ESTUARINE AND COASTAL SEDIMENTATION PROBLEMS[1]

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Abstract: This Keynote Lecture addresses engineering sedimentation problems in estuarine and coastal environments and practical solutions of these problems based on the results of field measurements, laboratory scale models and numerical models.
The three most basic design rules are: (1) try to understand the physical system based on available field data; perform new field measurements if the existing field data set is not sufficient (do not reduce on the budget for field measurements); (2) try to estimate the morphological effects of engineering works based on simple methods (rules of thumb, simplified models, analogy models, i.e. comparison with similar cases elsewhere); and (3) use detailed models for fine-tuning and determination of uncertainties (sensitivity study trying to find the most influencial parameters).
Engineering works should be designed in a such way that side effects (sand trapping, sand starvation, downdrift erosion) are minimum. Furthermore, engineering works should be designed and constructed or built in harmony rather than in conflict with nature. This 'building with nature' approach requires a profound understanding of the sediment transport processes in morphological systems.
Keywords: Sedimentation, sediment transport, morphological modelling

1. INTRODUCTION

This lecture addresses sedimentation and erosion engineering problems in estuaries and coastal seas and practical solutions of these problems based on the results of field measurements, laboratory scale models and numerical models.
Often, the sedimentation problem is a critical element in the economic feasibility of a project, particularly when each year relatively large quantities of sediment material have to be dredged and disposed at far-field locations.
Although engineering projects are aimed at solving problems, it has long been known that these projects can also contribute to creating problems at other nearby locations (side effects). Erosion often occurs in places where sediment cannot be supplied by nature in sufficient quantities because it is trapped in another part of the system. The trapping can be due to natural causes or due to man-made changes in the system. Dredging of ship channels, construction of jetties, groynes and seawalls always results in the redistribution of sand within the local system. Engineering works should be designed in a such way that side effects (sand trapping, sand starvation, downdrift erosion) are minimum. Dramatic examples of side effects are presented by Douglas et al. (2003), who state that about 1 billion m^3 (10^9 m^3) of sand are removed from the beaches of America by engineering works during the past century. Nourishment and bypassing of sand are often required to mitigate the inavoidable side-effects of engineering works. It is important to emphasize that engineering works should be designed and constructed or built in harmony rather than in conflict with nature. This 'building with nature' approach requires a profound understanding of the sediment transport processes in morphological systems (Van Rijn, 2005).

2. SEDIMENTATION PROBLEMS

Human interference in hydraulic systems often is necessary to maintain and extend economic activities related ports and associated navigation channels. In many situations engineering structures are required to stabilize the shoreline, shoals and inlets, to reduce sedimentation, to prevent or reduce erosion, or to increase the channel depth to allow larger vessels entering the harbour basin. Coastal protection against floods and navigability are the most basic problems in many estuaries in the world.

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Examples of engineering works in estuaries and coastal systems are shown in Figure 1.

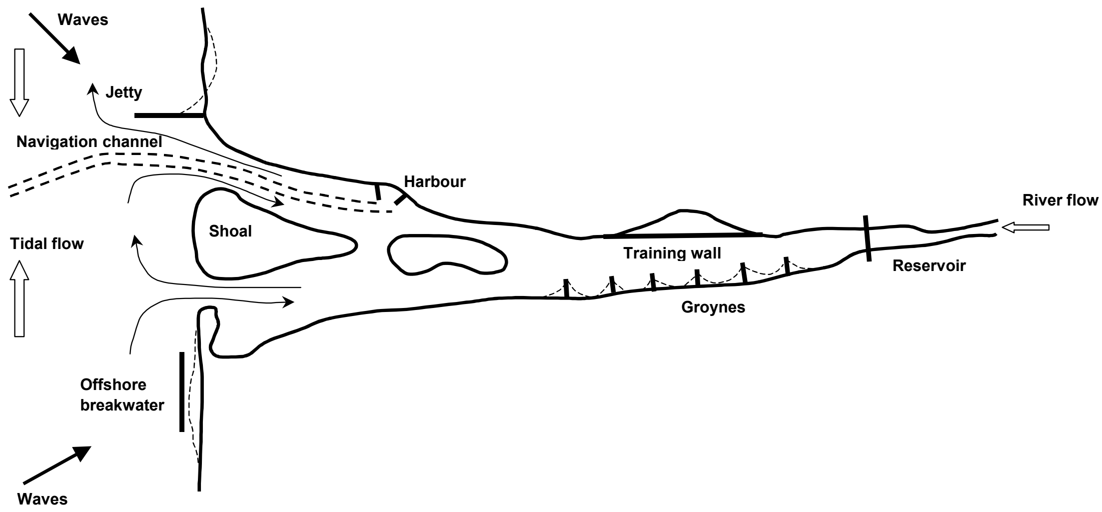

Figure 1 *Examples of man-made structures in river, eastuary and coastal systems*

Sedimentation problems generally occur at locations where the sediment transporting capacity of the hydraulic system is reduced due to the decrease of the steady (currents) and oscillatory (waves) flow velocities and related turbulent motions. Examples are: the expansion of the flow depth and width due to natural variations or artificial measures (dredging), the presence of vortex or eddy zones, flow separation zones, dead water zones and lee zones of structures. Expansions of the navigational depth will reduce velocities inducing shoaling. Similarly, the expansion of the width of turning and mooring basins inside a harbour area will reduce velocities stimulating shoaling conditions. Piers or piling structures create eddies resulting in increased shoaling.

Sedimentation problems are most often associated with human interference in the physical system such as the construction of artificial structures or the dredging of sediment from the bed to increase the flow depth or width. However, sedimentation (as well as erosion) also is a basic phenomenon of nature dealing with loose sediments within the transporting cycle from source to sink locations. Natural sedimentation areas are known as shoals, flats, banks, sheets, bars, etc. Human interference in these natural sedimentation areas will always lead to relatively large maintenance cost and should therefore be avoided as much as possible.

