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ON THE PARAMETER SETTING OF SEMI-EMPIRICAL LONG-TERM MORPHOLOGICAL MODELS FOR ESTUARIES AND TIDAL LAGOONS

Zheng Bing Wang[1], Huib J. De Vriend[1], Marcel J.F. Stive[2], Ian H. Townend[3]

[1] *WL | Delft Hydraulics & Delft University of Technology, Faculty of Civil Engineering and Geosciences*
[2] *Delft University of Technology, Faculty of Civil Engineering and Geosciences*
[3] *HR Wallingford*

Abstract

Predicting the long-term morphological development of estuaries and tidal lagoons is a challenging topic, despite the progress made recently. One of the advancements is the development and successful applications of the semi-empirical models ASMITA and ESTMORF. They combine empirical relations for morphological equilibriums with aggregated descriptions of physical processes. A difficulty in their application is that they rely on aggregated parameters, which are not directly measurable physical quantities. Here we try to relate the aggregated model parameters to the physical parameters used in the process-based models, by comparing the semi-empirical model concept with the process-based model concept, using analytical solutions. This results in relations between the aggregated model parameters and measurable physical quantities. The analysis also gives an indication of the data required for a good model calibration. It follows that with limited field data, the range of applicability of a 'calibrated' model is necessarily limited.

Introduction

Predicting the morphological development of estuaries and tidal lagoons, especially over the long-term, is a challenging topic, despite the progress made over recent years. Compared to non-tidal rivers, the interaction between morphological changes and the hydrodynamics is much more complex because the feedback from the morphology to the hydrodynamics is much stronger. The amount of water flowing through a river is determined by the rainfall in the river catchment area, whereas in a tidal lagoon such as the Wadden Sea it is both the geometry and the bathymetry that determine the tidal prism. This implies that when tidal flow is important the driving force for the morphological development is much more influenced by the morphology itself. A consequence of this feedback complexity is that the morphological equilibrium of an estuary, or a tidal lagoon, cannot simply be derived from the physical mathematical relations describing the morphological processes, as is the case for river morphology. In this sense morphodynamic simulations with tidal forcing are open-end simulations. Another complexity is due to the fact that morphological changes are determined by residual sediment transport, which is often a small difference between the much larger flood and ebb transport. Accurate calculation of the residual sediment transport by integrating the transport in a tidal cycle is thus prone to error.

Over recent years the semi-empirical models ASMITA and ESTMORF (Stive et al, 1998, Wang et al, 1998, Stive and Wang, 2003) have been developed. These models combine empirical relations for morphological equilibriums with aggregated descriptions of physical processes. By introducing the empirical relations for the morphological equilibrium, the problem concerning unknown equilibrium is overcome. By simulating directly the residual transport field these models overcome the difficulty concerning the accuracy mentioned above. These models have proved to be useful for many practical cases (Wang et al, 1999, Van Goor et al, 2003, Kragtwijk et al, 2004, Jeuken et al, 2003, Shi et al, 2003, Wang and Roelfzema, 2001, Townend et al, 2006).

A difficulty in the application of these semi-empirical models is that they rely on aggregated parameters, which are not directly measurable physical quantities. As such, there is a gap between this type of model and fully process-based models, such as Delft3D. The determination of these model parameters depends, to a large extent, on the calibration, which is only possible if data on long-term of morphological development are available. The experience on parameter setting obtained in one application is not necessarily applicable to another estuary or tidal lagoon. This makes the models difficult to use more widely.

In this paper we relate the aggregated model parameters to the physical parameters that are used in process-based models. To do this we compare the semi-empirical model concept to the process-based model concept, using analytical solutions of the linearised models for both concepts. This results in recommendations on how to determine the parameters in the semi-empirical models, which influence the morphological time scales, from measurable physical quantities. The results of the analysis also give an indication of the data requirement for a good model calibration. Based on a limited number of applications, we examine the ability to generalize parameter settings from one estuary to another and the restrictions this places on the range of the applicability of the model.

