Prof.dr.ir. J.C. Winterwerp

Regime Shifts in muddy open water systems

Intreerede 12 januari 2012

Faculteit Civiele Techniek
en Geowetenschappen

TU Delft
Delft University of Technology

Challenge the future

Regime Shifts in muddy open water systems

Intreerede

In verkorte vorm uitgesproken op 25 januari 2012
ter gelegenheid van de aanvaarding van
het ambt van hoogleraar Sediment Dynamica
aan de faculteit Civiele Techniek en Geowetenschappen
van de Technische Universiteit Delft

door

prof. dr. ir. J.C. Winterwerp

Hoogleraar Sediment Dynamica

Mijnheer de Rector Magnificus, leden van het College van Bestuur,
Collegae hoogleraren en andere leden van de academische gemeenschap,
beste familieleden en vrienden, zeer gewaardeerde toehoorders,
dames en heren.

The chair "Sediment Dynamics" is dedicated to the transport and fate of sediments in open water systems, such as seas, coastal waters, estuaries, rivers, lakes, and the like. Sediment is the name for granular and particulate matter encountered in and on the bed, and in the water column. The majority of these sediments consist of feldspar and quartz (sand), but many other minerals are encountered, in particular in the clay fractions. Moreover, larger or smaller amounts of organic material, in particular organic polymers, have a great influence on the properties of these sediments.

The size of sediment particles may vary by orders of magnitude. Coarse sands in rivers typically measure a few 100 μm, whereas dispersed clays can be much smaller than 1 μm. At the other side of the spectrum, we find gravel, which measures in the cm range.

Sediments on the bed may be picked up by the flow, and if flow velocities are large enough, transported over large distances. The coarser fractions induce bedforms, such as ripples and dunes, whereas the smaller fractions are transported primarily in the water column as suspended load.

Because of their mobility, the transport and fate of sediments always play an important role in hydraulic engineering studies, as their behavior governs the stability of coastlines, the integrity of hydraulic structures, and, with respect to the finer sediments, the light climate in the water column, important for the ecosystem.

Here, we focus on the behavior of the fine, cohesive fraction, i.e. the clays and organic polymers. These particles are characterized by a net electrical charge on their faces, or an uneven charge distribution; electro-static forces therefore play an important role in the properties of these sediments, in conjunction with the chemical features of the pore water. Because of their size, also Van der Waals forces are important.

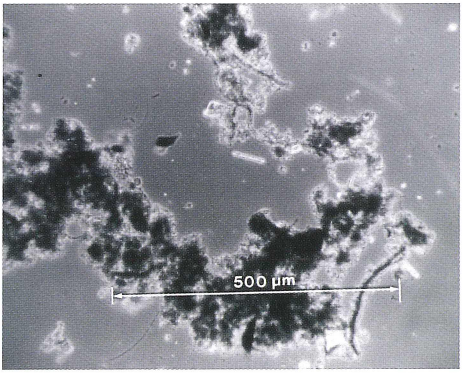


Fig. 1: Typical mud floc.

Because of these physico-chemical forces, cohesive sediments occur in the form of flocs, relatively large open structures, containing hundreds to thousands of clay and slit particles, and organic polymers. The polymers are produced by bacteria and diatoms, amongst others, which form small ecosystems within these flocs. Clays and polymers can bind large amounts of water, which, in conjunction with entrapped pore water, explains the large water content within the flocs. Flocs formed in the water column, as the one depicted in Fig. 1 may contain up to 95% of water, whereas flocs in the sediment bed still contain 70 - 80% of water. Mixtures of water and cohesive sediment may therefore behave as a fluid, as a soil, or something in between, depending on the water content. The mechanical behavior of these intermediate mixture is studied by the discipline of rheology.

Another consequence of their electrical charge is the adherence of organic and inorganic contaminants to the clays and organic polymers. As such, fine cohesive sediments play a key role in the transport and fate of aquatic pollution. When accumulating in fairways and harbor basins, the costs of maintenance dredging may become prohibitive for an economic exploitation of ports.

How it started

The first studies, and subsequent research on cohesive sediments, were driven by water quality problems, and the maintenance of fairways and harbor basins to safeguard navigation.

Fig. 2: Continuous dredging is required maintaining navigable depth in Zeebrugge, Belgium.

Fig. 3: Heavily contaminated sediments may threat public health; Passaic River, New Jersey, USA.

Fine cohesive sediments are easily remobilized from the bed, and stay in the water column for long times, thereby transported over large distances, and accumulating in still water areas. Contrary to sand, fine sediments can penetrate far into harbor basins, in between jetty pillars, and deeper navigational channels. Indeed, maintenance dredging in the ports of Rotterdam, Zeebrugge (Fig. 2), and many others implies removal of cohesive sediments mainly.

The immediate next question concerns locations and procedures where and how to dump the dredged sediments at minimal environmental impact, in particular when contaminated. Will the dumped sediments remain in place, will turbidity levels not exceed environmental standards?

Many open water systems suffer from historic contaminants, released in a period that the hazards of many chemicals were largely unknown. Today, with growing awareness, concerns arise on the stability of such legacy deposits, as in the case of sediments contaminated with dioxin and otherwise in the Passaic River, USA (Fig. 3).

Fig. 4: Intertidal mudflats in Western Scheldt, The Netherlands.

Later, studies and research were carried out on the stability of inter-tidal mudflats, as these comprise highly valuable ecosystems. Some of these systems are endangered by a variety of engineering works, such as river embankments, fairway deepening, etc. Local and European regulations require assessment of the environmental impact of such works. The stability of mudflats is governed by subtle interactions between physics and biology, which are still poorly understood, though.

Today, these interactions are subject of a number of research projects carried out with partners in The Netherlands, and abroad.

