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Net sediment transport by tidal asymmetry in the hyper-turbid Ems River

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Abstract

Fig. 1 presents the seasonal variations in SPM-values measured at Papenburg in the hyper-turbid Ems River, showing an inverse relationship between SPM-values and river discharge. In this paper, we investigate the physical processes which govern this inverse relationship.

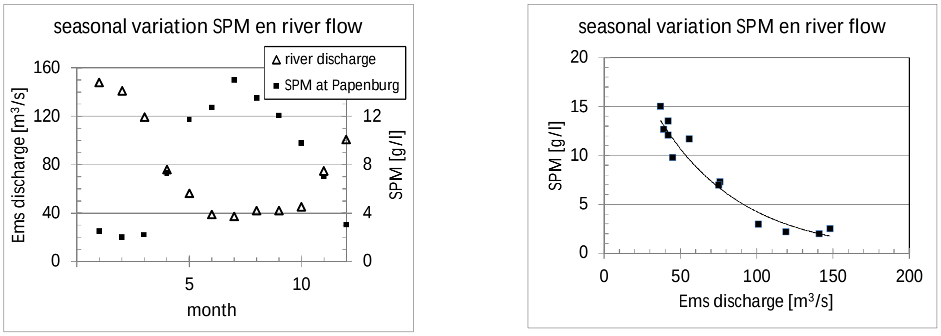

Fig. 1: Monthly mean SPM concentrations measured at Papenburg as function of river flow, data averaged over 10 years.

Winterwerp et al. (2016), analysed data on tidal water level, river discharge, SPM and salinity collected in 2010, in conjunction with velocity data obtained with a calibrated model of the Ems River, based on Delft3D (Van Maren et al., 2015). It is important to note that SPM-values where measured about 2 m above the bed – zero SPM therefore may imply that the sediments are not mixed up to that measuring point. In particular, Winterwerp et al. (2016) studied variations in tidal asymmetry along the river as a function of river discharge. Fig. 2 presents the results of that analysis, using three definitions for the tidal asymmetry, based on peak velocity (A_p), vertical mixing (A_m) and horizontal flux (A_t) – see caption for definitions. Because of the convergence of the river's plan form, the effects of river discharge decrease in down-estuary direction. Conditions for flood-dominance appear stricter for A_t, and less strict for A_p.

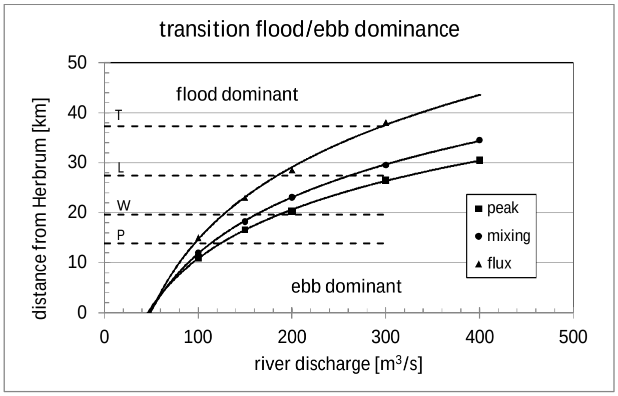

Fig. 2: Transition between ebb and flood dominance along the Ems River (T = Terborg, L = Leerort, W = Weener and P = Papenburg) as a function of river discharge, depicting asymmetry in peak velocities $A_p = \hat{u}_{flood} \big/ \hat{u}_{ebb}$ *, internal asymmetry* $A_m = \frac{T_{ebb}}{T_{fl}} \int_{LWS}^{HWS} u^2 \mathrm{d}t \Big/ \int_{HWS}^{LWS} u^2 \mathrm{d}t$ *and* $A_t = \frac{T_{ebb}}{T_{fl}} \int_{LWS}^{HWS} u^4 \mathrm{d}t \Big/ \int_{HWS}^{LWS} u^4 \mathrm{d}t$ *is asymmetry in along-river sediment transport. Flood-dominance is defined as* A_p, A_m, $A_t > 1$, *and ebb-dominance otherwise.*

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Fig. 2 suggests that the hydrodynamic conditions at Papenburg become ebb-dominant when the river discharge exceeds 90 – 130 m^3/s, depending on the definition used. On average, these flow rates are expected during about four months of the year, e.g. Fig. 1 (though periods of lower discharge may occur in those months as well). Hence, one would expect that mean SPM-values at Papenburg would reduce to zero during these months, while the mud would be flushed down-estuary by the ebb-dominant conditions. Obviously, this is not the case.

