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Introduction

1.1 Objectives and scope

This book aims to provide students, researchers, practising engineers and managers access to state-of-the-art knowledge, practical formulae and new hypotheses covering dynamics, mixing, sediment regimes and morphological evolution in estuaries. Many of these new developments assume strong tidal action; hence, the emphasis is on meso- and macro-tidal estuaries (i.e. tidal amplitudes at the mouth greater than 1 m).

For students and researchers, this book provides deductive descriptions of theoretical derivations, starting from basic dynamics through to the latest research publications. For engineers and managers, specific developments are presented in the form of new formulae encapsulated within generalised Theoretical Frameworks.

Each chapter is presented in a 'stand-alone' style and ends with a concise 'Summary of Results and Guidelines for Application' outlining the issues involved, the approach, salient results and how these can be used in practical terms. The goal throughout is to explain governing processes in a generalised form and synthesise results into guideline Frameworks. These provide perspectives to interpret and intercompare the history and conditions in any specific estuary against comparable experience elsewhere. Thus, a background can be established for developing monitoring strategies and commissioning of modelling studies to address immediate issues alongside longer-term concerns about impacts of global climate change.

1.1.1 Processes

Estuaries are where 'fresh' river water and saline sea water mix. They act as both sinks and sources for pollutants depending on (i) the geographical sources of the contaminants (marine, fluvial, internal and atmospheric), (ii) their biological and chemical nature and (iii) with temporal variations in tidal amplitude, river flow, seasons, winds and waves.

Tides, surges and waves are generally the major sources of energy input into estuaries. Pronounced seasonal cycles often occur in temperature, light, waves, river flows, stratification, nutrients, oxygen and plankton. These seasonal cycles alongside extreme episodic events may be extremely significant for estuarine ecology. As an example, adjustments in axial intrusion of sea water and variation in vertical stratification associated with salinity and temperature may lead to rapid colonisation or, conversely, extinction of sensitive species. Likewise, changes to the almost imperceptible larger-scale background circulations may affect the pathways and hence lead to accumulation of persistent tracers. Dyer (1997) provides further descriptions of these processes alongside useful definitions of much of the terminology used in this book.

Vertical and horizontal shear in tidal currents generate fine-scale turbulence, which determines the overall rate of mixing. However, interacting three-dimensional (3D) variations in the amplitude and phase of tidal cycles of currents and contaminants severely complicate the spatial and temporal patterns of tracer distributions and thereby the associated mixing. On neap tides, near-bed saline intrusion may enhance stability, while on springs, enhanced near-surface advection of sea water can lead to overturning. Temperature gradients may also be important; solar heating stabilises the vertical density profile, while winds promote surface cooling which can produce overturning. In highly turbid conditions, density differences associated with suspended sediment concentrations can also be important in suppressing turbulent mixing.

The spectrum of tidal energy input is effectively constrained within a few tidal constituents, and, in mid-latitudes, the lunar M_2 constituent is generally greater than the sum of all others – providing a convenient basis for linearisation of the equations for tidal propagation. However, ‘mixing’ involves a wider spectrum of interacting non-linear processes and is thus more difficult to simulate. The ‘decay time’ for tidal, surge, wave and associated turbulent energy in estuaries is usually measured in hours. By contrast, the flushing time for river inputs generally extends over days. Hence, simulation of the former is relatively independent of initial conditions, while simulation of the latter is complicated by ‘historical’ chronology resulting in accumulation of errors.

1.1.2 Historical developments

Following the end of the last ice age, retreating ice cover, tectonic rebound and the related rise in mean sea level (msl) resulted in receding coastlines and consequent major changes in both the morphology and the dynamics of estuaries. Large post-glacial melt-water flows gouged deep channels with the rate of subsequent in-filling dependent on localised availability of sediments. Deforestation and subsequent changes in farming practices substantially changed the patterns of river flows and both the quantity and the nature of fluvial sediments. Thus, present-day estuarine morphologies reflect adjustments to these longer-term, larger-scale effects alongside more recent, localised impacts from urban development and engineering 'interventions'.

Ports and cities have developed on almost all major estuaries, exploiting opportunities for both inland and coastal navigation, alongside supplies of freshwater and fisheries. In more recent times, the scale of inland navigation has generally declined and the historic benefit of an estuary counterbalanced by growing threats of flooding. Since estuaries often supported major industrial development, the legacy of contaminants can threaten ecological diversity and recreational use. The spread of national and international legislation relating to water quality can severely restrict development, not least because linking discharges with resulting concentrations is invariably complicated by uncertain contributions from wider-area sources and historical residues. This combination of legal constraints and uncertainties about impacts from future climate changes threatens planning-blight for estuarine development. This highlights the need for clearer understanding of the relative sensitivity of estuaries to provide realistic perspectives on their vulnerability to change.

