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ECO-HEALTHY ESTUARINE WETLANDS

# Eco-Morphological Problems in the Yangtze Estuary and the Western Scheldt

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**Abstract** This paper compares the Yangtze Estuary in China and the Western Scheldt Estuary in The Netherlands by their morphodynamic and ecological systems, their engineering works and estuarine management issues, and the major challenges in studying them. Physically speaking, the two estuaries are very different. The Yangtze Estuary is much larger and much more influenced by the upstream river than the Western Scheldt. Yet, they also have a number of morphological and ecological features in common. Both estuaries have a multi-channel system and extensive intertidal flats and wetlands with ecologically valuable flora and fauna. These eco-morphological systems are influenced by similar societal developments and human activities. Examples of the latter are engineering works and dredging activities for improving and maintaining the navigation channels, and shoreline management activities including land reclamations and setbacks. The fundamental eco-morphological phenomena that remain to be analysed and understood are the same for the two estuaries and will be discussed in this paper.

**Keywords** Eco-geomorphology · Human activities · Management issues · Research problems

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## Introduction

In this paper we compare two estuarine systems, the Western Scheldt estuary and the Yangtze estuary, that differ in many physical and biological aspects, but experience similar human interferences and developments. As such, both systems have several management issues in common, especially with respect to morphological changes and how these interact with ecological patterns and processes. The Western Scheldt estuary is situated in the southwest part of the Netherlands, and forms the estuarine part of the River Scheldt (355 km length, catchment area $21.86\times10^3$ km$^2$). The Western Scheldt estuary experiences a temperate climate, with predominant south–westerly winds, with relatively cool summers and mild winters, and with an annual average precipitation of almost 900 mm, evenly distributed in the year. The Yangtze estuary is part of the Yangtze River, the 3rd longest river in the world (6400 km) with a drainage area of $1.81\times10^6$ km$^2$. The Yangtze Estuary has a subtropical marine monsoon climate, with hot summers and cool winters, and with an annual average precipitation of about 1100 mm, nearly half of which falls between June and August.

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## Physical System Description

The two estuaries are very different in size. The Scheldt Estuary is about 5 km wide at the mouth (cross-section Vlissingen–Breskens; Fig. 1). The Dutch part of the estuary, called Western Scheldt, is about 60 km long. The Belgian part is much narrower and is about 100 km long. In this paper we focus on the Western Scheldt only. The Yangtze Estuary is about 90 km wide at the mouth (Fig. 1). The Xuliujing cross-section, about 100 km from the mouth, is often considered as the upstream end of the estuary, but the tide penetrates as far as Datong, about 640 km from the mouth.

Both estuaries are meso-tidal. The average tidal range in the Scheldt Estuary is about 3.75 m (Vlissingen) and 2.65 m in the Yangtze Estuary (Wusong). The influence of the upstream river, however, is much stronger for the Yangtze Estuary. The discharge of the Scheldt River is only about 100 $m^3$/s, on the order of 1/1000 of the tidal prism. Consequently, the Scheldt estuary is well-mixed and the fluvial sediment input is virtually nil. The discharge of the Yangtze Estuary is about 26,500 $m^3$/s on average and can be as high as about 100,000 $m^3$/s at peak flood. In combination with the relatively weaker tide, this makes the estuary partly mixed. In fact, it can vary between strongly stratified during neap tide in the wet season to well-mixed during spring tide in the dry season. Sediment transport from the river into the estuary is as high as 432 million ton per year (Datong station, 1951–2000) (Yang et al. 2005).

Due to the large sediment input from upstream, the Yangtze Estuary has been expanding over the years in a south-eastern direction. The sediment in the system mainly consists of silt. The sediment in the Scheldt estuary is mainly sandy, although mud is also found on part of the inter-tidal areas. In recent decades, the estuary has lost sediment, as the sediment import at the mouth of the estuary cannot keep up with sand mining in the estuary and with relative sea-level rise.

Both estuaries have a multi-channel system, but the channel structures are different. The morphology of the Western Scheldt displays a regular repetitive pattern that consists of mutually evasive meandering ebb channels and straight flood channels. These main channels are separated by subtidal and intertidal shoals and linked by connecting channels. (Van den Berg et al. 1996; Jeuken 2000; Van Veen et al. 2005; Toffolon and Crosato 2007). Winterwerp et al. (2001) schematized this system into a chain of so-called macro-cells and meso-cells (Fig. 2). Each macro-cell consists of a main ebb channel and a main flood channel, displaying a characteristic morphologic behaviour. Smaller-scale connecting channels link the large ebb and flood channels in macro-cells, forming meso-cells. These smaller channels often display a quasi-cyclic morphologic behaviour, characterized by processes of channel origination, migration and degeneration at a timescale of years to decades (Jeuken 2000; Van Veen et al. 2005).

The channels in the Yangtze Estuary have an ordered-branching character (Fig. 2): The estuary is first divided by Chongming Island into the North Branch and the South Branch. Then the South Branch is divided into the North Channel and South Channel by Changxing Island and Hengsha Island. The South Channel is again divided into the North Passage and the South Passage by the Jiuduansha Shoal, which is now developing into an island. This three-level bifurcation and four-outlet configuration appears to be a natural characteristic of the estuary that also occurred in the past (Chen et al. 1982).

