3 Tidal systems modelling: ASMITA model

3.1 Introduction

For many practical applications, simulation and prediction of coastal behaviour (morphological development of shoreface, beaches and dunes) at a certain level of accuracy require the use of mathematical models representing the basic hydrodynamic and sediment transport processes (Van Rijn, 1993). An important objective of morphological modelling is the long-term behaviour of morphological systems in relation to human interference and autonomous processes.

Stive et al. (1997) described a model representing the morphological interaction between a tidal basin and its adjacent coastal environment, including the ebb-tidal delta. From now on, we will focus on this model, the ASMITA model. First, variables describing the system need to be defined by a schematisation of tidal basins. Then, we will explain the basic concepts of ASMITA model and its formulation. One of the main ideas in this model is the hypotheses of the existence of an equilibrium state: under relatively constant hydrodynamic forcing conditions each element can undergo a self-organisation leading to a (quasi-) equilibrium morphological situation.

Finally, we will consider a tidal system and introduce the effect of a river discharge. This new condition will modify the model equations, as it change the boundary conditions of the system. We might keep in mind that rivers can supply large quantities of sediment into the coastal systems.

3.2 Predictability and scales

Tidal inlet and basin morphology is the result of a stochastically forced, non-linear interaction between the water and sediment motion and the bed topography. Understanding and predicting their functioning implies dealing with a wide range of space and time scales, with complex multi-scale interactions of the constituent processes, and with strong, partly stochastic variations of the forcing. Besides complexity, also the possibility of limited predictability has to be taken into account, because these systems seem to satisfy all conditions for inherently unpredictable behaviour (De Vriend, 1998). This would imply that large-scale behaviour cannot be derived in a deterministic way from the small-scale processes.

In order to tackle the problem of limited predictability we introduce the concept of dealing with our interest on a cascade of scales. According to Van Rijn (1993) these are:

- mega-scale coastline changes related to structural erosion and deposition due to interaction with neighbouring sediment-importing tidal inlet systems (10 to 100 km, 10 to 100 years)

- macro-scale, cyclic coastline changes related to the cyclic behaviour of morphological features such as sand banks, sand waves, rip and tidal channels

- meso-scale decaying coastline change related to transition to a new equilibrium, often induced by man-made structures (1 to 10 km, 1 to 10 years)

- micro-scale fluctuating coastline changes related to stochastic and deterministic variations of morphological features (0 to 1 km, 0 to 1 year)

In our case, we will to work with meso and macro scales, which are relevant for medium-term coastal zone management and policy formulation.

3.3 ASMITA model

ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast, Stive et al., 1998) model can be considered as an aggregation and an extension of ESTMORF model formulation for tidal basins (Wang et al, 1998). The aggregation concerns the fact that we characterise the system elements by only one state variable. The extension concerns the incorporation of formulations for the ebb tidal delta and directly adjacent coast as well, without modifying the basic concepts.

3.3.1 Schematisation of a tidal system: morphological elements

The ASMITA model is built on the idea that a tidal inlet system can be schematised into a number of morphological elements. The most important ones are the tidal flats and the tidal channels (together forming the tidal basin) and the ebb-tidal delta. Next figure shows this simplification:

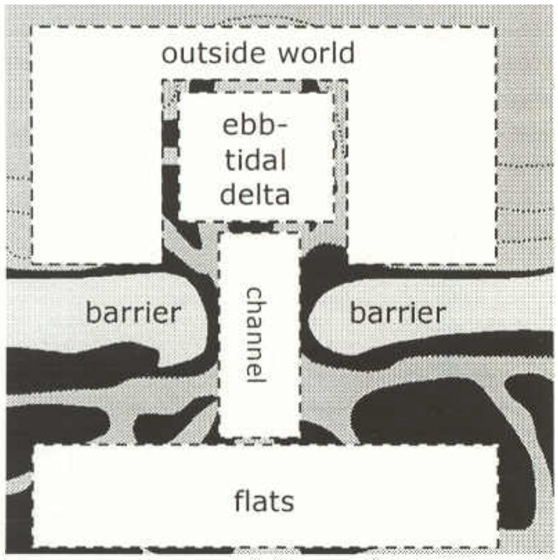

Figure 3-1 Elements used in ASMITA concept
After Van Goor (2001)

Next, a short description of each element is presented.

