Impact Analysis of Anthropogenic Stresses based on a Morphodynamic Long-term Approach

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Abstract

Morphodynamic processes in estuaries and subordinated tidal marsh-watercourses result from natural processes and anthropogenic changes in developed coastal zones. As a consequence of human activity, the complex natural system of tidal tributaries has been modified to enhance navigation, farming and settlement through flood defense structures, river regulation, land reclamation, and water management, however neglecting the ecosystem functions of estuaries.

This paper combines significant processes in tidal marsh-watercourses based on a research study, which were integrated into a specified long-term approach with special requirements according to anthropogenic stresses like barrier management and stagnant water. This long-term approach includes synthetic long-term boundary conditions for inland runoff, tides and anthropogenic stresses. By using a 2d-hydrodynamic and morphodynamic numerical model, which includes a sensitive morphological speed-up factor with respect to cohesive sediment properties, the ranges of uncertainty for different natural and anthropogenic impacts were considered. The resulting long-term riverbed evolution is compared with the measured morphological developments.

The unsteady behavior of hydrodynamics and sediment retention are the key indicators for changes in the morphology. Therefore hydro- and morphodynamic indicators, like changes in flood dominance, net sediment flux and the shift of turbidity maximum are taken into account. These indicators represent changes in dynamic behavior due to different anthropogenic stresses on meso- and macro-scale and also provided an instrument for further planning measures.

Introduction

Large estuaries are affected by natural influences, anthropogenic deformations and interacting processes with tidal tributaries and marsh-watercourses. These tidal marsh-watercourses form a significant link between marine and fluvial environment. As consequence bi-directional forces due to asymmetric tides and inland runoff deform morphodynamic processes with presence of cohesive and organic sediment. In combination with the high inter-tidal area proportion and anthropogenic deformations special requirements for morphodynamic long-term approaches restrict existing methods.

Processes and anthropogenic stress

Today marshlands in Northern Europe are the most anthropogenic reduced ones with remaining 15% natural marshes (Greenberg et al., 2004). This was caused inter alia by drained marshlands, diked watercourses and construction of storm surge barriers. By additional deformations like the cut-off of natural tidal creeks and river regulation due to navigation, two central consequences appeared: During low tide more than 70% of the riverbed is falling dry and high tides run-up further into backwater than in former times.

Due to the narrowed flow corridor between the dikes big sedimentation areas on the marshland are separated from the watercourse. As consequence high suspended sediment concentrations are not retained by natural intertidal shallow water zones on the forelands or in tidal creek systems, but amplifying the siltation at the banks and bays. On the other hand this separation of the marshland was carried out decades ago, and caused marshland subsidence. This development intensifies drainage management of cut-off tributaries in the hinterland by sluice (ARGE WRRL, 2006): Maximum storage water levels are maintained in order to avoid drying-out of these tributaries during summer in the vegetation period. During winter storage water levels are minimized in order to avoid permanent flood irrigation.

But also storm surge barriers at the mouth influence sediment transport and morphological changes (Figure 1). Recent studies (Gönnert, 1996) and practical experiences as in Lower Saxony (NLWKN, 2007) indicated siltation in the backwater, which requires a monthly up to weekly flushing of storm surge barriers. As consequence first changes in barrier management are realized by later closing and earlier opening against high tide (NLWKN, 2007).

All these anthropogenic impacts (Figure 1) causes severe problems for water management affairs as well as negative impacts on water ecology, which underlines the need for a sustainable water management, as postulated by WFD (EC 2006/60) and the EU Flood Directive (EC 2007/60). Apart from these legal requirements, climate change and the request for an optimum economic use of estuaries, force a rethinking on planning and realization of protection and compensation measures. Therefore, tidal marsh-watercourses should be taken into account in prospective holistic approaches.

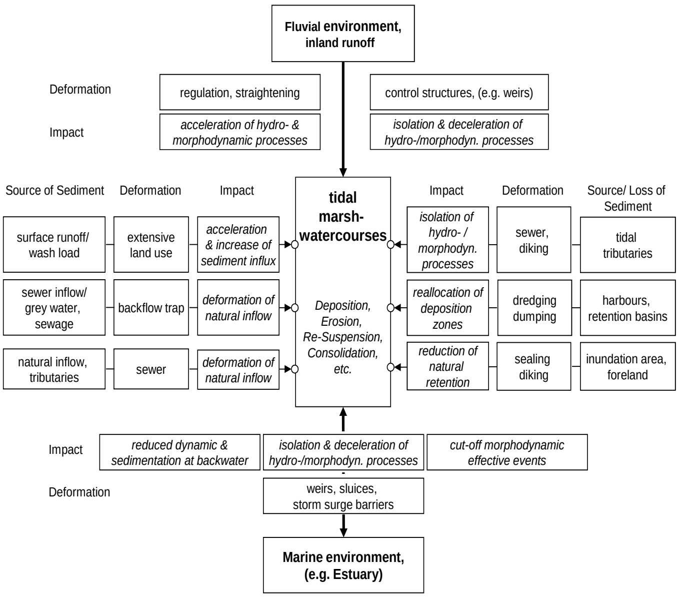

Figure 1: Anthropogenic stresses and their hydro- and morphodynamic impacts for tidal marsh-water courses

Field measurements and derived process zones

Representative for anthropogenic deformed marsh-watercourses is the meso-tidal, oligihaline river Krückau, which is a tidal tributary of the Elbe estuary in Northern Germany. Based on field-measurements of hydrodynamics, suspended particle matter (SPM) concentrations, sediment mixture and bathymetric evolution, hydro- and morphodynamic processes were divided into three process-zones for tidal marsh-watercourses: a tidal, a backwater and a runoff zone (Donner et al., 2010).

- In the tidal zone bi-directional, asymmetric tidal flow and sediment transport are dominating. Bed material consists of cohesive sediments, thus non-linear flocculation and consolidation occur.
- In the backwater zone flow is not bi-directional. Currents are forced by inland runoff, but during high tide the water level is still increasing. Sediment mixture, originated from fluvial sediments, consists of fine-sand, clay and high portions of organic matter (up to 30 %), caused by wash loads and fen grounds.
- In the runoff zone hydrodynamic and morphodynamic regime are purely forced by gravity. Due to changes from marshland to moraines (called Geest), suspended sediment mixture consists of fine and middle sand with decreasing organic fractions (10 - 5 %).

Consequently tides and inland runoff, as well as selected anthropogenic stresses are relevant for the long-term approach.

Methodology for long-term approach

Estimating techniques for long-term morphodynamic changes for marine or fluvial environments already exist: Approaches for estuaries for instance strongly simplify the inland runoff by neglecting discharge variability and flood events. This assumption is not sufficient for marsh-watercourses, where inland runoffs and tides act in a mutual dominance on hydrodynamics, sediment transport and river morphology. Due to hydraulic structures like storm surge barriers, additional hydro- and morphodynamic processes occur. Thus the approach of morphological tides (Latteux 1995, Steijn 1992) failed, due to the complexity of impact parameterization. For transitional waters between fluvial and marine environment with a temporally interrupted dynamic no holistic approach is available. For this long-term approach, special requirements due to asymmetric tides, anthropogenic impacts, cohesive sediments and high inter-tidal area portion are taken into account.

Process-based long-term approach

The concept of the process-based long-term approach for morphodynamic processes in tidal marsh-watercourses is subdivided into three components (Figure 2): long-term boundary, numerical methods incl. acceleration of simulation and data analysis.

The long-term boundary conditions describe water and suspended sediment inflow at open boundaries: For inflow boundaries in the runoff zone measured hydrographs were fragmented into classes by month-wise maximum. For each class the frequency distribution and the sequence of discharge events per hydrological year were determined and synthetic flood events were included. The discharge classes were re-distributed to significant seasonal occurrence into three basic NQ-MQ-, NQ-MHQ- and MQ-HQ-scenarios. These scenarios were modified in duration integrating the annual frequency variability of discharge.

For tidal boundaries a time-lag method superposes tidal cycles to mean neap-spring-tides. Due to preliminary filtering of barrier closure, the two management strategies (closure against low and high tide) were reconstructed. Both strategies were analyzed by using measured data. The impact on suspended sediment and hydrodynamics (Donner et al., 2009) due to gate closure and opening cause significant forms of down- and up-surges including sediment re-suspension depending on flow direction and gate operation. These operational processes were included with a fine numerical time resolution, while the open tidal boundary is closed or opened stepwise. During the stagnant period, numerical time steps were also reduced, considering the non-linear settling behavior of cohesive sediments. Based on seasonal characteristics and statistical analysis, duration and frequency of closure were included into the tidal boundaries. For closure against high tide selected spring tides were superposed with a simplified surge curve ΔH for integration into the basic neap-spring-tide. Depending on duration of closure, the increase ΔH cover 20, 50 and 100 cm for closure over 1.5, 3.0 h and 4.5 h. For closure against low tide the stagnant water level is fixed by operation rules (here +1.6 m.a.s.l.).

Discharge and tide-dependent suspended sediment influx at the boundaries was based on SPM field measurements. A regression analysis of SPM concentrations and inflow at the inflow boundaries results in logarithmic regression functions. Correlation of SPM concentrations with the tidal water level results in hysteretic functions, which differ between an ebb and flood phase (Donner et al., 2010).

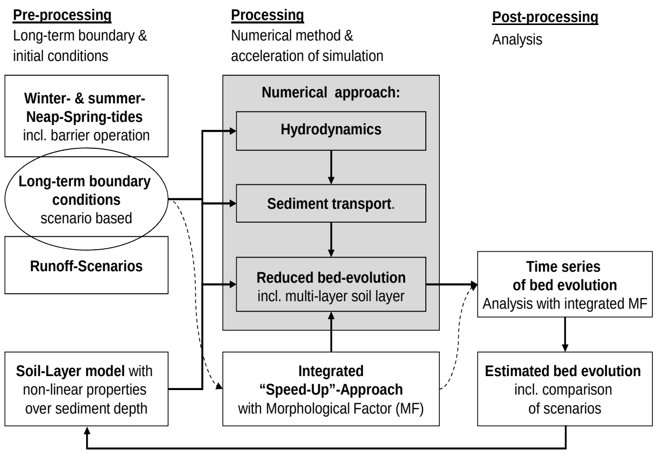

Figure 2: Concept for the long-term approach

Hydrodynamics, suspended sediment transport and a reduced bed evolution are solved two-dimensional, depth-integrated in a coupled scheme by FE-method (KALYPSO RMA): Hydrodynamics are solved by shallow water equations including flow resistance by Colebrook-White, drying and wetting as well as an eddy viscosity approach, which is superposing of a Smagorinsky enclosure with a bed shear stress induced approach. Suspended sediment transport is described with the 2d-advection-diffusion equation with erosion rates according to Partheniades (1965) and deposition rates according to Krone (1962) and Partheniades (1965). Based on laboratory studies settling velocities were derived for cohesive (0.025 to 0.35 mm/s for 100 to 1000 mg/l) and organic sediments (0.175 to 0.34 mm/s for 10 to 900 mg/l). A reduced Exner-equation by neglecting bed load transport is applied for bed evolution. Erosion or deposition initiates an evolution of the multi-layer soil model based on the Lagrange method including two layer-types: soft "suspended layers", which describes the non-linear behavior over a small bed depth, and consolidated "bed layers", which represent an almost linear behavior over the depth. All these layers include discrete characteristic soil properties like porosity, bulk density, critical shear stress and erodibility based on grain size distributions of bed material.

A reduction of simulation time is possible by integrating a variable morphological factors (MF) according to Latteux (1995, "lengthening"), which accumulates bed evolution for longer periods. Thus hydrodynamics and sediment transport are modeled for one numerical time step, while bed evolution and its underlying soil-model change MF-times faster. This accelerated evolution provides a direct feedback to hydrodynamics for the next numerical time step. As one restriction for this approach, bed evolution over the accelerated time-scale must be so small, that no significant errors for hydro- and morphodynamic processes arise.

$$\Delta z_{0,\mathrm{MF}\cdot\Delta t} = \frac{\left(\left\langle S_{dep}\right\rangle_{\mathrm{MF}\cdot\Delta t} - \left\langle S_{ero}\right\rangle_{\mathrm{MF}\cdot\Delta t}\right)}{\left\langle \rho_{b,dry}\right\rangle_{\mathrm{MF}\cdot\Delta t}} \cdot \Delta t \cdot \mathrm{MF} \tag{1}$$

where Δz_0 is the layer integrated bed change, $\left\langle S_{dep}\right\rangle_{MF,\Delta t}$ and $\left\langle S_{ero}\right\rangle_{MF,\Delta t}$ the layer integrated deposition and erosion rate, time averaged over MF-times Δt, $\left\langle \rho_{b,dry}\right\rangle_{MF,\Delta t}$ the dry bulk density of active layers, time averaged over MF-times Δt, MF the morphological factor, Δt the numerical time step.

Calibration and validation on meso-scale

For the calibration and validation of hydrodynamics and sediment transport on meso-scale, short simulated time spans over a few days are compared to measured time series (water level, currents and suspended sediment concentrations). For quantifying the model performance the Adjusted Relative Mean Absolute Error ARMAE according to Van Rijn et al. (2002) was used. For water level the ARMAE was excellent in the tidal zone with less than 0.05 and good with less than 0.3 in the backwater zone. For the currents an excellent range was achieved with an ARMAE less than 0.06. Also the suspended sediment concentration results in good accuracy.

Validation on macro-scale

The validation on macro-scale of the developed long-term approach is carried out in three steps by a comparison of final bed evolution for different approaches, morphological factors and boundary conditions. For evaluation of the

results statistic key parameters are applied: covariance R, mean error ME, mean square error MSE, Brier Score BS, and Brier Skill Score BSS according to Casati et al. (2007).
The first validation step (A) analyses how far an accelerated simulation is feasible by different morphological factors (MF) with 1, 3, 6, 12 and 24 for NQ-MQ to HQ-events. All morphological factors achieved good statistic parameters (R ≤ 0.99, BSS ≤ 0.98), but also showed some shortcomings: For HQ-events especially erosion in the backwater and runoff zone is overestimated, if MF was greater than 4. For NQ-MQ-events the bed evolution in the runoff zone is well performed with all factors, but at the riverbanks of the backwater and tidal zone deposition is overestimated for MF over 12. As consequence acceleration should be limited to MF 4 for flood events and to MF 12 for mean or low discharges, in order to reduce overestimation of morphological processes at the banks in shallow water zones.
The second validation-step (B) analyses, whether the synthetic discharge hydrograph including morphological factors cope with an equivalent, natural discharge hydrograph based on the duration curve. Therefore the measured discharge hydrograph was simulated without MF over 1 year and was compared to synthetic discharge hydrograph (long-term boundary conditions) accelerated by MF 1.2 to 5.9. The deltas at the riverbed are in the range of ±0.6 cm/a (R = 0.98, BSS = 0.96). The deviations are similar to the statistic key parameters from (A), so only a small error can be assumed for the application of synthetic discharge hydrographs in combination with morphological factors.

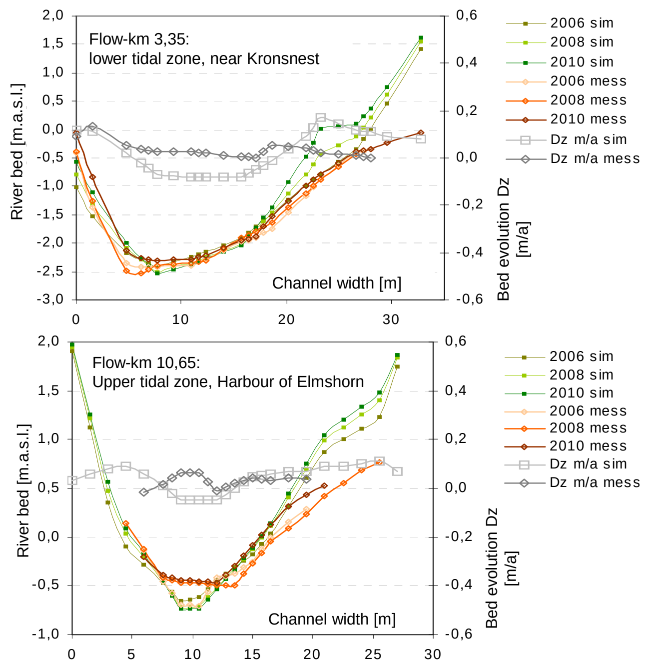

Figure 3: Simulated (based on the long-term approach, see “sim”) and measured (via Multibeam-Echo Sounder, see “mess”) river bed in selected cross-sections in the lower tidal zone (top) and in the upper tidal zone (bottom).

The final validation (C) applies the full long-term approach incl. morphological factors bed evolution. Simulated bed evolution from 2006 till 2010 is compared to measured evolution (Figure 5). This comparison gives the final and overall uncertainty of the long-term approach. The hydrological years are assigned to synthetic hydrographs, based on the natural range and their characteristics. The comparison between measured and simulated bed evolution by statistic key parameters results in quite good to adequate ranges with a mean error of -1.6 cm/a for 2006 till 2007 (BSS 0.91), -1.4 cm/2a for 2006 till 2008 (BSS 0.91), +0.03 cm/3a for 2006 till 2009 (BSS 0.68) and +1.87 cm/4a for 2006 till 2010 (BSS 0.72).

Results and discussion

The described and validated long-term approach is applied for an estimation of bed evolution by including sensitivity analysis concerning event sequence, boundary and initial conditions over 10 years. Bed evolution represented therein following characteristics for the river Krückau: In the middle reach of the tidal zone the riverbed is slightly eroded, while deposition occurs at the banks. In the backwater of the storm surge barrier (near the mouth) the riverbed slightly tends to deposition. Also at the upper end of the tidal zone (near the harbor of Elmshorn) depositions at the riverbed and at the banks occur. The tidal marsh-watercourse indicates an importing system with a net sediment flux pointing upstream in the lower tidal zone and downstream in the central and upper tidal zone. In the lower tidal zone low flood dominance appears, this characteristic changes in the central and upper tidal zone to ebb dominance. The flood dominance is given here by ratio of more than one, derived by the ratio between maximum flood and ebb flow currents. The turbidity maximum is located in the lower tidal zone.
For further analysis of anthropogenic stresses the impact of barrier management and the cut-off tidal tributaries is considered on meso- and macro-scale. Therefore the change of indicators is examined by flood dominance, turbidity maximum and net sediment flux on meso-scale and shift of this behavior based on bed evolution on macro-scale.

Effect of storm-surges barriers management

The barrier management is included into the long-term approach and represents some slight trends and behaviour characteristics in time series of bed evolution. The oscillating water level of the synthetic neap-spring-tides induces also a periodically oscillating bed evolution in the main channel of the tidal zone.

For summer periods, with low inland runoff and moderate high tides, closure against low tides due to irrigation is a typical event (Figure 5): During spring tides a slight trend of erosion appears, while neap tides evoke a trend of deposition phase. Barrier management against low tide initiates for an early evolution state (3 years) a short deposition, which is remobilised in the main channel soon afterwards. Consequently morphology is oscillating on a dynamic equilibrium (Wieprecht, 2007) with a slight erosion trend for the main channel. Regarding the long-term reaction of the riverbed morphology (10 years) not only the trend in the main channel changed from slight erosion to deposition, but also the impact of barrier operation against low tide caused a meta-stabile equilibrium with a long lasting increase of sedimentation after barrier management.

For winter periods higher inland runoffs and higher frequency of closure against high tides is usual (Figure 5): closure against high tide also initiates for an early evolution state (3 years) and also for the long-term morphology (10 years) a short deposition, which is remobilised soon afterwards. Thus morphology is oscillating on a dynamic equilibrium, which is not sustainably affected by barrier managing against high tides.

These deposition and remobilisation characteristics in the main channel change at the riverbanks and in shallow water sections, where a sustainable deposition appears during both barrier closures. These aggradations are not remobilised under tidal velocities.

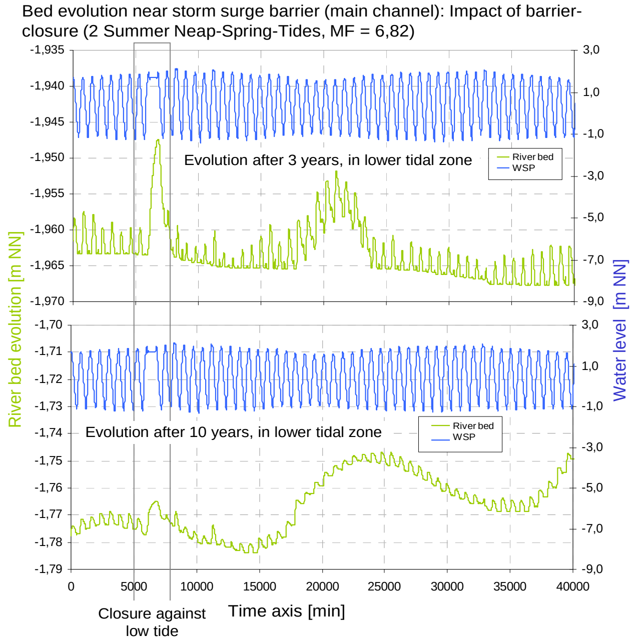

Figure 4: Bed evolution in the backwater of the storm surge barrier (main channel) with impact of barrier-closure after 3 and 10 years during summer neap-spring-tides with closure against low tides

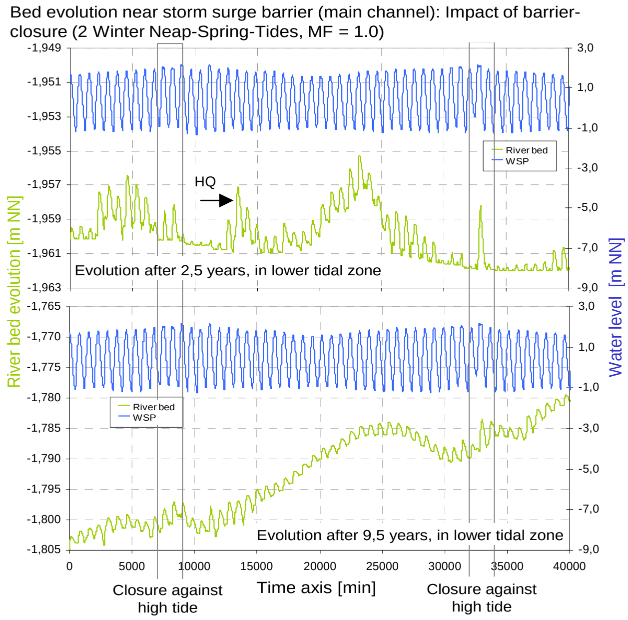

Figure 5: Bed evolution in the backwater of the storm surge barrier (main channel) with impact of barrier-closure after 3 and 10 years during winter neap-spring-tides with closure against high tides

The long-term impact of barrier management was examined in scenarios with sequenced closed and open tidal boundary for the initial state of the riverbed (2006) and for the morphological developed riverbed (10 a later). Constant inland runoffs (NQ, MQ and HQ) were combined with an open tidal boundary over several tides as well as sequenced closure against high and low tide:

- Depositional trend increased on the long-term morphology for depth water sections, but it is reduced at the banks and in shallow waters due to fast deposition during the initial time span.
- Turbidity maximum is reduced by 5 to 15 % and moved about 3 flow kilometers downstream due to morphological changes.

Due to morphological changes flood dominance is reduced slightly, which is forced by sedimentation.

Effect of cut-off and reactivated tributaries

As example for including restoration measures based on the developed long-term approach, the influence of cut-off and reactivated tidal tributaries was investigated here. The impact of cut-off tidal creeks was derived by processes, which appear in open tidal tributaries near the mouth of the river Krückau, based on the long-term approach. Therefore simulated sediment concentration, in- and outflow at the mouth of these tributaries were correlated with the tidal water level in the main water channel. In the lower tidal zone high concentrations of suspended sediment are flushed into the tidal tributary during flood flow (Figure 6, bottom) and settle during a longer phase of slack water and high tide. Mobilization of sediment during ebb flow stays below the flushed in suspended sediment concentration. Thus sediment is trapped in these tributaries, even though the peak outflow during low tide is significantly higher than the peak inflow during high tide (Figure 6, top). These characteristics were figured by all examined tidal creeks in the lower tidal zone. This sediment trapping and water retention behavior reduces the hydrodynamic forces in the upper tidal zone also.