1.2 Challenges

Over the next century, rising sea levels at cities bordering estuaries may require major investment in flood protection or even relocation of strategic facilities. The immediate questions concern the changing magnitudes of tides, surges and waves. However, the underlying longer-term (decadal) issue is how estuarine bathymetries will adjust to consequent impacts on these dynamics (Fig. 1.1; Prandle, 2004). In addition to the pressing flood risk, there is growing concern about sustainable exploitation of estuaries. A common issue is how economic and natural environment interests can be reconciled in the face of increasingly larger-scale developments.

1.2.1 Evolving science and technology agendas

Before computers became available, hydraulic scale models were widely used to simulate dynamics and mixing in estuaries. The scaling principles were based on maintaining the ratios of the leading terms in the equation describing tidal propagation. Ensuing model 'validation' was generally limited to reproduction of tidal heights along the estuary. Subsequent expansion in observational capabilities indicated how difficulties arose when such models were used to study saline intrusion, sediment regimes and morphological adjustments.

Even today, validation of sophisticated 3D numerical models may be restricted to simulation of an M_2 cycle – providing little guarantee of accurate reproduction of higher harmonics or residual features. Likewise, these fine-resolution 3D models

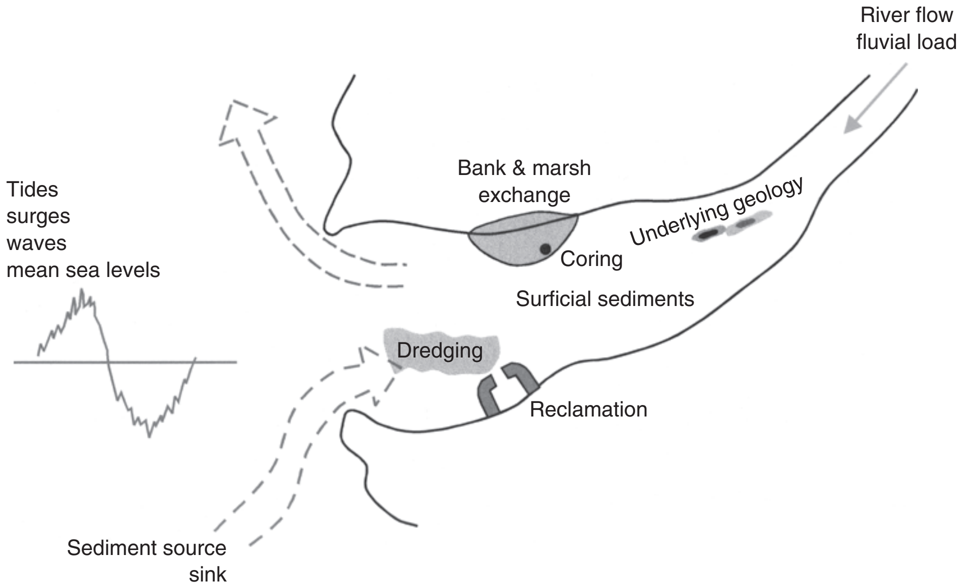

Fig. 1.1. Schematic of major factors influencing estuarine bathymetry.

may encounter difficulties in reproducing the complexity and diversity of mixing and sedimentary processes. Moreover, the paucity of observational data invariably limits interpretation of sensitivity tests. However, modelling is relatively cheap and continues to advance rapidly, whilst observations are expensive and technology developments often take decades. Thus, a major challenge in any estuary study is how to use theory to bridge the gaps between modelling and available observations. Both historical and 'proxy' data must be exploited, e.g. wave data constructed from wind records, flood statistics from adjacent locations, sedimentary records of flora and fauna as indicators of saline intrusion and anomalous fossilised bed features as evidence of extreme events.

The evolving foci for estuarine research are summarised in Fig. 1.2. These have evolved alongside successive advances in theory, modelling and observational technologies to address changing political agendas.

1.2.2 Key questions

Successive chapters address the following sequence of key questions:

(Q1) How can strategies for sustainable exploitation of estuaries be developed?

(Q2) How do tides in estuaries respond to shape, length, friction and river flow? Why are some tidal constituents amplified yet others reduced and why does this vary from one estuary to another?