Ebb-tidal delta:

Ebb-tidal deltas are sediment accumulations on the seaward side of tidal inlets, and they are also morphologically and dynamically connected to the tidal inlets. In the tidal system, deltas are important because they act as sediment reservoirs, so they can supply sediment when it is needed in the system. In case of no sediment enough in the delta, it will be delivered by the adjacent coast.

We may define the volume of the ebb-tidal delta via the no inlet-bathymetry (Dean and Walton, 1975) as if there was no inlet in the coast. In this case, the coastal slope is assumed undisturbed by the coastal inlet and therefore assumed equal to the bathymetry of the adjacent barrier coast. The volume of the ebb-tidal delta is equal to the volume above this fictitious no-inlet coast. This definition is also used in ASMITA.

Channel

One can say that the channels are the veins of the system: they transport considerable amounts of water and sediment. During flood, water enters into the inlet, and brings a large amount of sediment. Part of this sediment will be deposited in the channels and/or in the flats. Also, part of this sediment will be transported out of the system during the ebb. Referring to the shape of the channels, one can say they follow a branching pattern. Near the inlet, the depth and width of the channels is largest and close to the basin, they get smaller.

Flat

The flats are defined as the area that dries during low water and inundates during high water in a tidal cycle, so all areas between MHW and MLW (Eysink, 1990). Eysink found that, according to general classifications of coastal features, the presence of tidal flats mainly depends on the tidal range, basin area, shape of the basin and the orientation of the basin according to the dominating wind direction. Large tidal basins, specially when they are orientated in the direction of the dominant wind, allow significant wave action around high water because of the considerable fetch lengths.

As mentioned before, we assume that the morphological state of each element can be described by aggregated state variables: the total sand volume of the delta, the total water volume below low sea level and the area of the intertidal zone in the lagoon basin (Stive et al., 1998). This schematisation of the tidal basin bring us to the definition of the tidal prism (P). Moreover, the tidal range (h), that is to say, the difference between high and low mean sea levels; the area at the mean high water, the so called basin area (A_b); the area of the channels (A_c) and the flat areas (A_f) play a role in obtaining the tidal prism, as well as the volume of the flats (V_f). Next, we present a figure where the previous indications become clear (the volume of the channel (V_c) is been also included in the following scheme, although it is not necessary to calculate the tidal prism, but this will help to later explanations):

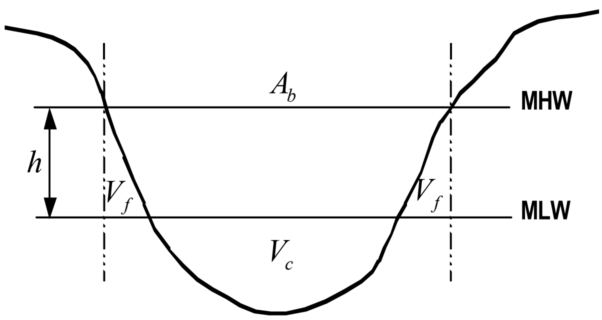

Figure 3-2 Tidal prism
After Van Goor (2001)

$$P = hA_b - V_f \tag{3.1}$$

where $A_b = A_c + A_f$ (3.2)

Implicitly, we assume that the basin is small compared to the length of the tide waves, hence, the water level change "simultaneously" everywhere in the basin.

