Developing Macroscale Indicators for Estuarine Morphology: The Case of the Scheldt Estuary

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ABSTRACT

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A set of quantitative parameters is derived for the morphological characterization of estuaries. This is the first part of a long-term project aiming at the ecological characterization of tidal environments, which should provide practical tools for the management of such systems. The parameters apply to the macroscale, that is, the scale of the estuarine cross-section, including channels and adjacent intertidal areas. They are derived from recent theoretical models for estuarine morphology, as well as data from the tide-dominated Scheldt estuary. The set of parameters is believed to be universally representative, although this needs to be supported by further research, including data from other estuaries. The analysis suggests that morphodynamic equilibria do not form a continuum but manifest themselves as discrete steps. For each step, there is a straightforward relation between the extension of the intertidal areas and the other parameters. For the Scheldt estuary, large width-to-depth changes are necessary to jump from one equilibrium state to the other.

ADDITIONAL INDEX WORDS: Morphodynamics, equilibrium, tidal.

INTRODUCTION

An estuary can be morphologically altered in such a way that the local biology is negatively affected, even though water and sediment are both clean. For management purposes, it is thus important to be able to measure also the morphological quality of a water system, which would allow quantifying the level of damage caused by physical changes exclusively and establish acceptability limits.

Chemical pollution is easily quantifiable and many standards are currently available. On the contrary, the morphological deterioration is still difficult to quantify. Chemical pollution often has visible and direct effects on water and organisms, while the effects of morphological changes are slow and not immediately visible. They can manifest themselves after a long period, in the form of alterations in the typical succession stages of salt marshes or as erosion of banks and intertidal areas. For this reason, men have first concentrated their efforts in identifying and treating chemical pollution and, only at a later stage, have realized the importance of recognizing and treating morphological deterioration.

The aim of the present analysis is to provide a morphological characterization tool at a macroscale level, through the definition of a set of parameters able to identify different morphological situations. This is the first step of a long-term project that should finally result in an ecomorphological characterization of the estuarine systems. The purpose is that of being able to measure the morphological quality, providing graphs or tables based on easily assessable parameters, where threshold lines separate different morphological typologies that are related to well-defined ecological environments. The selected quantitative indicators should become a useful support for decisions in the management of estuaries.

The macroscale has been selected as the most suitable scale for this study because all the morphological elements that are important for decision makers can be taken into account. They are intertidal areas, channels, and islands, to be considered in a common context and not as single entities. Thus, the morphological quality of macroscale estuarine sections is here linked to the presence and to the characteristics of intertidal areas, islands, and channels.

The parameters to be used as morphological indicators have been selected on the basis of their role in the morphological evolution, their range of variation within the estuary, and the feasibility of their measurement. The set of parameters is believed to be universally representative, although it
needs to be supported by further research, including data from other estuaries.

The analysis of data has been conducted exploiting the theoretical results obtained so far. Conceptual models provide a simplified description of reality and allow selecting the relevant aspects of the natural system. In particular, a careful investigation of the sensitivity of model results with respect to the range of variation of the variables can provide an estimate of the role of the different factors.

The analysis suggests that morphodynamic equilibria in estuaries, rather than forming a continuum, manifest themselves as discrete steps. For each step, characterized by the number of channels per cross-section, there seems to be a straightforward relation between the extension of the intertidal areas and the other parameters.

These results provide a way to understand the impact of some artificial changes on the morphological characteristics of the estuary such as channel widening and narrowing. Instead, the methodology adopted in this study cannot assess the impact of those activities that alter the motion of sediment in the estuary, such as regular dredging and dumping.

The Scale Issue

A physical phenomenon can be investigated at different spatial and temporal scales. In the present analysis, we focus our attention on the macroscale, which corresponds to a reach of estuary comprising all the morphological components in which we are interested: channels, islands, and intertidal areas. The characteristic length scale is somehow related to the width of the estuary. Channels, islands, and intertidal areas can be separately studied at the mesoscale level, whereas the whole estuary is conventionally regarded at the megascale.

The goal of the analysis is to find out the parameters that can be relevant for the assessment of the macroscale morphological character (e.g., the number of channels, the extension of islands and shoals, etc.)

From a morphological point of view, the definition of a length scale strongly affects the period of time that it is necessary to consider to see any change. This means that the time scale of observation is strictly related to the choice of the length scale: the larger the length scale, the longer the time scale. Basically, the time scale of the morphological developments is related to the intensity of the sediment transport process and to the amount of sediment that has to be moved. Furthermore, there are more or less strong interrelations among different scales, as pointed out by DE VRIEND (1998) through the concept of the cascade of scales. In some cases, the evolution of the smaller scales can be parametrically incorporated, while the large-scale variations modify the boundary conditions of the smaller scale subsystems.

Morphologists are often interested in the definition of equilibrium conditions, e.g., those conditions for which the system reaches a stable configuration, provided that the boundary conditions are kept steady. In any case, the morphological equilibrium of tidal systems is dynamic because those systems undergo cyclic modifications, for instance, during the tidal cycle. It is also important to note that the boundary conditions (sea level, river discharge, human interventions) may vary on the time scale of the morphological evolution. Thus, only a tendency toward an equilibrium configuration can be regarded.

Referring to a given scale, we can think about the morphological variations of the smaller scale elements as higher-frequency oscillations. Thus, even if the system is not in equilibrium at the megascale, which corresponds to the whole estuary, it could be considered stable at the macroscale, with periodic variations at the lower scales.

The Study Site

The object of the analysis is the estuarine part of the river Scheldt, which crosses the border between The Netherlands and Belgium (see Figure 1). The study site has been selected for the large amount of data available and the variety of morphological studies that have been carried out, which can provide both measured quantities and descriptions of the system. Besides, this estuary presents three distinct morphologies and this is a valuable feature for the selection of the morphological indicators, which should be able to discriminate between different situations.

The Scheldt estuary can be considered a relatively young estuary because its evolution started only a thousand years ago (VAN DEN BERG et al., 1996). The surface of intertidal areas has strongly decreased since the 17th century (~40% for the tidal basin surface), but the amount of water exchanged with the open sea has not changed or has even increased. The importance of the human interventions in driving the development of the system cannot be neglected. It is well known that a large amount of land was separated from the sea through the construction of dykes and polders. Currently the estuary is almost completely bounded by dykes and its planimetric evolution is prevented.

An important activity of dredging occurs within the estuary: two major dredging phases took place in the periods 1970–74 and 1998 and large amounts of mud have been removed from the Lower Sea Scheldt since 1992. Further increasing the navigation channel depth is currently a subject of discussion because it is feared that it might cause undesirable morphological and ecological changes in the estuary. Furthermore, special attention is being given to the present policy of dredging and dumping in the estuary.

