives

5.1 Proposed link to ´understandingTIDE´

To position this document within the TIDE-project we look at figure 7, especially the left side of it. In chapters 1–4 is explained how a sand (sediment) balance approach contributes to increased understanding of the system. This, in turn, helps to better set objectives for the short and long term (understanding estuary functions). Insight in required sediment budgets (for various functions) and in morphological developments is used in designing measures within sediment management and, more specific, a disposal strategy. The introduction in the application of the approach for the Scheldt estuary (chapter 4) provided an example and best practice.

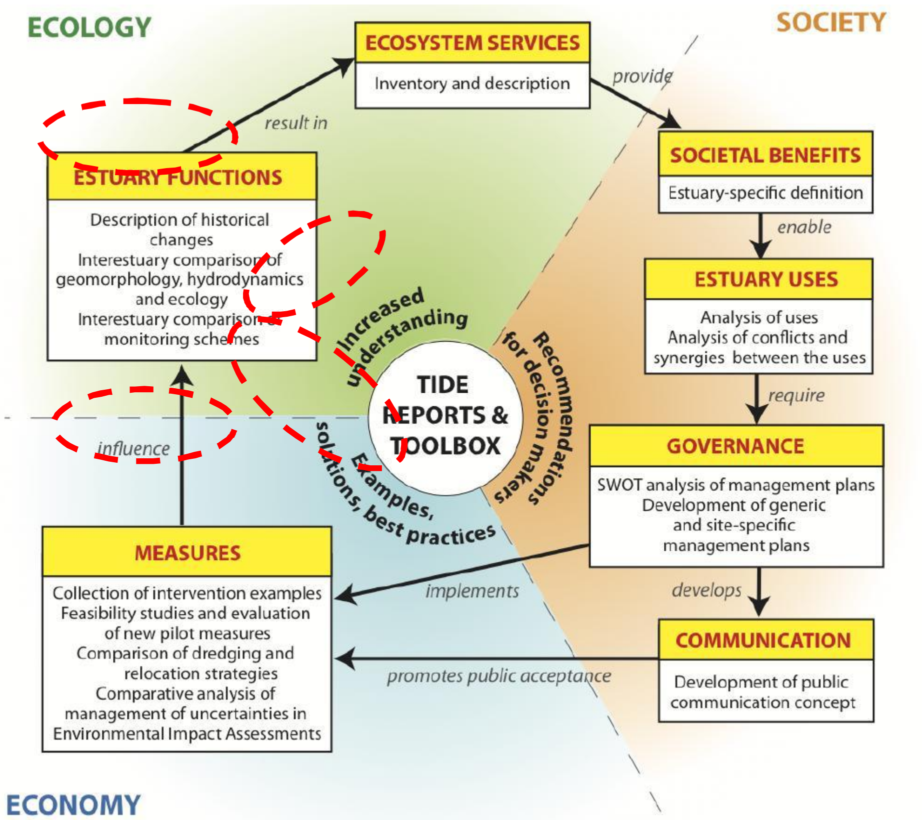

Figure 7: TIDE Inter-relations between various general estuary processes, TIDE activities and expected outputs (derived from memo 'understanding TIDE', November 2010)

5.2 Using the approach for elaborating objectives

Large-scale development and long term safety:

Soft coastal systems have the ability to adapt to sea level rise by capturing sediment and growing vertically according the rate of sea level rise. This principle is the basic philosophy of Dutch coastline management. The sand (sediment) balance approach offers tools to calculate the required sediment (on average per year), either by natural transport or by man (e.g. nourishments). This approach can be applied for morphologically interconnected units.

<u>Smaller scales: habitats and dynamic stability:</u>
To help and preserve the dynamic equilibrium of channels and shoals, the approach is used to study and monitor the natural development. Are changes in trends visible? Which trends are desired or non-desired (increasing or decreasing sediment budgets) for the individual channels or shoals? Chapter 4.2 gave an introduction in the determination of critical thresholds for disposal of sediment in secondary channels.

Finally, the ‘sand balance approach’ also introduces a conceptual model, based on identifying morphologically interrelated units on the relevant scale of time. Such concept is relatively easy to communicate as the basis for sediment management to a wider audience. This holds for a general policy as well as for individual measures.