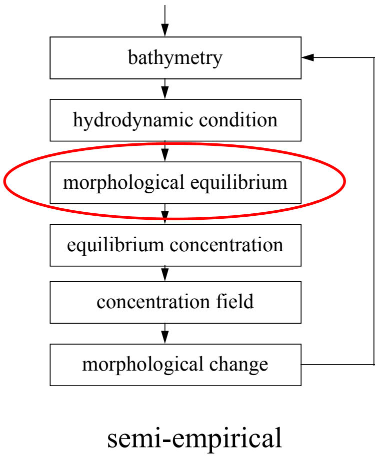
2. Model concept and model parameters

The most important hypothesis used in the semi-empirical model concept is that an equilibrium state can be defined for each morphological element of the system, depending on the hydrodynamic conditions. For each element an empirical relation is required to define the morphological equilibrium state. This kind of empirical relationship has been extensively explored for tidal systems (O'Brien, 1931; Renger & Partenscky, 1974; Townend, 2005).

Various morphological models for estuaries and tidal inlets are based on such relations, in combination with a transient model describing the evolution of the actual state towards this equilibrium state as an exponential decay process (O’Connor et al., 1990, Eysink, 1990, Eysink, 1992). If this model concept is applied to a system consisting of a set of interlinked element, additional assumptions are required to guarantee the mass-balance of sediment (Allersma, 1988, Van Dongeren and De Vriend, 1994). This can make the model results sensitive to the sequence in which the various elements are dealt with in the computation: e.g. computations starting from the sea side give different results than computations starting from the land side.

In the tidal basin model of Di Silvio (1989) this problem is overcome by introducing a characteristic sediment concentration in each element of the model. The concentration field is governed by the advection-diffusion equation based on a residual flow field, which guarantees the fulfilment of the sediment mass-balance. This concept is adopted in the semi-empirical models ASMITA and ESTMORF.

The basic philosophy is as follows: If all elements in the morphological system are in equilibrium, there is no accumulation of sediment or water anywhere in the area. If the sediment is mainly transported in suspension, the sediment flux field is therefore likely to be proportional to the flow rate. The ratio between sediment flux and flow rate can be considered as a sediment concentration and is called the overall equilibrium concentration c_E. For each element in the system a local equilibrium sediment concentration c_e is defined such that it equals c_E if the element is in morphological equilibrium. If it is larger than c_E, a tendency for erosion exists (e.g. the cross-sectional area of a channel is smaller than the equilibrium value), and if it is smaller than c_E, a tendency for sedimentation exists. However, erosion does not necessarily occur in an element with an erosional tendency because the morphological change of an element also depends on the sediment exchange with the surrounding. Similarly to the process-based models for suspended sediment transport, it is assumed that morphological changes occur when the actual sediment concentration at a point in space and time deviates from its equilibrium value. Erosion occurs when the sediment concentration is smaller than its equilibrium value and sedimentation occurs if it is larger than its equilibrium value. The actual sediment concentration field is governed by the advection-diffusion equation.



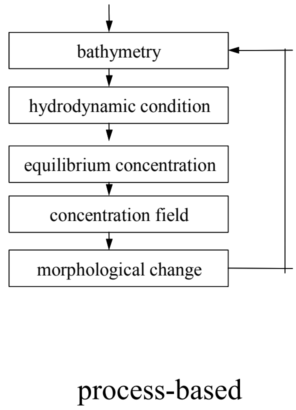


Figure 1 Computational procedure

The model concept described here is semi-empirical, according to the classification proposed by De Vriend (1996). Sometimes it is also referred to as a hybrid model. An important difference between this type of model and a process-based model is that the equilibrium concentration is not directly computed from the hydrodynamic parameters, but via the morphological equilibrium state (see Figure 1). This makes the model always converge to a state in which the equilibrium relations are satisfied. Another difference between the two types of model, which is not indicated in Figure 1, is that the semi-empirical models do not simulate sediment transport processes within a tidal cycle but operate on a tidally averaged basis.