Globally, the Western Scheldt is a well-mixed, macrotidal estuary: the tidal range is around 4 m at the mouth and the ratio between the tidal prism (volume of water that flows through a cross-section during half a tidal cycle) and the volume of freshwater entering through the landward boundary is large. The value of this ratio ranges from 100s at Vlissingen (the mouth of the estuary) to 10s at the border between The Netherlands and Belgium. Thus, for the Dutch part, the role of the river discharge can be considered negligible but, in the landward part of the estuary, the influence of freshwater discharge increases upstream and the hydrodynamic behavior tends to that typical of a tidal river.

For the present analysis, we examine the Dutch part (Western Scheldt) and that part of the Belgian reach that is strongly affected by tidal oscillation of the free surface (Sea Scheldt). In particular, we consider the Belgian part from the
Figure 1. The estuarine part of the River Scheldt (Belgium and The Netherlands).

national border to Rupelmonde, where the river Rupel joins the river Scheldt. The study site can be qualitatively subdivided into three parts through the identification of three different kinds of morphological features:

1. The seaward part of the Western Scheldt, from Vlissingen to Baarland (corresponding to sections 1 and 2 in Figure 2), can be described as a multiple-channel system, where two main channels are separated by intertidal areas, but with other large or deep longitudinal channels.

2. The landward part of the Western Scheldt, from Baarland to the border between The Netherlands and Belgium, where a two-channel system is present: The channels are separated by one intertidal area.

3. The Belgian part of the estuary, or Sea Scheldt, which is a single-channel system, where the intertidal areas are present only near the banks, mainly at the inner side of the channel bends.

METHODS AND MATERIALS

Sources of Data

The data available for the present analysis come from several different sources. Most of the publications provide aggregated data for the estuarine sections, such as lengths, volumes, tidal ranges, and sediment characteristics (e.g., JEUKEN, 2000). The first hydrographical surveys date back to the 19th century, but the main bathymetric surveys were made after 1931. Important measuring campaigns were carried out in 1955 and 1968. The bathymetries of the Scheldt estuary used for runs of the numerical model Delft3D (WL|Delft Hydraulics) have been the main sources of quantitative data. The geometrical data have been extracted from two different bathymetries: the first, from the outer delta to Gent, dates to 1992; the second, from the outer delta to Antwerp, dates to 1996.

Subdivision in Estuarine Sections

The Scheldt estuary can be subdivided into macroscale zones, here called estuarine sections. JEUKEN (2000) proposes a subdivision for the Western Scheldt that is strongly influenced by the curvilinear pattern of the estuary (the Scheldt estuary is roughly a meandering tidal channel). The length scale involved appears to be the meander wavelength (precisely half wavelength, from an inflection point to the other). Both theoretical results and field observations on tidal networks (MARANT et al., 2002; SOLARI et al., 2002) suggest that the meander wavelength typically scales with the channel width. A similar behavior is also displayed by river meanders (SEMINARA and TUBINO, 1992). Thus the width of the channels + intertidal areas system seems to be a relevant length scale of the estuarine sections because it is easy to measure and physically relevant.

VAN DER SPEK (1994) proposed another subdivision, for the whole estuary from Vlissingen to Gent (thus, considering also the part of the river upstream of Rupelmonde). The estuarine sections almost coincide with those defined by JEUKEN (2000)
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Figure 2. The subdivision of the Scheldt estuary into estuarine sections: numbers from 1 to 15. In the figure, it is possible to distinguish the main channels and the intertidal areas (\( z \) is the bed elevation, NAP is the Dutch mean sea level).

in the Western Scheldt, with small differences in the region near Bath. The subdivision of the present analysis is represented in Figure 2 and follows the indications given by the above authors as much as possible. For further details on the characteristics of the estuarine sections, see TOFFOLON (2002a).

Parameter Selection

The goal is the definition of parameters and thresholds that are able to indicate the morphological aspect of an estuarine section (number and type of intertidal areas, etc.).

The analysis is restricted to a single type of tidal environment, namely the macrotidal estuary. The methodological approach selected for such a choice has been planned according to the following steps:

1. Definition of the variables involved in the problem, with particular reference to the dimensional units, the scale of observation, the ease of measurement, and the significance for the purpose of the analysis.
2. Identification of the parameters that are likely to be relevant, based on theoretical considerations, on their use in conceptual models and on the analysis of data from the Scheldt estuary.
3. Sensitivity analysis of the results of theoretical models with respect to the range of variation of the chosen parameters.
4. Analysis of the available data from different sections of the Scheldt estuary, displaying different morphological features.

Two further steps can be delineated: the analysis of historical data of the Scheldt estuary and the comparison with data from analogous estuaries (for instance, Humber, Ord, Delaware, Severn, St. Lawrence, Nooghly, Thames, Gironde, Elbe). The former is useful to assess the influence of the parameters upon the evolution and the latter allows verifying and generalizing the results obtained. However, due to lack of quantitative information, in the present contribution, the analysis has been restricted to the first four points.

Hereafter, we will use the terms variable and parameter to refer, respectively, to the measure of an entity and to the combination of several variables into an aggregated form. The method of selection of the relevant parameters can be summarized as follows. Each of the different aspects of the problem, like the water discharges, the property of the sediments, the geometrical characteristics of the water body, etc., is represented by a variable, to which a direct measure can

\[
\begin{align*}
\bullet & \quad \text{NAP} + 2 \, \text{m} < z \\
\bullet & \quad \text{NAP} < z < \text{NAP} + 2 \, \text{m} \\
\bullet & \quad \text{NAP} - 2 \, \text{m} < z < \text{NAP} \\
\bullet & \quad \text{NAP} - 10 \, \text{m} < z < \text{NAP} - 2 \, \text{m} \\
\bullet & \quad z < \text{NAP} - 10 \, \text{m}
\end{align*}
\]
be given. Variables are then grouped to define suitable parameters, which include the influence of different aspects and their reciprocal interaction. Each parameter influences the morphological behavior primarily at certain spatial–temporal scales. Thus, the first selection retains those parameters that are important for the scale we are studying, disregarding the others. For example, we can take into account the width-to-depth ratio, but probably we do not need to consider the Froude number, which is mainly important at a smaller scale.

Other examples are the energy dissipation rate and the inundation time, which have been shown to be crucial factors for the local biota (CROSATO et al., 1999). Energy dissipation rate is defined using local velocities and also takes into account the energy arising from nonbreaking and breaking waves; inundation time defines the local duration of flooding. They are both typical microscale phenomena. However, these parameters cannot be used to distinguish the macroscale morphological typologies in which we are interested because their value varies locally within the estuarine sections, but their average over the characteristic length scale does not significantly vary along the estuary. In particular for the Scheldt estuary, those microscale parameters do not show a noticeable difference between the Dutch and the Belgian parts, whereas the morphology of these parts is remarkably distinct. In practice, those microscale parameters cannot be used as macroscale morphological indicators.