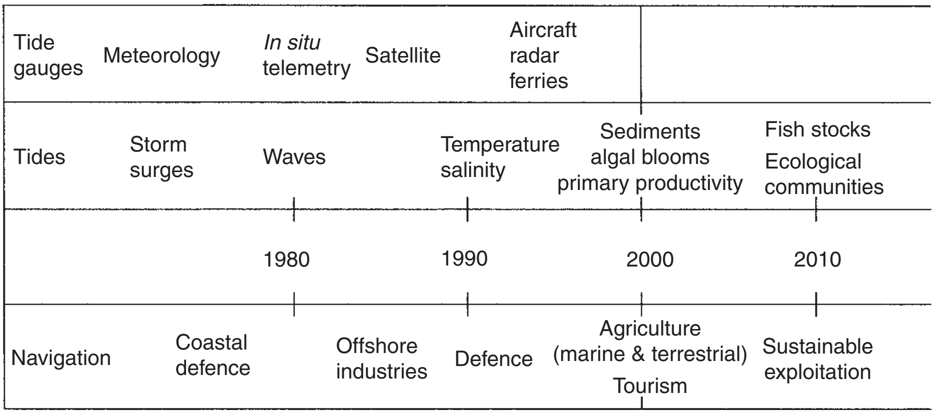

Fig. 1.2. Historical development in key processes, 'end-users' and observational technologies.

(Q3) How do tidal currents vary with depth, friction, latitude and tidal period?
(Q4) How does salt water intrude and mix and how does this change over the cycles of Spring–Neap tides and flood-to-drought river flows?
(Q5) How are the spectra of suspended sediments determined by estuarine dynamics?
(Q6) What determines estuarine shape, length and depth?
(Q7) What causes trapping, sorting and high concentrations of suspended sediments? How does the balance of ebb and flood sediment fluxes adjust to maintain bathymetric stability?
(Q8) How will estuaries adapt to Global Climate Change?

1.3 Contents

1.3.1 Sequence

The chapters follow a deductive sequence describing (2) Tidal Dynamics, (3) Currents, (4) Saline Intrusion, (5) Sediment Regimes, (6) Synchronous Estuary: Dynamics, Saline Intrusion and Bathymetry, (7) Synchronous Estuary: Sediment Trapping and Sorting – Stable Morphology and (8) Strategies for Sustainability. Analytical solutions for the first-order dynamics of estuaries are derived in Chapter 2 and provide the basic framework of our understanding. Details of associated currents are described in Chapter 3. Tidal currents and elevations in estuaries are largely independent of biological, chemical and sedimentary processes – except for their influences on the bed friction coefficient. Conversely, these latter processes are generally highly dependent on tidal motions. Thus, in Chapters 4 and 5, we consider how estuarine mixing and sedimentation are influenced by tidal action. Chapters 6 and 7 apply these theories to synchronous estuaries, yielding explicit algorithms for tidal currents, estuarine lengths and depths, sediment sorting and trapping and a bathymetric framework based on tidal amplitude and river flow.

1.3.2 Tidal dynamics

Chapter 2 examines the propagation of tides, generated in ocean basins, into estuaries, explaining how and why tidal elevations and currents vary within estuaries (Fig. 1.3; Prandle, 2004). The mechanisms by which semi-diurnal and diurnal constituents of ocean tides produce additional higher-harmonic and residual components within estuaries are illustrated. Since the expedient of linearising the relevant equations in terms of a predominant (M_2) constituent is extensively used throughout this book, the details of this process are described. Many earlier texts and much of the literature focus on large, deep estuaries with relatively low friction effects. Here, it is indicated how to differentiate between such deep estuaries and shallower frictionally dominated systems and the vast differences in their response characteristics are illustrated.