The model formulation of ESTMORF is given in detail by Wang et al (1998) and the description of ASMITA can be found in Stive and Wang (2003). In this paper we only consider the simplified case of a tidal channel without inter-tidal flat. Furthermore, only tidal flow is considered, such that the residual flow is negligible. For such a case the non-linear ESTMORF model reads:

$$-\frac{\partial}{\partial x}\left(AD\frac{\partial c}{\partial x}\right) = Bw_s\left(c_e - c\right) \tag{1}$$

$$\frac{\partial A}{\partial t} = Bw_s\left(c_e - c\right) \tag{2}$$

In these equations: x=longitudinal coordinate, A=cross-sectional area of channel, D=inter-tidal dispersion coefficient, c=sediment

concentration (volume bottom / volume water), B=width of channel, w_s=vertical exchange coefficient, c_e =local equilibrium sediment concentration, t=time.
The local equilibrium sediment concentration is related to the ratio between the cross-sectional area and its equilibrium value according to

$$c_e = c_E \left(\frac{A_e}{A} \right)^n \tag{3}$$

The equilibrium cross-sectional area A_e follows from the empirical relation. Here we use the simplest form of such a relation, viz. the equilibrium cross-sectional area is proportional to the tidal prism volume P:

$$A_e = \alpha P \tag{4}$$

It is noted that the physical parameters in a semi-empirical model can be divided into two groups: parameters that define the morphological equilibrium state and parameters that determine the morphological time scales.

The former group contains all the coefficients in the empirical relations for the morphological equilibrium state. To determine these coefficients we have to rely on the field data and little use can be made of experience gained elsewhere, for two reasons. Firstly, the values of these coefficients are not universal (e.g. Allersma, 1988). Secondly, schematisation errors often make these coefficients spatially variable. This means that, even if theoretically they should be constant, they are variable in a model of a practical situation, because the schematisation of the cross-sectional areas always contains errors. In practice these coefficients are often determined by assuming that the system at a certain stage is in (dynamic) equilibrium. For example, the set-up of the Western Scheldt model assumed that the estuary was in equilibrium in 1968, just before the first deepening of the navigation channels. For the Humber Estuary the ESTMORF model is set up by assuming that the estuary is in dynamic equilibrium with the present rate of sea-level rise. As Van Goor et al (2003) concluded, a tidal basin adjusts to a dynamic equilibrium with an over depth after a sustained period of sea-level rise.

The latter group of coefficients, determining the morphological time scales, includes the overall equilibrium sediment concentration c_E, the power n in the formulation for the local equilibrium concentration, the vertical exchange coefficient w_s, and the horizontal inter-tidal dispersion coefficient D. In the following sections we will discuss how to determine these parameters.

It is further noted that the parameters in ASMITA and those in ESTMORF are related to each other. The parameters c_E, n and w_s are in principle the same in both models. The only difference concerns the horizontal exchange process. ESTMORF works with a (discretised) continuous model domain and uses the dispersion coefficient D (m^2/s), whereas ASMITA works with discrete aggregated elements and uses the horizontal exchange coefficient δ (m^3/s). By comparing the finite-difference representation of the ESTMORF formulation and the ASMITA formulation, the following relation between the two parameters can be found:

$$\delta = \frac{DA}{L} \tag{5}$$

Herein A is the cross-sectional area linking the two elements in ASMITA and L is the distance between the two elements.

3. Theoretical analysis

Consider a small disturbance of the basic equilibrium situation c=c_E and A=A_0, such that:

$$B = B(x), \quad A = A_0(x) + A', \quad A_e = A_0(x) + A_e'$$
$$c = c_E + c', \quad c_e = c_E + c_e' \tag{6}$$