In short, the parameters should be

1. distinctive;
2. applicable: the definition of parameters that involve unknown or hardly obtainable variables is useless;
3. independent: it is necessary to restrict the number of parameters by avoiding repetitions of the same information in related parameters;
4. dimensionless: the parameters must not depend on the adopted units and should be valid for different systems.

Geometrical Characterization

Because the goal is the morphological characterization of entire estuarine sections, the definition of the geometrical variables is adapted to the macroscale framework. Instead of measuring depth, area, and width of the cross-sections, the most suitable choice is to use volumes, planimetric surfaces, and reference lengths of the estuarine section under consideration. Thus, we define the volume, \( V \), of the estuarine section as the volume of water below a given free surface level; the surface, \( S \), as the measure of the planimetric wet surface occupied by the free surface at the given level; and the length, \( L \), as the curvilinear length of the estuarine section, which does not depend on the water level. The other geometrical variables are defined in terms of the previous ones.

The depth, \( D = \frac{V}{S} \) (1)

is an average measure of the water depth within the estuarine section. Note that \( D \) is not the mean value of the cross-sectional averaged depths along the estuarine section, but it is somehow related. The definition has the main advantage that it does not require identifying single cross-sections, which are strongly nonuniform; furthermore, the operational definition is much simpler, and the synthetic information is univocally determined. Consistently, the macroscale cross-sectional area can be evaluated as \( A = \frac{V}{L} \) and the corresponding macroscale width as \( B = \frac{S}{L} \). Again, these definitions are different from the mean values of the variables of the cross-sections along the estuarine section and can be regarded as derived from an averaging procedure.

The basic geometrical features can be evaluated at different water levels. Three different elevations are significant when considering a reference semidiurnal tide: the high water level (\( hw \)), the mean water level (\( mw \)), and the low water level (\( lw \)). In particular, the ratios between the values of the same variable at different water levels are significant when considering tidal environments. Figures 3 and 4 show the variations of the reference area and of the width of the mac-
Figure 5. Macroscale averaged depth, $D$, for high-water (HW), mean-water (MW), and low-water (LW) conditions. The depth, $D_{hw}$ at high water, as estimated from Equation (3), is plotted for comparison.

Figure 6. The width-to-depth ratio, $\beta$, for high-water level (HW), mean water (MW), and low water (LW).

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roscale estuarine sections along the estuary. While the area varies smoothly along the estuary, the width exhibits a transition between two different behaviors, which can explain the abrupt change of the morphological features of the estuary.

The difference of water level between high tide and low tide is an important parameter. Thus, we define the tidal range $R = H_{hw} - H_{lw}$, where $H$ is the water level with respect to a horizontal reference system. The tidal amplitude is usually defined as half the tidal range. It is important to note that the difference $D_{hw} - D_{lw}$ between the average depths at high and low tide, defined according to Equation (1), might be significantly dissimilar from the tidal range, $R$.

Following DRONKERS (1998), the parameter controlling the equilibrium configuration of a tidal basin is the ratio

$$r_D^* = \frac{D_{hw}}{D_{lw}} = 1 + rD_{lw},$$

where $D_{lw}$ is the average depth at low tide, evaluated with Equation (1), and

$$D_{hw}^* = D_{lw} + R$$

is a different reference depth at high tide. It is important to note that $D_{lw}$ is different from $D_{lw}$. In fact, whereas $r_D^*$ accounts for the effect of tidal range, when using $D_{lw}$, the parameter

$$r_D = \frac{D_{hw}}{D_{lw}}$$

can be employed to describe the morphological features of the estuarine section at high and low tide because it reflects the influence of the width-to-depth ratio. Figure 5 shows the variation of the average depth along the estuary. A distinction between two different zones can be clearly identified:

1. In the Dutch part, the value attained by the depth at high tide $D_{hw}$ is different from the average high-water depth $D_{hw}$; besides, the average depth does not significantly vary at low $(D_{lw})$ and at high tide $(D_{lw})$;
2. In the Belgian part, the estuarine morphology changes

and the difference between averaged depths at different water levels increases.

One of the most important parameters for the morphological characterization is the ratio between width and depth,

$$\beta = B/D.$$  (5)

The definition of width and depth is not unequivocal because it depends on the water level. Consistently, we use three different values of $\beta$, which refer to high $(\beta_{hw})$, mean $(\beta_{mw})$, and low $(\beta_{lw})$ water levels. In Figure 6, we can observe that the distinction between the two morphological zones in the Scheldt estuary, single-channel (Belgian part) and multiple-channel (Dutch part), can be given also in terms of the width-to-depth ratio:

1. In the Dutch part, $\beta$ at high tide is larger than $\beta$ at low tide;
2. In the Belgian part, the trend is the opposite.

This behavior can be easily explained if we consider three schematized types of cross-sections (in the $y$-$z$ plane: $y$ transverse coordinate, $z$ vertical coordinate; see Figure 7). If we consider a cross-section such that

$$Y(z) = z^n,$$  (6)

where $z$ is the maximum local depth (different from the average depth $D$), we obtain

$$\beta = (n + 1)z^{n-1}. $$  (7)

We can fit the data of the real sections using the simple law of Equation (6) to obtain their schematized shapes. As already noted, the planimetric surface, $S$, is related to the average width, $B$, by means of the length, $L$. Thus, we consider the hypsometric curve, $S(H)$, that is the planimetric surface $S$ as a function of the water level along the vertical coordinate $z$ to describe the overall shape of an estuarine section. The advantage is that $S$ is a direct measure of the whole estuarine section, while the definition of $B$ requires the iden-
Figure 7. Examples of schematized sections: U-shaped \((n = 0.5)\), V-shaped \((n = 1)\) and Y-shaped \((n = 2)\).

tification of the cross-section. The hypsometric curve should be rewritten in the form

\[
\frac{S(H)}{S_{mw}} = \alpha \left( \frac{H - z_0}{H_{mw} - z_0} \right)^n
\]  

(8)

to obtain a proper dimensionless relationship. In Equation (8), we choose the values at mean water level (subscript \(mw\)) as reference values, while \(z_0\) is the conventional level of the deepest point of the schematized section. The parameter \(\alpha\) introduces a degree of freedom in the interpolation; however, its value is always close to unity. The hypsometric curves of the 15 cross-sections considered in the estuary are drawn in Figure 8 with the corresponding interpolating curves; the coefficients \(n\), \(\alpha\), and \(z_0\) of Equation (8) are plotted in Figure 9.
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The characteristics of the hypsometric curves and the values of the geometrical ratios are not very sensitive to the choice of the boundaries of the estuarine section. Within a reasonable range of variation of, for instance, the length of the estuarine section, the trend of the geometrical parameters along the estuary is preserved.

Different shapes of cross-sections can be described through the relationships Equations (6) and (7) by changing the value of the exponent $n$:

1. U-shaped section ($n < 1$, limiting case $n = 0$ for rectangular section), $\beta$ decreases when the water level increases;
2. V-shaped section ($n = 1$, triangular section), $\beta$ remains constant as the water level changes;
3. Y-shaped section ($n > 1$), $\beta$ increases with the water level.