Thus, the volume of each element is defined as it follows:

Delta: sediment volume above a fictitious no-inlet coast (Dean and Walton, 1975)
Flats: sediment volume in the tidal flat between MLW and MHW (V_f)
Channel: water volume below the MLW (V_{ch}), see figure 3.2.

3.3.2 Morphological development in tidal basins: equilibrium concept

Morphological development in tidal basins is mainly related to the tide. One of the main hypotheses assumed in the model is that each element in the system tends to evolve towards a morphological equilibrium (a steady state where there will be no morphological changes with time), which is determined by the local, long term averaged hydrodynamic and morphometric conditions. Theoretical arguments for the existence of such equilibrium were given by Dronkers (1998), but also supported by various field investigations. An empirical relation is required for each element to define the morphological equilibrium state, they can be derived from literature, Eysink (1990). In this state, the volume in each element is called the equilibrium volume (V_{ie}), and it depends on:

$$V_{ie} = f\left(P, h\right) \tag{3.3}$$

Morphological changes towards an equilibrium state occur by tide-residual sediment transport. Then, the long-term (time scale much larger than tidal period) mass-balance can be considered for every element:

$$\pm \frac{dV_n}{dt} = \sum_i T_{ni} \tag{3.4}$$

The left-hand side of this equation represents the erosion rate within an element. The positive sign corresponds to a wet volume (wet volume increases when erosion is larger) and the negative sign corresponds to a dry volume (sand volume decrease when erosion increases). The right-hand side represents the sum of transports from the element to its adjacent elements in the system, including the outside world (if that is the case). The rate of volume change is assumed to be proportional to the difference between the local equilibrium concentration and the actual concentration (Galappatti and Vreugdenhil, 1985):

$$\pm\frac{dV_n}{dt} = w_s A_n \left(c_{ne} - c_n\right) \tag{3.5}$$

where

A_n is the horizontal area of the element $\left[\mathrm{m}^2\right]$

w_s is the vertical exchange rate $[\mathrm{m/s}]$

c_{ne} is the local equilibrium concentration $[-]$

c_n is the actual concentration $[-]$

For each element in the system, a local equilibrium concentration c_{ne} is defined, so that if the element is in morphological equilibrium, the actual concentration equals to the local equilibrium concentration, hence, $c_n = c_{ne}$. When they differ from each other, morphological changes take place. Erosion within an element will occur when the actual sediment concentration is smaller than the equilibrium concentration. Accretion will occur when the actual concentration of an element is larger than the equilibrium concentration. If we think about the delta and the flat areas (both defined as a dry volume), when c_n is smaller than c_{ne}, the derivative of the volume becomes negative, hence, there is erosion as the amount of sediment in the elements is decreasing with time. In the channel (defined by a wet volume), when the equilibrium concentration is smaller than the actual concentration, the derivative is positive; sedimentation will take place.

A key element in the modelling concept is the global equilibrium concentration c_E. The definition is based on the following arguments. When all elements in the system are in equilibrium, a constant sediment concentration is present in the whole system. This overall equilibrium concentration is identical to the global equilibrium concentration. Therefore, $c_i = c_{ie} = c_E$.

Concentrations and volumes are related by the following equation:

$$c_{ie} = c_E \left(\frac{V_{ie}}{V_i} \right)^n \qquad (3.6)$$

$n > 0$ for wet volumes: channel

$n < 0$ for dry volumes: delta and flats

The power n is larger than one, usually the value of this power is 2, based on the usual assumption in sediment transport formulas that the sediment transport is proportional to the third power of the flow velocity (Stive, 1997).

When the local equilibrium concentration in an element is smaller than the global equilibrium concentration, a tendency to accrete exists; when it is higher than the global equilibrium concentration, there is a tendency to erode.

Let's consider a case where the local equilibrium concentration in an element defined by a dry volume is larger than c_E. The actual volume of sediment will be larger than the equilibrium volume, so it means there is an excess of sediment in the element (compared to the equilibrium state) so it tends to erode; and vice-versa if the local concentration is smaller than c_E.