The linearised equation for the morphological development is then given by:

$$F_1 \frac{\partial A'}{\partial t} + F_2 \frac{\partial^3 A'}{\partial t \partial x^2} + F_3 \frac{\partial^2 A'}{\partial t \partial x} + F_4 \frac{\partial^2 A'}{\partial x^2} + F_5 \frac{\partial A'}{\partial x} + F_6 A' = 0 \tag{7}$$

with

$$F_1 = 1 + \frac{A_0 D}{B^2 w_s}\frac{\partial^2 B}{\partial x^2} - \frac{2A_0 D}{B^3 w_s}\left(\frac{\partial B}{\partial x}\right)^2 + \frac{1}{B^2 w_s}\frac{\partial B}{\partial x}\frac{\partial\left(DA_0\right)}{\partial x}$$

$$F_2 = -\frac{A_0 D}{B w_s}, \quad F_3 = \frac{2A_0 D}{B^2 w_s}\frac{\partial B}{\partial x} - \frac{1}{B w_s}\frac{\partial\left(DA_0\right)}{\partial x}$$

$$F_4 = -n c_E D, \quad F_5 = \frac{2n c_E D}{A_0}\frac{\partial A_0}{\partial x} - \frac{n c_E}{A_0}\frac{\partial\left(DA_0\right)}{\partial x}$$

$$F_6 = \frac{n c_E D}{A_0}\frac{\partial^2 A_0}{\partial x^2} - \frac{2n c_E D}{A_0^2}\left(\frac{\partial A_0}{\partial x}\right)^2 + \frac{n c_E}{A_0^2}\frac{\partial A_0}{\partial x}\frac{\partial\left(DA_0\right)}{\partial x} \tag{8}$$

The detailed derivation can be found in Wang (2005) and Wang and Townend (2007).

Consider the development of a harmonic perturbation of the equilibrium situation in an infinitely long channel. For this case the development of the disturbance can be analysed by finding a solution of Equation (7) in the form:

$$A' = \hat{A} e^{i(\omega t + kx)} \tag{9}$$

Herein $\hat{A}$=amplitude of the disturbance, ω=complex frequency, k=wave number of the disturbance. Substitution of Equation (9) into Equation (7) yields a dispersion relationship between ω and k. Here we only consider the simplest case of a prismatic channel. This can also be interpreted as assuming that the wave length of the harmonic disturbance is much smaller than the length scale of the variation of A_0 and B. For this case, noting that the hydraulic depth is given by, $H_0=A_0/B$, we have:

$$F_1 = 1, \; F_2 = -\frac{A_0 D}{B w_s} = -\frac{H_0 D}{w_s}, \; F_3 = F_5 = F_6 = 0, \; F_4 = -n c_E D \tag{10}$$

So the dispersion relation becomes:

$$\omega = \frac{n c_E D k^2}{1 + k^2 \frac{H_0 D}{w_s}} i \tag{11}$$

The frequency is purely imaginary, which means that the disturbance does not propagate (due to the fact that no residual flow is taken into account) and decays exponentially in time. The time scale, defined as the time in which the disturbance decreases its amplitude by a factor *e,* is:

$$T = \frac{T_s + T_D}{c_E \, n} \tag{12}$$

Where $T_s = \frac{H_0}{w_s}$ and $T_D = \frac{1}{k^2 D}$ are two time scales, one for the vertical exchange process and one for the horizontal exchange process. Furthermore, it is clear that the morphological time scale is inversely proportional to the overall sediment concentration c_E and the exponent n. Apparently, c_E plays the same role as the coefficient of proportionality in the sediment transport formula in a process-based model, which can be used to calibrate the model for the morphological time scale. The exponent n plays the same role as the velocity exponent if a power-law sediment transport formula is applied.

4. Determination of the model parameters

The semi-empirical models work with the morphological time scale and do not consider variations within a tidal period. They simply compute the tide-averaged, or residual, transport. This is one of the reasons why the relation between model parameters and physical processes is not entirely obvious. In order to find a way to relate the model parameters to measurable physical quantities, we first consider a schematic case in which the tidal flow is strongly simplified: in half of the tidal period the flow is steady in one direction and in the other half period it is steady in the other direction. In such a case the residual sediment transport is zero in the undisturbed (equilibrium) case. However, if a small disturbance like the one considered in the previous section is present, the residual sediment transport will no longer vanish. The disturbance will then be damped out and the damping rate for the semi-empirical model will be as determined in the previous section. For such a simplified case, the damping rate can also be derived from a process-based model. This can be done, for instance, by using the results of an analysis for steady uniform flow (Wang, 1989, 1992). In that case, the disturbance propagates in the flow direction while decaying. For the simplified tidal flow case it is then obvious that the residual propagation of the disturbance is zero, because half of the time the propagation is in one direction and half of the time it is in the opposite direction with the same magnitude. As a result the disturbance will only decay at the same rate as in uniform flow. This rationale applies as long as the morphological time scale is much larger than the tidal period. This means that both types of models show the same behaviour for the morphological development. The decay rate of the disturbance can thus be expressed in the parameters of either model, which makes a direct comparison between the two models possible.