The first case is typical of the Belgian part (see Figure 10), while the third case can approximately describe the Dutch part (see Figure 11). The U-shaped section is a compact section, while a Y-shaped section corresponds to a cross-section characterized by a deep, narrow channel (or channels) with adjacent shallow areas that are inundated at high water levels.

From Figure 10c, it is possible to recognize a behavior that resembles that of the U-shaped section, with decreasing values of the width-to-depth ratio for increasing water level in the region close to the tidally averaged level. This is typical of a concave cross-section, like the one shown in Figure 10a, where the increase of width with the water level is limited. It is noteworthy that it is possible to recognize within the section a single main channel with a transverse structure of the alternate-bar type, which is typical of meandering channels.

Figure 11c shows the hypsometric curve of an estuarine section within the Dutch part of the Scheldt estuary. It is not difficult to recognize that the general behavior looks like that of the theoretical Y-shaped section, with the width-to-depth ratio increasing with the water level. This can be easily explained considering Figure 11a: though each single channel
Figure 11. Estuarine section 4 (Valkenisse, Western Scheldt): (a) an example of a real cross-section; (b) bathymetry (light grey thick lines: \( z = \text{NAP}-10 \) m, grey thick lines: \( z = \text{NAP} \)); (c) hypsometric curve, \( S(H) \); (d) width-to-depth ratio, \( \beta/H \).

displays a more or less concave shape, the overall shape of the whole section is convex, i.e., the width of the free surface increases more rapidly than the cross-sectional area as the water level rises. The presence of more than one channel has important morphological consequences and the overall shape is related to the extent of the intertidal areas.

The width-to-depth ratio is an easily assessable parameter and is distinctive; it is thus a good candidate for being a macroscale morphological indicator. Conclusions on the role of this parameter are drawn through the analysis of morphodynamic theories.

**Intertidal Characterization**

The relative importance of the volume of water flooding the intertidal areas at high tide can be expressed in terms of the parameter \( r_V = V_{hw}/V_{lw} \). This parameter is strongly related to the ratio

\[
r_R = R/D_{lw} = r_D^0 - 1
\]

between the tidal range and the average depth at low water, which is a largely used parameter. In fact, the difference between \( r_R \) or equivalently \( r_D^0 \) according to Equation (9), and \( r_V \) (see also Figure 12) is related to the volume \( \Delta V_d \) of water stored within the intertidal areas at high tide:

\[
r_V = r_D^0 + \Delta V_d/V_{lw}.
\]  

The ratio between the wet planimetric surface at high tide and at low tide,

\[
r_S = S_{hw}/S_{lw} = 1 + S_d/S_{lw},
\]

gives quantitative information on the extension of intertidal areas because the difference \( S_d = S_{hw} - S_{lw} \) is exactly the definition of the planimetric surface of the intertidal areas. The parameter \( r_S \) can be measured very easily; however, it does not allow one to distinguish among different types of intertidal areas (i.e., whether they lie in the middle of the channel or close to the banks).

One may expect that the surface of the intertidal areas
Increases with the increase of the tidal range. This is confirmed in the seaward part of the estuary, as can be seen in Figure 12, where the parameter $r_S$ is compared with $r_D$ and $r_D^0$ (or equivalently $r_0$); from Vlissingen to Bath, these parameters show the same increasing trend. An abrupt fall in $r_S$ occurs landward of Bath, at the border between The Netherlands and Belgium, while the other two parameters do not seem to change in the same way. These considerations help to understand why the border between The Netherlands and Belgium represents a transition between two different morphologies.

The geometrical ratios can be defined also referring to the simplified shape of the cross-section introduced above. In fact, Relation (8) can be integrated along the vertical to give the volume $V(H)$ and the average depth,

$$D(H) = (H - z_0)/(1 + n).$$

Following this definition, the ratio $r_D$ reads

$$r_D = (H_{bw} - z_0)/(H_{lw} - z_0) = 1 + R/(H_{lw} - z_0)$$

and we can express the other ratios as functions of $r_D$,

$$r_S = r_D^0,$$

$$r_V = r_D^{0 - 1}.$$  

In this way, the geometrical characterization mainly relies on the parameters $n$ and $z_0$. The ratios $r_D$, $r_S$, and $r_V$ evaluated with this method are plotted in Figure 13: the behavior is similar to that drawn in Figure 12, but it is slightly smoother, probably because of the filtering effect of the interpolation procedure, which reduces the influence of the direct measure of the geometric variables at the different water levels.

Equation (12) can be substituted in Equation (2) to obtain, using also Equation (13), the relationship

$$r_D^0 = r_C(1 + n) - n,$$

which states the influence of the shape of the cross-section (parameter $n$) upon the difference between the two depth ratios $r_D^0$ and $r_D$.

The parameters $r_D$ and $r_S$ can be used in the process of macroscale characterization because they can distinguish the three morphological zones in which the Scheldt can be subdivided. Figure 14 suggests that the field data can be grouped in clusters, in particular if the ratio $r_D$ is considered instead of $r_D^0$. One group consists of data from the Sea Scheldt (squares, Belgian part of the estuary). Data from the estuarine sections of the Western Scheldt (circles, Dutch part) do not form such a consistent group, but they can be further subdivided into two parts: one comprises the sections 3, 4, 5, and 6 (see Figure 2; from Baarland to the border); the other, the sections 1 and 2, Vlissingen and Terneuzen (the seaward part of the estuary). This subdivision is confirmed by observations: the sections near the mouth show a multiple-channel system, the others a two-channel system.

The three different morphological situations can also be distinguished by $\beta$ and $r_S$, based on the clustering observable in Figure 15. The parameter $\beta$ quantifies the wide and shallow character of the cross-section, $r_S$ the extension of the intertidal areas. The combination of the two parameters can be

Figure 13. Values of depth ratio, $r_D$, surface ratio, $r_S$, and volume ratio, $r_V$, evaluated through the interpolation of hypsometric data with the simplified law (8) and the relationships (14) and (15).

Figure 14. Characteristics of the estuarine sections in the $r_S$-$r_D$ plane, based on macroscale averages of field data of the estuarine sections (numbered circles: Western Scheldt, estuarine sections 1–6; squares: Sea Scheldt, estuarine sections 7–15): (a) the ratio $\beta_D$ between depths at high and low water is computed following (2); (b) the ratio $r_D$ is computed with the definition of macroscale averaged depths following (4). The theoretical equilibrium (17) is plotted with a continuous line.
regarded as an index of presence of islands. Intertidal areas in narrow and deep channels tend to form near the bank, whereas, in wide and shallow channels, they may form also in the central area of the section.