Sedimentation problems in estuaries and coastal seas are herein classified, as follows:

Channel sedimentation	**Basin sedimentation**	**Shoreline sedimentation**
1) Navigation channels; 2) Inlet channels; 3) Entrance channels of harbours, docks and water intakes; 4) Trenches for tunnels, pipelines and cables;	1) Harbour and port basins, Docks 2) Open settling basins, turning and mooring basins, mining pits 3) Water intake basins; 4) Flood plains and reservoirs.	1) Updrift area of groynes and breakwaters normal to shore; 2) lee-side area of offshore breakwaters parallel to shore.

2.1 Navigation channels

Ports are of vital importance for the economy of coastal countries. The increasing draft of vessels requires the dredging of deep-draft channels connecting the port to deep water. Generally, these channels suffer from sedimentation requiring mainenance dredging to ensure safe passage of the ships under most conditions. The costs related to capital and maintenance dredging often are critical in the economic functioning of ports. Therefore, the channel should be designed in such a way that sedimentation is minimum.

When the flow passes a channel, the velocities decrease due to the increase of the water depths in the channel and hence the transport capacity of bed load and suspended load decreases. As a result the bed-load particles and a certain amount of the suspended sediment particles will be deposited in the channel (see Figure 2).

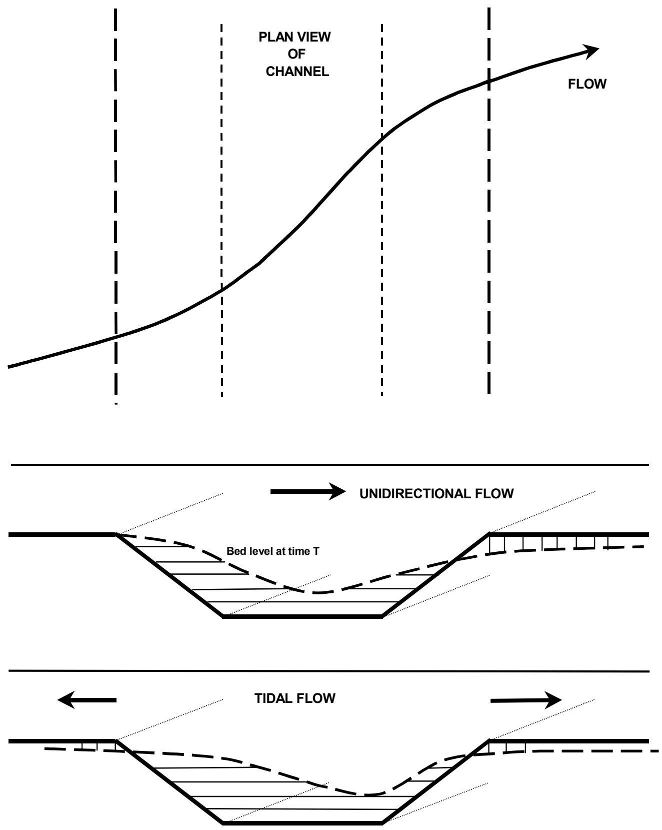

Figure 2 *Channel sedimentation (plan view and cross-sections)*

When waves are present, this process is considerably enhanced due to the sediment stirring action of the wave motions in the near-bed region resulting in larger sediment concentrations, which are subsequently transported by the flow.

Factors enhancing sedimentation, are:

- deep and wide channel;
- orientation almost normal to the flow;
- strong flows and large waves passing the channel;
- fine sediment (fine sand and mud);
- alignment through shoaling areas.

Natural navigation channels in estuaries often suffer from the generation of bars/shoals at the transition of flood-domiated and ebb-dominated channels.

2.2 Inlet channels

Natural tidal inlet channels generally suffer from heavy sedimentation due to wave-induced longshore input of sediments thereby reducing the navigability of the channel. Jetties (long dam-like structures) are commonly build to eliminate the input of sediment by the longshore current, creating an inlet channel (see Figure 3). The jetties should be so long that the sedimentation at the entrance of the channel due to longshore bypassing of sediments is minimum. Sediment accumulation will generally take place on the updrift side of the jetties and erosion on the downdrift side. Mechanical bypassing of sediment may be required to reduce downdrift erosion.