Before elaborating this quantitatively, we can already state that:

- The overall equilibrium sediment concentration c_E is related to the sediment transport capacity in general and should be equal to the equilibrium sediment concentration under the undisturbed flow in this particular case. Like the coefficient of proportionality in the sediment transport formula in process-based models, it should be considered as a calibration parameter.
- The power n is related to the velocity exponent in the power-law sediment transport formula (sediment transport capacity is proportional to the flow velocity to some power); this can also be derived from a general sediment transport formula.
- The parameter w_s is proportional to, but not necessary equal to the settling velocity of sediment particles.

Less obvious are the properties of the inter-tidal dispersion coefficient D, representing the horizontal mixing process by the tidal motion. It has no directly corresponding parameter in the process-based model, as it is the result of averaging over the tidal cycle. In general a diffusion/dispersion coefficient can be considered as the product of the velocity-scale and the length-scale of the mixing process. The mixing agent is the oscillating tidal flow. For this particular case it is obvious that the velocity scale is simply the constant flow velocity taken equal during ebb and flood. For the length scale there are two alternatives: the tidal excursion and the adaptation length of the sediment concentration. The tidal excursion is the distance travelled by a water particle during the flood or ebb period. In the simplified case under consideration it is equal to half the tidal period multiplied by the flow velocity. The adaptation length for sediment concentration is proportional to the distance a sediment particle travels in the time it needs to settle from the water surface to the bottom (Galappatti and Vreugdenhil, 1985). As long as the tidal period is much smaller than the morphological time scale but large enough for the tidal excursion to be much larger than the adaptation length of the sediment concentration, the decay rate for the disturbance in the uniform flow case also applies to the simplified tidal flow case. This means that the decay rate is independent of the tidal period, thus also independent of the tidal excursion length. This suggests that the adaptation length for sediment concentration is preferable over the tidal excursion as a length scale determining the inter-tidal dispersion coefficient for semi-empirical models. However, if the tidal period is small compared with the time required for a sediment particle to settle from the water surface to the bottom, it is obvious that the relevant length scale for the inter-tidal mixing should be the tidal excursion. These considerations lead to the conclusion that the minimum of the two alternatives should probably be used as mixing length for determining the inter-tidal dispersion coefficient D.

We now compare the damping rates between the two types of model quantitatively for the simplified case. The damping rate according to the semi-empirical model is represented by the imaginary part of ω, as given in (11). It is the reciprocal of the time scale of decay of the disturbance.

The corresponding damping coefficient according to the process-based model can be written in the following form (Wang, 1992):

$$\frac{\mathrm{Im}\,\omega}{kbs_0 / H_0} = \frac{\mathrm{Im}\,\omega}{kbu_0 c_E} = F\left(k\frac{q}{w_s}\right) \tag{13}$$

in which b=power in the power-law sediment transport formula, u_0=undisturbed flow velocity, q=specific discharge = u_0H_0, $s_0=qc_E$, w_{s0}=settling velocity of sediment particles.
The imaginary part from Equation (11) can be written in the same form as Equation (12) if

$$D = \alpha u_0 \frac{q}{w_{s0}} = \alpha u_0 \frac{u_0 H_0}{w_{s0}} \quad \text{and} \quad w_s = \beta w_{s0} \tag{14}$$

In these two equations α and β are constant coefficients. Then it follows from Equation (11):

$$\frac{\mathrm{Im}\,\omega}{knu_0 c_E} = \frac{\alpha\left(k\dfrac{q}{w_{s0}}\right)}{1+\dfrac{\alpha}{\beta}\left(k\dfrac{q}{w_{s0}}\right)^2} \tag{15}$$