In Figure 16, the clusters are determined using the relation (14); the subdivision is even clearer. Plotting the curves \( r_S = r_D \) for different values of \( n \), we find that the estuarine sections corresponding to the Western Scheldt are close to the line with \( n = 2 \). This result is interesting because we recover a relationship similar to the one proposed by Dronkers (1998),

\[
    r_D^n = \sqrt{r_S}, \quad (17)
\]

which is based on the concept of a megascale \( i.e., \) considering the whole estuary \( \) morphological equilibrium. In fact, if we interpret the relation (17) substituting \( r_D^n \) with \( r_D \), now (17) appears as a special case of the law (14) in the case of Y-shaped sections. Therefore, even if the extension of the equilibrium relationship (17) to the macroscale analysis does not seem to be adequate, in particular, when considering \( r_D \), the corresponding curve is plotted in Figure 16, a new link between the hydrodynamic behavior and the shape of the section is pointed out.

In conclusion, the two parameters \( r_S \) and \( r_D \) been have shown to be important for the distinction of the morphological zones, for which they should be used together. Besides, they are easily assessable; thus they have the qualities to be macroscale morphological indicators.

Hydrodynamic and Sedimentological Characterization

The estuarine hydrodynamics are induced by the tidal oscillation of the free surface at the mouth, with a contribution of the river discharge that can be considered negligible in most macrotidal estuaries. The tidal wave spectrum shows several components; the most important is the semidiurnal astronomical tide \( M_2 \). Another important component is the first overtide \( M_4 \), whose frequency is twice the frequency of the \( M_2 \). Overtides are present at the mouth of the estuary when the offshore shelf is wide and flat \( \) see, for instance, Van Dongeren and de Vriend, 1994). However, also in the case of a purely sinusoidal \( M_2 \) tidal forcing, frictional and topographic effects give rise to overtides that change also the phase between velocity and free surface during the propagation of the tidal wave (Friedrichs et al., 1998). The variation of the tidal amplitude during the month gives rise to spring and neap tides: the most relevant morphological phenomena occur during the first condition, when both amplitude and velocity are larger.

Field data about velocities in the cross-section are not easily found in estuaries because they require a large number of samples in different locations at different times during the tidal cycle. Only recently, through ADCP methods, the evaluation of a cross-sectional averaged velocity is going to be more accessible. The definition of the reference velocity for the problem under consideration is not straightforward: tidally averaged, cross-sectional averaged, local maximum, ebb or flood maxima are only a few of the possible choices. A simple macroscale reference velocity (tidally and cross-sectional averaged) can be derived using the tidal volumes \( W \) (\( i.e., \) the total volume of water flowing through a cross-section during the time \( T \)) and the corresponding cross-sectional areas \( A \),

\[
    U = \frac{W}{A T}, \quad (18)
\]

where the subscripts \( e \) and \( f \) refer to the ebb or the flood phase, respectively. Following the above definition, it is possible to estimate the reference velocity in the Western Scheldt, \( e.g., \) by using a plot presented by de Jong and Ger-
Ritsen (1984) showing the total ebb discharge (volume) versus the cross-sectional area below NAP (the Dutch reference sea level) for different locations: the average velocity is almost constant along all the estuary. Such field observation is confirmed by numerical simulations, where the cross-sectional average velocity is defined as the ratio of the discharge and the flow area. The ebb peak of the velocity range is about 0.8 and 1.0 m/s and the flood peak about 0.9 and 1.2 m/s, with a decrease in the landward direction; however, the tidal averaged velocity is nearly 0.7 m/s and does not show significant variations along the 60 km of the Western Scheldt.

The average velocity is an important parameter, but the values of the peaks of ebb and flood velocity are crucial from a morphological point of view. The dependence of sediment transport on velocity is described approximately by a power law with an exponent that is significantly larger than unity; thus, small differences in the maximum values during the ebb and flood phase (i.e., the tidal asymmetry) produce large differences in sediment transport, which drive the evolution of the estuary at the megascale (e.g., Toffolon, 2002b). At the macroscale level, the influence of the peaks of velocity and the tidal asymmetry is not so relevant, but the value of the reference velocity is important to define the order of magnitude of the sediment transport, which requires the introduction of the Shields parameter, as discussed below.

The sediment transport strongly depends on grain size and composition of the sediments at the bed; typically, in many tidal systems, the presence of finer sands makes the suspended load predominate with respect to bed load. Sediment composition varies along the Scheldt estuary. Sandy sediments are dominant in the seaward part, with coarser grain sizes in the channels and finer sizes in the shoals. Upstream of Bath, the percentage of clay and silt increases because finer sediments, which are carried by the river, are deposited here, in the zone of maximum turbidity (Verlaan, 1998). The location of the zone of maximum turbidity is governed by salinity and thus by the local rate between salt and freshwater, which is a macroscale parameter. The part of the estuary upstream of Antwerp shows coarser sandy sediments, with a diminishing fraction of silt and clay. Usually the grain size is made dimensionless by introducing the particle Reynolds number,

\[ R_p = \sqrt{\frac{g (\rho_s - \rho) d_s^3}{\rho \nu}}, \]  

where \( \rho \) is the density of water, \( \rho_s \) the density of sediment, \( g \) the acceleration of gravity, \( \nu \) the kinematic viscosity of water, and \( d_s \) the characteristic sediment grain size.

The intensity of the sediment transport depends on few dimensionless parameters. The most important one is the Shields parameter,

\[ \theta = \frac{\tau}{(\rho_s - \rho) g d_s}, \]

where

\[ \tau = \rho(U/C_s)^2 \]

is the bottom shear stress, which can be expressed in terms of the depth-averaged velocity \( U \) and the dimensionless Chézy factor \( C_s \). The Shields parameter represents the ratio between destabilizing (shear stress) and stabilizing (submerged weight) forces. Thus it incorporates the role of the grain size on sediment transport. Unfortunately, the Shields parameter is not easily assessable, mainly due to the roughness term represented by the Chézy factor. This term depends on the dimensionless grain size,

\[ d_s^* = \frac{d_s}{D}. \]  

where \( D \) is a reference depth, but it is also strongly influenced by the presence of macroroughness elements, like dunes, which form or disappear depending on the hydrodynamic conditions. This, along with the uncertainties related to the use of empirical relationships, makes the correct evaluation of the Shields parameter difficult in the field. Thus, even if these parameters are known to play an important role in the morphological behavior, they are not easily assessable indicators.

The presence of multiple grain sizes and, in particular, the presence of a fraction of cohesive sediments complicates the evaluation of these parameters. Moreover, the spatial distribution of different sediments within the estuarine sections, as typically occurs with finer sediments in the intertidal areas, makes it very difficult to estimate average values and to evaluate their role in view of the morphological characterization.

The variation of sediment composition and reference velocity within the Scheldt estuary is not large enough to fully recognize its role, and the lack of models dealing with cohesive sediments does not allow having reliable suggestions. For this reason and for the insufficient quantity of field data, we restrict the quantitative analysis to the geometrical parameters introduced above, which appear to be strongly relevant. The use of theoretical models can give some suggestions about the importance of sediments and sediment transport.

**External Factors**

External factors may strongly affect the evolution of natural systems; extreme events (storms, sea surge, etc.) and the complex human interference (dyke construction, dredging, dumping, navigation) can be the main causes of morphological modifications.

The construction of dykes stops the lateral migration and the meander amplification of the estuary; in this way, the natural evolution of the system is inhibited by the fixed boundaries along the estuary. Moreover, the presence of artificial banks leads to a deeper scour in the outer bend, which can be observed along the Scheldt estuary. The passage of big ships and cargo can be relevant, mainly due to the wave formation and the effect of propellers, but more important are the dredging and dumping activities, which are conducted in order to preserve the navigational channel toward the Port of Antwerp.

In the present analysis, the external forces are considered by means of their impact on one or more parameters: narrowing or widening the estuary alter, for instance, the local width-to-depth ratio. It may be possible that a strong alter-
ation of this geometric parameter changes (in the long-term, say 10s of years) the morphological equilibrium state, for instance, a multichannel system into a single-channel system, with large environmental consequences. Thus, the identification of the morphological indicators and of the thresholds between morphological zones will allow also for the quantification of the long-term impact of some human activities on the morphological quality of single estuarine sections.

MORPHODYNAMIC THEORIES

Morphodynamic theories can provide valuable and complementary suggestions in the research of the most relevant parameters for the characterization of estuarine sections. Theoretical models, which are based on several assumptions, simplify the behavior of natural systems by taking into account only a restricted number of basic factors. The morphological evolution of estuaries has been theoretically studied only recently, though empirical observations and qualitative explanations of the morphological phenomena were also given in the past (see, for instance, Van Veen, 1950). Herein, we shortly present a few examples of recent morphological models.

Simplified conceptual models are the semiempirical ones, based on the assumption that every morphological element tends toward an equilibrium state depending on the hydrodynamic conditions. This state is determined by means of empirical relationships. Examples for estuarine morphology are given, among others, by Van Dongeren and De Vriend (1994) and by Wang et al. (1998). For instance, the latter model is one-dimensional and the cross-sectional area is divided into three parts, which are considered separately: channel, low tidal flat (between low- and mean-water level), and high tidal flat (between mean- and high-water level). It is assumed that an equilibrium state can be defined and that the morphological development tends to restore the equilibrium when it is disturbed. In this way, the model makes use of three variables, for which an equilibrium relationship is given: the cross-sectional area of the channel is related to the tidal volume; the height of low tidal flats and the height of high tidal flats are related to the tidal range and to the total area of the basin. In this way, it is possible to study the effect of each of the parameters on the morphological evolution of the estuary.

An even more simplified kind of idealized model is the group of models that are known as zero-dimensional because they involve only equations of balance for the whole system under investigation, introducing some empirical closures for lower scale phenomena. For instance, the relationship (17) introduced above has been founded by Dronkers (1998) within the framework of such a model: it involves the ratio between wet planimetric surfaces at high and low tide and the ratio between depths. These models can introduce useful parameters for the morphological characterization.

Nowadays, there is not a single conceptual model able to describe all the macroscale features in which we are interested, but we can look at the theoretical process-based models that have been developed so far, in particular, at some mesoscale models for the analysis of a single channel. They allow studying the behavior of the estuarine channel (that has a complex topography) as that of a schematized and compact channel. However, some attempts to consider the stability of the complex system of channels and shoals have been proposed in a schematic way, for example, by Wang and Winterwerp (2001) and Winterwerp et al. (2001), who refer to the Western Scheldt.

One of the most relevant features to be considered for the macroscale morphological characterization is the growth of large bed deformations, which, once fully developed, may take the form of shallows and intertidal areas. Such perturbations of the channel bed, which are generally called bars, have been analytically investigated during the past 20 years, with particular reference to the fluvial case (see, for instance, Colombini et al., 1987; Seminara, 1998; Struijsma and Crosato, 1989). The alternate bars are the basic type—nearbank bars alternate from one side to the other side of the channel, giving rise to a sinuous thalweg. Wide channels may also present multiple bars, with bars also in the middle, creating a complicated system of braiding thalweg. Bars may develop because of an instability phenomenon and, in this case, they are referred to as free bars; or because of external forcing, such as a local change of channel curvature or width, and in this case they are called forced bars. In rivers, an important feature differentiating the two types of bars is that free bars migrate, whereas forced bars are steady.

Models such as that of Seminara and Tubino (1989), developed for rivers, allow defining threshold lines that separate the conditions in which alternate or multiple bars tend to develop from the conditions in which those bars are damped down and do not form. Among the several parameters involved, the width-to-depth ratio β, defined in (5), appears to be the controlling one: above a critical value of β, alternate bars can freely develop in straight channels; a further increase of β leads to the formation of multiple bars.

Different theoretical approaches dealing with the bed evolution in tidal channels can be identified, with respect to the description of the final equilibrium conditions. Two recent contributions are the estuarine approach, by Schutteelaars and de Swart (1999, 2000), and the extended fluvial approach by Seminara and Tubino (2001) and Solari et al. (2002). The main difference between the two groups of theories is that the former considers the tidal basin to be of finite length, while the latter considers infinitely long tidal channels.

In the analysis of the Scheldt estuary, we have used the model of Seminara and Tubino (2001), which allows us to study the importance of several parameters on the morphological development of a single tidal channel (thus, considering the estuary as a single infinitely long channel). This model tackles the problem of free instability in straight channels leading to the formation of free bars. Some limitations of the model should be pointed out. The most important one is that it is based on a linear analysis and therefore bars are considered as small perturbations of the channel bed, whereas we use the results to get an insight in the development of intertidal areas, having a considerable height. Furthermore, the model deals with a single uniform channel and not with the complex system of channels and shoals of the macroscale
Estuaries sections. The tide is considered purely sinusoidal and with negligible oscillations of the free surface, which is in contrast with the situation of the Scheldt estuary. Nevertheless, always aware of these limitations, the analysis of the results of the model allows us to assess the role of the different parameters on the morphological response of the system.