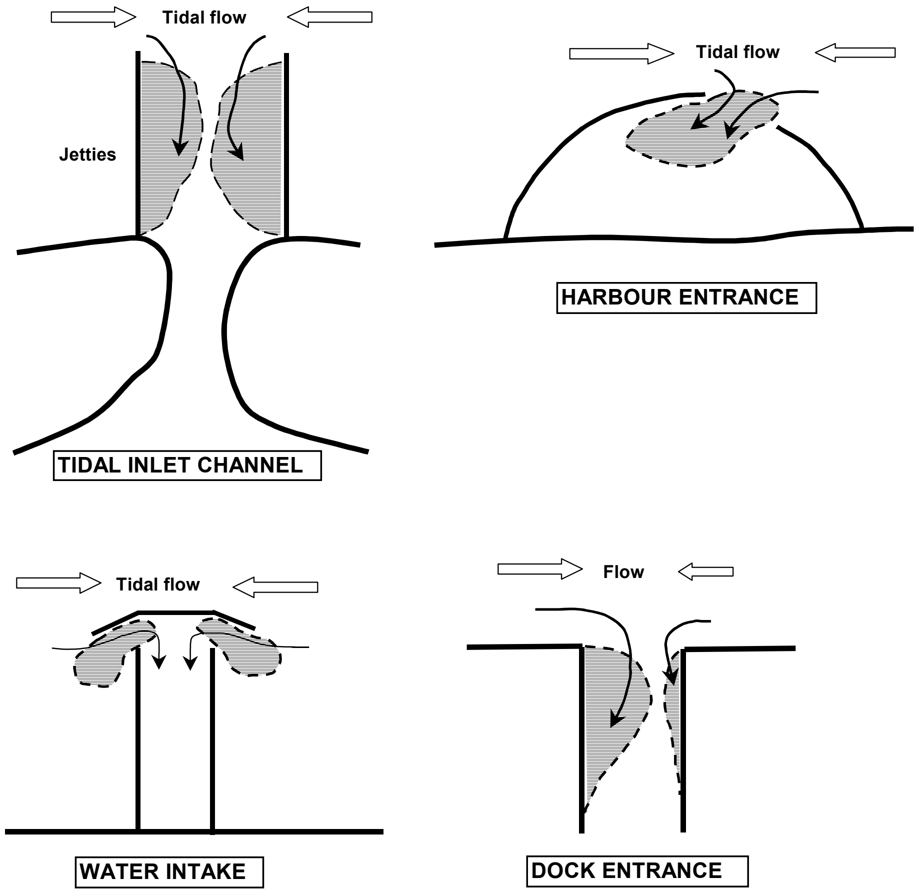

Figure 3 *Sedimentation of inlets, entrances and intakes (plan view)*

Jetty design requires the following considerations to reduce sedimentation:

- the length of the jetties should extend beyond the littoral transport zone;
- the jetty spacing should be narrow, but not leading to excessively large channel velocities undermining the jetties (wide jetties may lead to shoaling and meandering of the channel);
- the jetties should be impermeable to prevent lateral passage of water and littoral sediments;
- the jetties should be parallel, rather than curved or tapered (narrow entrance, channel widening); parallel jetties tend to confine the ebb flow, raising ebb velocities and therby flushing sediment out of the channel into the sea;
- three jetties creating two parallel channels, may be build to separate the inlet channel from the river outflow;
- a settling basin/trap may be dredged at the entrance of the channel as a bufffer for sedimentation to ensure navigability of the channel.

2.3 Entrance channels of harbours, docks and water intakes

The entrance to a harbour basin, dock or water intake basin generally suffers from sedimentation due to the reduction of flow velocities and wave activity (see Figure 3). Often, a circulation cell is generated in the entrance of the basin due to the geometry involved, which attracts sediments by exchange processes with the main flow system outside the entrance. The breakwaters should be streamlined or training walls may be built to reduce eddies and dead-water areas. Harbour entrances should never be built on the inside of bends, where natural shoaling processes (point bars) generally occur.

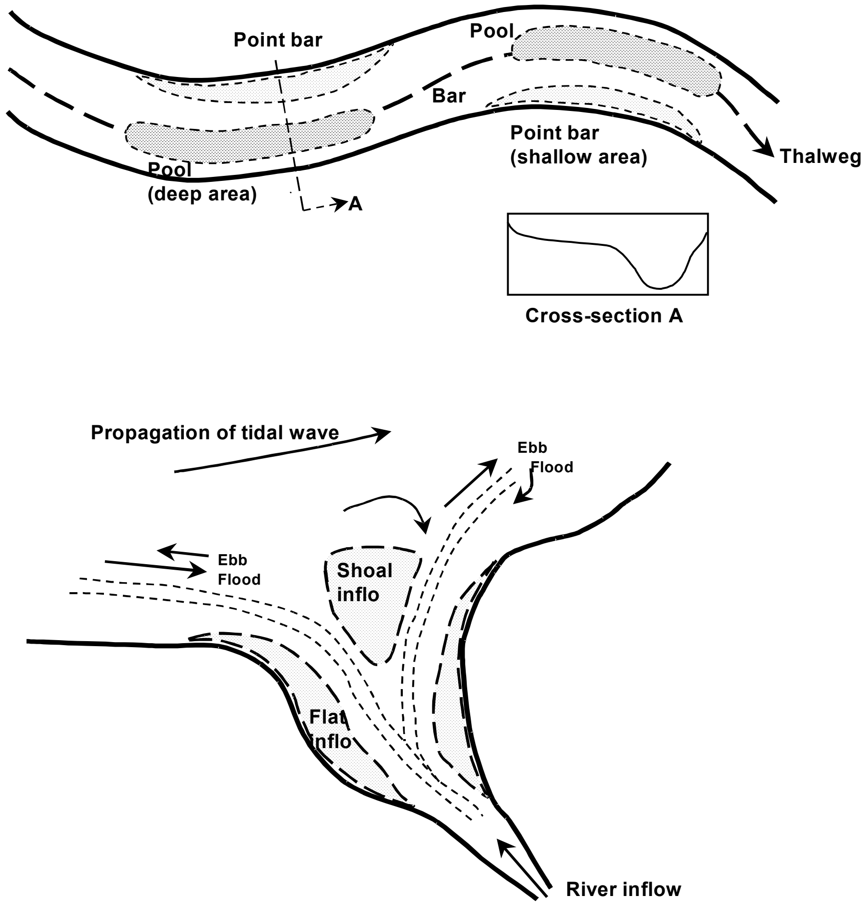

Figure 4 *Deposition patterns*

Top: River flow; deposition (point bars) near inner bend; erosion (pools) near outer bend

Bottom: Tidal flow; deposition (flats) near inner channel bends and between channels (shoal)

Entrance design requires the following considerations to reduce sedimentation:

- the entrance should not be located in shallow depth on the inside of a bend or close to other natural shoaling areas (see Figure 4);
- the entrance should be narrow and streamlined to reduce the generation of eddies, and circulation zones;
- the breakwaters should be impermeable to prevent lateral passage of water and sediments;
- a settling basin/trap may be dredged at the entrance of the channel as a buffer for sedimentation.