Mud deposits along some coasts may be so thick and soft, that profound damping of incoming surface waves occurs through viscous dissipation within the fluid mud. In southern Brazil, these deposits are highly mobile as well, and may end up on the normally sandy beaches, seriously affecting their safe use for e.g. recreation, as shown in Fig. 5.

In collaboration with overseas partners, we have developed mathematical tools describing these observations, and implemented this description in a special version of the TU Delft's open source model SWAN, the SWAN-mud model.

The cohesive sediment community has made considerable progress over the last few decades in understanding the processes relevant to analyze the various topics mentioned above. Yet, many basic questions remain, owing to the complex and time-dependent behavior of cohesive sediments. Moreover, these processes are not only driven by physics, but by chemical and biological effects as well. Therefore, basic research into these processes remains mandatory, for some time at least. The major research questions to be addressed are:

- how are the mud flocs of Fig. 1 formed in relation to environmental factors, such as water chemistry, turbulence levels, etc.?
- what is the stability (e.g. erodibility) of cohesive sediment deposits?
- how are the properties of cohesive sediment mixtures affected by grain size distributions, and by chemical and biological effects?
- what is the transient behavior of these sediment properties?

Fig. 5: Fluid mud induced wave damping (note foam generated by breaking waves in right-hand side of the photograph) at Cassino Beach, Brazil. The left panel shows landing of mobile fluid mud on the beach.

Our research tools

To address these questions, we developed a series of tools and methods. Basically, we carry out laboratory experiments and field work, and apply numerical modeling and analytical assessments. Here we give a few examples, giving a taste of the current possibilities.

Fig. 6 shows the microcosm, a small device to measure erodibility of soft, cohesive sediments under shear flow conditions. The shear flow is induced by a rotating disk, whereas water is pumped out radially to minimize secondary currents. Dimensions of the microcosm match those of cores taken from the field, so that these can be inserted directly into the instrument.

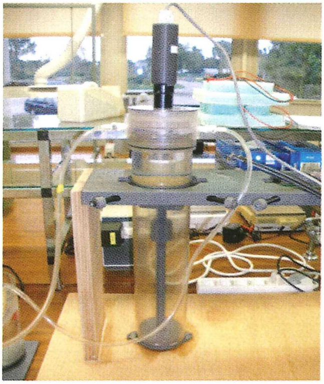


Fig. 6: The microcosm, an instrument measuring erodibility on cores taken from the sediment bed.

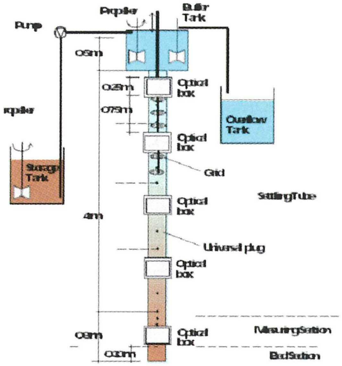


Fig. 7: The settling column, a full-scale device to study flocculation in the water column.

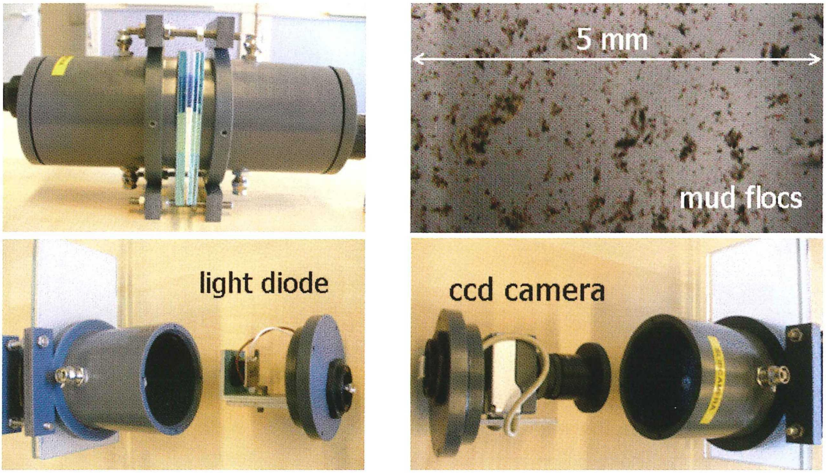


Fig. 8: The in-situ floc camera to measure the distributions of floc size and settling velocity.

Fig. 7 shows a schematic diagram of the 4 m high settling column at TU Delft to measure the flocculation behavior of cohesive sediments as a function of turbulence level, sediment concentration and pore water chemistry at full scale. We developed tools and software to assess the distribution of floc size and settling velocity in this column. These tools are used for the in-situ floc camera as well, which is shown in Fig. 8. This camera is operated from a laptop computer, and can be deployed in-situ from a boat easily, to measure floc properties in the field directly.

In our studies and consultancy work, numerical models are often used. As an example, Fig. 9 presents results of simulations with a Delft3D model of the Markermeer, The Netherlands, showing near-surface suspended sediment concentrations as a function of wind direction and speed. Comparison with remote sensing observations is favorable. At the university, we develop algorithms improving the applicability of such models, and use the models themselves for research.