Let's think now about the channel, since a wet volume defines it. If one consider a situation where the local concentration is larger than the equilibrium concentration, the actual volume in the channel will be smaller than the equilibrium one. This corresponds to a situation where there is an excess of sediment in the element, so then a tendency to erode exists.

Morphological changes in the elements let the system evolve to an equilibrium state. Sediment transport make this changes occur. There is a tendency to erode or to accrete depending on the local equilibrium concentration and the overall equilibrium concentration. However, and as mentioned before when the parameter T_{ni} was introduced, there exists also an exchange of sediment between adjacent elements in the system, and also between the system and the outside world. It can be expressed as it follows:

$$T_{ni} = \delta_{ni} \left(c_n - c_i \right) \qquad (3.7)$$

where

δ_{ni} is the horizontal exchange parameter between elements n and i

As the equation shows, sediment exchange between two elements occurs depending on the difference in sediment concentration between those elements. This sediment transport will always take place from high concentration to lower concentration. Hence, if an element has a larger concentration compared to its adjacent element, the sediment is transported towards the element with the lower concentration. This transported sediment can settle in the latter element or be transported again to the next element (it might have an even lower concentration). An important hypotheses is that the outside world is able to provide or accept sediment unconditionally as demanded by the tidal inlet system. And vice-versa, the morphological development of the tidal inlet does not influence the outside world.

To complete this explanation, we can summarise sediment exchange occur depending on:

the surplus or deficit of sediment in individual morphological elements (determined by how the actual state deviates from the equilibrium state of this element)

the capacity to exchange sediment between elements (determined by the difference in concentration between different elements)

the availability of sediment in the system boundary

If we establish a mass balance between the horizontal transport and the vertical exchange, see equation (3.5) and equation (3.7) we obtain:

$$\sum_i T_{ni} = \sum_i \delta_{ni}\left(c_n - c_i\right) = w_s A_n \left(c_{ne} - c_n\right) = \pm \frac{dV_n}{dt} \tag{3.8}$$

From here, we can relate horizontal and vertical sediment exchange.

3.4 Original ASMITA model equations

Before writing the equations for a tidal system with a channel, flat areas and a delta, we will present a scheme showing equilibrium relations and sediment exchange between elements:

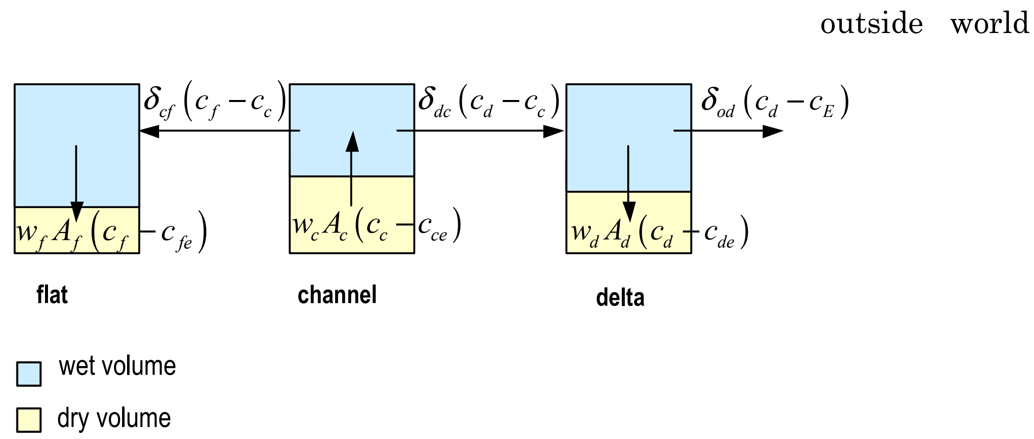

Figure 3-3 Sediment exchange lines
After Kragtwijk (2001)