2.4 Trenches for tunnels, pipelines and cables

Small scale trenches for pipelines and cables (Figure 5) are characterised by relatively small dimensions; width of about 2 to 10 m and depth of 1 to 2 m, while the side slopes may be rather steep (1 to 3), depending on soil conditions. These trenches generally have a triangular shape due to the construction method (plowing). The depth of such a trench often only is a fraction of the water depth resulting in flow separation and the generation of vortex cells inside the major part of the trench area. In mobile bed conditions (surf zone near beach) the trench should have a considerable overwidth to serve as a buffer for sediment trapped in the period between trenching and pipe/cable laying.
Tunnel trenches have dimensions similar to those of navigation channels and show the same sedimentation patterns.

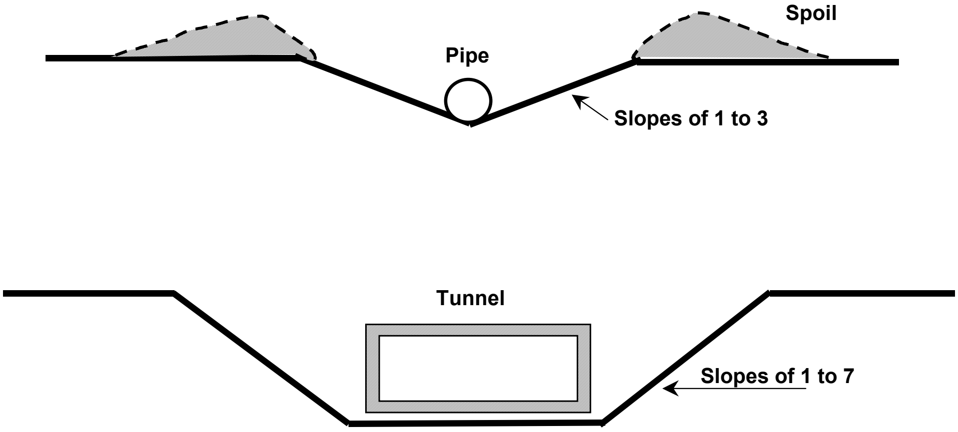

Figure 5 *Trenches for pipelines, cables and tunnels*

2.5 Harbours and ports

Sedimentation in harbours and ports is a problem that exists as long as harbours and ports exist and is related to their basic function, providing shelter by creating quiescent conditions. In general, a harbour is a place that provides shelter and mooring for ships, whereas a port is a place where cargoes are loaded and unloaded from ships. Both types of places require quiescent conditions protected from wave penetration and strong currents.
The design and construction of harbour basins is one of the oldest branches of engineering. One of the oldest known artificial harbours was PHAROS, located on the open coast of Egypt at about 2000 B.C. It had two parallel breakwaters, each about 2.5 km long which consisted of rubble-mound structures of very large blocks of rock and this harbour undoubtly suffered from sedimentation.

There are various types of **natural** harbours:

- well protected bays;
- lee areas of islands or headlands;
- lee areas of reefs;
- lee areas in river mouths.

Artificial harbours can, in principle, be made at any place along the water front, but should preferably be located in areas where the sedimentation is observed or estimated to be minimum.

Artificial harbour basins can be classified into:

- ***open basins***; basins or berthing places which are open to flow and/ or waves; these basins can be situated in nearshore coastal areas and along river banks, see Figure 6; the basin generally is substantially deeper than the surrounding area so that an acces channel is required for vessels to enter the basin; mooring is only possible in conditions with weak cross-currents and mild wave motions;
- ***sheltered basins (enclosed)***; these types of enclosed basins are typified by a single entrance to reduce the flow and wave motion as much as possible; three subclasses can be identified:
  - <u>*coastal basin*</u> with a controlled entrance, generally consisting of twin-armed breakwaters or jetties (Figure 6); the breakwaters may block the longshore sediment transport requiring sediment bypassing methods; eddies and turbulence may produced in the entrance; a semi-enclosed basin is obtained when only one breakwater or jetty is present on the updrift side;
  - <u>*coastal dredged lagoon*</u> with an uncontrolled entrance (Figure 6), which may migrate along the shore or may suffer from severe sedimentation due to wave-induced processes or may even be closed by wave-induced sedimentation during storms; the entrance may suffer from migrating channels and bars; relatively strong currents may be present due to tidal filling of the basin; entrance may also be controlled by jetties
  - <u>*interior basin*</u> (docks) along esturial or river channels (Figure 6) and/or lakes; eddies are generally present in the entrance area, where sedimentation of silty and muddy materials usually is maximum.

The most important and difficult part of a sheltered harbour basin is the entrance. Many harbour entrances have been found to be difficult for ships to navigate owing to currents, waves and morphology (sedimentation).

In previous centuries many harbours suffered from heavy sedimentation threatening the economic functioning of the harbour. Some harbours deteriorated completely due to heavy sedimentation in the entrance area of the basin. For example, the harbour of Amsterdam (The Netherlands) located in the southwestern part of an inner sea (former South Sea) was one of the most powerful harbours in the world in the 16^{th} and 17^{th} centuries, but lost its dominating position due to problematic sedimentation processes which could not be solved at that time. Owing to better dredges, it is now possible to keep almost each harbour entrance at the required navigation level, although this may be a financial burden on the economic performance of a harbour suffering from heavy sedimentation.
From observed sedimentation rates it can be concluded that harbour sedimentation in fresh water conditions is much less (factor 5) than in salt and brackish water conditions. The generation of stratified flow with a clear salt water wedge is a well known phenomenon in the tidal zone of major rivers (tidal volume about equal to fresh water volume over tidal period). The maximum silt and mud concentrations are generally found in the area where the edge of the salt water front is moving up and down the river channel. This zone where soft fluid mud layers are formed due to deposition at slack tides (especially neap tides) is known as the turbidity maximum. Harbour basins should preferably be situated outside this zone to avoid that the deposited fluid mud layers penetrate into nearby harbour basins.