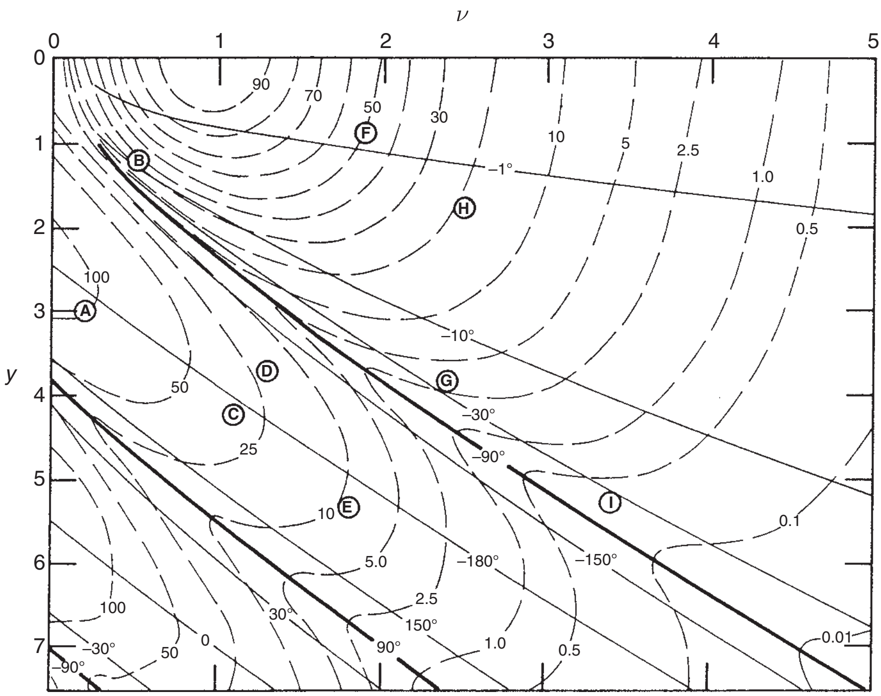

Fig. 1.3. Tidal elevation responses for funnel-shaped estuaries. ν represents degree of bathymetric funnelling and y distance from the mouth, $y = 0$. Dashed contours indicate relative amplitudes and continuous contours relative phases. Lengths, y (for M_2), and shapes, ν, for estuaries (A)–(I) shown in Table 2.1.

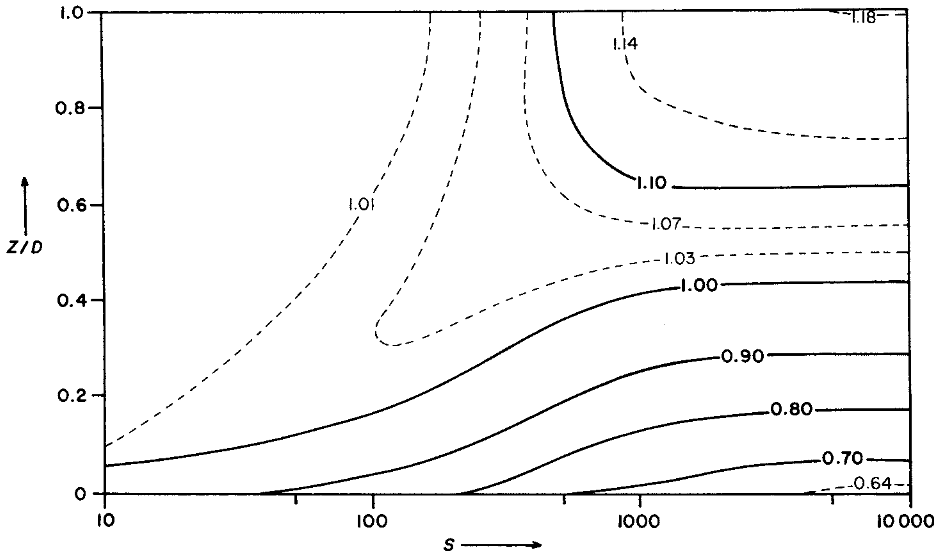

Fig. 1.4. Vertical profiles of tidal current, $U^*(z)/U^*_{mean}$, versus the Strouhal number, S_R, U^* tidal current amplitude, P tidal period, D depth, $S_R = U^*P/D$.

1.3.3 Currents

Chapter 3 examines how tidal currents vary along (axially) and across estuaries and from surface to bed. Changes in current speed, direction and phase (timing of peak or slack values) are explained by decomposition of the tidal current ellipse into clockwise and anti-clockwise rotating components. While the main focus is on explaining the nature and range of tidal currents, the characteristics of wind- and density-driven currents are also described. A particular emphasis is on deriving the scaling factors which encapsulate the influence of the ambient environmental parameters, namely depth, friction factor and Coriolis coefficient, i.e. latitude (Fig. 1.4; Prandle, 1982).

1.3.4 Saline intrusion

Noting the earlier definition of estuaries as regions where salt and fresh water mix, Chapter 4 examines the details of this mixing. It is shown how existing theories derived for saline intrusion in channels of constant cross section can be adapted for mixing in funnel-shaped estuaries. Saline intrusion undergoes simultaneous adjustments in axial location and mixing length – explaining traditional problems in understanding observed variations over spring–neap and flood-drought conditions (Fig. 1.5; Liu *et al.*, 2008).