SEMINARA and TUBINO (2001) found that the width-to-depth ratio, $\beta$, plays a crucial role for the development of bars (for us, intertidal areas) not only in rivers, but also in tidal systems. This theoretical result is confirmed by a different and independent analysis of field data from several estuaries (ALLERSMA, 1994), wherein an increase of the width-to-depth ratio results in a higher number of channels and bars. Considering alternate bars as a repetitive (harmonic) phenomenon, Seminara and Tubino defined their dimensionless wave number as

$$\lambda = \frac{2\pi B/L_0}{n},$$

where $L_0$ is the longitudinal wavelength of the bars and is plotted for a given set of dimensionless parameters (Shields parameter $\theta$, dimensionless grain size $d_0^*$, particle Reynolds number, $R_p$) the threshold line in the $\beta$-$\lambda$ plane for which alternate bars do not grow nor tend to disappear. In this way, it is possible to define two regions in the $\beta$-$\lambda$ plane (see also Figure 17): where the bed remains flat (bars are damped), below the threshold line, and where bars are supposed to form, above the threshold line. A critical value, $\beta_{cr}$, can be estimated from the figure as the lowest value of $\beta$ on the curve. In this way, when the width-to-depth ratio of the channel is known, along with the other parameters, we can predict the type of morphological configuration. However, the limitations of the model restrict the possibility of prediction. Especially when the conditions coincide with the development of multiple bars, the model does not allow determining which final configuration will be reached, in terms of number of bars and channels. This kind of result should only be interpreted as an indication of high probability that, at that location, the estuary presents (or will present) more than one intertidal area in the middle of the channel. The uncertainty is mainly due to the linear approach. Nonlinear interactions have been demonstrated to play a crucial role when the bars grow in size, with the result that they tend to merge, leading to an equilibrium characterized by fewer bars than those predicted by the linear model (ENGGRUB and TJERRY, 1999; MOSSelman, 1993).

The evolution of the system can be driven not only by free instability phenomena but also by the forcing effects of curvature or width variation, which can lead to the development of repetitive patterns of pools and bars. The Scheldt estuary can be seen as a large meandering channel, in which the variations of the curvature act as forcing factors and, as a result, inside the bends areas of deposition (forced bars) are clearly observable. SOLARI et al. (2002) studied the forced response in tidal channels, leading to the formation of forced bars. An improvement of the model has been given by SOLARI and TOFFOLON (2001) and TOFFOLON (2002b). The models to study the forced response are similar to those dealing with the free response, but in addition, they consider the infinitely long channel as nonuniform, presenting weak planimetric variations.

With the aim of assessing the inherent response of the Scheldt estuary, depending on hydrodynamics and sediment transport and not on the external forcing, the model of SEMINARA and TUBINO (2001) is here preferred. Applying this model to the Dutch and to the Belgian parts of the estuary, the threshold lines for alternate, central, and multiple bars are plotted in the $\beta$-$\lambda$ plane (see Figure 17). In the Dutch (seaward) part, $\beta$ ranges approximately between 250 and 500; in the Belgian part, $\beta$ decreases to 40–130, as can be noticed in Figure 6. The width-to-depth ratio, $\beta$, is here considered at mean water level, when the velocity is approximately the largest. As previously discussed, the evaluation of the frictional parameters is difficult and somehow arbitrary; hence, the adopted roughness factor, $C_s$, is assumed constant and based on the value of the Manning coefficient calibrated for numerical simulations. Characteristic values of peak velocities, reference depths at mean water level, and grain sizes are used (JEUKEN, 2000; VAN LEDDEN, 2003).

The main results can be qualitatively summarized as follows. The seaward (Dutch) part of the estuary is suitable for

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**Figure 17.** Regions of formation of free bars in straight tidal channels in the $\beta$-$\lambda$ plane for characteristic values of the parameters (a) in the Belgian part ($U \sim 0.85$ m/s, $D \sim 9$ m, $d_0 = 150$ $\mu$m; corresponding to $\theta \sim 0.65$, $R_p \sim 7.5$, $d_0^* \sim 1.7 \times 10^{-5}$) and (b) in the Dutch part ($U \sim 1$ m/s, $D \sim 12$ m, $d_0 = 170$ $\mu$m; corresponding to $\theta \sim 0.8$, $R_p \sim 9$, $d_0^* \sim 1.4 \times 10^{-5}$). A value of the roughness parameter, $C_s \sim 21$, has been imposed on the basis of calibration of numerical models. Only the odd modes are plotted.
the development of multiple bars (more than one bar in the middle of the channel), while the upper part (Belgian) results are suitable for alternate bars (with near-bank bars alternating from one side to the other). For the Belgian part (Figure 17a), one can observe that a single channel system with alternate bars is supposed to develop for the lower width-to-depth ratios, while for higher values, a central bar might form, even without emerging (one can be seen in the cross-section of Figure 10); the region of multiple bars is reached only for the highest values of β. For the Dutch part (Figure 17b), all values of β fall in the region of multiple bars; this condition determines the complex pattern in the seaward part of the estuary. Considering the limitations of the model, the results are in fair agreement with the observations. In practice, the results indicate also that, for the Scheldt estuary, only large variations of the width-to-depth ratio can change the morphological equilibrium (i.e., in the long-term from a multiple channel system to a single channel system).

The most relevant parameters for the morphological characterization can be identified by looking at their relative importance to obtain different solutions. The variation of the parameters θ, R_{p}, and d^v within their characteristic range in the estuary does not have a striking effect on the topographic pattern predicted by the model. A larger effect is related to the uncertainty of the evaluation of the roughness parameter C_{b}. However, the type of topographic pattern is predominantly affected by the width-to-depth ratio, β, which changes dramatically from the Dutch to the Belgian part of the estuary.

Analogous studies for the characterization of the river morphology (MIDDLEKOOP, 2001; SCHOOK et al., 1999) confirm that the main controlling parameter is the width-to-depth ratio, β, which is also related to the number of channels in the cross-section.

The role of tidal asymmetry on the macroscale morphological characterization is not clear. In the model of SEMINARA and TUBINO (2001), bar formation is similar for a sinusoidal tide and a unidirectional flow having the same peak velocity. This kind of behavior can be explained if we consider that the bed-forming conditions occur when the velocity is largest. On the other hand, the asymmetry of the tidal wave and the presence of overtopping might play a role on the migration of free bars. When the tide is symmetric, the net result is that these bars are steady, but if residual effects are present, bed forms can move on a time scale that is dependent on the order of magnitude of the net sediment transport and on the wavelength and size of the bed forms. Besides, tidal asymmetry is important for the morphological equilibrium of the whole estuary (megascale) because it determines the direction of the net sediment transport, but plays a minor role on the topographic patterns at the macroscale level.

Finally, we want to point out that, though the Scheldt estuary can be substantially described as a channel, the morphology of its seaward part can be strongly affected by the interactions with the outer sea. The mechanisms of formation of the multiple-channel system (estuarine sections 1 and 2) and its difference from the other sections of the Dutch part can be also related to the mechanisms acting in short tidal basins, like the Wadden Sea. These basins typically show a dendritic structure, with the presence of tree-like branching features, which cannot be described in the framework of dominantly one-dimensional models like those used in channels (HIBMA, 2004; MARCIONI, 2003; MARCIONI et al., 2004).

On the other hand, in the Scheldt estuary, these kinds of two-dimensional features are forced by the prevailing longitudinal variations to take the form of a network of ebb- and flood-dominated channels. Further developments in the modeling of this part of the estuary are advisable and will be crucial to give a reliable explanation of the second morphological threshold that we have recognized within the Dutch part of the estuary.

