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Regime shifts in muddy estuaries: tidal response to river deepening and canalization

J.C. Winterwerp (1,2) and Z.B. Wang (1,2)

(1) Delft University of Technology, Environmental Fluid Mechanics, Delft, The Netherlands, (2) Deltares (Delft Hydraulics), Delft, The Netherlands

Johan C. Winterwerp, Zheng Bing Wang

A number of tidal rivers in Europe, amongst which the Ems River in Germany/Netherlands, and the Loire River in France are characterized by hyper-concentrated conditions with pronounced layers of fluid mud and suspended sediment concentrations exceeding 30 g/l. From an ecological point of view the sedimentary conditions in these rivers are highly problematic, as oxygen levels and primary production are very low.

The present study aims at defining the conditions at which a regime shift in these rivers may occur, yielding a transition from a “normal estuary” with a classical estuarine turbidity maximum governed by estuarine circulation mainly, to hyper-concentrated conditions where sediment dynamics are mainly governed by tidal asymmetry. We hypothesize that these hyper-concentrated conditions are the result of large amplification of the tide and strong flood-dominant conditions, induced by ongoing deepening and embanking of the tidal river. Indeed, today many European rivers, amongst which the Loire and Ems, can be classified as synchronous, with an almost constant tidal amplitude along the main part of the river.

Here we present the behavior of tidal asymmetry in response to deepening and embanking based on an analytical solution of the one-dimensional, linearized water movement in a converging channel, with or without intertidal area. The continuity and linearized momentum equation read:

$$\frac{\partial \eta}{\partial t} + \frac{A_c}{b_c+\Delta b}\frac{\partial u}{\partial x} - \frac{A_c}{b_c+\Delta b}\frac{u}{L_b} = 0\,;\ \frac{\partial u}{\partial t} + g\frac{\partial \eta}{\partial x} + \frac{ru}{h} = 0 \qquad (1)$$

The real and imaginary wave number can be obtained from the dispersion relation, and read:

$$\begin{aligned} k_r^* &= \tfrac{1}{2}\left[2\sqrt{\left(b_* L_*^2 - 1\right)^2 + \left(b_* L_*^2 r_*\right)^2} + 2\left(b_* L_*^2 - 1\right)\right]^{1/2} \\ k_i^* &= 1 - \tfrac{1}{2}\left[2\sqrt{\left(b_* L_*^2 - 1\right)^2 + \left(b_* L_*^2 r_*\right)^2} - 2\left(b_* L_*^2 - 1\right)\right]^{1/2} \end{aligned} \qquad (2)$$

in which an asterisk represents dimensionless parameters defined as $k_* \equiv L_b k$, $L_* \equiv L_b\omega\big/\sqrt{gh}$, $b_* \equiv 1 + \Delta b/b_c$, and $r_* \equiv r/\omega h$.

Further to the amplification of the tidal wave into the estuary, given by the imaginary wave number, we can derive formulations for the tidal asymmetry, the phase angle between flow velocity and tidal elevation, and times of high water along the estuary. The evolution of these parameters is elaborated as a function of water depth and intertidal area, assessing the effects of river deepening and canalization. It is shown that at water depth between 4 and 10 m, the tide is very sensitive to deepening, in particular when intertidal area is lost as well because of canalization: tidal amplification and flood dominance increase rapidly. Moreover, it is shown that the phase difference between flow velocity and tidal elevation rapidly approaches 90^o, in particular when suspended sediment concentrations are high, as in the Loire and Ems. The river gets into a quasi-resonant mode, and highly insensitive to interventions to mitigate the unfavorable conditions which result from the amplification of the tide and profound flood dominance.

We compare our analytical approach with field data, using the dimensionless parameters defined above, allowing for identification of the environmental parameters, which may lead to regime shifts towards hyper-concentrated conditions.