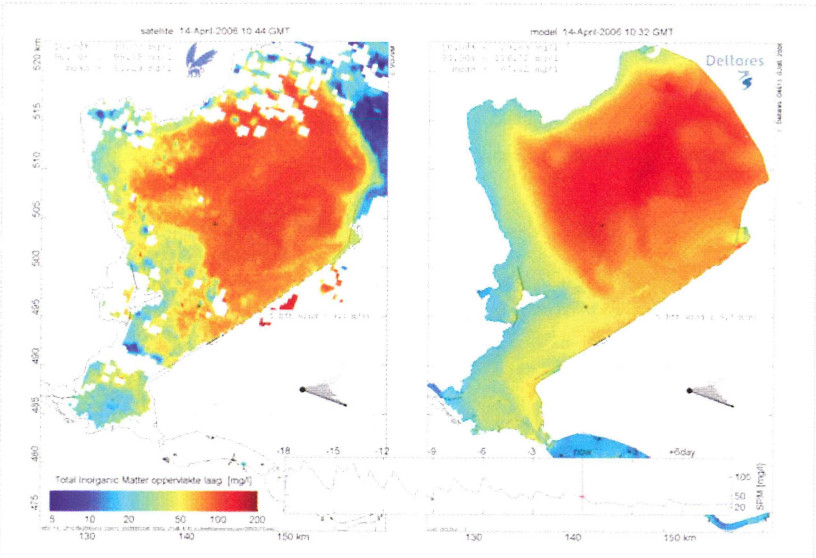


Fig. 9: Comparison of suspended sediment concentration in Markermeer, The Netherlands computed with Delft3D (right panel) and remote sensing observations (left panel; courtesy T. Van Kessel, 2009).

An example of the latter is given in Fig. 10, presenting results of SWAN-mud, a special within the TU Delft model SWAN, simulating dissipation of surface waves over fluid mud. Fig. 10 shows planes of equal wave damping as a function of fluid mud viscosity and thickness, and wave period. These planes are curved/folded, implying multiple solutions for one set of environmental conditions. Such mathematical behavior has great consequences for the application of such models, of course.

Finally, we apply analytical techniques, allowing for in-depth analysis of various processes. As an example, we refer to the generation and behavior of fluid mud, flocculation processes in depth-limited aquatic systems, and tidal amplification in response to fairway deepening, elaborated below.

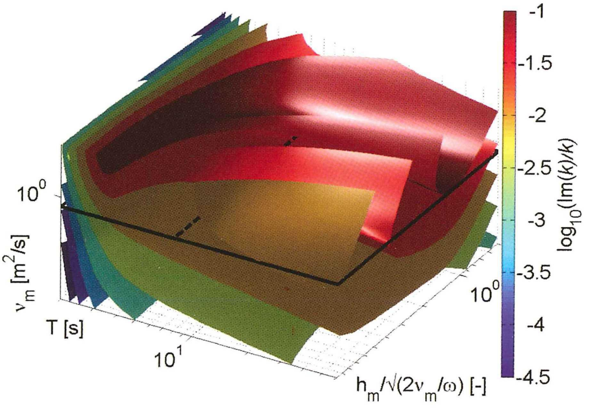


Fig. 10: Solution space of SWAN-mud, showing multiple roots for one set of environmental conditions. Such analyses are crucial in understanding the behavior of complex numerical models.

The cohesive sediment multi-disciplinary network

The societal questions to be addressed, and the cohesive sediment processes themselves bring together many disciplines, e.g. Fig. 11. It is impossible to host them all in our small research team. Therefore, we established intensive and long-lasting collaborations with a number of researchers and institutes. Within The Netherlands, we are active within the Netherlands Centre for Coastal Research, and close co-operations exist with Deltares, NIOO-CEME, NIOZ, University of Utrecht, WUR/Imares, Institute of Marine Studies (Amsterdam), Rijkswaterstaat, Port of Rotterdam, and many consultants and contractors through the Building of Nature program, amongst others. Also we work with partners abroad, such as the National University of Singapore, Flanders Hydraulics (Belgium), Ifremer (France), University of Plymouth (UK), Office of

Naval Research (USA), Federal University of Rio de Janeiro (Brazil), and State Key Laboratory for Estuarine and Coastal Studies (Shanghai, China), to name a few.

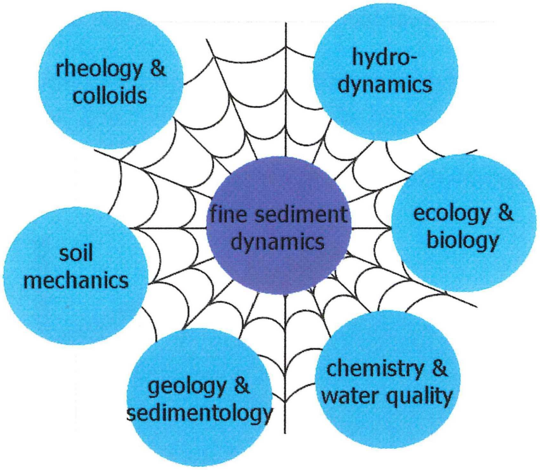


Fig. 11: Cohesive sediment research is carried out within a multi-disciplinary network, with partners in The Netherlands and abroad.

Regime shifts

In the early years of cohesive sediment studies and research, we analyzed linear processes mainly, in the sense that the water movement governs the transport and fate of fine cohesive sediments in a hierarchal way. Only in the case of the formation and behavior of fluid mud, water movement and suspended sediments interact mutually, as vertical suspended sediment concentration profiles affect vertical turbulent mixing.

Recently, our focus diverted to the stability of entire open water systems, such as coast, lakes and estuaries. Some have been engineered beyond a so-called tipping point, bringing that system from one stable state/regime into a second, also stable regime. Such regime shifts are characterized by:

- a change in features (symptoms), and
- a change in the dominant processes driving that system,
- bringing the system into a second stable state, which is often highly irreversible, whereas
- often positive feed-back processes play a role, as a result of which small disturbances can have large effects.

Currently, these regime shifts are understood qualitatively, at best. As more studies on such regime shifts are anticipated, a full, quantitative understanding is required, which needs considerable more research. The remainder of this speech focuses on such regime shifts, and we present a series of examples in which fine cohesive sediments play a major role in lakes, coasts and estuaries.