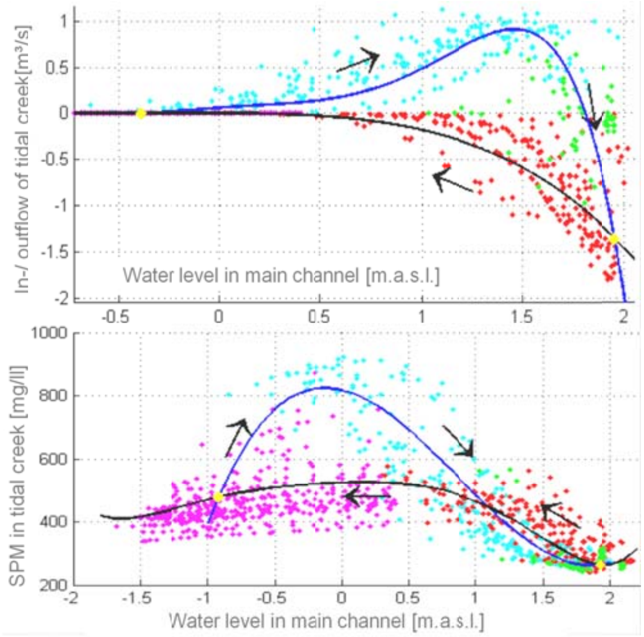

Figure 6: Water level - discharge correlation (top) and water level – suspended sediment concentration correlation (bottom) with flood flow (light blue), ebb flow (red), slack tide from ebb to flood flow (green), almost dry tributary (magenta), polynomial regression in sections (blue and black line), intercept of regressions (yellow) and tidal cycle (black vector), from Karagounis (2011).

A sensitivity study for reactivation of former tidal tributaries, along the tidal zone of the river Krückau (Karagounis, 2011), which are cut-off in nowadays, demonstrated the spatial impact of their retention potential. All numerical reactivated tidal tributaries were analyzed under MQ events and tidal cycle without barrier operation. The retention volume was derived by existent tidal creek with about 5000 m³. The wetting of these tributaries was assumed on an altitude of mean tidal water level. The qualitative results of this meso-scale study represented consequences for the main channel:

Reactivated tidal tributaries in the central tidal zone indicated a minor increase of flood dominance, between the mouth of the main channel and the inflow to the tributary. Due to this reduction suspended sediment concentration decreases slightly, which initiates a strengthening of the sediment flux downstream near the central tidal zone and a reduction of net sediment flux upstream near the lower tidal zone. Due to this reactivation, sedimentation increase in the upper tidal zone.

Reactivated tidal tributaries in the upper tidal zone indicated almost no changes in the key indicators. Only deposition is slightly reduced in the central part of the tidal zone. The reason for this minor effect is the minimal tidal currents and tidal range in this section of the tidal marsh-watercourse.

Attention should be paid to the fact, that due to subsided forelands a reactivation of cut-off tributaries is almost impossible. But in areas were relocation of the dikes or an extensive land use is probable, comparable measures like suggested by ARGE WRRL (2006) by lateral retentions zones are able to restrain water and suspended sediment concentrations.

Conclusion and Outlook

The advantages and limits of the developed long-term approach in order to analyze anthropogenic stresses were examined here for a specific tidal marsh-watercourse Krückau by including and in comparison to dense spatial field measurements. Based on these measurements characteristics of barrier operation were included, because a long-term effect on morphological changes was feared. This inclusion combined with scenario based sensitivity analysis figured out, that there is a temporal sedimentation impact for deep water channels, which may increase after a few years of operation. Especially barrier management against low tide initiates longer lasting sedimentation effects than the classical operation of barriers.

A further application of the long-term methodology for restoration measures was investigated in addition for cut-off tidal tributaries. Therefore key indicators were selected to describe hydrodynamic and sediment transport behavior of the actual state. Based on correlations and a meso-scale based sensitivity study the impact and potential of this reactivation was examined for different locations.

A transfer of this analysis long-term methodology is feasible for estuaries or any tidal influenced rivers in lowlands with cohesive sediments. So a restricted acceleration of morphological changes, due to shallow-water zones and inland flood dynamics, and scenario-based long-term approach can be extended to tidal rivers, if processes as described above and driving forces are comparable.

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