5.3 Application in dynamic sediment management

Dynamic sediment management is based on monitoring the morphological development and adjusting strategies on these observations. The flexible disposal strategy (see TIDE-factsheet and Sas et al, 2011) operationalises this. It tries to combine the ‘freedom’ that is offered by sediment management (much more reversible than ‘hard’ measures’)[10] and the possibility to vary the measure along the estuary. We can distinguish four disposal strategies (figure 8):

A. In the deepest parts of the primary channel
B. In the secondary channels, but in such way that primary and secondary channels stay in balance
C. Enlarge intertidal areas
D. Bring the sediment outside the macro-cell and/or outside the estuary (incl. sand mining and relocation within the estuary, but over larger distances)

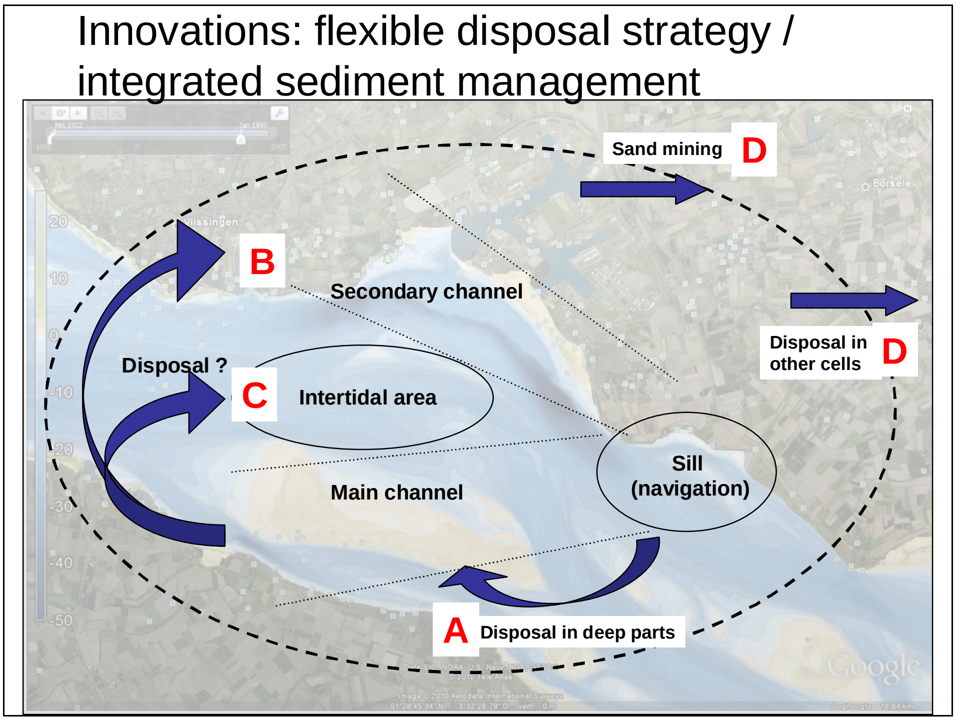

Figure 8: schematization of possibilities within a flexible disposal strategy

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10. *We distinguish ‘hard’ and ‘soft’ measures. Structures are typical hard measures. They influence hydrodynamics and/or connectivity of morphological units and, as result, sediment budgets change. Sediment management has a direct influence on sand budgets.*

The disposal strategies have an influence on two levels:

1. They directly influence the sediment balance of the areas;
2. They change the bathymetry and influence hydrodynamics (flow velocities, tidal asymmetry etc). In this way they can influence the net transport and future sediment balance.

A flexible disposal strategy has the choice to vary the disposal within a macro-cell (primary channel, secondary channel or intertidal area) and to adjust on a large-scale (disposal in the same macro-cell, other macro-cells or in adjacent morphological units like the mouth and the coastal zone or combine this with sand mining). Insight in the sediment budgets supports the assessment of the strategies.

Dredging and disposal in the same morphological active area (like a macro-cell in the Western Scheldt) will have less impact on the large-scale sediment budgets. Disposal in the primary channel has usually smallest morphological effects, but can lead to increase of dredging volumes. When sediment is brought outside the macro-cell, the morphological effect will depend on the capacity of the receiving unit and the large-scale trends.

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