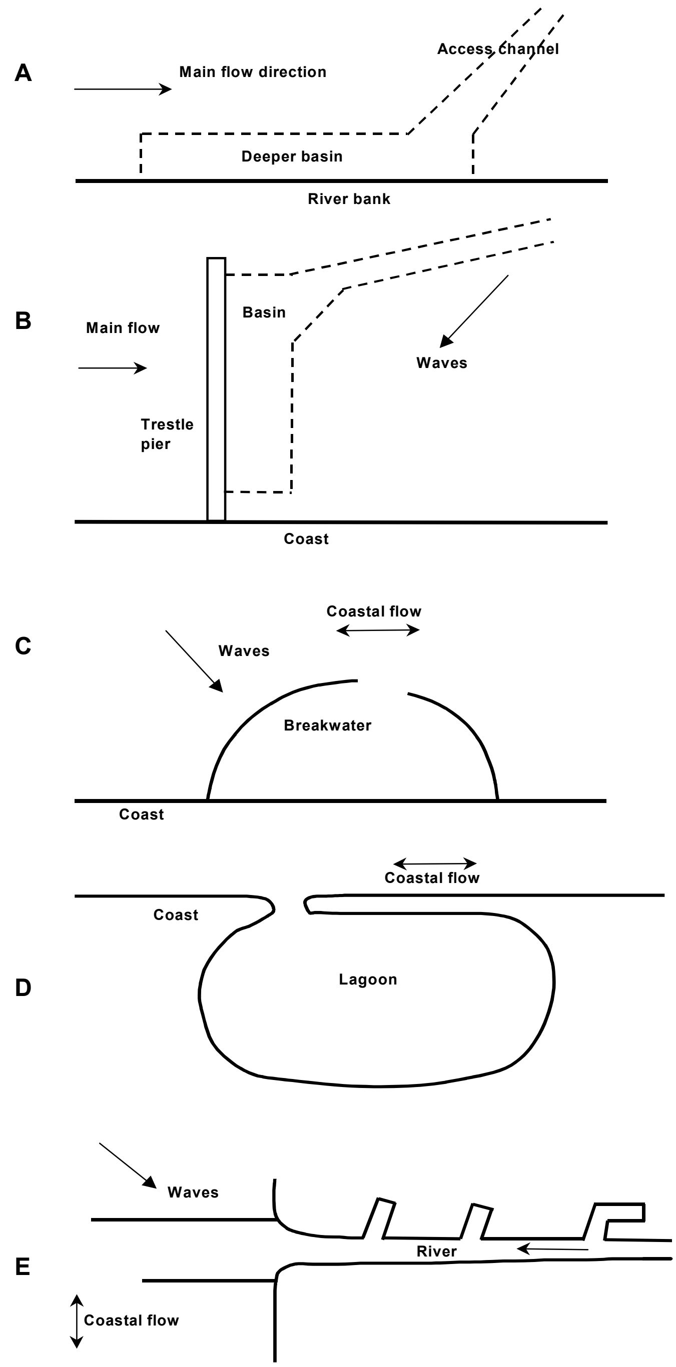

Figure 6 *Types of harbour basins*
Open basins: (A= basin along river bank; B= basin along trestle pier perpendicular to coast)
Sheltered basins: (C= basin protected by breakwaters, D= coastal lagoon; E= interior basin along river)

2.6 Turning, mooring and settling basins

Expansions of width and depth are often required outside and inside harbours or docks for navigational reasons. The flow in these basins is reduced considerably in proportion to the expansion dimensions resulting in rapid siltation of fine material. This principle can also be used for the design of a settling basin in areas of rapid shoaling to create a buffer (overdepth) for sediment from which dredging activities can be performed to remove the sediment from the system.

