Article, Published Version

Kösters, Frank; Grabemann, Iris; Schubert, Reiner

On SPM Dynamics in the Turbidity Maximum Zone of the Weser Estuary

Die Küste

Zur Verfügung gestellt in Kooperation mit/Provided in Cooperation with:
Kuratorium für Forschung im Küsteningenieurwesen (KFKI)

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/101702

Vorgeschlagene Zitierweise/Suggested citation:
Kösters, Frank; Grabemann, Iris; Schubert, Reiner (2014): On SPM Dynamics in the Turbidity Maximum Zone of the Weser Estuary. In: Die Küste 81. Karlsruhe: Bundesanstalt für Wasserbau. S. 393-408.

Die Küste, 81 (2014), 393-408

On SPM Dynamics in the Turbidity Maximum Zone of the Weser Estuary

Frank Kösters, Iris Grabemann and Reiner Schubert

Summary

The estuarine turbidity maximum zone (ETM) of high suspended sediment concentration is highly variable on different time scales. As the ETM is closely linked to river siltation problems, an improved understanding can help to optimise sediment management within the estuary. Variability on intratidal, spring-neap and river discharge-related (seasonal) time scales is reviewed based on data from older measurements and recent monitoring and compared with modelling results. Previous results describing intratidal dynamics as a cyclic process of advection, deposition and resuspension are corroborated. Strong coupling is evident between the ETM and the mixing zone, not only on the intratidal movement but also as a shift of both in reaction to changes in river discharge. Spring-neap variations are mainly evident as changes in suspended sediment concentration and small changes in the ETM extension.

Keywords

suspended sediment transport, Weser estuary, estuarine turbidity maximum, mixing zone

Zusammenfassung

In der Trübungszone eines Ästuars schwanken die hohen Schwebstoffkonzentrationen auf unterschiedlichen Zeitskalen. Da mit der hohen Schwebstoffkonzentration auch hohe Sedimentationsraten und eine Verschlickung von Hafenanlagen verbunden sein können, ist ein umfassendes Systemverständnis zur Optimierung des Sedimentmanagements notwendig. Auf der Basis von zurückliegenden Messkampagnen und Daten aus Dauermessungen wird die Variabilität der Trübungszone auf intratidalen Zeitskalen, dem Spring-Nipp-Zyklus und verbunden mit Änderungen des Oberwasserabflusses (saisonale Zeitskala) untersucht und mit Modellergebnissen verglichen. Vorhergehende Ergebnisse, die die intratidale Variabilität als zyklischen Prozess aus Advektion suspendierten Materials, Deposition und Resuspension beschreiben, werden auf Basis der aktuellen Ergebnisse bestätigt. Eine starke Kopplung von Brackwasserzone und Trübungszone ist nicht nur auf der intratidalen Zeitskala sichtbar, sondern auch auf längeren Zeitskalen als Reaktion auf geänderte Oberwasserabflüsse. Der Spring-Nipp-Zyklus zeigt sich in den Schwebstoffkonzentrationen, die bei Springtide deutlich größer sind als bei Nipptide, und geringfügig in der Ausdehnung der Trübungszone.

Schlagwörter

Schwebstofftransport, Weserästuar, Trübungszone, Brackwasserzone

Contents

1 Introduction 394
2 Regional setting 395
3 Materials and methods 397
3.1 Measurements 397
3.2 Numerical modelling system 398
4 Results and discussion 398
4.1 Intratidal variability 399
4.2 Spring-neap variability 401
4.3 River discharge-related variability 403
5 Summary and conclusions 405
6 Acknowledgements 406
7 References 406

1 Introduction

In estuaries like the Weser estuary (Germany), large amounts of sediment are resuspended, transported and partly deposited during every tidal cycle frequently resulting in the development of regions of relatively high suspended particulate matter (SPM) concentration. These estuarine turbidity maximum (ETM) zones are often associated with high siltation rates. As an example, DE NIJS et al. (2009) have shown for the port of Rotterdam that tidal variations in the ETM location are the dominant mechanisms in harbour siltation. In the Weser estuary, SCHROTTKE et al. (2006) found fluid mud formation in the ETM region potentially affecting the nautical depth in the navigational channel. The ETM region of a river may therefore require a high level of dredging of muddy sediments, as shown e.g. in LANGE et al. (2008) for the Weser estuary.