Hence, considering these exchanges of sediment between elements, the mass-balance for each element can be written as:

$$\delta_{od}(c_d - c_E) + \delta_{dc}(c_d - c_c) = w_{sd} A_d (c_{de} - c_d) \tag{3.9}$$

$$\delta_{cf}(c_c - c_f) + \delta_{dc}(c_c - c_d) = w_{sc} A_c (c_{ce} - c_c) \tag{3.10}$$

$$\delta_{cf}(c_f - c_c) = w_{sf} A_f (c_{fe} - c_f) \tag{3.11}$$

Hereby we present the rest of the model equations when the system is formed by a channel, flats and delta, that means rewriting equations (3.5) and (3.6), applied to each element in the system:

$$\frac{dV_d}{dt} = w_{sd} A_d (c_d - c_{de}) \tag{3.12}$$

$$\frac{dV_c}{dt} = w_{sc} A_c (c_{ce} - c_c) \tag{3.13}$$

$$\frac{dV_f}{dt} = w_{sf} A_f (c_f - c_{fe}) \tag{3.14}$$

$$c_{fe} = c_E \left(\frac{V_f}{V_{fe}} \right)^r \tag{3.15}$$

$$c_{ce} = c_E \left(\frac{V_{ce}}{V_c} \right)^r \tag{3.16}$$

$$c_{de} = c_E \left(\frac{V_d}{V_{de}} \right)^r \tag{3.17}$$

Notice that, compared to equation (3.6), we have considered r as the power in previous expressions, and r is always positive. To be in agreement with equation (3.6), in case n is negative, nominator and denominator are inverted.

From equations above we can see there are different kind of parameters, which are needed to know how elements evolve with time. We can classify these input data in different groups, such as: geometrical parameters (these are physical parameters), process parameters (we cannot measure them directly) and numerical parameters (needed to make the model run).

Geometrical parameters

Areas and initial volumes

Initial volumes form the boundary condition for solving the model equations.

Tidal range

Although the tidal range is not explicitly used in the model, it determines among other things the equilibrium volumes, as they depend on the tidal prism (P).

Process parameters

Equilibrium volumes

They can be obtained from certain empirical relations. In general, they depend on the tidal prism and the tidal range, see equation (3.3).

Horizontal exchange coefficient

This corresponds to the long-term horizontal transport between adjacent elements. The value of this parameter must be given, and it bears the dimension m^3/s, like a discharge.

Equilibrium concentration

The equilibrium concentration is a necessary input to make the model run. It can be obtained as the integral of the vertical distribution of the suspended sediment concentration (Van Rijn et al., 2001). However, in ASMITA model, concentrations are dimensionless, and the equilibrium concentration becomes an empirical parameter.

Vertical exchange coefficient

It represents the vertical exchange and it is measured by m/s. Vertical exchange represents both the long-term residual sedimentation and erosion.

Numerical parameters

r parameter

The value of this parameter is 2.

Time-step and number of time-steps

They also must be given as an input parameter in the model. Its value depends on our interest.

3.5 New condition in the system: river discharge.

How we do consider the influence of a river:

The effect of the river will be taken into account considering two new conditions: an input of sediment (S) and a water discharge (Q_w). Then, the lines of sediment exchange will be modified. The idea is to consider that the discharge flows to the channel, and from there goes, throw the delta, to the outside world, in other words, there is no direct influence to the flat areas.

Furthermore, we have considered that tides do not affect the river, hence in our approach, sediment cannot be transported from the channel into the river; the discharge is always positive and independent of the tide. The river is not a new element in the system but it forms a new boundary condition for the channel, as it adds a water flow and a sediment input.