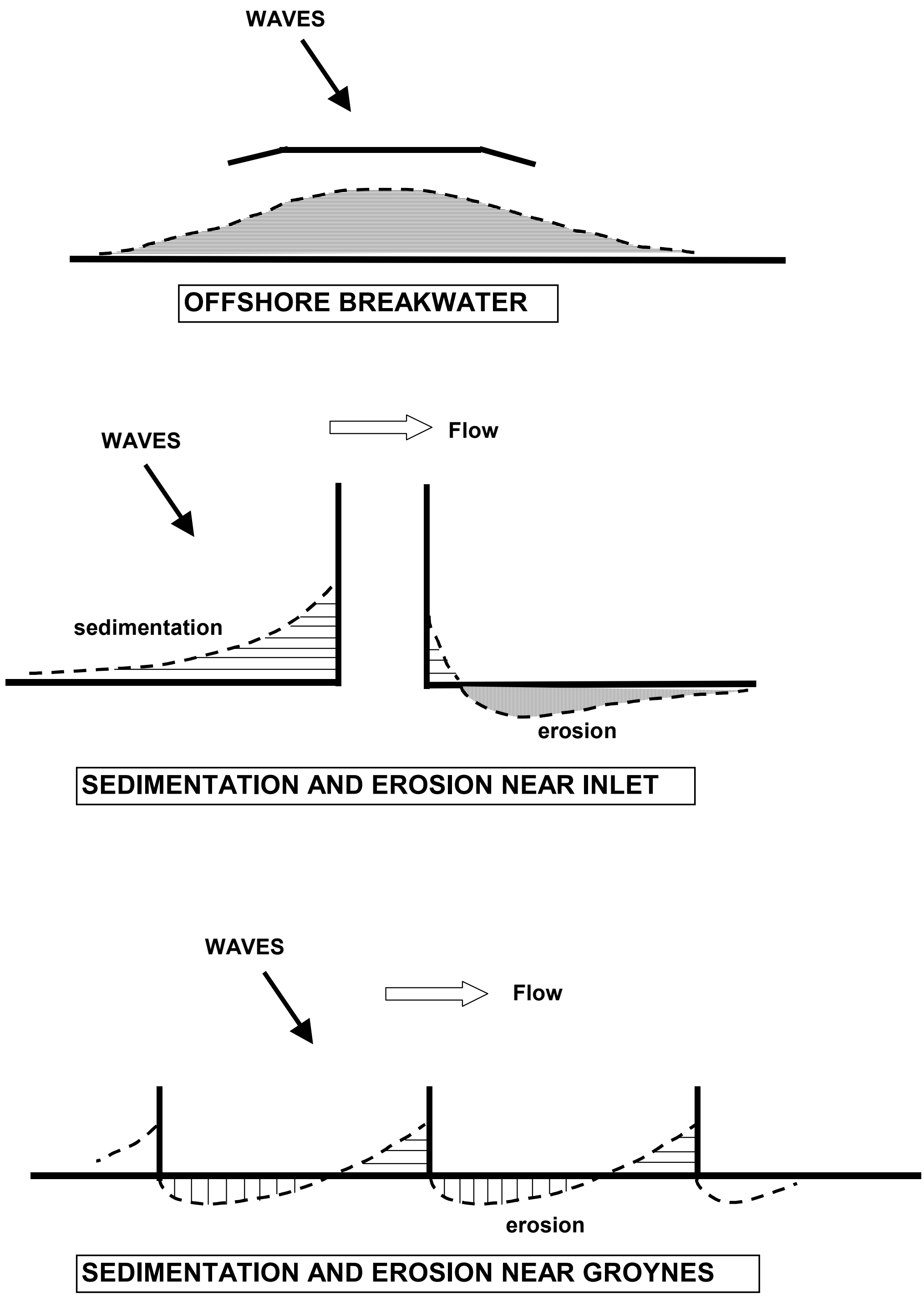

Figure 7 *Shoreline accretion and erosion near coastal structures (plan view)*

2.7 Shorelines

Shorelines may suffer from large-scale and small-scale sedimentation and erosion processes. Structures such as groynes or breakwaters perpendicular or oblique to the shoreline (Figure 7) will lead to sedimentation on the updrift side of the structure due to the blocking of the sediment transport (current-induced and wave-induced transport of sediment). Similarly, sedimentation will occur in the lee of a shoreparallel breakwater (Figure 7). Generally, erosion will take place on the downdrift side, because the sediment transport will gradually

restore itself eroding sediment particles from the downdrift side. Mechanical bypassing of sediment may be necessary to deal with the downdrift erosion near structures.
Large scale shoreline sedimentation and erosion generally are caused by:

- episodic flood or storm-induced processes;
- obstruction of the sediment transport processes due to the presence of natural barriers or artificial barriers;
- fluctuations in sediment supply and transport;
- onshore/offshore-directed sediment transport to or away from the shoreline;
- mining/dredging and dumping of sediment.

The available options to deal with typical erosion problems, are: (1) to accept retreat in areas where the shorelines/banks are wide and high; (2) to maintain the shoreline at a fixed position (by hard and/or soft structures or by dredging activities) and (3) to bring the shoreline forward by reclaiming land.

3 APPROACH OF THE SEDIMENTATION PROBLEMS

3.1 Approach

The general approach to solve sedimentation and erosion problems consists of the following major elements:

1. Specification of the problem and definition of wider context (socio-economic, legal, political, environmental, administrative aspects, etc.).
2. Formulation of general objectives and desired state of knowledge,
   - required level of accuracy,
   - available time and budget.
3. Determination of problem dimensions and analysis of physical system (current state of knowledge),
   - relevant user functions,
   - physical parameters of interest,
   - space and time scales involved,
   - state of the system (indicators).
   - existing knowledge (literature, charts, interviews).
4. Formulation of hypotheses related to problem,
5. Generation of alternative solutions and cost estimates,
   - selection and application of tools (existing databases, measurements/monitoring, models),
   - application of specialist knowledge.
6. Selection of optimum solution.

The three most basic rules are:

1. try to understand the physical system based on available field data; perform new field measurements if the existing field data set is not sufficient (do not reduce on the budget for field measurements);
2. try to estimate the morphological effects of engineering works based on simple methods (rules of thumb, simplified models, analogy models, i.e. comparison with similar cases elsewhere);
3. use detailed models for fine-tuning and determination of uncertainties (sensitivity study trying to find the most influencial parameters).

3.2 Analysis of the physical system

One of the most important activities within an engineering approach is a sound analysis of the physical system considered, involving:

- **Geometry and scales of the system,**
  - plan shape of coast,
  - dimensions of shoals and bed forms,
  - depths of natural channels,
  - sediment composition and distribution,
  - time scales of natural sedimentation and erosion patterns (migration rates),
  - dredging volumes.
- **Tides and currents,**
  - vertical tidal ranges (micro<1 m, meso1 to 4 m, macro> 4 m),
  - peak current velocities of flood and ebb phases (incl. velocity profiles),
  - duration and asymmetry of flood and ebb phases,
  - penetration length into estuary,
  - residual (tide-averaged) flow velocities,
  - three-dimensional flow patterns (flow in bends, stratified flow),
  - wind-driven currents.
- **Sediment transport,**
  - bed forms (type and dimensions),
  - mud, silt and sand concentration profiles,
  - suspended size composition (sand), percentatages of mud and organic material,
  - in-situ settling velocities (for mud),
- **Wave climate,**
  - dominant wind and wave direction,
  - frequency and intensity of storms,
  - types of coastal exposure (open, sheltered or exposed),
  - presence of breaker bars.
- **River discharge,**
  - frequency and intensity of flood waves,
  - water levels and flow strenghts,
  - presence of upstream control structures (weirs, barrages and reservors).
- **Estuary phenomena**
  - stratification effects (salt wedge) near outlet,
  - turbidity maximum (null zone),
  - tidal flats and shoals (migration rates),
  - flood and ebb channel crossings,
  - tidal ebb delta and migrating mouth bars.

3.3 Tools

The **tools** available for solving problems are:

- existing databases,
- measurements and monitoring (field studies),
- numerical and or physical modelling.