Equation (14) implies that the mixing length is proportional to the adaptation length of the sediment concentration. This is in agreement with the reasoning in the previous subsection, since the uniform flow solution from the process-based model applies to the case that the tidal period is relatively large. As has been shown by Wang (1989, 1992), the exact shape of the function F in Equation (13) depends on the value of the parameter w_{s0}/u_* which describes the shape of the sediment concentration profile (here u_* is the friction velocity). The comparison between the two types of model, as well as physical considerations, leads to the conclusion that the two coefficients α and β should also be dependent on this parameter. Figures 2 and 3 show the damping coefficient from the process-based model for two values of the parameter w_{s0}/u_* and Figure 4 shows the same coefficient from the semi-empirical model for two combinations of α and β. It is, indeed, possible to select a combination of α and β that makes the solution behave in a similar manner to the process-based model.

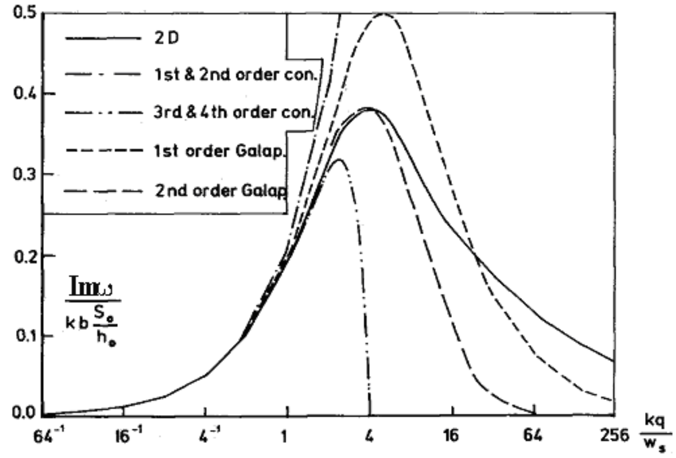


Figure 2 Damping coefficient from the process-based model w_s/u_*=0.1 (From Wang, 1989)

For the general tidal flow case it is not possible to make such a quantitative comparison between the two types of model. Nor is it clear how to select the required flow velocity scale in Equation (14). One may choose the mean absolute flow velocity, or the maximum flow velocity, or any other representative velocity. It is therefore not very useful to try and find an exact relation between the two parameters α and β and the parameter w_{s0}/u_*. This means that α and β remain as calibration coefficients. Nevertheless, the present analysis is useful for determining the model parameters, since it relates them to physical parameters.

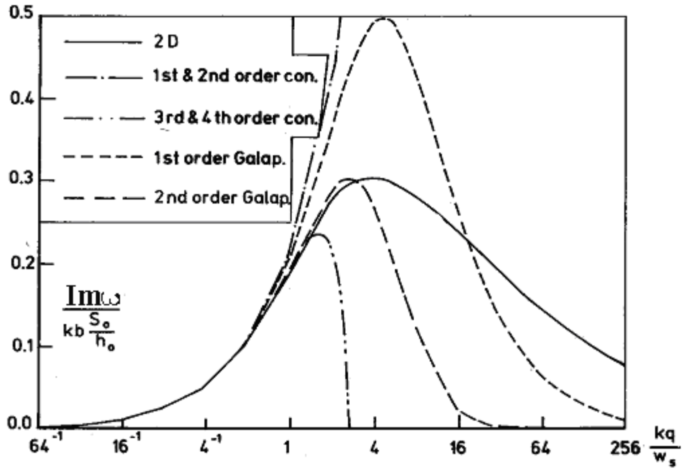


Figure 3 Damping coefficient from the process-based model w_s/u_*=0.4 (From Wang, 1989)