Discussion of the dynamics of the ETM have to distinguish between different processes and time scales. ETM formation processes on seasonal to multi-annual time scales result in the accumulation of mud deposits while sub-tidal to tidal time scales describe the dynamics of the ETM once local sediment sources are present. The generation and maintenance of the ETM are related to different mechanisms which vary in their impact on particular estuaries as well as in different environmental conditions (e.g. high or low river discharge) in a specific estuary. 'These processes include the residual "estuarine gravitational circulation" due to the near bottom inflow of salty water (e.g. FESTA and HANSEN 1978) and the net upstream transport of sediments resulting from higher flood peak velocities than ebb peak velocities ("tidal pumping", e.g. OFFICER 1981) and due to changes in vertical mixing efficiency during times of stratification ("tidal mixing asymmetry", e.g. JAY and MUSIAK 1994). In some estuaries a second ETM can develop further upstream of the mixing zone (e.g. in the Ems estuary, TALKE et al. 2009). A general overview of the relevant processes is given in e.g. DYER (1997).

For the Weser estuary, the importance of local sediment sources and their resuspension within the tidal cycle has already been pointed out by WELLERSHAUS (1982) and the intratidal displacement of material has been described in detail by RIETHMÜLLER et al.

(1988) and GRABEMANN and KRAUSE (1989) based on measurements and corroborated by LANG et al. (1989) and LANG (1990) using a numerical model. On longer time scales, the position of the ETM in the Weser estuary varies together with the mixing zone forced by changes in river discharge (GRABEMANN and KRAUSE 1989, GRABEMANN and KRAUSE 2001). Although river discharge-related changes have been observed, to date they have not been reproduced in numerical models for the Weser estuary.

The ETM dynamics of the Weser estuary on different time scales are reviewed in the following based on previous research, analysis of new measurements and on numerical modelling results. The main focus is on intratidal SPM displacement, spring-neap variability and on river discharge-related changes in the position of the ETM. This study corroborates previous results which were based only on measurements with process studies illustrating ETM variability on different time scales.

2 Regional setting

The Weser estuary (Fig. 1), which is located in the southeastern North Sea, is a generally well-mixed meso- to macrotidal estuary. The upper reach of the Weser estuary (km 0-65) from Bremen to Bremerhaven has a channel-like character and has been repeatedly deepened in the past to its present minimum depth of about 9 m below German nautical chart datum (SKN -9 m) in the navigation channel (see review by LANGE et al. 2008). The outer Weser estuary (km 65-120) is funnel-shaped and characterised by two main tidal channels, extensive tidal flats and numerous smaller tidal channels and creeks. The western channel has been permanently stabilised for navigation by the construction of training works and groynes and is kept at a minimum depth of about SKN -14 m. Outside of this artificially stabilised area strong morphological changes can be observed (e.g. DIECKMANN 1989).

Surface sediments in the navigational channel are sand dominated. In the outer Weser estuary the river bed consists mainly of fine to medium sands, in the lower estuary of medium to coarse sands. A noticeable exception is the region between km 55 and km 66 which is dominated by mud (median grain size <63 μm) consisting of silt and clay with variable amounts of organic matter. This transect is part of the region from about km 45 to about km 70 in which the ETM typically occurs. The composition of sediments varies temporally in the mud stretch. On tidal time scales patches of fluid mud can form (SCHROTTKE et al. 2006) and on longer time scales the silt content can vary; i.e. after times of high river discharge the silt fraction is reduced.

The long-term mean (average for the years 1970 to 2010) discharge (MQ) is 325 m^3/s; the long-term mean of the annual minimum (MLQ) and maximum discharges (MHQ) are 117 m^3/s and 1220 m^3/s, respectively, measured at the gauge station Intschede 32.5 km upstream of the tidal weir (DEUTSCHES GEWÄSSERKUNDLICHES JAHRBUCH 2013). An analysis of daily discharge values for 1955-2012 shows that the most frequent discharge is about 150 m^3/s; 50 % and 75 % of the time the discharge is between 100 m^3/s and 250 m^3/s and between 100 m^3/s and 400 m^3/s, respectively.