Field studies comprise:

- **Hydrodynamic measurements**,
  - water level recordings,
  - current velocity at fixed positions,
  - current velocity profiling (ADCP method) from moving vessel,
  - discharge measurements across main channels,

- float trackings of curved streamlines,
- wave field close to shore.

- **Sediment transport measurements**,
  - types and composition of sediment (mud, silt, sand, gravel, mixtures),
  - critical bed-shear stresses for erosion and deposition (mud),
  - settling velocity (flocculation of mud),
  - bed load transport in lowest 0.1 m of water column,
  - sediment concentrations at various levels above bed,
  - bulk density of bed material (consolidation of mud).
- **Morphology**,
  - bathymetry as function of time,
  - bed form trackings,
  - sedimentation and erosion volumes from bathymetry data.

Laboratory scale models consist of:

- ***Fixed bed engineering or design models***,
  - tide levels and flow patterns,
  - nearshore wave conditions,
  - configuration of structures,
  - strength of structures (breakwaters),
- ***Movable bed engineering models,***
  - valuable for small-scale 3D phenomena (local scour and deposition patterns),
  - scale effects due to incorrect representation of sediment mobility and bed forms,
  - laboratory effects due to space limitations and simplified boundary conditions,
- ***Process models***,
  - data for understanding of physics involved,
  - data for calibration and validation of numerical models,
  - systematic variation of parameters,
  - immediate and repeatable results of experiments.

Mathematical models consist of:

- ***1 dimensional models (1D)***,
  - suitable for rivers and network system of ebb and flood channels in estuaries (non stratified),
  - suitable for longshore coastal flows,
  - cross-section-integrated equations,
  - sediment transport capacity formulae,
  - *advantages:* easy to apply, good results for tide levels and discharges, long term morphology,
  - *disadvantages:*poor results for local currents; no information of lateral morphology,
- ***2 dimensional-vertical models (2DV)***,
  - suitable for modelling of streamtubes (information of streamtubes from 2DH model),
  - vertical structure of velocity and sediment concentration is included,
  - space and time lag effects are included,
  - *advantages:* easy to apply, operational on PC, long term estimates,
  - *disadvantages:* schematization into streamtubes required, geometry of each tube must be known,
- ***2 dimensional-horizontal models (2DH)***,
  - suitable for coastal seas and estuaries,
  - depth-averaged mass and momentum equations in two horizontal directions,

- depth-averaged suspended sediment equations (including lag effects),
- flooding and drying procedures,
- curvi-linear grid for efficient computations,
- nesting of models for detailed computations,
- *advantages:* standard tool, operational on advanced PC, easy to combine with wave models,
- *disadvantages:* not for very irregular geometry, not for stratified flow, not for secondary flow,

- **3 dimensional models (3D),**
  - mass and momentum in three coordinates (hydrostatic pressure is generally assumed),
  - curvi-linear grid for efficient computations,
  - *advantages:* all effects included (stratified and non-stratified flow, secondary flow), many details,
  - *disadvantages:* not easy to apply (not much experience), only for local problems, short duration.

Sedimentation predictions can only be done accurately, if there is sufficient understanding of the physical processes based on field measurements. These types of measurements require experienced personnel to handle the sophisticated electronic instruments under extreme conditions and are often expensive to cover the long term natural variations of the hydraulic system considered. Fixed bed laboratory scale models can be operated to determine the local flow and wave fields; movable bed models may be applied to get information of local, small-scale morphological developments near structures. The results of these laboratory models suffer, however, from scale errors and interpretation errors related to the schematized boundary conditions. Mathematical models donot suffer from scale effects, but the interpretation errors due to simplified model formulations and boundary conditions also limit the use of model results. Mathematical models are relatively easy to use but are not particularly cheap to operate, as many runs performed by experts are required to get a good feeling of the most important parameters and uncertainties involved.

3.4 Mathematical models and guidelines

Models available for morphological predictions can roughly be divided into two groups:

- **Behaviour-oriented models**, including:
  - simple engineering rules,
  - statistical models,
  - equilibrium river regime models,
  - equilibrium coastal profile models,
  - advection-diffusion type models,
  - plan shape shoreline models,
- **Process-based models**, including:
  - longitudinal river bed models,
  - cross-shore coastal profile models,
  - network estuary models,
  - area models (initial sedimentation/erosion, sequential morphodynamic models).

The applicability ranges of process-related and behaviour-related models are given in Table 1.

Behaviour-oriented models have long been used in engineering practice. Many of these models are however oversimplifications of complex systems that are poorly understood.

Illustrative arguments are: (1) poor assumptions and important omissions in model formulations, (2) use of relationships of questionable validity, (3) crude representation of boundary conditions, (4) incorrect model calibration and verification and (5) unknown model uncertainties.

Profile and Area models are the two main generic types of process-based models. Bed level changes follow from numerical solution of the mass conservation balance.
Profile models consider the physical processes in one (streamwise or cross-sectionwise) direction, assuming uniformity in the other direction. The flood and ebb channels in an estuary system can be simulated by a network of 1D bed profile models.
Area models are 2-dimensional horizontal (or quasi 3-dimensional) models consisting of, and linking, a number of submodels describing the wave field, the tide-, wind- and wave-driven flow field, the sediment transport fluxes and the bed evolution in a loop (feed back) system. Various numerical upscaling techniques are available to regularly extrapolate the morphological bed evolution from the computed bed levels at intermediate time steps. Using this upscaling technique (Rapid Assessment Method, RAM), the prediction horizon can be extended to about 50 years.
Fully 3D-models describing the currents on a three-dimensional grid are in an early stage of development, but the application possibilities of these models for realistic cases are rapidly increasing owing to improved computer technology.
In any modelling approach, assumptions are being made regarding the natural system (alongshore uniform or not) and the physics included (sort of processes included and type of simplification). These assumptions limit the application of a model to specific spatial and temporal scales.