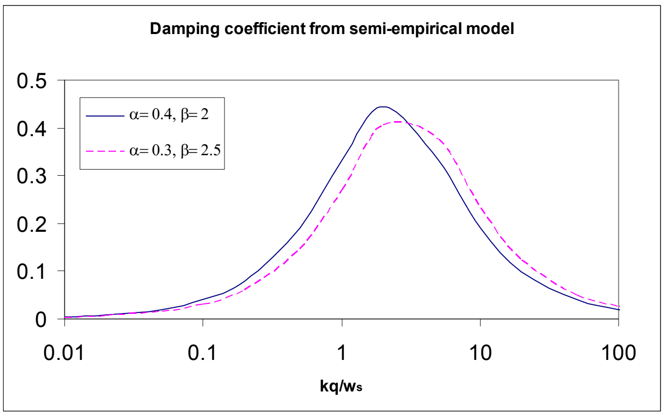


Figure 4 Damping coefficient from the empirical model

It is further noted that in practical cases the tidal period can mostly be considered as relatively long compared to the time needed for a sediment particle to settle from water surface to bottom. This means that the adaptation length will usually be selected in preference to the tidal excursion.

Another interesting observation is made by comparing equations (13) and (15). The power n in the semi-empirical models should be equal to the power b in the sediment transport formula and not b-1 as is often assumed.

5. Considerations of calibration

As the results of the theoretical analysis have revealed, the time scale of the damping of a disturbance to the morphological equilibrium state consists of two time scales (see Equation (12)). It is noted that one of these time scales is dependent on the length scale of the disturbance and the other is not. It may happen that one time scale is much larger than the other, given the length scales to be considered. In such a case, the model results will become insensitive to some of the model parameters. It is then difficult to determine these parameters by calibration. Caution should be exercised if a model is applied to problems with length scales that are very different from those in the calibration data.

Finally, it is noted that the parameters determining the morphological time scales are not fully independent of each other, in that more than one combination of the parameters is possible for exactly the same behaviour of the model. By halving the value of c_E and doubling the values of w_s and D the morphological time scale according to Equation (12) will remain exactly the same. As a matter of fact, as long as the values of $w_s c_E$ and $D c_E$ are kept the same, the model will behave exactly the same for any combination of the three parameters c_E, w_s and D. According to Equation (12) the parameters n and c_E are not independent either, since the morphological time scale remains the same as long as $n c_E$ is the same. However, it is important to recognise that this conclusion results from the adoption of a linear model. Whether or not the value on n can be determined independently from the value of c_E depends on the applicability of the linearised model. For cases where the linear solution is valid, they remain dependent. Whereas, if the calibration data provide sufficient information to identify changes that are not addressed by the linear solution, then it is possible to obtain independent values.

6. Review existing applications

In order to provide an indication of the range of the various parameters, the settings of the ESTMORF models for a number of applications are given in Table 1. Only recent applications where calibrations were possible have been included.

Table 1 Coefficients in recent ESTMORF applications.

Application	w_s (m/s)	D (m^2/s)	c_E (-)	n
Western Scheldt	0.001	1250	0.00005	4
Friesche Zeegat	0.01	200-50	0.0001	3
Humber Estuary	0.0003	2000	0.0002	2
Southampton Water	0.0003	2000	0.0002	2

More details of the Western Scheldt model are given by Wang et al (1999), of the Frische Zeegat model by Wang et al (1998), of the Humber Estuary model by Wang and Jeuken (2003) and ABPmer (2004), of the Southampton Water model by Wang (2000).

7. Concluding discussions

In summary, the following conclusions concerning the model parameters which influence the morphological time scales haven been drawn from the theoretical arguments presented:

- The power n in the formulation of the local equilibrium sediment concentration should be equal to the velocity exponent in the power law sediment transport formula, not this exponent minus 1, as assumed in many applications of the models so far.
- The overall equilibrium sediment concentration c_E is a parameter indicating the level of morphological activity in the area. From a calibration point of view, it has the same function as the coefficient of proportionality in the sediment transport formula in a process-based morphodynamic model.