Mangrove-mud coasts

Mangrove-mud coasts are rich ecosystems with many so-called ecosystem services. Healthy mangrove-mud coasts are dynamic and grow with sea level rise, provide wood and livestock for local habitants, contribute to water quality by their filtering capacity, and provide shelter and spawning grounds for numerous species - some figures suggest that about 50% of all commercial fish in the tropics depends on mangroves. Moreover, mangrove forests can sequester large amounts of CO_2. Yet, mangrove-mud coasts are under high pressure. Over the last 60 years, the area of mangrove mud coasts has been more than halved, down to about 15 million ha in 2007, declining further at a rate of 150,000 ha per year. These losses are often accompanied by severe coastal erosion, as shown in Fig. 12, lower panel.

Fig. 12: A healthy mangrove-mud coast in Suriname (Saramacca, upper left panel), and eroding mangrove-mud coast in Suriname (Coronie, upper right panel), and a fully eroded coast in British Guyana (lower left panel, close to Georgetown).

To stop erosion and/or to compensate for losses in mangrove habitat, large efforts have been undertaken to rehabilitate eroding mangrove-mud coasts.

With little success though. In the Philippines, for instance, only 5 - 10% of all rehabilitating works was successful over the last two decades.

We now start to understand that thoughtless land-use is one of the major causes of the huge losses in mangrove-mud coasts, and of the difficulties in rehabilitation. Bunds and dams are erected to build fish ponds etc. in the mangrove habitat, which is found between mean high water (MHW) and high-high water spring (HHWS). Then, onshore sediment transport is reduced owing to a reduction in tidal filling velocities, as sketched in Fig. 13. When the eroding agents, e.g. the waves continue to attack the mangrove-mud coast, mobilized fine sediments are washed away from the mud flat by tidal currents. Then the shape of the mudflat changes towards convex-up, enhancing wave activity further. In the end, net coastal retreat results, as the eroding sediments are no longer sufficiently replaced by new sediments.

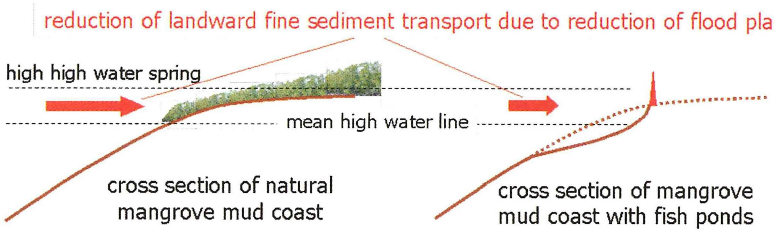


Fig. 13: Diagram explaining the impact of land-use on onshore fine sediment transport due to reduction of the large flood plains between mean high water and high-high water spring, the habitat of mangroves.

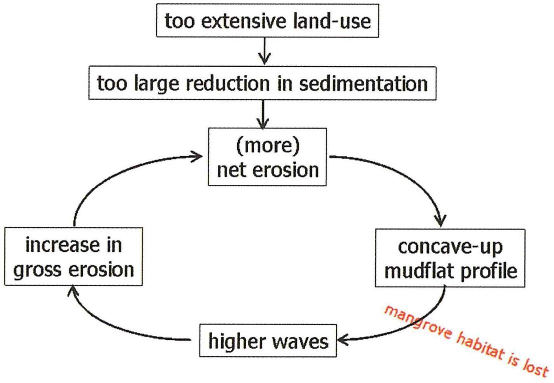


Fig. 14: Diagram showing the feed-back cycle in mangrove-mud coastal erosion following a reduction in onshore sediment flux in response to land-use in the mangrove forests.

The one-time stable/dynamic or accreting mangrove-mud coast has now changed into an eroding system. When too much hinterland (the intertidal area between MHW and HHWS) is lost, onshore sediment transport cannot be re-established, and this regime shift is effectively irreversible. We do not need to stress that studies of these eroding mangrove-mud coasts require close collaboration with biologists with mangrove expertise. The cycle of events ultimately leading to the entire collapse of the mangrove-mud system is sketched in Fig. 14, and the consequences in Fig. 13, right panel, and Fig. 12, lower panel.

Shallow lakes - Markermeer

Many shallow peat lakes are found in The Netherlands, and many are extremely turbid. This high turbidity is the result of a complicated interplay between physical, biological and chemical processes. It has been shown that eutrification was the primary trigger for regime shifts in these lakes, from clear water systems, with vegetation, prey fish and moderate primary production, to turbid systems with high primary production, no vegetation, and abundant white fish agitating the sediments on the lake bed further.

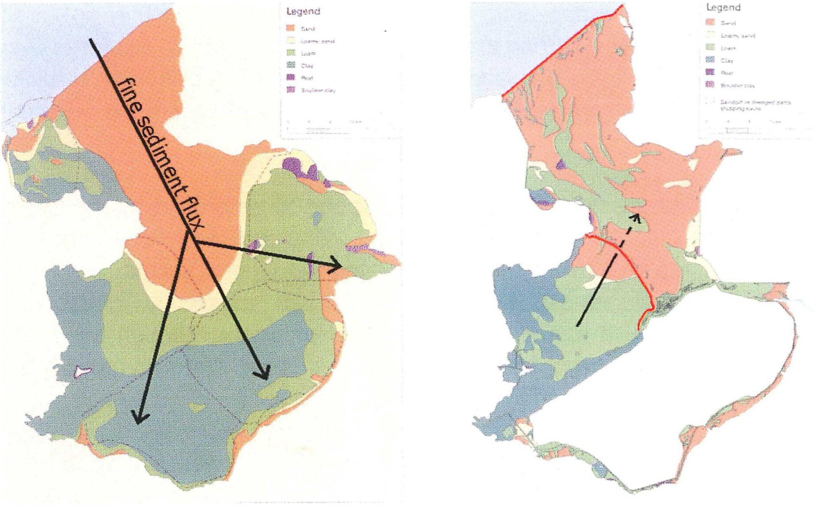
The Markermeer is a special case in the sense that not so long ago it formed part of Zuiderzee. Then, tidal asymmetry and estuarine circulation pumped large amounts of fine, cohesive sediments towards its head. That explains why the soil of the three IJsselmeer polders and of the Markermeer consists of clay and loam mainly, whereas the rest of the IJsselmeer is characterized by a sandy bed, e.g. Fig. 15.

After construction of the Aflsuitdijk (1933), and later the Houtribdijk, tide and estuarine circulation disappeared, and sediment dispersion is mainly governed by wind-induced waves, stirring up fine sediments from the bed, dispersed over the lake by wind-induced circulations. Fig. 15 shows the current high turbidity of the lake from a remote sensing image, and the composition of the sediment bed.

Today, the Zuiderzee deposits are still too strong to be eroded by the waves in the Markermeer, even after the (originally) saline pore water was rinsed out from the bed, replaced by fresh water. However, meio-fauna, such as nematode and ostracoda can remold (bioturbation) the bed sufficiently to decrease bed strength so much that it can be mobilized by waves. Though this fauna measures less than 1 mm, their abundance is so large that they govern the sediment dynamics of the entire ~700 km^2 large lake.

The regime shift towards a highly turbid Markermeer was abrupt, as tide and estuarine circulation were cut off after closure of the Zuiderzee. Next, fine sediments were trapped within the Markermeer upon construction of the Houtribdijk (1976). Today, the fine sediment dynamics in the lake are governed by a subtle interplay between physical, biological and chemical processes. Resuspension, deposition and horizontal dispersion of fine sediments are governed by the hydrodynamics in the lake; the organic content of these sediments increases by primary production, which is affected by the light climate, i.e. the fines in the water column. On the bed, oxidation and reduction of the sediment deposits govern the occurrence of bioturbation, affecting the erodibility of these sediment deposits.

Fig. 15: The Markermeer is highly turbid (courtesy M. Eleveld), with suspended sediment concentrations well over 100 mg/l. These fine sediments stem partly from primary production within the water column, but are composed mainly of marine sediment deposits from pre-IJsselmeer era (left lower panel). The two lower panels show that the bed of the Markermeer and of the IJsselmeerpolders consists of loam and clay mainly. Eroded fines cannot escape, being trapped by the Houtribdijk (1976).



Estuaries - the Ems and Loire River

Our last example concerns the behavior of narrow estuaries in response to deepening and canalization, accommodating for navigation to ports along these estuaries. Some of these estuaries have been engineered for decades, and sometimes even longer, such as the Loire River. With increasing vessel size, depths proved difficult to maintain, and the estuaries were narrowed as well, reducing intertidal areas considerably, or even entirely. Fig. 16 summarizes the canalization works in the Loire.

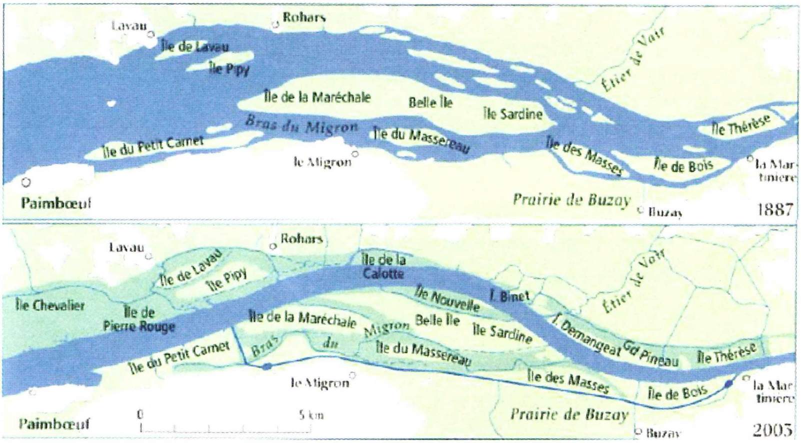


Fig. 16: Canalization of the Loire River (Sogreah, 2006) over a century by reducing secondary channels and intertidal area.

Most estuaries have a sandy riverbed, and the tide dissipates along the river by hydraulic friction. In the vicinity of the mouth, at the head of salinity intrusion, a so-called estuarine turbidity maximum (ETM) is generally found with elevated suspended sediment concentrations (up to a few 100 mg/l).

When such rivers are deepened, the tide is amplified, as shown in Fig. 17. This graph was obtained from an analytical solution of the linearized water movement equations. The amplification increases when canalization takes place at the same time. When the damping of the tidal wave becomes small, the tidal amplitude becomes more or less constant along the entire river.

More important, also the tidal asymmetry in the river is affected - tidal asymmetry governs the net transport (direction) of fine sediment. Fig. 18 shows that upon canalization, the loss of intertidal area changes the direction of this net transport into flood dominant conditions, i.e. net transport is up-estuary. If such conditions prevail long enough, so much cohesive sediments are pumped into the estuary that fluid mud is formed, because of which the effective hydraulic roughness of the estuary decreases to the extend that further tidal amplification is induced (Fig. 17), and conditions become even more flood dominant (Fig. 18).

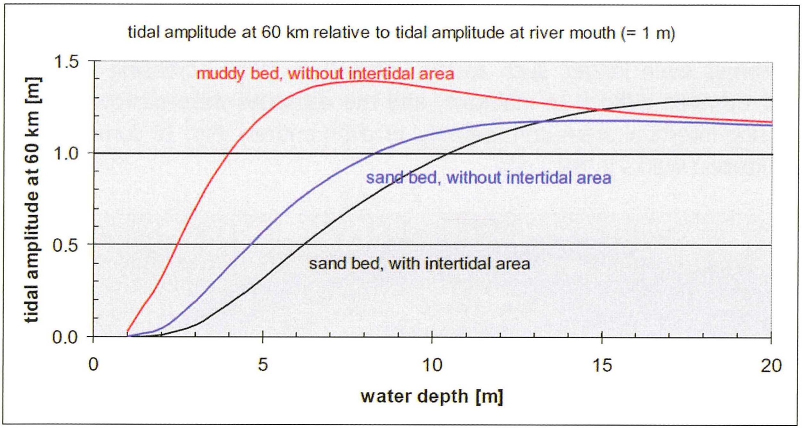


Fig. 17: Tidal amplification along an estuary in response to deepening, and to canalization and the formation of fluid mud.

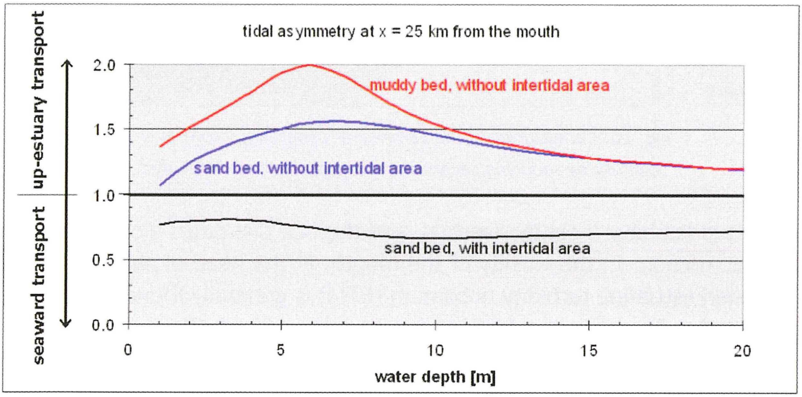
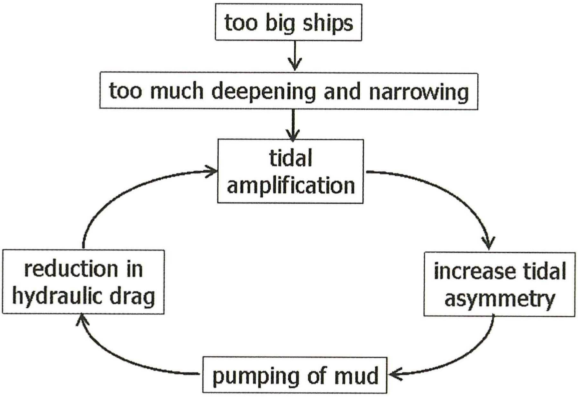


Fig. 18: Tidal asymmetry along an estuary in response to deepening, and to canalization and the formation of fluid mud. This graph shows strong up-estuary pumping of mud in response to canalization.

The interplay between tidal amplification, tidal asymmetry, fine sediment import and hydraulic drag in response to ongoing deepening and canalization is sketched in the feed-back loop of Fig. 19. Hyper-concentrated conditions (the symptoms) become manifest only when sufficient fine sediments have been pumped up-river, which may take decades.



this takes time (decades?)

Fig. 19: Diagram showing the feed-back cycle in deepened and canalized estuaries leading to very small tidal damping and hyper-concentrated conditions.

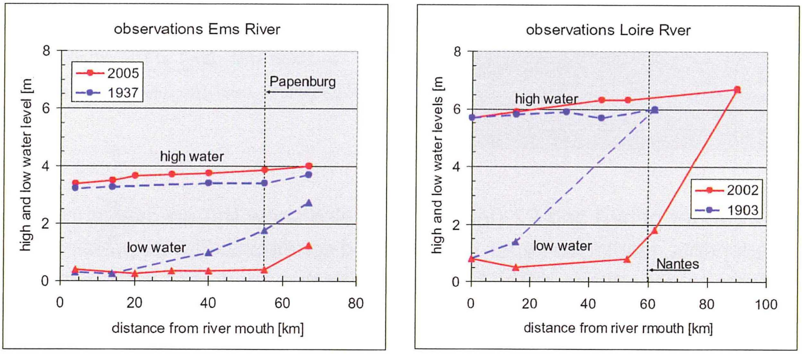


Fig. 20: Observed evolution with time in Ems and Loire River of high and low water levels, in response to deepening and canalization.

In the following, we focus on the Ems River (Germany) and Loire River (France). Fig. 20 presents the measured evolution of low and high waters along the Ems and Loire estuaries over a period of 70 and 100 years, respectively, showing large amplification of the tide, as explained above, in response to ongoing deepening and canalization. Both graphs show that the tidal amplitude has become almost constant over a major part of the river. In particular, amplification along the Loire River has been dramatic.

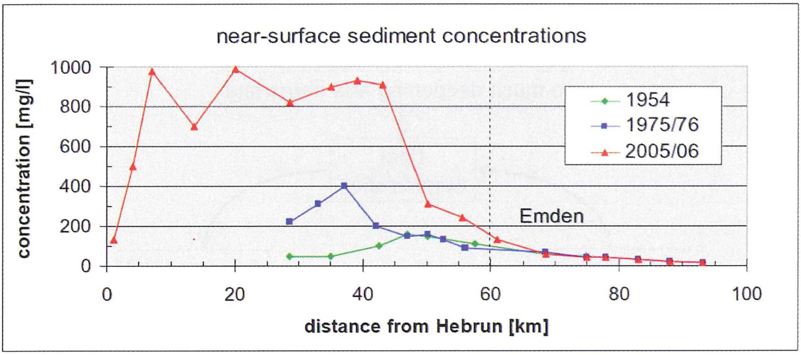


Fig. 21: Evolution of estuarine turbidity maximum in Ems River (upper panel; after de Jonge, 2009) with suspended sediment concentrations up to 40 g/l. The left panel depicts conditions in the river upon passage of a cruise ship, built at the wharf at Papenburg, near the head of the river.

Fig. 21 (upper panel) and 22 (lower panel) also show the up-river pumping of fine sediments, leading to hyper-concentrated conditions. Fig. 21 presents some symptoms to get a flavor of the hyper-concentrated conditions in the Ems River, and Fig. 22 shows the evolution of turbidity and fluid mud intrusion in the Loire River. Moreover, Fig. 22 shows the impact of the large tidal amplification over time on the historical city of Nantes - the low water levels had a devastating effect on the stability of the foundations of many buildings along the Loire River.

In both cases, the systems developed from a "normal" estuary with a moderate turbidity maximum at the head of salinity intrusion to a hyper-turbid system. These conditions are characterized by low primary production, stratification, and low oxygen contents. Initially, the sediment dynamics were governed by estuarine circulation mainly, whereas today tidal asymmetry plays a major role. Reversal to more acceptable conditions is probably only possible at large costs, decreasing water depth, and re-establishment of intertidal areas.

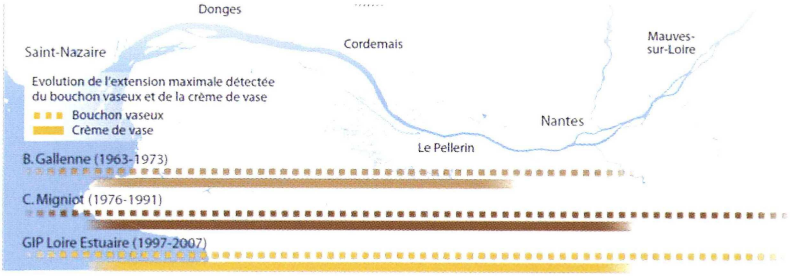


Fig. 22: Deepening and canalization pump large amounts of mud up the Loire estuary (lower panel; after Sogreah, 2006). Low and mean water levels became so low, lowering groundwater levels so much that foundations in the old city of Nantes became damaged, distorting the historic scenery at large scale (right panel).

The future

With respect to process research, we will pursue further work on sediment mixtures and further integration with other disciplines, such as chemistry and biology. Next to current and future scientific and engineering questions, we expect that developments in computational power, and in measuring and observation techniques will give forceful stimuli to our discipline.

From a societal point of view, the management of abundance and shortage of (fine) sediments will become even more important than today, especially in relation to climate change. Two areas in particular emerge:

- thawing of permafrost low lands - most permafrost areas contain large amounts of fine sediments, which may have dramatic effects on the light climate in the currently crystal-clear arctic waters, when mobilized,
- low lying deltas, suffering from sea level rise, subsidence, and shortage of sediment supply by reservoir construction.

Fig. 23 presents an overview of the larger reservoirs in the world (i.e. with a volume in excess of 0.5 km^3) in operation at the beginning of this century (Vörömarty et al., 2003). However, many more smaller dams and reservoirs have been constructed; to get a flavor: China - 50,000; USA - 75,000; and Brazil - 300,000. Such reservoirs and dams trap large amounts of sediments, to the extend that many deltas become depleted of new sediments to keep pace with sea level rise. Fig. 24 presents some examples, and today serious erosion problems exist in many large deltas, such as the Indus, the Yellow River, the Nile and the Mississippi deltas.

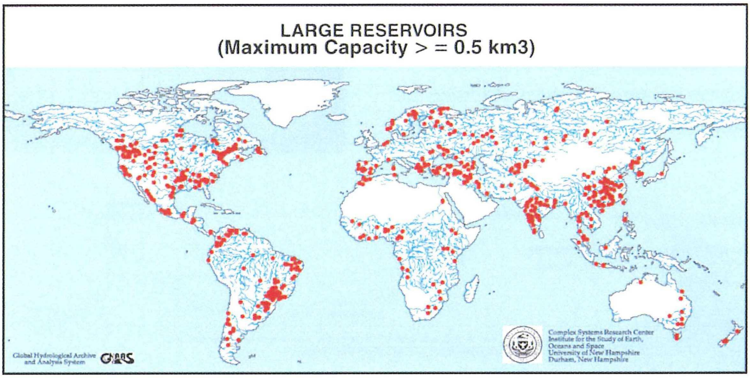


Fig. 23: Overview of large reservoirs at beginning of 20st century (after Vörösmartya et al, 2003).

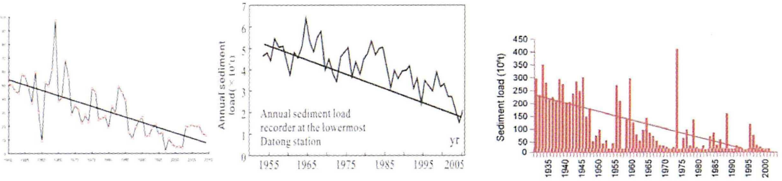


Fig. 24: Decrease in sediment load towards the deltas of the Yellow River, the Yangtze River and the Indus River (from left to right, Walling, 2009).

Accumulation of effects

We should realize that no one in Brazil, for instance, decides erecting 300,000 dams. One dam is built here, and then another one there, and a third one is planned by another agency. At best, the environmental impact of one such a dam on the river's ecosystem is studied.

Also fish and shrimp ponds, rice fields and plantations are erected one by one, often in an even more unplanned manner, by local habitants of the mangrove forest. These people are often driven by poverty, and seek for means to improve their living standards, and provide proper schooling for their children. Most likely, even the impact of small scale land-use on mangrove-mud systems has never been studied by governing agencies.

Similarly, no one took steps to deepen estuaries and rivers by several meters at once, from a few meter to 10 m, for instance, though today, such huge interventions happen occasionally. In general, though, deepening and narrowing is carried out in relatively small steps, by decimeters at a time. Also canalization, by reclamation of intertidal areas, is done in small steps, sometimes with the sole purpose to obtain agricultural land. By law, the impact of such interventions has to be evaluated in environmental impact assessments, at least in Europe, but not the accumulation of effects.