**DISCUSSION**

**Morphodynamic models**

At present, we do not have any theoretical model able to describe the overall behavior of tidal environments at the macroscale; an attempt toward this kind of conceptual schematization is highly desirable. Theoretical models are often linear and mostly refer to the case of a single channel; numerical models can be used to estimate the evolution of the system only for relatively short times because several uncertainties arise when considering long simulations.

Furthermore, it is not always easy to separate the problem into different and independent scales, in particular the macroscale from the upper (megascale) and lower (mesoscale) scales. Relevant feedback mechanisms occur between the mega- and the mesoscale evolution on a time scale that is probably similar to the scale of evolution typical of the macroscale morphological elements. For this reason, isolated macroscale features can be hardly detected.

The role of vegetation on the morphological evolution of tidal environments is not clear yet. This topic should be investigated with the combined effort of morphologists, biologists, and ecologists because the feedback mechanisms between the biotic and abiotic components may be relevant. Research to include the effects of vegetation in morphological models is in progress (CROSATO et al., 2002; ROEYINK et al., 2002).

Finally, the role of sediment composition is believed to be relevant, although its variation within the Scheldt estuary is not large enough to fully recognize its role and the lack of models dealing with cohesive sediments does not allow for reliable suggestions (however, a theoretical model has recently been developed by VAN LEDDEN, 2003).

**Attractor Points**

The points in the $r_{D} - r_{S}$ plane, one for each estuarine section, are found to form clusters in Figure 14. A similar clustering is also observable in the plane $\beta - r_{S}$ (Figure 15). Each cluster can be related to a well-defined morphological zone of the Scheldt estuary. It is then believed that the clusters refer to different equilibrium states, such as single channel with alternate bars or two-channel system, and that every equilibrium state can be ideally represented by a point, an attractor, around which the points cluster.

This would indicate that, for each (idealized) morphody-
The macroscale morphological quality of an estuary is here linked to the presence and characteristics of intertidal areas and channels. The number of intertidal areas, their position near the banks or in the middle of the channel, and their extension are among the most important features for the environmental management of estuaries. A set of parameters is derived for the morphological characterization of estuaries. They have been selected on the basis of their role in the morphological evolution, their range of variation within the estuary, and the feasibility of their measurement. The definitions of such parameters, in particular the geometrical ones, mainly refer to the macroscale averaged lengths, surfaces, and volumes.

The three morphologically different zones of the Scheldt estuary (multiple-channel, two-channel, and single-channel) appear to be identifiable by using the following parameters:

1. the width-to-depth ratio of the estuarine section, \( \beta \), defined in (5), evaluated at mean water level (or when the velocity is highest);
2. the ratio between the wetted planimetric surfaces at high and low water level during the tidal cycle, or wet surfaces ratio, \( r_{sw} \), defined in (11);
3. the ratio between the depths at high- and low-water level, \( r_D \), defined in (4); another possibility, with a different meaning, is to consider the ratio \( r_{sp} \), defined in (2), or equivalently, the tidal range-to-depth ratio, \( r_{rs} \), defined in (9);
4. the Shields parameter, \( \theta \), defined in (20);
5. the Chézy parameter, \( C_v \), defined through (21): it can be related to the dimensionless grain size \( d^*_v \), but has to be calibrated;
6. the particle Reynolds number, \( R_p \), defined in (19).

Alternative definitions of the geometrical ratios \( r_D, r_{rs}, r_{sv} \), and \( \beta \) are based on the identification of simplified cross-sections by means of the power law (8). This kind of procedure tends to slightly reduce the fluctuations of the values along the estuary, while the overall behavior does not change. The added value of this approach is that the different shapes of the interpolated cross-sections allow for a better description of the morphological subdivision of the estuary.

The width-to-depth ratio, \( \beta \), in combination with other parameters, namely the Shields parameter, \( \theta \), the dimensionless grain size, \( d^*_v \), and the particle Reynolds number, \( R_p \), has been shown to be the most important factor for the macroscale morphological characterization of estuaries because it determines number and type of bars and channels that form in an estuarine section (in equilibrium conditions). Shields parameter, dimensionless grain size, and particle Reynolds number are less strongly distinctive and their determination presents a number of uncertainties that are related to, for instance, the roughness represented by the Chézy parameter.

The model of Seminara and Tubino (2001) may be used to assess which equilibrium state, characterized by the presence of alternate or multiple bars, to which the system tends. The model should be properly calibrated.

Parameters 4, 5, and 6 allow determining the threshold lines in the \( \beta-\lambda \) plane designed by Seminara and Tubino. Each threshold line refers to a morphological typology (alternate bars, multiple bars, etc.), separating the conditions in which alternate or multiple bars tend to develop from the conditions in which those bars are damped down and do not form. The lowest value of the width-to-depth ratio on the line, or \( \beta_{sw} \), is the threshold between the two conditions. The actual width-to-depth ratio (parameter 1) of the estuarine section determines which are the morphological characteristics of the equilibrium to which the system is supposed to tend. The development of bars is here interpreted as the potential development of shoals and intertidal areas, and the results of the model are considered as mere indications.

Parameters 2 and 3, namely \( r_{sw} \), planimetric surfaces ratio, and \( r_D \), depth ratio, are found to be able to discriminate the morphological zones of the Scheldt estuary. The points in the \( r_{sw} - r_D \) plane, one for each estuarine section, are found to form clusters. Each cluster can be related to one of the three morphological zones of the Scheldt estuary. A similar clustering is also observable in the plane \( \beta - r_D \). The clustering of the \( (r_D, r_{sw}) \) and \( (\beta, r_{sw}) \) points indicates that morphodynamic equi-
libria do not form a continuum but manifest themselves as discrete steps. For each step, there is a straightforward relation between the extension of the intertidal areas and the other parameters.

It is believed that the clustering of such points is a general feature of estuaries and not just a peculiarity or coincidence of the Scheldt estuary, and that the points cluster around attractor points, each of them representing an ideal equilibrium state. However, these suppositions need to be proven by further research. The determination of the attractor points would then allow for prediction of the extension of the intertidal areas, once the values of width-to-depth ratio, tidal range-to-depth ratio, Shields parameter, Chezy parameter, and particle Reynolds number, and consequently the morphological equilibrium are known.

The set of parameters is believed to be universally representative, although this needs to be supported by further research, including data from other estuaries.

The results indicate that, for the Scheldt estuary, large width-to-depth changes are necessary to jump from one equilibrium state to the other. Deepening of the navigation channel seems not sufficient to induce such changes, while widening of the estuary (set-back of the dams) might be. The impact of regular dredging and dumping activities cannot be assessed within the approach adopted in this study. The presence of the attractor points, which implies that the system, when not subject to major changes, tends to restore the same type of equilibrium and the interrelation between a number of parameters, including the extension of the intertidal areas, justify the use of semiempirical models, such as that derived by Wang et al. (1998), when used to predict the effects of ordinary interventions in the estuary.

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LITERATURE CITEd


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