From an analysis of the SPM-values in the Ems River, Winterwerp et al. (2016) found that the sediments mix vertically during flood and ebb, while settling around slack water. In particular, it was found that the highest SPM-values in the river are formed directly after Low Water Slack, when the flow velocity increases rapidly to its maximal value. Thus, the peak flood velocity governs the amounts of sediments in the water column. The data further showed that when this peak velocity decreases below a critical value of about U_{crit} = 1 – 1.2 m/s, in response to river discharge and tidal range (spring-neap cycle), the sediments cannot be mixed anymore after LWS, and SPM-profiles collapse. Then, when velocities again surpass their critical value towards spring tide and/or during decreasing river flow, sediments are remixed, and the SPM-profile is restored. At these high flow velocities, up-estuary fluxes are large.

In line with the above, it may be argued, that at very high river discharges also the peak ebb velocity shall exceed U_{crit}, maximal mixing would occur during ebb, and sediment would be transported down-estuary. However, even at the highest river flow in our data series (Fig. 3, January 2011, $Q_{riv} \approx 400$ m^3/s, $\hat{u}_{ebb}$ = 2.5 – 3 m/s), no vertical mixing of SPM is observed during ebb – in fact, SPM values measured at Papenburg, Leerort and Weener were virtually zero. Thus, down-estuary transport can only occur by erosion of the soft (fluid) mud layers during ebb.

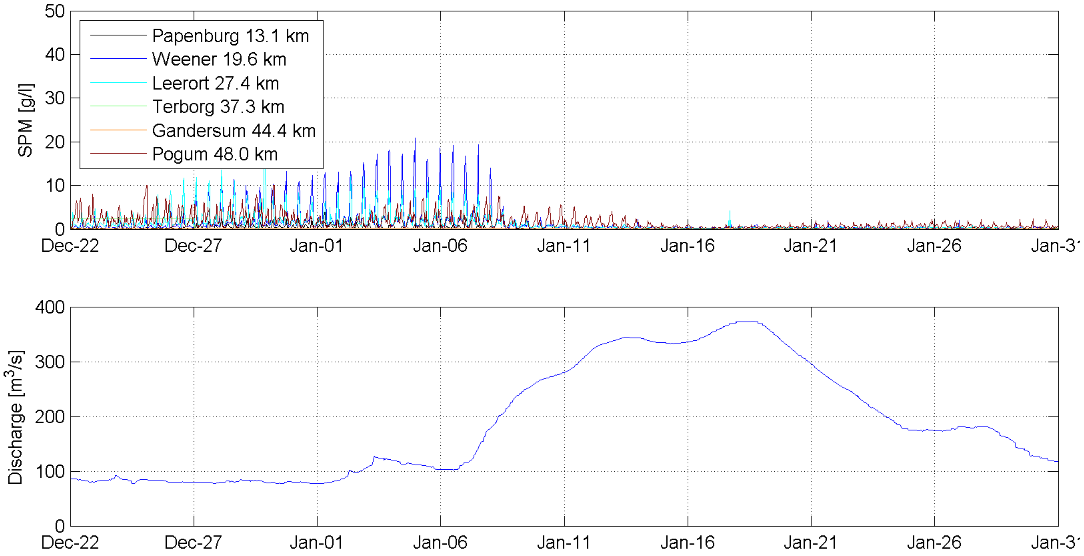

Fig. 3: Collapse of SPM at Papenburg at high river discharge.

Thus the following picture emerges. For conditions at which $\hat{u}_{flood} > U_{crit}$, high SPM conditions are found in the Ems River, with the higher values during flood. Hence, the sediments are highly mobile during these conditions, but flood-dominance prevails. Net up-estuary sediment fluxes are likely to be high.

When $\hat{u}_{flood} < U_{crit}$, sediments cannot be sufficiently mixed and stay close to the bed. Horizontal transport of the sediments is likely governed by the erosion rates of the soft mud layers close to the bed. Then, ebb and flood conditions are more in balance, and the analysis of asymmetric conditions in Fig. 2 applies.

In summary, the seasonal response of monthly mean SPM values can be assumed to be governed by the asymmetry in ebb/flood velocities, inducing relatively small horizontal SPM fluxes. However, when $\hat{u}_{flood} > U_{crit}$, sediments are rapidly pushed back up-estuary, at fluxes largely exceeding the $\hat{u}_{flood} < U_{crit}$ conditions. The effects of river discharge on tidal asymmetry decreases in down-estuary direction, which explains the difference in behaviour of the upstream stations Papenburg, Weener and Leerort with respect to the stations further down-estuary, e.g. Terborg, Gandersun, etc.

References

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