In this speech, I have tried to show that the accumulation of all these small effects can be dramatic, affecting the largest rivers in the world, and entire coastal systems. That upon passing a tipping point, nature may develop in ways not foreseen. Nature can bring the river or coast into a new regime. And such regimes are often unfavorable for humankind, and difficult to reverse to the original state. We should realize further, that the symptoms of such a new regime may become visible only decades after passing a tipping point, as it takes time to supply the sediments needed for these symptoms.

We should also realize ourselves, that even if we have not surpassed a tipping point, we still may alter systems considerably, if nature does not get the time to recuperate from our interventions.

Education and research

Currently, MSc-students in Civil Engineering are taught some basics of the discipline Sediment Dynamics, scattered over a number of courses. This speech shows that there exists an increasing demand in understanding the response of entire ecosystems to engineering works. In some cases, such understanding becomes crucial for the survival of these ecosystems.

The examples presented are all the result of relatively small interventions in the ecosystem (except maybe for the Markermeer): a few fishponds are erected in the mangrove forests, fairways in estuaries are deepened by a few dm, etc. However, the accumulation of effects by these interventions can be huge, and may lead to full shifts in the regimes of aquatic ecosystems. I believe that Civil Engineering students should be made aware of such impacts, and that the underlying feedback mechanisms should be taught, further than the basic processes alone. I hope that this speech may stimulate steps in this direction.

All examples in this speech are ultimately driven by processes at very small scale, the scale of flocs and turbulent eddies (Kolmogorov scale). Many of these small-scale processes are not yet fully understood, in particular in relation to biological and chemical effects, and further research is required.

Furthermore, between these micro-scales and the scale of entire rivers and coastal system, a cascade of scales is relevant. Also at these scales, a series of unanswered open questions remain.

With respect to the regime shifts discussed in this speech, a number of fundamental questions have to be addressed. Only then will we be able to predict, or better, to prevent such shifts and/or to mitigate their effects:

- Can we define tipping points in sedimentary systems, and if so, which environmental parameters rule these tipping points?
- What are the time scales involved - when will the symptoms become visible after passing a tipping point?
- What measures are required, at minimum, to reverse the often unfavorable effects of regime shifts?

The Chair of Sediment Dynamics should contribute in answering these questions.

Ik heb gezegd.

Acknowledgements

I am indebted to Guus Stelling, Marcel Stive, Wim Uijttewaal, Huib de Vriend and Ad van Os. They have pursued the establishment of the chair on Sediment Dynamics over a number of years, and made my appointment possible. During my long carrier, I was fortunate working with many outstanding colleagues, whom taught me many things, and who where highly inspiring. It is dangerous to give names, as easily someone is overlooked. However, at least the following persons should be acknowledged, who have contributed profoundly to my scientific development; in alphabetical order: Jurjen Battjes, Walther van Kesteren, Cees Kranenburg, Ad van Os, Rob Uittenbogaard and Zheng Bing Wang.

The management of both Deltares (Delft Hydraulics) and Delft University of Technology have always confided in me, allowing me to do the things I liked, and thought useful. I am very grateful to Jurjen Battjes, Ad van Os, Guus Stelling, Tom Schilperoort and Wim Uijttewaal. My direct superiors have kept me out of the daily winds of project management etc.; thank you Johan Boon, Tony Minns, Arno Nolte, Andries Roelfzema and Arjan van der Weck.

The chair on Sediment Dynamics is a recognition of the work carried out by a large team over the last 20 - 30 years. Too many Master and PhD students, colleague engineers and scientists, technicians and modelers have contributed to name them personally. Yet, I wish to acknowledge our core team, which today consists of Gerben de Boer, Claire Chassagne, Thijs van Kessel, Walther van Kesteren, Cees Kuijper, Bas van Maren, Bram van Prooijen and Luca Sittoni. I am proud to be one of you.

Finally, I wish to say a few more personal words. I have always been encouraged by my family and friends, always patient with my impatience. I always found a willing ear for my stories, my journeys. With my children Peter and Ineke and with Mary-Ann, I shared many good years of my life, but I realize that for them, these years may not always have been easy. My brother Frans is the great link to my youth and parents, who sadly cannot witness these days. Our ever growing affection means much to me. With Susana I can share all ideas and thoughts, scientific and otherwise, a truly wonderful experience. My many friends are gratefully thanked for their friendship, in good and difficult times.

References

Fig. 9: T. Van Kessel, 2009. Modeling fine sediments in Markermeer.

Fig. 10: G.J. de Boer, 2010. Analysis of SWAN-mud wave model.

Fig. 15, remote sensing image: M. Eleveld.
Fig. 15: IJsselmeer bed composition: Winkels, 1997.

Fig. 16, 20, 21: Sogreah, 2006. Expertise et connaissance du system estuarien; Tome 1 - Analyse historique. Report 1711457R2 - Tome 1.

Fig. 20, 21: S.A. Talke, H.E. de Swart, V.N. de Jonge, 2009. An Idealized Model and Systematic Process Study of Oxygen - Depletion in Highly Turbid Estuaries. Estuaries and Coasts. 32.602-620.

Fig. 23: C.J. Vörösmartya, M. Meybeckc, B. Feketea, K. Sharmad, P. Greena, J.P.M. Syvitskie, 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change, 39, 169-190.

Fig. 24: D.E. Walling, 2009. The impact of global change on erosion and sediment transport by rivers: current progress and future challenges. The United Nations World Water Assessment Programme.

Fig's. 1, 2, 3, 4, 5, 6, 7, 8, 11, 12, 13, 14, 17, 18, 19 & 22: J.C. Winterwerp, personal archive.