3.5.1 New equations and other considerations

Next we present a scheme to understand how the river has been considered in the tidal system:

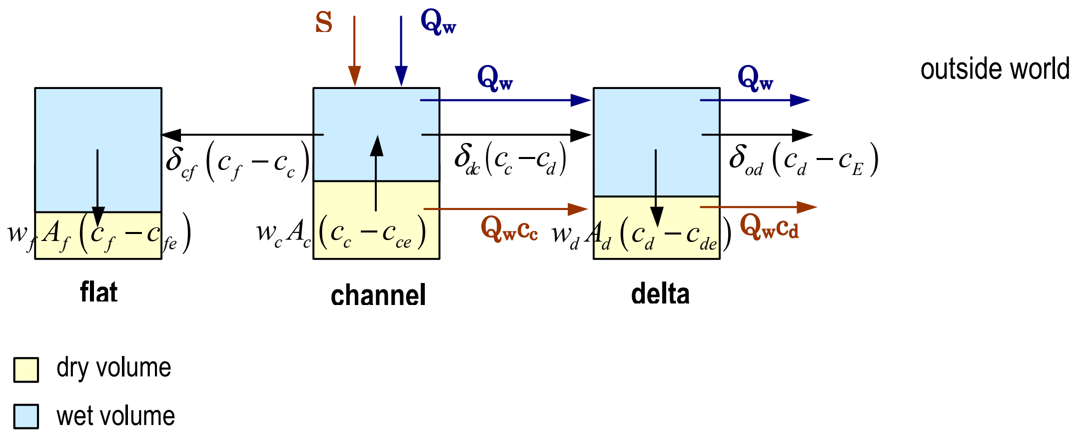

Figure 3-4 Exchange lines in case of river discharge
After this report

With the above considerations, the mass balance equations become:

$$\delta_{od}(c_d - c_E) + \delta_{dc}(c_d - c_c) - Qc_c + Qc_d = w_{sd} A_d (c_{de} - c_d) \tag{3.18}$$

$$\delta_{cf}(c_c - c_f) + \delta_{dc}(c_c - c_d) + Qc_c - S = w_{sc} A_c (c_{ce} - c_c) \tag{3.19}$$

$$\delta_{cf}(c_f - c_c) = w_{sf} A_f (c_{fe} - c_f) \tag{3.20}$$

One might notice that we have substituted Q_w for Q, just to simplify the writing.

Indeed, these are the only equations that change in the model, equations that relate equilibrium volumes with concentrations remain the same, as the hypotheses of the equilibrium state existence do not disappear.

Keeping with the idea that the river is like a new boundary condition, we could think about which is the condition that determines the behaviour of the system: is the global equilibrium concentration the concentration at

the steady state in each element or does the concentration in the river have an influence in this steady state? In other words, we wonder which will be the concentration at the equilibrium state for each element.

Looking at the channel, one could think there are two equilibrium possibilities for it. One could be reached when the concentration in the channel would equal the concentration of the river, as the river represents a boundary condition for the channel, and, on the other hand, the channel could also be in equilibrium when its concentration would equal the outside world concentration, as the equilibrium tendency of each element shows. But, of course, one element tends to evolve to only one situation, so it is clear that the channel will evolve to a certain concentration which will put it in an equilibrium state. Whether this equilibrium situation is given with a concentration equal to the global equilibrium concentration or equal to the river concentration still has to be studied (and this is what we will do in next chapters).

However, to take into account the fact that there are two boundary conditions for the channel, we could consider that the outside world equilibrium concentration changes due to the river, so that a new global equilibrium concentration might be considered. There are different ways to obtain a new equilibrium concentration, but, as we do not know the real influence of the river in the boundary conditions, the easiest way to obtain this new concentration could be just calculating an average of both concentrations:

$$c_{E,new} = \frac{\left(c_{Eriver} + c_{Esea}\right)}{2} \tag{3.21}$$

Nevertheless, we will not consider a new global equilibrium concentration in order to see more clearly which is the influence of a river in a tidal basin. But, of course, this could also be considered in later works as a way to represent morphology changes with the ASMITA model.