## Ecological Systems

The physical and morphological differences between the two systems are reflected in the overall ecosystem functioning of the Yangtze and Western Scheldt estuaries. The Western Scheldt can be categorized as a coastal plain estuary with low sediment input from the river, whereas the Yangtze estuary is more a large-river delta-front estuary with a huge input of sediment from the river. The salinity gradient is well-pronounced within the Western Scheldt estuary, whereas in the Yangtze estuary the salinity gradient is situated more at the delta front. Although the Yangtze estuary has a much heavier load of suspended solids than the Western Scheldt, the latter system is also turbid, with primary production being light-limited in the brackish zone (Kromkamp and Peene 2005). Both systems are eutrophic and receive large amounts of nutrients from their respective river basins (Soetaert et al. 2006; Zhang et al. 2007; Rabouille et al. 2008). In the Scheldt estuary, primary production, recycling, and burial of organic matter mostly take place within the estuary. In the Yangtze estuary, the high turbidity does not allow significant primary production until most sediment has settled at the delta front. Primary production, deposition, burial, and transformation of organic matter take place at this delta front and on the coastal shelf.

Being meso-/macro-tidal systems, both the Western Scheldt estuary and the Yangtze estuary have a rich variety of tidal habitats and wetlands, such as shallow open water, mudflats, sand flats, and salt marshes. Salt marshes in the Western Scheldt are present as isolated patches fringing the estuary, and one large (3000 ha) salt marsh in the brackish zone. The pioneer vegetation consists mainly of the perennial common cord grass (*Spartina anglica*) (Table 1), which was introduced in the Westerschelde in 1925 to enhance reclamation schemes. Other pioneer species in-

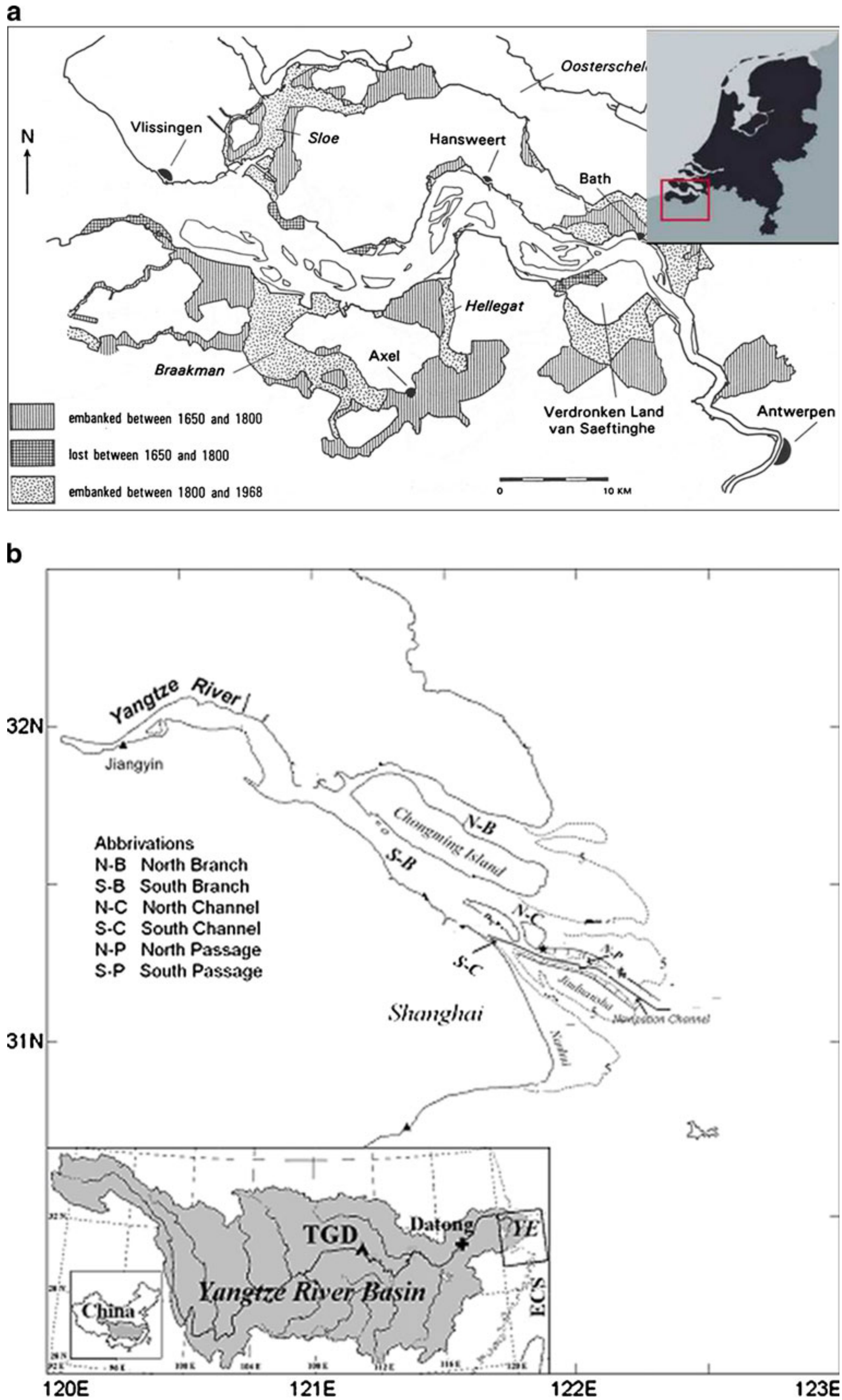


**Fig. 1** **a** The Scheldt Estuary (upper panel) in The Netherlands and **b** Yangtze Estuary in China (lower panel)

clude the annual glasswort (*Salicornia* spp.). Higher in the marsh, vegetation communities include among others common saltmarsh grass (*Puccinellia maritima*) and sea aster (*Aster tripolium*) (Table 1). In the brackish saltmarshes, seaside bulrush (*Scirpus maritimus*) and common reed (*Phragmites australis*) have established apart from

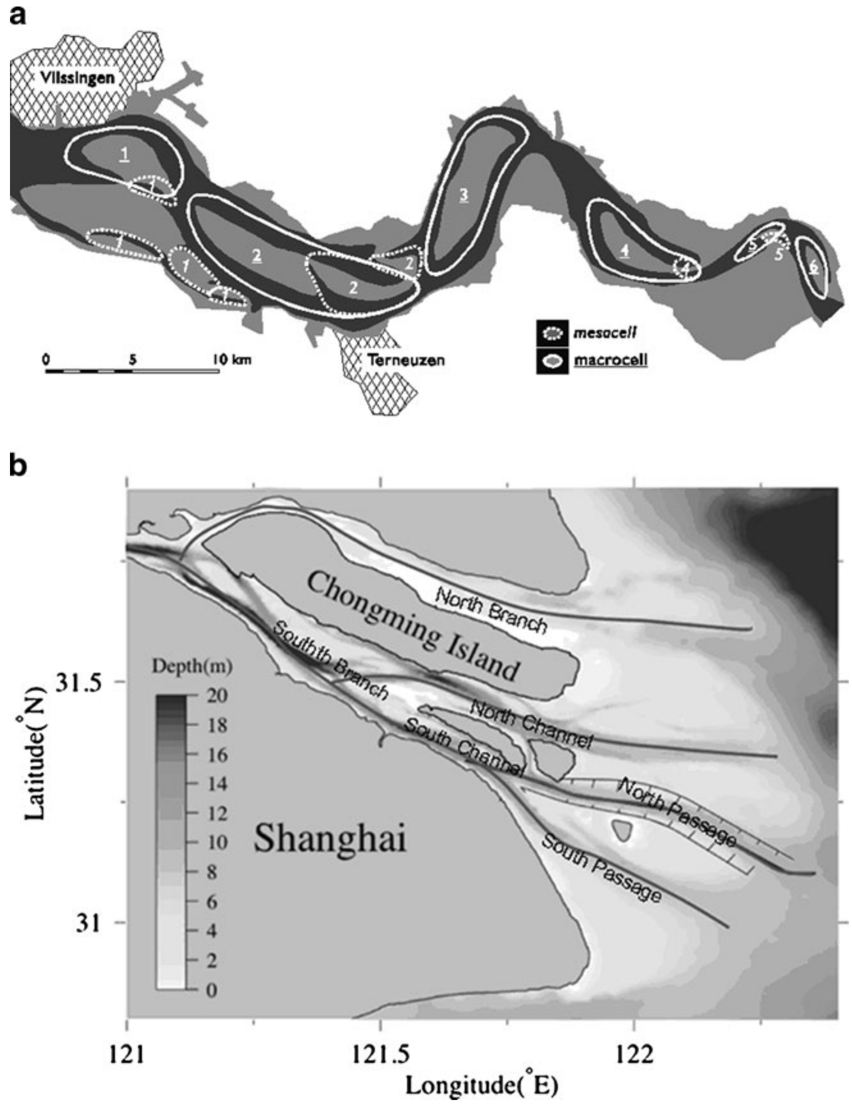


**Fig. 2** **a** Cells of flood- and ebb-channels in the Western Scheldt and **b** ordered branching channels in the Yangtze Estuary

*Spartina*. Substantial parts of the salt marshes in the Western Scheldt estuary have reached final stages of succession with vegetation characterized by *Elymus athericus*. Extensive pioneer communities are rare.

In the salt marshes of the Yangtze estuary, sedge meadows are present in the pioneer zone, dominated mainly by native *Scirpus mariqueter* and *Scirpus triqueter*, and in the high marsh, by *Phragmites australis* (Table 1). For the same reason as *Spartina anglica* was introduced to the Western Scheldt in the 1920s, *Spartina alterniflora*, native to the Atlantic and Gulf coasts of North America, was introduced in China in 1979 and in the Yangtze estuary in the 1990s. In the Dongtan area of Chongming Island, *S. alterniflora* was transplanted into the mudflats and marshes dominated by *S. mariqueter* in April 2001. Since then, this species has expanded rapidly. *Spartina alterniflora* monocultures accounted for 49.4% of the vegetated area in Dongtan marshes in 2005, and these marshes continue to expand today (Li et al. 2009; Xiao et al. 2009). Reclamation of these growing marshes is still ongoing, although

**Table 1** Common salt marsh plant species in the Western Scheldt and Yangtze estuary. Species are ordered following succession development (pioneer species to mature marsh species).

| Western Scheldt | Yangtze |
|---|---|
| *Salicornia* spp. | *Scirpus mariqueter* |
| *Spartina anglica* | *Scirpus triqueter* |
| *Scirpus maritimus* (brackish) | *Carex scabrifolia* |
| *Puccinellia maritima* | *Spartina alterniflora* |
| *Aster tripolium* | *Phragmites australis* |
| *Atriplex portulacoides* | |
| *Triglochin maritimum* | |
| *Phragmites australis* (brackish) | |
| *Elymus athericus* | |

sedimentation rates might decline in the future due to decreasing sediment input from the Yangtze River since the completion of the Three Gorges Dam (see below).

Both Western Scheldt and Yangtze estuary contain high diversity of benthic macrofauna (Ysebaert et al. 2003; Jing et al. 2007), that support migratory, wintering and breeding birds, demersal fish, crustaceans, and humans. Being situated along the East Atlantic Flyway and the East Asian–Australasian Flyway, respectively, both systems are critical sites for several endangered and protected bird species (Ysebaert et al. 2000; Ma et al. 2009). Both systems have areas that are designated as a Wetlands of International Importance by the Ramsar Convention. The Western Scheldt estuary is also protected under the European Bird and Habitat Directive and designated as a Natura 2000 area.

## Management Issues

Despite the differences between the physical and ecological systems, the two estuaries have common management issues. In both cases, management has to deal with the interaction between social-economic activities and the estuarine environment. The common key issues are protection from flooding, accessibility to navigation, maintaining water quality, and nature conservation. The surroundings of both estuaries are densely populated and are sensitive to flooding. Floods can come from the sea via storm surges as well as from river flooding. Both estuaries contain important navigation routes to major harbours along and upstream of the estuaries.

Water is also an important management issue. In the Scheldt estuary, water quality has been poor for several decades, and is still a major concern. In the last two decades, water quality of the estuary has improved considerably, due to increased efforts to treat wastewater before it is discharged into the Scheldt River (Soetaert et al. 2006). Changes in nutrient concentrations and water quality were recently summarized by Van Damme et al. (2005) and Soetaert et al. (2006) for the Western Scheldt estuary. In the Yangtze estuary eutrophication has become an overwhelming problem in recent decades, especially in the coastal environment and shelf margin, illustrated by an increase in nutrient concentrations, frequent red-tide events, and hypoxia in near-bottom waters (Zhang et al. 2007; Rabouille et al. 2008).

## Human Activities

Two categories of human activities influence the eco-morphological development of the estuaries: 1) activities for improving and maintaining navigability; and 2) activities related to shoreline management, especially land reclamation. Initially, human activity in the Scheldt Estuary was restricted to reclaiming land that had silted up by natural processes. This reclamation resulted in a permanent loss of intertidal areas, creation of embankments, and permanently fixing the overall alignment of the estuary (Figs. 1 and 3) (Meire et al. 2005). Since the beginning of the 20th century, human activities have shifted from land reclamation to sand extractions, about 2 million $m^3\ yr^{-1}$, as well as dredging and dumping to deepen and maintain the channel to the port of Antwerp.

During the first deepening in the 1970s, the navigation depth was increased from 12 to 14.5 m. During a deepening, carried out in 1997/1998, this depth was increased by another 1–1.5 m. As a result, maintenance dredging increased from less than 0.5 million $m^3\ yr^{-1}$ before 1950 to about 7–10 million $m^3\ yr^{-1}$ at present. Further deepening and enlargement is currently being executed.

Reclamation in the Yangtze estuary is not only carried out for land use purposes but also for fresh water reservoirs such as the Qingcaosha Reservoir. In contrast to the Scheldt Estuary, reclamation of mud flats and salt marshes is still going on today. Approximately 967 $km^2$ of intertidal flats were reclaimed between 1953 and 2004. The rate of land reclamation has sharply increased since 1980 with the fast socio-economic development of Shanghai (Fig. 3).

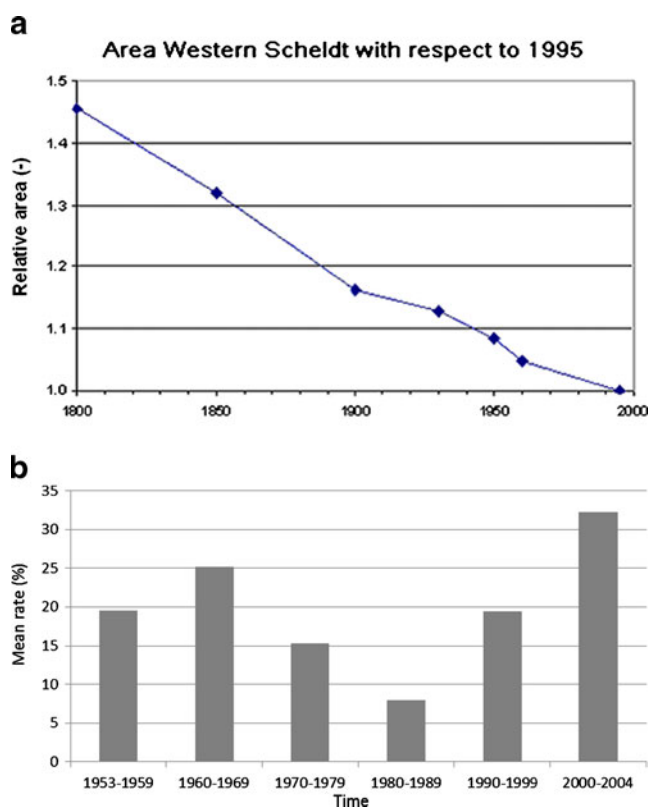


**Fig. 3** Land reclamation in (**a**) Western Scheldt and (**b**) Yangtze Estuary

The main navigation channel in the Yangtze Estuary was the South Passage, which, over the last century, was the primary outlet. Since 1983, the main navigation route lies in the North Passage. This was caused by blocking of the South Passage by Typhoon Forrest in 1983 (see Hu et al. 2009). To maintain a navigation depth of 8 m, guide bunds were constructed in the North Passage in 1998 (see Fig. 1). Initially, this led to a reduction in maintenance dredging. More recently, the dams were extended and the target navigation depth was increased to 12.5 m, which required a significant increase in dredging, up to ca 70 million $m^3$ $yr^{-1}$.

The developments of the two estuaries are also influenced by activities upstream in river basins and along the adjacent coasts. In the Yangtze River, the construction of a large number of dams, including the Three Gorges Dam, and increased diversion of water have substantial impacts on river discharge. Not only is the total amount of annual runoff affected, but peak discharge is also reduced. This has resulted in a substantial decrease in sediment transport to the estuary (Fig. 4), which will inevitably influence the eco-morphological development of the estuary in future (Yang et al. 2011). The planned large scale land reclamation (more than 700 $km^2$) along the Jiangsu Coast, north of the estuary, may also influence future development of the estuary.

For the Scheldt Estuary, developments along the adjacent coasts are important. The Delta Works in the past and the ongoing dynamic conservation of the coast (preventing the coastline from retreat by sand nourishment) may influence the sediment exchange between the estuary and the coasts. The Belgian plan to build a number of offshore islands fixing the Flemish Banks, an important source of fine sediments in the Southern North Sea, may also influence the import of sediment to this estuary (see http://www.vlaamsebaaien.com/flanders-bays-2100).

## Eco-Morphological Problems

### Mega-Scale Developments

The sediment balance of the Scheldt Estuary is determined by import–export at the mouth of the estuary and sand mining, as

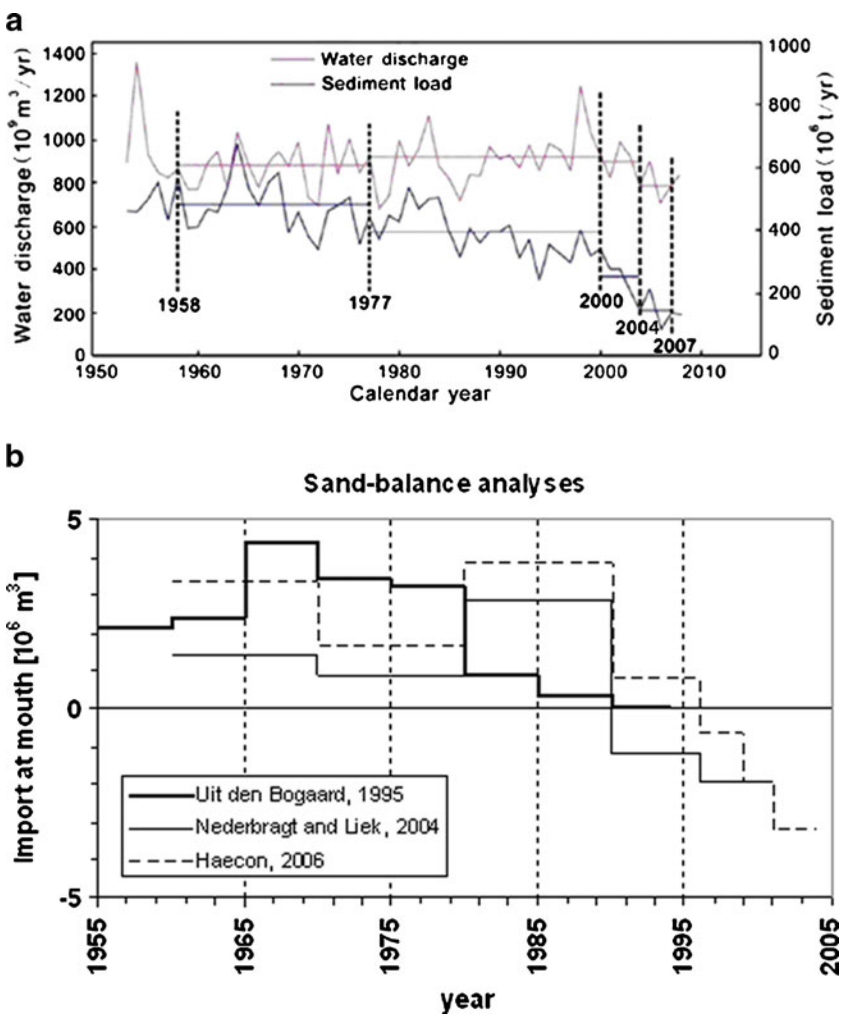


Fig. 4 **a** Yearly discharge and sediment transport at Datong station (after Yang et al. 2011) and **b** Import of sediment at the mouth of Western Scheldt fluvial sediment input is almost nil and dredged material for maintenance of navigation channel has to be dumped within the estuary. Figure 4 shows the sediment balance of the Western Scheldt derived from historical bathymetric data (Uit den Bogaard 1995; Nederbragt and Liek 2004; Haecon 2006). The relatively large differences between the results from the various studies show the uncertainty/inaccuracy of such analyses. Nevertheless, it is clear that the system has been changing since the 1980's, when a formerly more or less constant import rate started to decrease, even converting into a net export. Even before 1980, the import of sediment at the mouth hardly balanced the amount removed by sand mining. As a result the water volume of the estuary (below a certain reference level) is increasing. Together with relative sea-level rise of about 20 cm/century, the estuary is becoming deeper.

The recent decrease of the sediment import from the Yangtze River, primarily due to engineering works in the upstream river basin, raises the question whether progradation of the delta into the East China Sea will continue in the future. No doubt, the rate of extension will decrease, but it is not clear if and when the extension will turn into retreat. The answer to this question is also dependent on the scenario of sea-level rise. This trend in the mega-scale development of the estuary will inevitably influence land reclamation practices in and around the estuary. Furthermore, it is important to note that the Yangtze Estuary is a high-concentration estuary in the sense that the sediment concentration significantly influences the flow.

The ecological consequences of changing import–export mechanisms of sediment (both from the sea and river sides) are obvious. A rise in sea level will shift the land/water boundary of the estuary inland, bringing about more frequent inundation of intertidal habitats. The extent to which estuaries can adapt by creating new natural intertidal environments will depend on the rate of sea level rise, the amount of sediment available, physical disturbances within the estuary (e.g., land reclamation, channel deepening and enlarging, disposal of dredged spoil), and the actions of humans to protect developed land (e.g., building dykes). Fixed man-made structures such as seawalls prevent or severely limit the landward movement. Coastal habitats are therefore '*squeezed out*' between rising sea levels and fixed defence lines, resulting in a loss of valuable intertidal habitat (mudflats, salt marshes) in front of the defences. This also has consequences for coastal protection. In case of the Yangtze estuary, the anticipated decrease in sediment input from the river will likely slow development of intertidal habitats including salt marshes, and might even result in erosion of intertidal habitats (Yang et al. 2005).

## Macro-Scale Developments

On the macro-scale, the two estuaries are facing a common problem: the deepening and maintenance of navigation channels is influencing the natural channel structure. In both estuaries, parallel competing channels are present. In the Western Scheldt, these are the two channels in each macro cell, and in the Yangtze Estuary these are the South Passage and North Passage channels. Most navigation goes through one of these channels and the deepening influences the competition of one channel with the other.

In the Scheldt Estuary, deepening and maintenance are mainly done by dredging, with dredged material being dumped back into the estuary. Wang and Winterwerp (2001) showed that there is a limit to the rate of dumping in the competing channel if the multiple channel structure of the estuary is to be conserved. If the dumping rate in a macro cell exceeds this limit, the two-channel system will ultimately develop into a single channel (Jeuken and Wang 2010). Collapse of the multi-channel system into a single channel system would imply loss of ecologically valuable intertidal and shallow subtidal areas, besides important hydrographic changes. Therefore, tests of dumping dredged material near (eroding) tidal flats were initiated in 2004 (Van der Wal et al. 2011).This alternative disposal strategy was proposed to make beneficial use of the dredged material for forthcoming dredging operations. The strategy involves the disposal of material near (eroding) tidal flats, allowing the material to move slowly towards the flats, enhancing both shallow subtidal and intertidal habitats. By reshaping these areas, a more effective ebb–flood current distribution would be created so that the multiple channel system is sustained and dredging efforts could be reduced in the long-term. Five years of intensive monitoring revealed that part of the disposed sediment moved slowly towards the flat, increasing the very shallow subtidal and intertidal area, as planned (Van der Wal et al. 2011). However, despite morphological success and absence of detected negative ecological impacts of the experiment, new, ecologically productive habitat was not created (Van der Wal et al. 2011). Prolonged monitoring and upscaling of the experiment is needed to demonstrate the effectiveness of this strategy.

The navigability of the Yangtze Estuary was improved in recent years by the Deep Navigation Channel Project. The channel through the North Passage has been deepened from about 6–12.5 m by building two 50-km long guide bunds and a series of groins (Fig. 1) in combination with intensified dredging. Before the project, the North Passage, used as a navigation route since 1983, was the main channel of this bifurcating system. At present the two passages have changed roles: the South Passage is now the main channel for transporting water and sediment. This worrying development started after the second phase of the project when the two guide bunds were extended seaward to their present length. It appears that the second phase of the project has passed a critical point beyond which adverse effects on the eco-morphology will occur.

### Meso-Scale Developments

Meso-scale developments, occurring in both estuaries, include changes in connecting channels, intertidal flats, and sills. Connecting channels provide a link between two main channels by intersecting the shallow sub- and intertidal areas between them, and are characteristic of multi-channel systems like the Western Scheldt and the Yangtze Estuary. A recent trend in the Western Scheldt is that connecting channels are disappearing (Swinkels et al. 2009) and marsh is forming on top of the shoals. As a consequence, the area of shallow subtidal water, i.e. the area with bed level between −5 m and −2 m NAP (Dutch ordnance, about MSL), has been decreasing (Fig. 5). The area of intertidal flat, i.e. the area with bed level between −2 m and +2 m NAP, first increased and later decreased (Fig. 5).

Connecting channels in the Yangtze Estuary occur especially in the early stage of development of a shoal complex, when it is still low lying and the connecting channels divide it into smaller shoals. In the later stage of its development, the shoal complex becomes elevated, the connecting channels disappear, and an island is formed. The engineering works in the Deep Navigation Channel Project have accelerated this process around the Jiuduansha Shoal.

Sills refer to the shallow parts of the main channels. In the Western Scheldt they are present at the seaward ends of ebb channels and the landward ends of flood channels. In the Yangtze Estuary, all four outlet channels have sills near the mouth of the estuary, forming the so called “mouth bar” that presents obstacles to navigation and results in the initiation of dredging. Figure 6 shows the amount of dredging required to enlarge and maintain the navigation channels in the two estuaries. Most dredging targets lowering sills and maintaining required navigation s, and only a small part is for widening navigation channels.

Morphological developments at the meso-scale have important ecological consequences, as they influence habitat quality as well as the spatial distributions of the intertidal and shallow subtidal habitats. In the Western Scheldt estuary, tidal flats have become higher and drier, and shallow subtidal area has decreased in recent decades. Highly dynamic areas where abiotic stresses are great have increased at the expense of less dynamic areas. It is the rich variety of habitats, especially those areas with low current speeds in the shallow subtidal and intertidal zones, that makes the Western Scheldt such a biologically rich and productive system (Ysebaert et al. 2003). Long-term monitoring is needed to further evaluate the effect of ongoing morphological developments on the ecosystem functioning of the estuary.

## Common Challenges and Research Demands

It is clear that many issues are common to the two estuaries. From these we identify a number of challenges to scientific research for both estuaries.

*Morphological equilibrium* is a fundamental issue demanding attention. Specifically two issues of morpho-

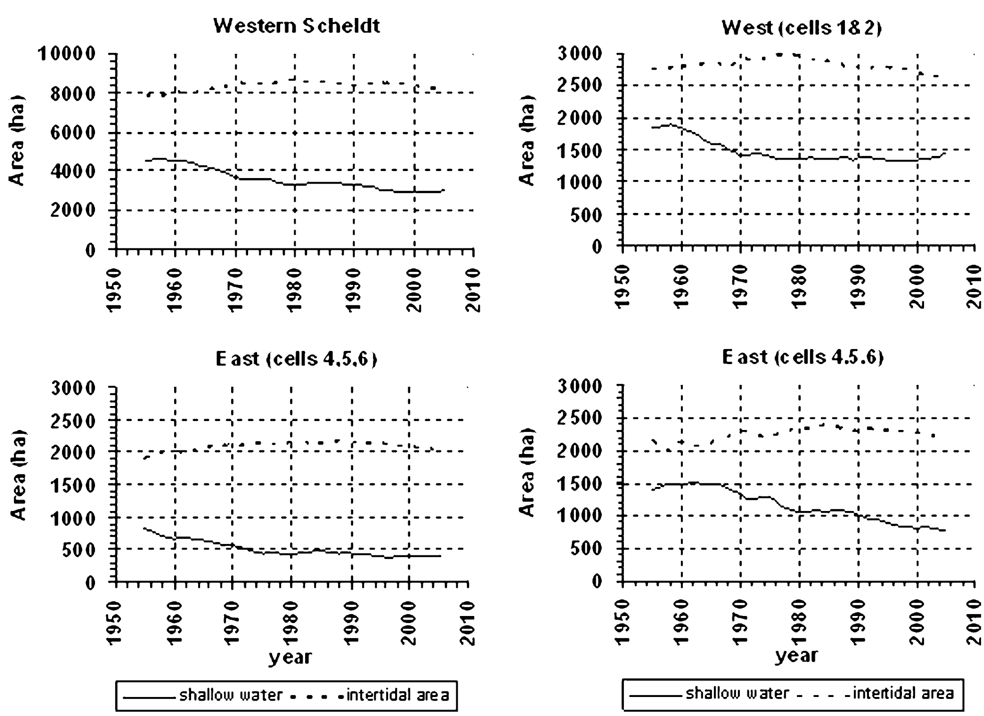


**Fig. 5** Development of intertidal area and shallow water area in Western Scheldt

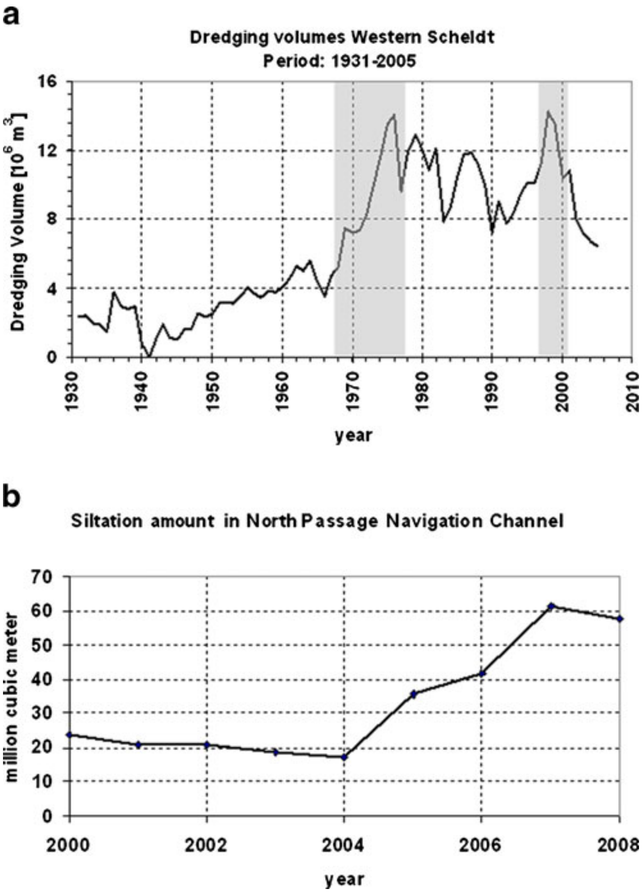


**Fig. 6** **a** Annual dredging amount in the Western Scheldt (note that the two deepening periods are indicated by yellow shades) and **b** Annual dredging amount in the North Passage Navigation Channel in Yangtze Estuary

logical equilibrium, relevant for both estuaries as well as for many other estuaries, that require attention include *channel–shoal/flat interaction* and *bifurcating channels*. Predicting the changes of intertidal flats, in area and elevation, is important for ecological studies, and a problem complicating morphological studies. Understanding the channel–shoal/flat interaction is also important for predicting demands for dredging to maintain navigation channels.

*Sand–mud* interaction, interaction between *physical and biological processes*, and *flow–sediment* interaction all require further research attention. Sand-mud composition of the bottom is an essential factor influencing macroalgae and macrobenthos communities (Gray 1974; Herman et al. 2001; Thrush et al. 2004; Montserrat et al. 2008; Van der Wal et al. 2010). In the Western Scheldt estuary, Montserrat et al. (2008) demonstrated the importance of benthic macrofauna to intertidal sediment dynamics, and Yang et al. (2008) showed the importance of salt marsh vegetation for the distribution of sediment grain size in the Yangtze estuary. The interaction between these biological and physical processes creates the spatial structure in estuarine ecosystems. For example, in salt marsh, the interaction of plants with hydrodynamic forces influences sedimentary processes (Bouma et al. 2007), and in the end, results in the formation of a spatially structured levee-creek salt marsh landscape (Temmerman et al. 2005, 2007).

Recent insights stress the importance of integrating the different spatial and temporal scales at which morphological and ecological processes operate and interact. An example is the dependence of salt marsh development on tidal flat topography (Van der Wal et al. 2008; Callaghan et al. 2010). Requirements that the total area of salt marshes remains constant leads to management interventions to defend marshes (e.g., with stone walls) when the tidal flat recedes as a consequence of enlarging navigation channels. The desire to conserve natural areas and natural processes will require a more proactive strategy to expand the estuary to retain morphological equilibrium among channels, flats, and marshes.

In summary, we draw the following conclusions:

- Estuarine eco-morphodynamics present practically important, scientifically interesting, and complex problems for which more research is urgently needed.
- While the physical and ecological systems of the two estuaries considered, Yangtze in China and Scheldt in The Netherlands, are very different from each other, the key management issues for the two estuaries are very much the same.
- The relevant morphodynamic and ecomorphological problems in the two estuaries are very similar, and become even more similar when finer temporal and spatial scales are considered.

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