- The vertical exchange coefficient w_s should be proportional to and of the same order of magnitude as the settling velocity of the sediment particles.
- The inter-tidal dispersion coefficient D should be proportional to u^2H/w_s in which u is scale of the tidal flow velocity and H is the hydraulic water depth. This can also be written as

$$\frac{D}{uH} \propto \frac{u}{w_s} \tag{16}$$

It is now interesting to compare the values used in the existing applications of ESTMORF, as listed in Table 1, to these theoretical rules. By doing so we immediately observe the following discrepancies between the used parameter settings and the theoretical rules:

- In all the applications the values of n are chosen too low.
- The value of w_s varies strongly from case to case, especially the difference between the Western Scheldt model and the Friesche Zeegat model is remarkable, since the sediments in the two systems are comparable. The value used in the Western Scheldt model seems to be too low.
- The value of c_E is the same for the Humber and Southampton Water even though the level of morphological activity is very different.

The parameter values in all these applications have been chosen in a model calibration process, attempting to find the best fit between the model results and the field observations. Some explanation of the observed discrepancies is therefore needed.

That the value of n used is too small, apparently without serious consequences for the model behaviour, is explained by the finding that within the domain of applicability of the linearised model (i.e. not too large disturbances from the morphological equilibrium), the morphological time scale according to the model is the same as long as the product nc_E is the same, as explained earlier. This means that the effect of a value of n that is too low can be compensated by a higher value of c_E. This explanation is supported by the fact that the product nc_E has indeed a similar value in the Western Scheldt model and in the Friesche Zeegat model.

Similarly, for the Humber and Southampton Water, the value of nc_E used was the same, as were the individual values of n and c_E. Given the differences between the two estuaries in terms of sediment type, transport mechanisms and the magnitude of the morphological response, it seems more likely that the individual values should have been different. However, as already discussed, these are only possible to identify if suitable calibration data are available for cases that are non-linear in character.

The explanation for the setting of w_s is similar: the field data used for calibration of the models are not sufficient to determine unique values of w_s and D. From Table 1 it is noted that, despite the strong variation of the values of these two parameters from case to case, the theoretical rule (16) is roughly satisfied. As long as this rule is satisfied, the effect of bi-directional tidal flow is correctly represented by the inter-tidal dispersion formulation. A difference in the choice of w_s physically means working with a different type of sediment. This difference is irrelevant if only the large-scale morphological changes are considered. In the Western Scheldt case, for instance, the model calibration is mainly based on morphological changes on the scale of the sounding maps, i.e. the whole estuary is divided into six parts. This means that the relevant length scale is in the order of tens of kms. This means that the value of kq/w_s is in the order of 1. In this range, the model behaviour is insensitive to the parameter w_s/u_*, as can be observed by comparing Figure 2 and 3.

In summary it has been concluded that:

- The product nc_E determines the order of magnitude of the morphological time scale. In a calibration procedure, these two parameters can only be separated if the field data available concern a situation beyond the application domain of the linear model, i.e. far from morphological equilibrium.

- As long as Equation (16) is satisfied, the mixing by the tidal flow is correctly represented by the inter-tidal dispersion formulation. The parameters w_s and D can only be separated in a calibration procedure if the field data available encompass a sufficiently wide range of spatial scales in the morphological changes. Especially the smaller-scale changes are essential.
- The field data used to calibrate the existing applications of ESTMORF did not cover a sufficiently wide range to allow the model parameters to be separated. As long as the calibrated models are applied to problems in the same range of morphological change, this should not be of relevance.

Based on these conclusions it is recommended that the results from the theoretical analysis are used to inform the process of model calibration. The following calibration procedure is recommended:

- Chose the value of n based on an applicable sediment transport formula.
- Chose w_s based on the settling velocity of the sediment particles.
- Chose D based on Equation (16) and the experience gained from the existing applications, i.e.

$$\frac{D}{uH} = \varepsilon \frac{u}{w_s} \tag{17}$$

with ε in the order of 0.1 (final value to be chosen during calibration). Here the tidal flow velocity scale is assumed to be of the order of 1 m/s.

- Adjust c_E to give the correct morphological time scale.

In this way the number of the calibration parameters reduces to 2, viz. ε and c_E.

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HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk