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Simulation of High Suspended Sediment Concentrations and Options for a Reduction in the Lower Ems

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Summary

Estuaries with hyper-concentrated suspended sediment concentration (SSC) provide critical conditions for water management, channel shipping and ecological affairs. Due to the extreme situation of the Ems concerning the SSC, ecologists and water management authorities try to find solutions by different restoration measures, which aim to damp the hydrodynamic asymmetry and to reduce the suspended sediment concentration. Indicators especially for mobilization, resuspension and settling of fine cohesive sediments provide important benchmarks to evaluate restoration potential. Therefore hydro- and morphodynamic indicators like changes in flood and ebb currents, in flood- and ebb current gradients, net sediment flux and the shift of the turbidity zone were assessed. Especially indicators for fine sediments were selected to analyze the potential of meso-scale suspended sediment reduction.

Numerical simulations were performed to increase the Understanding of this estuary. But it shows limits to the existing physical approaches for cohesive sediment transport. For a performance of high suspended sediment concentrations two approaches, one with a simplified flocculation and typical hindered settling, and one with a new flocculation approach taking turbulence and salinity into account, were compared for the Ems Estuary. The hydrodynamic processes, salinity and suspended sediment transport were resolved by a numerical three dimensional finite volume model for the Outer and Lower Ems.

Considering the uncertainties already inherent in meso-scale simulations the long-term effects are difficult to anticipate. Based on an existing long-term approach for a tidal marsh river with cohesive sediments, first conclusions for a promising long-term concept in an estuarine environment are presented.

Keywords

hyper-concentrated suspended sediments, restoration measures, flocculation, indicators, long-term

Zusammenfassung

Ästuare mit extrem hohen Schwebstoffkonzentrationen beeinträchtigen die wasserwirtschaftlichen Nutzungen, die Schifffahrt und die Gewässerökologie. Derzeit versuchen Ökologen und Wasserwirtschaftsbehörden Lösungen für die Ems in Form verschiedener Sanierungsvarianten, die die Tideasymmetrie abmindern und die Schwebstoffkonzentration absenken, zu finden. Indikatoren, die insbesondere für die Mobilisierung, die Resuspension und das Absinken von kohäsiven Sedimenten stehen, liefern für die Einstufung der Sanierungsvarianten wichtige Bewertungsgrößen. Hierzu wurden hydro- und *morphodynamische Indikatoren, wie die Veränderungen der Ebb- und Flutströmung, der Ebb- und Flutströmungsgradienten, des Nettosedimenttransports und die Verschiebung der Trübungszone bewertet. Insbesondere Indikatoren für Feinsedimente wurden gewählt, um eine mittelfristige Reduktion der Schwebstoffkonzentration zu bewerten.*

Für die Prozessbeschreibung dieser Ästuare wurden numerische Simulationen durchgeführt. Allerdings können bestehende physikalische Ansätze für kohäsive Sedimente nur bedingt angewandt werden. So wurden für die Abbildung hochkonzentrierter Schwebstofftransportprozesse zwei verschiedene Ansätze für die Ems gegenübergestellt: Ein Ansatz mit einem vereinfachten Flokkulationsterm und behindertem Absinken sowie ein neuer Flokkulationsansatz, der die Veränderung der Turbulenz und der Salinität mitberücksichtigt. Die Hydrodynamik, der Salz- und der Schwebstofftransport wurden dreidimensional mittels finiter Volumenmethode für die Außen- und Unterems aufgelöst.

Die hier durchgeführte Simulation mittelfristiger Tendenzen unterliegt bereits Unsicherheiten, so dass langfristige Tendenzen nur schwierig abzuschätzen sind. Auf Basis eines bestehenden Langzeitansatzes für tidebeeinflusste Marschgewässer mit kohäsivem Sediment werden erste Schlussfolgerungen für ein Langzeitkonzept in ästuariner Umgebung beschrieben.

Schlagwörter

Hochkonzentrierte Schwebstoffe, Sanierungsmaßnahmen, Flokkulation, Indikatoren, Langzeitverfahren

Contents

1 Introduction

Estuaries form a significant connection between marine and fluvial environments. Due to human pressure, especially the Ems Estuary was impaired inter alia by river regulations, deepening and reduced shallow water zones. The key reason for the high suspended sediment concentration in the Ems today was induced by the hydro- and morphodynamic changes due to the deepening of the Ems (WEILBEER 2005).

Hydrodynamic changes were indicated due to the reduction of the low tide and the increase in of high tide water level, thus the tidal range in Herbrum increased from 1 m up to 3.5 m within the last 70 years (JÜRGES and WINKEL 2003). In addition the asymmetry of flood and ebb increases the flood dominance with higher flood maximum currents while ebb currents are almost constant. The gradient of slack water to flood flow is up to 8 times steeper than, the gradient of slack water to ebb flow.

Currently the Ems estuary indicated a dramatic turbidity increase over the last 15 years: The annual averaged suspended sediment concentration rose from 1 g/l in 1992/93 (SCHUTTELAARS et al. 2009) up to 10 g/l in 2008/09 (NLWKN Aurich 2009) accompanied by an extreme shift of the estuarine turbidity maximum (ETM) to upstream locations. The historical progress of the annual averaged suspended sediment concentration demonstrates that during the 50^{s} the ETM was located in Emden with about 0.2 g/l. After deepening the Outer Ems (1975-76) the ETM was shifted upstream to Terborg with an increase to 0.4 g/l. In 2005 a broad-crested ETM with 1 g/l from Terborg to Papenburg was found. Especially from the mouth of the Lower Ems in the so-called Emder Fairway sediments are imported from the sea side during low and mean discharge events into the Ems Estuary. In addition fluid-mud layers evolve near the river bed. These fluid-mud layers in the upper part of the Lower Ems can be detected by extreme suspended sediment concentration gradients with 3 to 7 g/l/min.

Today ecologists and water management authorities are working together, like for example in the joint research project called "Perspective revitalized Lower Ems" in order to find solutions by restoration measures (Fig. 1) to reduce suspended sediment concentrations and to increase oxygen supply. Therefore different ideas of restoration elements were developed by water authorities, nature protection associations and international experts:

- Tidal polders (retention basins): Tidal polders, which are able to retard tidal volume and sediments and to reduce the tidal volume upstream of these polders.
- Shallow water zones including reactivated historical oxbows: Bifurcations and shallow-water zones on the foreland act like a macro-scale resistance due to the geomorphology. Due to the separation of flow, dissipation reduces currents and consequently the dynamics.
- Lengthening: An increased length of the Ems Estuary by a removal of the weir in Herbrum will change the tidal wave propagation and especially reduce the reflection of the tidal wave.
- Re-leveling: This increase of bed level stands for a reduction of water depth in the deep fairway between Leer and Papenburg, which will result in morphological effect due to a change of the width-to-depth ratio.
- Technical options with different regulations at the storm surge barrier (WURPTS 2012).

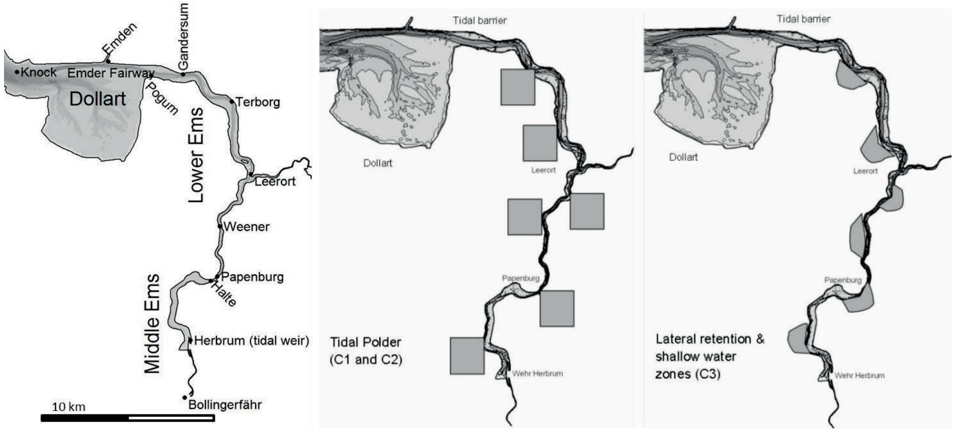

Figure 1: Overview for the Lower Ems (left), sketches of the restoration variants for the Ems Estuary, tidal polders (center) and shallow water zones (right).

This paper will only focus on effects of re-leveling, lengthening, tidal polders and lateral retention, with focus on restoration of the Ems estuary.

2 Methodology

In order to analyze the effect of restoration variants, at first the present situation of the Ems Estuary with its hydrodynamics and high suspended sediment concentrations were recovered by a numerical approach by taking two different approaches for the sediment transport into account.

2.1 Numerical approach

The numerical analysis is based on a three-dimensional resolution of the hydrodynamic processes, the salinity and suspended sediment transport for the Ems Estuary between Borkum and Bollingerfähr (Fig. 1). Therefore a finite volume method with a sigma layer approach in an unstructured grid (MIKE 3 FM) was applied. The hydrodynamics are solved based on the Reynolds-averaged Navier-Stokes equations, with a density coupled to the salinity transport. For the turbulence closure a k-ε approach in the vertical and the mixing length Smagorinsky approach with a coefficient of 0.28 in the horizontal direction was applied. The flow resistance effect of the almost frictionless riverbed, due to the cohesive and muddy sediments, was included based on a roughness approach according to Nikuradse with a roughness height between 0.5 and 5 mm in the supratidal area.

Two different methods (Mud Transport (MT) method and ECO Lab (EL) method) for the sediment dynamics were used and compared. Their main differentiator is the approach for settling velocities. The suspended sediment transport is solved for both methods with the 3d-advection-diffusion equation, taking hindered settling and cohesive sediment properties into account. Due to the presence and a high ratio of fine sand, silt and clay fraction, sand fractions and bed load transport play a less important role for the suspended sediment dynamics, but will gain importance for the morphological changes (WEILBEER 2003).

The erosion rate is based on the formula according to PARTHENIADES (1965) for consolidated cohesive sediments:

$$S_{ero} = \beta_{ero}\left(\frac{\tau_0}{\tau_{c,ero}} - 1\right) \quad \text{for } \tau_0 > \tau_{c,ero} \tag{1}$$

where β_{ero} is the erodibility factor [g/m²/s], $\tau_{c,ero}$ the critical erosion shear stress [N/m²], S_{ero} the erosion rate [g/m²/s], and τ_0 the bed shear stress [N/m²]. For both methods the general empirical erosion and deposition parameters were approximated based on empirical approaches, literature values and grain size distributions for the Ems, which were provided by the BAW and the NLWKN. The dry bulk density of the bed material was estimated based on an empirical approach according to Allersma (1988, in VAN RIJN 2007), which resulted in an interval of 170 to 1290 kg/m³ for the dry bulk density. The critical erosion shear stress was limited based on an approach according to ZANKE (1982) for soft and unconsolidated mud between 0.12 and 0.45 N/m². The erodibility factor was estimated based on the approach according to SCHWEIM (2005) taking the varying range of literature values from 0.01 up to 5 g/m²/s into account.

The deposition rate D is described according to KRONE (1962) by:

$$D = w_s \cdot c_b \cdot \left(1 - \frac{\tau_0}{\tau_{c,dep}}\right) \quad \text{for } \tau_0 \le \tau_{c,dep} \tag{2}$$

where w_s is the settling velocity [m/s], c_b the near-bed concentration [g/m³], $\tau_{c,dep}$ the critical shear stress for deposition [N/m²], D the deposition rate [g/m²/s], and τ_0 the bed shear stress [N/m²]. The critical shear stress for deposition values are given by PARTHENIADES (1965) with 0.04 up to 0.15 N/m² and by LI et al. (1994) with 0.3 up to 0.5 N/m². For the Ems a constant value of 0.07 N/m² was applied.

For the MT method the settling velocities were based on an empirical flocculation approach according to BURT (1986) and a hindered settling for $c > c_{hinder}$ approach according to WINTERWERP (1999):

$$w_s = \begin{cases} \text{constant or linear} & \text{for } c < c_{floc} \\ k \cdot c^{\gamma} & \text{for } c_{floc} \le c \le c_{hinder} \\ w_{s,r}\dfrac{(1-\Phi*)(1-\Phi_p)}{1+2.5\cdot\Phi} \quad \text{with } \Phi_p = \dfrac{c}{\rho_s};\ \Phi* = \dfrac{c}{c_{gel}} & \text{for } c > c_{hinder} \end{cases} \tag{3}$$

where w_s is the settling velocity [m/s], k and γ are coefficients [-], c sediment concentration [kg/m³], Φ the volumetric concentration of sediment [m³/m³], c_{floc} is the threshold concentration for the gelling point [kg/m³], ρ_s is the sediment density [kg/m³]. In the alternative EL method a new approach for the flocculation developed by NGUYEN (2010, 2012) was applied and compared to the MT method. This method is based on the same description and solution of the hydrodynamic as described above (MIKE 3 FM). Also the sediment transport (3d advection-diffusion), as well as erosion and deposition rates are computed analogous based on the approaches by PARTHENIADES (1965) and KRONE (1962). The difference is given by the settling velocity, which is taking the floc size, floc density and drag coefficient into account under consideration of effects caused by salinity and turbulence; the computation of the settling velocity is based on the modified Stokes law:

$$w_S = (1-\phi)\sqrt{\frac{4\cdot(\rho_f-\rho_m)\cdot g\cdot D_f}{3\cdot\rho_m\cdot C_{D,mt}}} \tag{4}$$

where w_s is the settling velocity under turbulence [m/s], ϕ the volumetric concentration of flocs in the mixture [m³/m³], ρ_f the floc density [kg/m³], ρ_m the density of sediment-fluid mixture [kg/m³], gravity acceleration [m/s²], D_f is the floc size [m], and $C_{D,mt}$ the drag coefficient of flocs [-]. The floc size is computed as a result of aggregation and breakup processes. So an increase of suspended sediment concentration leads to a higher probability of primary particle collisions, which is encouraging aggregation. High salinity is considered to support the formation of flocs as well by compression of the electric double layer of the particles and for this reason growing effect of van-der-Waals force. High turbulence will cause a breakup of flocs. Based on the floc size, the floc density is calculated subsequently. The drag coefficient depends on the shape and size of the primary particles or flocs and furthermore on the viscosity of the sediment-fluid mixture. Consideration of turbulence in the calculation of floc size and drag coefficient can be regarded to be a unique characteristic of the approach implemented in EL method.

2.2 Calibration and comparison of the different approaches

The numerical model was calibrated and validated against existing measurements for water levels, currents, salinity and suspended sediment concentrations (Fig. 2). Three summer events in 2008 with a low fluvial discharge (ca. 40 m³/s), a mean discharge (ca. 80 m³/s) and an annual mean flood discharge (ca. 110 m³/s) were taken into account. Winter events and storm surges are not relevant for the high turbidity in the Ems.

For quantifying the model performance the mean error (ME) was used. For water level and the tidal currents the ME was good with less than 0.12 m for the water level (0.05 to 0.24 m) and about 0.14 m/s for the currents (0.07 to 0.22 m/s). A delay appears in the phase between the simulated and measured tidal curve. The amplitude of the high tide is reproduced with variations below 10 cm (mean value) quite well, while the amplitude of the low tide is slightly overestimated with up to about 20 cm. The tidal asymmetry based on the water level gradient over the time is reproduced in the numerical model with a difference between simulated and measured gradients below 0.003 m/min, which is a very good result.

Due to the seasonal variability of the salinity at the sea boundary, which was derived by measured salinity time series at the station in Knock (Ems-km 51, Fig. 1), different boundary values between 30 and 32 PSU at Borkum were analyzed in a sensitivity study. For low fluvial discharges (MHQ to 40 m³/s), which are relevant for the high suspended sediment concentrations in the Ems estuary, the approach of 30 PSU at the sea side represented the measured salinity condition between Knock and Herbrum (Fig.1) with a mean error of 3.1 down to less than 0.01 PSU (Fig. 2).

The calibration of suspended sediment transport results in good accuracy with differences between measured and simulated suspended sediment concentrations of 0.2 up to

3.9 g/l (for MT method) and 0.3 up to 3.7 g/l (for EL method). The high delta of more than 3 g/l is for both methods generated by an underestimation of a local suspended concentration peak in the measured time series. The measured suspended sediment concentration in- and decreases during slack water at low tide from 5 g/l up to 40 g/l with a gradient of ±7.8 g/l/min near Weener (Ems-km 7, Fig. 1) and ±3.7 g/l/min near Papenburg (Ems-km 0, Fig. 1). Both measurement positions are located about 3 m above the river bed.

This peak concentration is only approximately resolved by the numerical model with significant lower amplitude. There might be three reasons for these temporary peak concentrations under minimal flow velocities near slack water:

- Suspended sediments are settling in the water column during slack water and due to hindered settling a very high concentrated near bed layer with an increasing thickness appears
- With the incoming flood flow very high concentrated near bed layer (fluid mud) is moved upstream and is accumulated between Weener and Papenburg.
- Suspended near bed sediments are re-suspended into the water column due to the high velocity gradient after slack water.

Apart from the concentration peaks upstream the tidal oscillation of the SSC is recovered by the numerical model (Fig. 2).

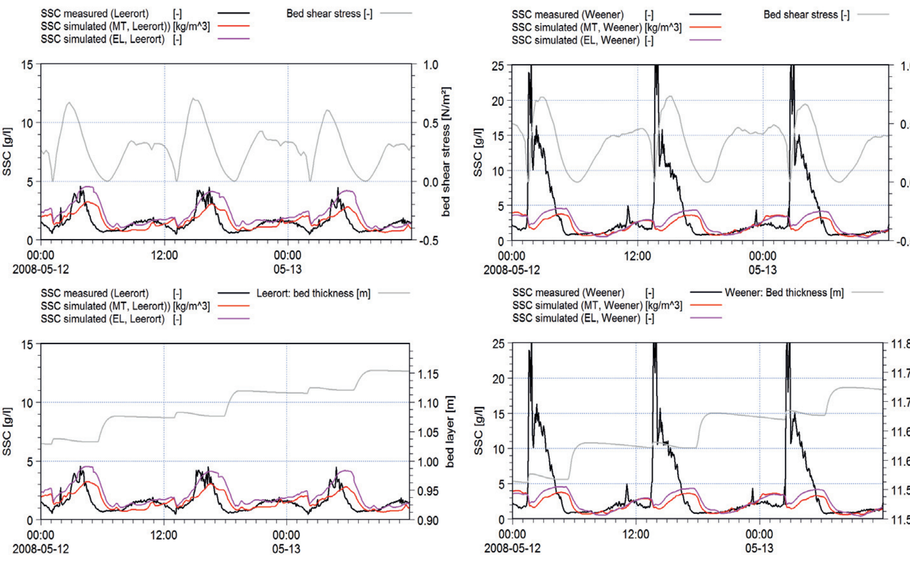

Figure 2: Comparison of simulated and measured time series in 2008 for suspended sediment concentrations at the Station in Leerort (Ems-km 14, left) and in Weener (Ems-km 7, right) in comparison with the simulated bed shear stress and the bed layer thickness, the measured data was provided by NWLKN Aurich (SSC).

The comparison between the two methods for the settling velocity showed, that the refined EL method is able to represent slightly higher suspended sediment concentrations especially during flood flow (see sharp peak in bed shear stress on the right side in Fig. 2). But both methods are not able to refigure the sharp increase and decrease of the suspended sediment concentration in Weener. The reason for that can be found in the shear stress based erosion and deposition rate, which is used for both. Based on this approach the high concentrated suspension can only be refigured in the soft bed layer increase (here with a density of 360 kg/m³). The reaction of the bed layer is represented immediately. The growth of the soft bed layer in both upstream locations is representative for the aggregation of fine soft sediment at the river bed. The morphological feedback due to this growth was not included.

2.3 Assessment of restoration potentials

For the assessment of the restoration variants and their shortcomings so-called key indicators for hydrodynamics and sediment transport, which are representative for fine sediments, were selected. Therefore indicators for flood dominance, tidal asymmetries, tidal range and sediment import where categorized based on their importance on fine sediment transport. The ranking of the indictors is based on the experience of different analyses as well as existing literature (e.g. LANG 2003).

One important objective is the reduction of flood flow, which postulates a reduction of sediment import. The longitudinal section of the maximum gradient ratio between flood and ebb currents represents a rough pointer for position of the ETM in the longitudinal section, with high ratios near the ETM. A reduction of the ratio of maximum currents (flood dominance) and an additional reduction in tidal range, especially a reduction in the upstream increase of both parameters, represent a damping of the hyper-synchronous character. The hydrodynamic key indicators for a restoration assessment are:

- Reduction of tidal asymmetry based on the net flow ratio below 1, which is describing the ratio between flood flow/ (ebb flow – fluvial inflow). This includes a decrease of flood flow as indicator for reduction of flood flow induced sediment transport and an increase of ebb flow.
- Reduction of ratio of maximum gradient between flood /ebb currents (dv/dt) in the main channel, which is an indicator for fine sediment transport acc. to DRONKERS (1986) and is relevant for the duration and intensity of re-suspension or sedimentation near slack water.
- Reduction of flood dominance based on the ratio of maximum flood/ ebb currents in the main channel below 1 (flood dominance with a ratio > 1), which is also representing the hyper-synchronous character of the Estuary and is an indicator for coarse sediment transport acc. to DRONKERS (1986).
- Increase of low tide as general indicator for an effect on the hydrodynamic behavior, which is resulting in a reduction of maximum flood currents and in an increase of maximum ebb currents.
- Decrease of tidal range by avoiding an increase of the tidal range from the mouth to upstream sections (hyper-synchronous character), which a general indicator for an effect on the hydrodynamic behavior.

The restoration effect is evaluated based on a change of the net sediment transport near the mouth and a shift of the ETM. An annual averaged sediment export at the mouth extended to upstream sections will reduce the suspended sediment concentration on larger time scales in the Lower Ems. Therefore a turn from sediment import to export in the Emder Fairway (which is corresponding with the mouth of Lower Ems) is an essential change. Due to this export an accumulation of fine sediments in the fairway can be reduced and enables a change of the grain size distribution in the main channel. On the other hand local sediment import zones in upstream sections are regarded as less critical for the overall situation.

A reduction of the cross-sectional integrated and tidal averaged suspended sediment concentration with a downstream-shift of the ETM should be achieved. This shift indicates a lower sediment transport and consequently a lower mobilization or re-suspension of sediment due to reduced tidal dynamics. The downstream shift is consequently an indicator of a change to lower turbidities. Sediment key indicators for an assessment are:

- Decrease of net sediment import, with a turn to sediment export near the mouth to upstream sections based on a cross-sectional and tidal integrated sediment transport
- Downstream shift and reduction of the ETM based on a mean suspended sediment concentration by a cross-sectional and tidal averaged suspended sediment concentration
- Decrease of cross-sectional and tidal averaged suspended sediment concentration below a critical threshold according to ecologists with 100 mg/l for the fresh water section.

3 Results and discussion

The presented methods were applied to analyze the effect of tidal polder and lateral retentions by a combination of shallow-water zones and reactivated oxbows with the following scenarios:

- Scenario A1 includes a decrease of the water depth between Ems-km 14 up to 0 (Leer to Papenburg) from about -8 to -5 m NN to a constant level of -3.0 m NN (re-leveling). Here two sub-scenarios with the present sediments and with a sandy bed at the re-leveling area were compared
- Scenario B describes a lengthened Ems Estuary with a removed weir in Herbrum and a combination of two downstream polders, one at Ems-km 24 with 200 ha and Ems-km 12 with 400 ha. Both tidal polders are able to store a volume of about 18 million m³.
- Scenario C1 with six polders between Ems kilometer 23.5 up to -7 (7 km upstream of Papenburg) includes a restoration area of 1200 ha with polders between 400 and 50 ha and a tidal retention volume of about 29 Mio m³.
- Scenario C2 with nine polders between Ems kilometer 14 up to -6 (6 km upstream of Papenburg) includes a restoration area of 850 ha with polders between 150 and 50 ha and a tidal retention volume of about 14.2 Mio m³.
- Scenario C3 with eight bifurcations with shallow-water zones on the foreland between Ems kilometer 22 up to -7 (7 km upstream of Papenburg) including an area of 400 ha with new wetted areas between 130 and 30 ha with a tidal volume of about 10 Mio m³.

The re-leveling (Scenario A1) describes an artificial return to a historical bed level before deepening took place. This scenario would require an artificial channel between Ems-km 14 and 0 (Papenburg to Leer) for navigation. Due to this navigation channel downstream of Leer and upstream of Papenburg a deep river bed is necessary, which results in a bed slope between the navigation channel depth and the re-leveling section. This results in a longitudinal section with a plateau between Ems-km 14 and 0. For the re-leveling two sediment types were analyzed: one with the actual grain size distributions (silty bed) and one with sand fractions (sandy bed).

The effect of lengthening was developed and analyzed in detail by SCHUTTERLAARS and DE JONGE (2011). They proved based on an analytical 1d-approach, which is simplifying the detailed geomorphology, but is taking the tidal propagation and cohesive sediment transport into account, that the location of the tidal weir has an effect on the location of the estuarine turbidity maximum. The most important outcomes of their study were: For the actual bed level (here 2005) including the weir at Herbrum the Ems estuary has a length which is close to the M2-tide resonance length, so the tidal wave has a standing wave character. Due to an upstream lengthening of more than 10 kilometer by removing the weir, the model predicted an ETM shift from Leer and Papenburg down to Emden. Similar but less significant effects were represented by a detailed numerical 3d-analysis for the Ems estuary of the BAW (ROLLENHAGEN 2011), which regarded a crest reduction of the weir in Herbrum from +1.8 m NN down to -0.5 m NN. This reduction of the weir height resulted in slight downstream reduction of the tidal averaged suspended sediment concentration and a very small shift of the ETM. Based on these experiences the lengthening was regarded in Scenario B with a full removal of the weir in Herbrum down to the bed level of about -1.5 m NN and was combined with two downstream polders in order to enhance the effect of ETM reduction and to reduce the tidal range by additional measures.

For tidal polders several parameters like the altitude of the bed, its size (volume and shape), position, form and type of the inlet are variable. In order to reduce these parameters, the following assumptions were made for all tidal polders: the polder bed was defined based on the mean low tide of the present situation, polders are connected perpendicular to the main channel, the length of the inlet is reduced to a few hundred meters and the form of the polder is simplified to a rectangle. Only position and size were varied, while the inlet width was narrowed downstream. Here a phase-shifted effect was achieved for the polders near and downstream of Leerort (Ems-km 14) with an inlet width of 30 to 40 % of the main channel width. For the upstream polders an in-phase inlet was used with about 50 to 70 % of the main channel width.

The lateral retention combines deep branches (outer bends) with a flat foreland, which is only wetted during high tide. Analogue to the polders several parameters like the width-to-depth-ratio, the altitude of the branch and the foreland bed, the position, form and types of branches are variable. Thus the following assumptions were made: the width of the branches varies between 75 to 90 % of main channel width, the altitude of the branches is about 1.5 m below the mean low tide, the altitude of foreland is about 1 m below the high tide and the position of the branches was based on historical oxbows.

All scenarios were simulated based on the above outlined numerical approaches for hydrodynamics, salinity and sediment transport by including the described restoration elements based on a short-term period, with measured tidal cycles from May 2008 at Borkum over about 3.5 weeks (MLW +1.27 m NN, MHW -1.97 m NN, tidal range 3.25 m at Knock) and a constant fluvial discharge of 88.11 m^3/s (MQ) at the upstream boundary (Bollingerfähr). For the suspended sediment concentration and salinity 30 PSU and 0.02 g/l were defined at the sea side and 0.34 PSU and 0.05 g/l were set at the upstream boundary.

3.1 Effect on hydrodynamics

The hydrodynamics showed quite different effects for the scenarios: The re-leveling (A1) represented negative effect downstream of the re-leveling and positive effects at the re-leveling section and upstream: The negative effects downstream are characterized by a slight increase of the tidal range with a few centimeters, a reduction of the low tide and an increase of the high tide (Fig. 3). Additionally the maximum flood currents rose, which results in an increase of the flood dominance. At the re-leveling and upstream tidal range is reduced up to 1.4 m (A1, Fig. 3, top right).

The lengthening (B) showed an improvement for tidal water levels with a continuous reduction of the mean tidal range up to 1.1 m (Fig. 3, top right). All polder and shallow water zone scenarios showed a continuous reduction of the mean tidal range with up to 2 m (C1 and C2) and 0.8 m (C3). The maximum tidal range in the longitudinal section is slightly reduced to about 3.4 m for all scenarios (B, C1 to C3) and position of the maximum between Ems-km 10 to 40 is shifted downstream to Ems-km 30 to 40.

The polder and shallow water zone scenarios showed a reduction in flood dominance based on the ratio of maximum flood to ebb currents (Fig. 3, bottom left) by 30 % (C1), 25 % (C2) and 15 % (C3) between Ems-km 40 and 15 and by 20 % (C1, C2 and C3) between Ems-km 15 and -5. The local maximum of the flood dominance is decreasing from a flood-dominance ratio of 1.3 (present situation, Fig. 3) down to a slight ebb-dominance with about 0.9 (C1 and C2, Fig. 3), but is not shifted downstream. Only for scenario C3 the local maximum is shifted about 10 km downstream, but still remains flood dominant with 1.0 between Ems-km 10 to 20. The ratio of the maximum flood to ebb gradients, which has is maximum with 8.0 for the present situation near Papenburg (Ems-km 0, Fig. 3), is shifted downstream to Ems-km 20 to 40 for all scenarios. The reduction of the ratio due to the scenarios reaches 3.0 for C3, 2.5 for C2 and 2.0 for C1.

One important effect was represented by the net balance of flood/ ebb flow without fluvial discharge (here MQ) as a ratio for the tide-driven volume flow (Fig. 3, top right). The net flow ratio, which represents a peak value of factor 2.0 near Ems-km 0 (Papenburg) was shifted downstream with about 5 km by A1, but only a slight reduction to 1.6 (A1). For B no downstream shift appears, but the peak value is reduced to about 1 (Fig. 3). By C1 and C2 the peak of net flow ratio was shifted downstream with about 10 km and reduced to 1.0 (C1) and 1.1 (C2). For C3 the downstream shift increases to about 20 km and the peak value is reduced to 1 (Fig. 3).

Regarding the flood flow (volume/ duration), displayed in Fig. 3 (bottom left) in addition different effects of the extended polder section in C1 and the reduced upstream polders in C2 are obvious. Due to any tidal polder the tidal volume (flood and ebb volume) is increasing downstream due to an increasing wetted area (geomorphology) and reduced upstream. In addition the duration of the ebb and flood flow is slightly shifted to a more symmetric distribution (shortening of the ebb duration and lengthening of the flood duration). Thus downstream of tidal polders two different effects are superposed: an increase of flood volume as negative effect and an increase of flood duration as positive effect. In a certain distance downstream of the polders, the flood flow (volume / duration) represents a positive effect with a reduction in the flood flow. This reduction is extended in length and increasing in intensity, if tidal polders are shifted to upstream positions

(Fig. 3). This positive effect of upstream polders was also examined by ROLLENHAGEN (2011) and in a detailed analysis by CHERNETSKY (2012).

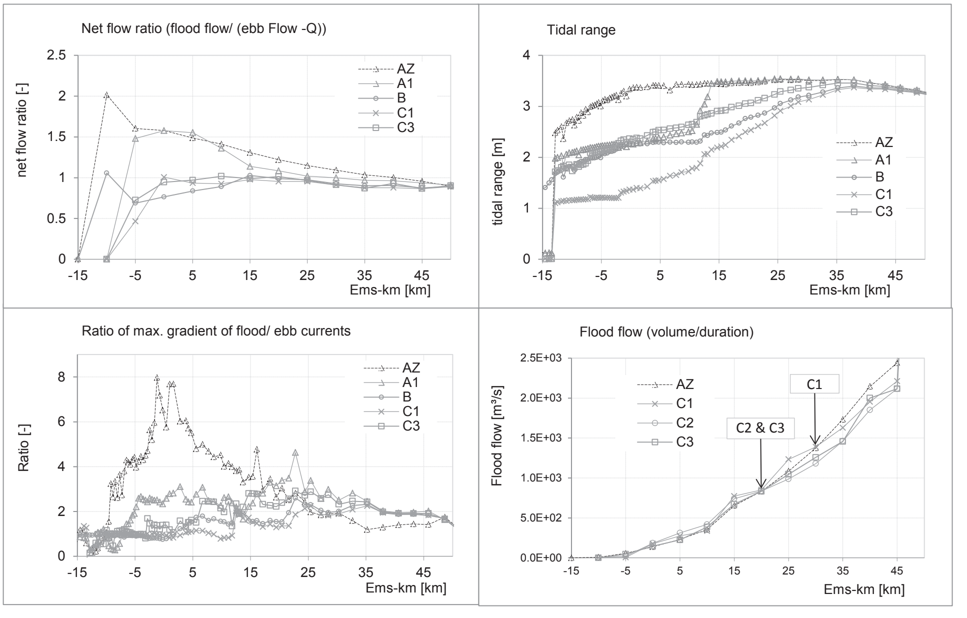

Figure 3: Longitudinal sections for the hydrodynamic indicators net ratio of flow (top left), tidal range (top right), ratio of maximum flood/ ebb currents (bottom left) and flood flow (bottom right) and for the present situation (AZ), for the scenario A1, B, C1, C2 (displayed for flood flow) and C3.

For hydrodynamics, the scenario C2 with a 30 % reduced and upstream shifted polder section represented the most positive effects on the tidal currents, tidal range and the tidal induced volume flow. The scenario C3 with its lateral retention has the smallest effects on the hydrodynamic side.

Scenario A1 showed shortcomings downstream, while the effects on tidal range and tidal currents were distinct in at the re-leveling and in upstream section. The main reason for this negative impact is the sharp increase in the bed level at the re-leveling, which is comparable to a fixed ground sill. So the tidal wave is reflected and tidal asymmetry is increasing in this downstream section. Upstream of the re-leveling, backwater effects with long-lasting reduced currents and significant reduced tidal water level oscillation appears. The rising low tide is induced by the elevation of the bed level and a reduction of the wetted area in the re-leveling section. This is also displayed by a reduction of the flood volume and ebb volume flow.

3.2 Effect on suspended sediments

For all scenarios sediment transport indicators like net sediment flux, a shift of the estuary turbidity maximum (ETM) and suspended sediment concentration (SSC, tidal averaged and cross-sectional integrated) were taken into account. An important indicator for a meso-scale change for the suspended sediment concentration was derived by the extension and the intensity of sediment export from the mouth of the Ems estuary (Emder fairway). For the present situation at a mean fluvial discharge (MQ) an import near the mouth with about 2000 t/tide appears.

For the re-leveling (A1) the ETM is shifted downstream near to Ems-km 15, combined with a slight reduction of sediment import, but a lengthening of the import zone to upstream. The different sediments at the re-leveling (A1), silty sediments (like in the present situation) and sandy sediments (A1s), had only slight effects on the hydrodynamic behavior. With regard to the sediment dynamics the sediment types play an important role. For the silty river bed the ETM is shifted downstream from Ems-km -5 to Ems-km 15 with a strong increase from 3.2 g/l up to 4.5 g/l (A1). For a sandy bed at the re-leveling the import and export characteristics is the same, and also the estuary turbidity maximum is shifted downstream from Ems-km -5 to Ems-km 15, but with a decrease from 3.2 g/l up to 2.4 g/l (A1s). Additionally the natural water depth is higher than the proposed one. Therefore the re-leveling will be eroded and causes extra turbidity.

For the lengthening (B) the ETM is slightly reduced from 3.2 to 2.5 g/l, but shifted upstream by 5 km, but has a positive effect on the relevant sediment export over the Emder Fairway. The upstream shift of the ETM reveals two effects: the increase of tidal influence, which is already display in the hydrodynamic behavior, but also the mobilization of sediments upstream of the former weir at Ems-km -15. Due to the removal of the weir water level is tidal influence with a range of about 1.5 m (see Fig. 3). Consequently currents are increasing compared to former backwater currents to ebb-dominant currents. Upstream of the removed weir (Ems-km -15 to -20) only tidal water levels, but no flood currents (upstream velocities) appear anymore, so sediment is mobilized especially during low tide and higher currents (increase of about 200 %). These processes are increasing sediment concentration up to 0.9 g/l upstream of Ems-km -15 due to a short term mobilization of fine sediments there.

For tidal polders (C1, C2) and lateral retention (C3) the suspended sediment concentration on short-term is only slightly reduced, but the ETM is shifted downstream by 14 km with a reduction to 2.3 g/l (C1), by 16 km with a reduction to 2.7 g/l (C2) and by 5 km with a reduction to 2.0 g/l (C3). By C1 a reduced extension of sediment export up to about Ems-km 20, which was already analyzed for the hydrodynamics (see flood flow) with about 10000 t/ tide was initiated. For C2 and C3 this export is lengthened to Ems-km 15 with about 9000 t/tide (C2) and 8000 t/tide (C3).

The re-leveling scenarios based on the actual sediment characteristics demonstrated on short-term negative impacts on the sediment transport with an increase of the ETM. These high turbidities at the re-leveling are forced additionally by the discontinuity between the re-leveling and the downstream navigation section. The downstream shift of ETM is evaluated as a positive effect, which is representative for an improvement of the situation at the re-leveling and in upstream section. The increasing reach of the net sediment import from the Emder Fairyway indicates a medium-term worsening of the situation in the Ems, which fit together with the negative effect on the hydrodynamics in this section with an increasing flood dominance, tidal range and tidal asymmetry. For the sandy bed a reduction of the ETM but a comparable behavior of sediment dynamics including the same net sediment import and export zones were revealed.

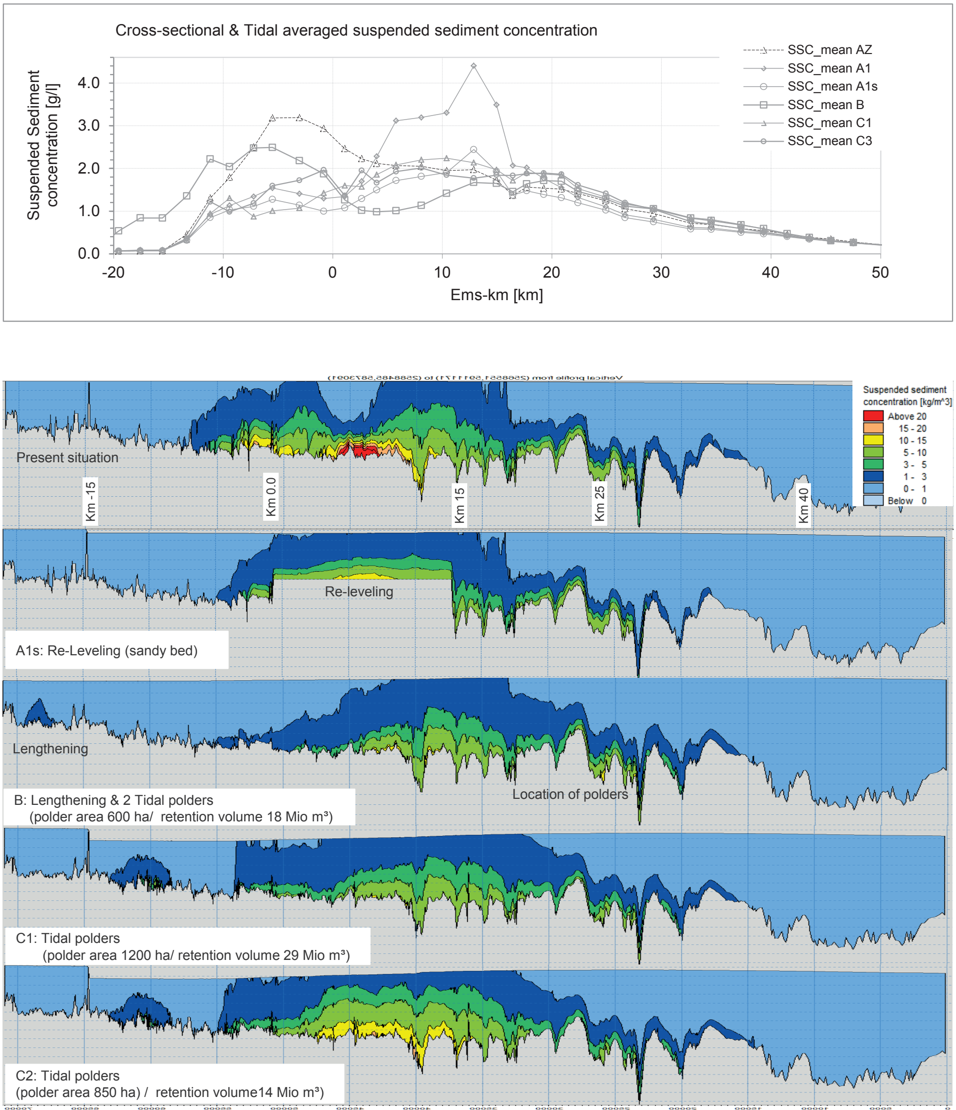

Figure 4: Longitudinal sections of cross-sectional averaged and tidal integrated suspended sediment concentration (top) and 2d-longitudinal sections of suspended sediment concentration in the river axis during high tide for the present situation (second figure), for the re-leveling with a sandy bed (A1s, 3th figure), for the lengthening and two tidal polders (B, 4th figure), for six tidal polders (C1, 5th figure) and for nine tidal polders (C2, 6th figure).

4 Conclusion

4.1 Restoration potential

For scenario A1 the re-leveled flow section, which can develop morphologically without any maintenances, provide an additional restoration potential for sediment trapping in this section. Due to the assumed sandy sediments at the river bed the ETM was reduced and shifted downstream with about 17 km, while the net sediment transport near the mouth is only slightly reduced, but lengthened to upstream sections. This import zone is evaluated as a strong negative impact for both (silty & sandy) scenarios, which stands for an on-going fine sediment import from sea side and worsening of turbidity. No changes in the sediment characteristic under assumed maintenance (preservation of the existing morphology) appear downstream of the re-leveling. Together the restoration potential and free development of the Ems at the re-leveling section of both scenarios resulted in low to moderate, keeping the above mentioned shortcomings in mind.

The lengthening of the Ems combined with the tidal polders near Emden show on short term deficits with an upstream shift and only a slight decrease of the ETM. The most positive effect, which will result in a medium-term reduction of fine sediments in the lower Ems, is shown in a turn from net sediment import to an export. Due to the negative effects of the mention upstream shift of the ETM the restoration potential of the analysed scenario was evaluated with low.

On short-term significant changes with a strong improvement of the hydrodynamic indicators were achieved for tidal polders and lateral retention variants. For the sediment dynamics a slight downstream shift of the ETM was achieved, but the suspended sediment concentration was not reduced below the defined critical threshold of 100 mg/l. But all scenarios showed a turn from sediment import to an export near the mouth, which is an indicator for a further improvement and reduction of the suspended sediment concentration. But this reduction is strongly linked to a morphodynamic change and changes in the composition of sediments, which should turn to coarser sediment fractions in the lower Ems. Due to anthropogenic pressures, like regular channel deepening for navigation, revetments at the banks and water management for the hinterland, only a small corridor of morphodynamic changes is feasible. As consequence new wetted areas like polders or shallow water zones with endorsed morphodynamic changes, provide an increased restoration potential (Tab. 1).