SPATIAL AND TEMPORAL SCALES	**STORMS**	**MONTHS TO SEASONS**	**1 TO 5 YEARS**	**5 TO 10 YEARS**	**10 TO 100 YEARS**
0 - 10 KM		**Coastal profile-models**		**Coastal profile-models**	
		Area-models (2DH)		**Area-models (2DH; RAM)**	
	Area models ((quasi) 3D)				
			Behaviour-oriented	**models**	
10 - 100 KM			**River bed**	**models (1D)**	
			Network estuary	**models (1D)**	
			Behaviour-oriented	**models**	

Table 1 *Applicability ranges of process-related and behaviour-related models*

Basic questions for coastal managers are:
- What type of model should be used (process-based or behaviour-oriented model)?
- When to select a Line model, Profile model or an Area model? Is the site considered sufficiently uniform to warrant the use of a cross-shore Profile model? Are morphological changes due to rip currents important?

- What is the uncertainty in the model predictions? What is the bandwidth around the predictions given all the possible values of free model parameters? How does the bandwidth ('model variability') compare to the natural variability in morphological change?
- What is the prediction horizon of the model? What are the most relevant time and spatial scales for modelling?

Model users should have a basic understanding of the main sources of model uncertainty, being:

- errors in input data (schematization errors of past, present and future conditions),
- errors in model formulations (model parameter settings, including processes not modelled),
- extrapolation errors using the model outside its validity range,
- accumulation of errors through the simulation time.

Various methods are available to quantify the uncertainties involved:

- use local field data to validate the model for the problem considered and express the results in objective statistical parameters and/or state indicators,
- use multiple runs varying input data and model parameter settings (sensitivity runs),
- identify worst case scenarios (most extreme extrapolation cases),
- use probabilistic methods to present results in terms of mean values and standard errors at a certain level of confidence.

The model results should always be evaluated with respect to the natural variability of the physical system at the relevant time and space scales involved. For example, the long term erosion of the coast may be relatively small, but the short term variability of the sand volume in the nearshore zone may be relatively large due to storm sequential effects. Model predictions of this parameter (sand volume in nearshore zone) are only meaningful if the model variability (due to variation of model settings) is smaller than the natural variability. The selection of the most appropriate model approach for the problem at hand often is a difficult decision for the manager in charge, depending on many things such as: spatial and temporal scales involved, available boundary data (bathymetry and hydrodynamics), accuracy and capability of existing models, available budget, etc. Models generally are in a certain stage of development and the model specialist always suggests to improve the model before actually applying it on the problem at hand. This dualism between model improvement by the specialist and model application by the generalist can be overcome by making a 'snapshot' evaluation of the existing model (see Figure 8).

The 'snapshot' of what a model in its present state can do, first of all helps model users (modellers) to show how a model study should be set up, what data are required and how the results can be usefully interpreted. Secondly it will identify the (un)certainties in the model predictions. This helps the modellers to identify strengths and weaknesses of their models and to suggest future improvements. It also helps the coastal managers to see how the model results can improve their understanding of the system. The model results should be presented in terms of relevant State Indicators (SI's). Morphological data should be as much as possible aggregated to bulk volumes in relevant zones. In an ideal situation, a model prediction of relevant aspects of a pilot case should be made at the beginning of the project, with the means then available including estimated (un)certainties. At the end of the project a similar prediction should be made with the hopefully improved means (better model, better boundary data based on additional measurements).

The achieved reduction of the uncertainties (or possibly their improved estimation) could be a measure of the project's success.

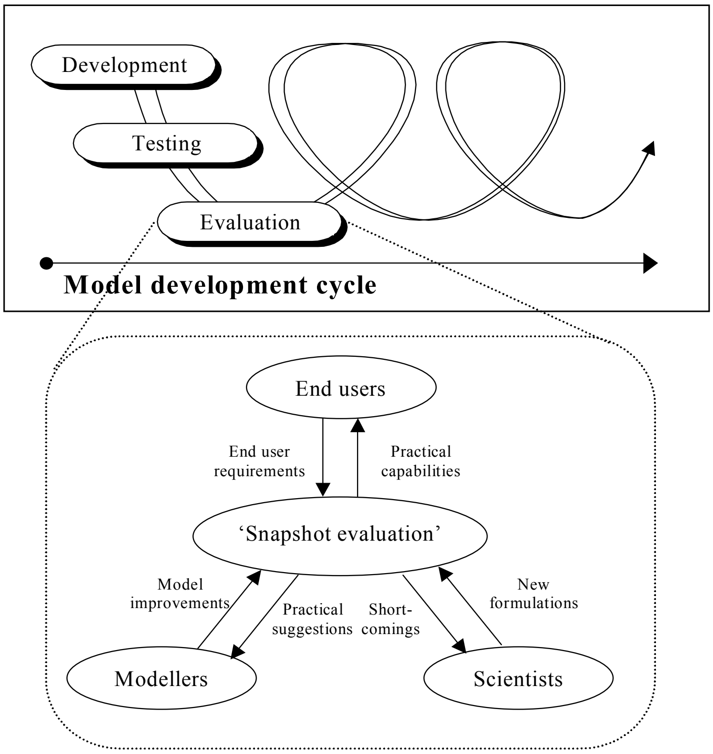

Figure 8 *Evaluation of enduser-oriented model development*

Guidelines for model application are:

- select relevant State Indicators, such as:
  - characteristic current velocities; focus on low tide for maximum currents;
  - characteristic bed levels, water depths at specific locations
  - bulk sand volumes in selected zones (precise bed levels cannot be simulated accurately);
- use standard settings for initial runs;
- apply additional calibration of model settings using measured bathymetry (if available) for storm, seasonal and decadal time scales;
- apply sensitivity computations to estimate the effects of model settings and input wave/ current/sediment conditions; identify worst case scenarios; select appropriate time scales;
- use probabilistic methods to present results;
- evaluate results in comparison with natural variability;
- use appropriate safety margins.

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