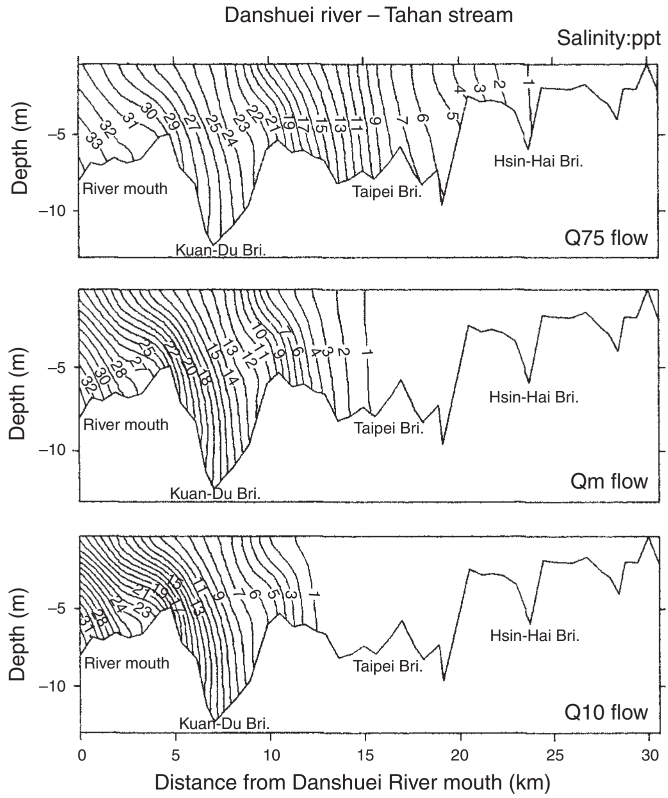

Fig. 1.5. Axial variations in salinity, ‰, in the Danshuei River, Taiwan Q75, flow rate exceeded 75% of time, Q10 flow exceeded 10% of time.

The predominance of mixing by vertical stirring driven by tidally induced turbulence has long been recognised. Here, the importance of incorporating the effects of tidal straining and resultant convective overturning is described.

The ratio of currents, U_0/U^*, associated with river flow and tides, is shown to be the most direct determinant of stratification in estuaries.

1.3.5 Sediment regimes

Chapter 5 focuses on the character of sediment regimes in strongly tidal estuaries, adopting a radically different approach to traditional studies of sediment regimes.

Analytical solutions are derived encapsulating and integrating the processes of erosion, suspension and deposition to provide descriptions of the magnitude, time series and vertical structure of sediment concentrations. These descriptions enable the complete range of sediment regimes to be characterised in terms of varying sediment type, tidal current speed and water depth (Fig. 1.6; Prandle, 2004). Theories are

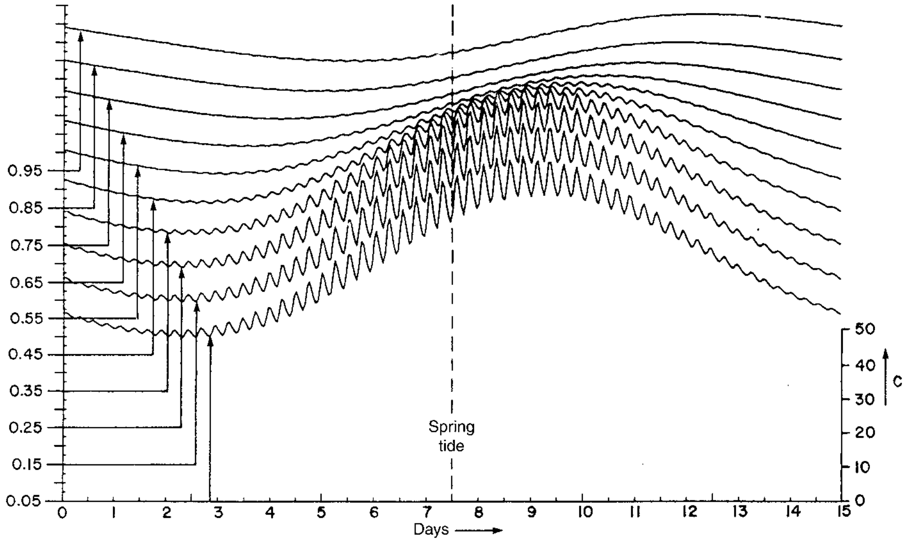

Fig. 1.6. Spring–neap patterns of sediment concentrations at fractional heights above the bed.

developed by which tidal analyses of suspended sediment time series, obtained from either model simulations or observations, can be used to explain the underlying characteristics.

1.3.6 Synchronous estuary: dynamics, saline intrusion and bathymetry

A 'synchronous estuary' is where the sea surface slope due to the axial gradient in phase of tidal elevation significantly exceeds the gradient from changes in tidal amplitude. The adoption of this assumption in Chapters 6 and 7 enables the theoretical developments described in earlier chapters to be integrated into an analytical emulator, incorporating tidal dynamics, saline intrusion and sediment mechanics. Chapter 6 re-examines the tidal response characteristics for any specific location within an estuary. The 'synchronous' assumption yields explicit expressions for both the amplitude and phase of tidal currents and the slope of the sea bed. Integration of the latter expression provides an estimate of the shape and length of an estuary. By combining these results with existing expressions for the length of saline intrusion and further assuming that mixing occurs close to the seaward limit, an expression linking depth at the mouth with river flow is derived. Hence, a framework for estuarine bathymetry is formulated showing how size and shape are determined by the 'boundary conditions' of tidal amplitude and river flow (Fig. 1.7; Prandle *et al.*, 2005).

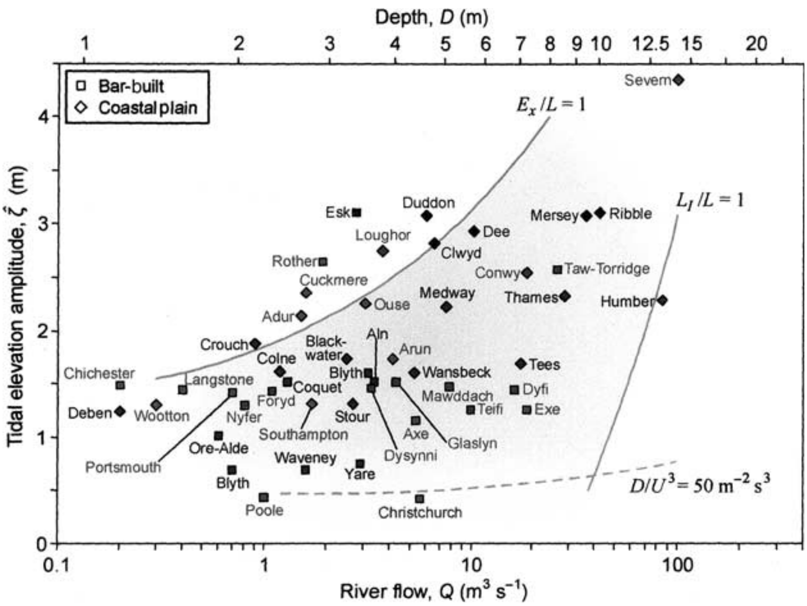

Fig. 1.7. Zone of estuarine bathymetry. Coordinates (Q, ς) for Coastal Plain and Bar-Built estuaries, Q river Flow and ς elevation amplitude. Bathymetric zone bounded by $E_x < L$, $L_I < L$ and $D/U^3 < 50\ m^2\ s^{-3}$.

1.3.7 Synchronous estuary: sediment trapping and sorting – stable morphology

Chapter 7 indicates how, in 'synchronous' estuaries, bathymetric stability is maintained via a combination of tidal dynamics and 'delayed' settlement of sediments in suspension. An analytical emulator integrates explicit formulations for tidal and residual current structures together with sediment erosion, suspension and deposition. The emulator provides estimates of suspended concentrations and net sediment fluxes and indicates the nature of their functional dependencies. Scaling analyses reveal the relative impacts of terms related to tidal non-linearities, gravitational circulation and 'delayed' settling.

The emulator is used to derive conditions necessary to maintain zero net flux of sediments, i.e. bathymetric stability. Thus, it is shown how finer sediments are imported and coarser ones are exported, with more imports on spring tides than on neaps, i.e. selective trapping and sorting and consequent formation of a turbidity maximum. The conditions derived for maintaining stable bathymetry extend earlier concepts of flood- and ebb-dominated regimes. Interestingly, these derived conditions correspond with maximum sediment suspensions. Moreover, the associated sediment-fall velocities are in close agreement with settling rates observed in many estuaries. Figure 1.8 (Lane and Prandle, 2006) encapsulates these results, illustrating the dependency on