Together with the qualitative classification of the net sediment export to upstream sec-tions, the short-term- shift and reduction of turbidity a meso-scale restoration potential was derived. The evaluation of the restoration potential on meso-scale, which is only pro-vided in a qualitative way (Tab. 1), delivers the highest potential for scenario C2 due to the positive effect of the upstream polders, the extended net sediment transport and sig-nificant downstream shift of the ETM. The scenario C1 represents some shortcoming based on the negative effect of the polder near the mouth. In addition the sediment export is higher but does not extend as far as in the scenario C2 with the smaller upstream polders. In shallow water zones of the lateral retention areas (C3) sediments will accumulate and reduce the trapping effects on medium-term.

Table 1: Medium-term restoration potential of restoration variants for the Ems

Key indicator	Scenario A1s (re-leveling with sandy bed)	Scenario B (lengthening & tidal polders)	Scenario C1 (tidal polder)	Scenario C2 (tidal polder)	Scenario C3 (lateral retention)
Potential for a morphological development: area and section	re-leveling over 14 flow-km	Polder areas 600 ha, Lengthening over 9 flow-km	Polder areas 1200 ha over 31 flow-km	Polder areas 850 ha over 20 flow-km	Retention area 400 ha over 29 flow km
Net sediment transport (flood – ebb): Export from the mouth (intensity and extending)	Increase of sediment import in length up to Ems-km 35 with 800 t/tide	Extension up to Ems-km 20 with export 10.000 t/tide Negative effect of polder near the mouth	Extension up to Ems-km 20 with export 10000 t/tide Negative effect of the polder near the mouth	Extension up to Ems-km 15 with export 9000 t/tide No negative effect near the mouth	Extension up to Ems-km 15 with export 8000 t/tide No negative effect near the mouth
Downstream shift of the ETM: intensity and distance of the shift	Downstream shift with 17 km, reduction to 2.4 g/l	Upstream shift with 5 km, but reduction to 2.5 g/l	Downstream shift with 14 km, reduction to 2.3 g/l	Downstream shift with 16 km, reduction to 2.7 g/l	Downstream shift with 5 km, reduction to 2.0 g/l
Restoration potential	low	low	moderate	high	moderate

A powerful correlation between hydrodynamic changes, like the tidal range or flood dominance, and sediment transport like net sediment transport or ETM was not feasible. Thus an isolated interpretation of the restoration potential exclusively based on the hydrodynamic indicators, might deliver an insufficient priority variant.

4.2 General conclusion

The re-leveling which is acting like a fixed ground sill showed on short-term negative impacts on the hydrodynamics and sediment transport. Due to this bed level change a discontinuity appears. A simplified analysis of morphological stability of the re-leveling showed, that erosion of this ground sill will take place. Consequently this horizontal re-leveling will turn to a sloped shape. Positive effects on hydrodynamics are increasing and sediment concentration is strongly reduced due to the sandy river bed at the re-leveling.

The lengthening combined with two polders downstream, resulted in differing results, compared to the findings of previous studies. Thus a downstream shift of the ETM was examined by a 1d-approach of Schuttelaars and De Jonge (2011) and reduction without a significant downstream shift of the ETM was examined by a 3d-analysis by Rollenhagen (2011). The reason for different results is based on different assumptions: here the weir was fully removed, which resulted in an extension of the tidal influenced estuary length. This tidal influence induces on short-term a mobilization of fine sediments near the former weir. This lengthening shifts the ETM to upstream sections, but also displayed a split into two separate diverging ETMs, which was also revealed in the 1d-analysis (Schuttelaars and De Jonge 2011). A newer 3d-analysis by Jürges

(2013) with a lengthening and shortening of the Ems estuary showed a similar behavior of hydro- and sediment dynamics as presented here.

Different locations, distributions as well as retention volume influence the retention and sediment trapping potential. Especially tidal polders (in C1, near Ems-km 25) near Emden as well as big polders along the river showed shortcomings on hydro- and sediment dynamics with an increase of flood dominance, due to an earlier slack water and ebb flow phase in the polder. Consequently a draining of the polder starts before slack water in main channel takes place, strengthens flood currents and amplifies local sediment import. But also big polders with more than 250 ha in upstream parts showed negative local effects with an increase of flood currents near the inlet accompanied by an erosion tendency, which is derived from the change from net sediment export downstream to sediment import upstream.

5 Outlook

The analysis on short-term does not deliver a final answer on the sustainability of restoration measures, but is indispensable to analyze shortcomings and allow an optimization of future restoration variants. Only for scenarios with a high restoration potential further analysis of long-term morphodynamic changes are recommended.

Therefore already central findings for a cohesive sediment dynamic system in DONNER and NEHLSEN (2012) can be transferred to a long-term concept for the Ems estuary. The first requirement for any long-term concept is the availability of observational data on sediment dynamics and on morphological changes including dredged amounts and volumes. Only based on observed bed level changes any simulation of bed level change can be assessed. In addition different for example month-wise scenarios of fluvial discharge and tide need to be selected and combined in order to reproduce a typical annual cycle. A comparable long-term concept for an estuary with significant low suspended sediment concentrations (DONNER and NEHLSEN 2012) already revealed, that any morphological speed-up combined with the strong non-linear behavior of all settling and erosion processes will be limited to very low factors. Thus for sediment concentrations up to 1 g/l the morphological speed-up was limited between 1 and 6 in order to avoid any overestimation of deposition at least in shallow water zones due to missing morphological feedback. Thus any long-term approach for the Ems estuary will be strongly limited to data and additional restrictions due to very high suspended sediment concentrations, results in non-linear behavior, which cannot be simplified to an almost linear behavior on short-term, which is feasible for sandy river beds.

Nevertheless an estimation of long-term effects on suspended sediments and sediment composition is necessary, to show if any restoration scenario is able to reduce sediment import and the extreme high suspended sediment concentrations on longer time scales. Thus already a further reduction and downstream shift of the ETM after a short time period might indicate a tendency to improve the situation in the Ems.

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