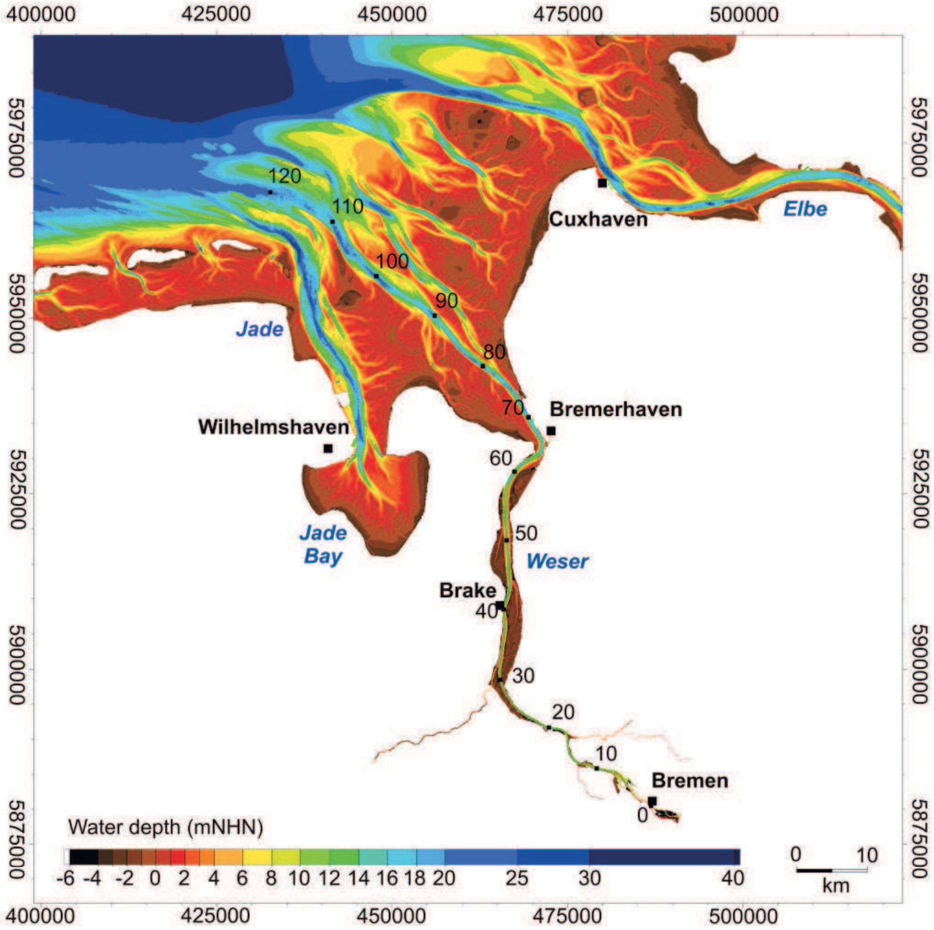

Figure 1: Morphology of the Weser estuary. Numbers along the main shipping channel denote the distance from the Wilhelm-Kaisen-Bridge ("Große Weserbrücke") about 5 km downstream of the weir in Bremen.

The long-term mean SPM concentration of the river water for the years 1970 to 2010 is 38 g/m^3 (Deutsches Gewässerkundliches Jahrbuch 2013). Thus, the long-term mean fluvial input of suspended sediment into the estuary is about 450 tons per half tide. On an annual time scale it varies strongly. The amount of suspended sediments entering the estuary from the adjacent sea is unknown, but upstream movement of marine material across the freshwater-saltwater interface (FSI) has been detected (e.g. Irion et al. 1987). Within the ETM, the SPM concentration increases with depth for most of the tidal cycle (e.g. Riethmüller et al. 1988, Figs. 3 and 4; see also Fig. 2 in this section). The SPM concentration can exceed 1000 g/m^3 near the bottom. Outside of the ETM region, the SPM concentration is generally less than 50 g/m^3.

Generally, the ETM is associated with the low-salinity region of the mixing zone. The location of the upstream limit of the mixing zone defined by the tidally averaged freshwater-saltwater interface (FSI), in the Weser commonly defined based on the 2 PSU isohaline, depends on the river discharge. During times of low river discharge the location of the FSI can occur about 15 km further upstream than in times of MQ (SEIFFERT et al. 2012). For a typical summer situation after several weeks of low river discharge, a snapshot of measured sediment concentrations during flood tide shows the ETM between km 45 and km 65 (Fig. 2).

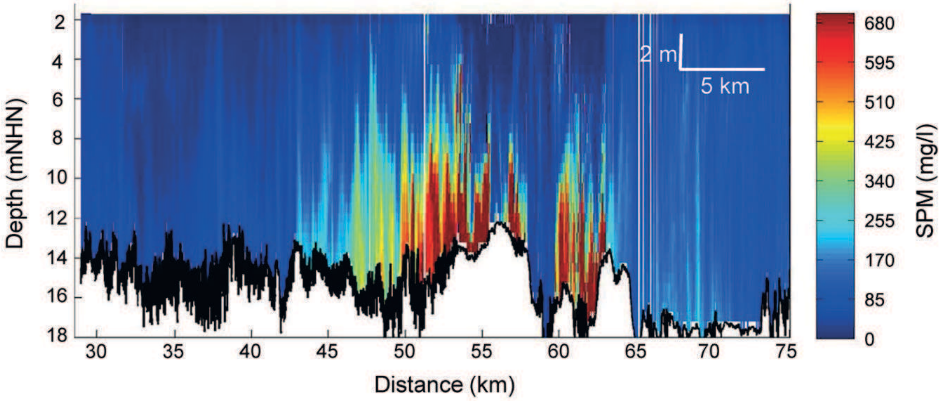

Figure 2: Along-stream transect of SPM concentration in June 2009 during a cruise from Bremerhaven to Bremen at flood tide (AquaVision BV 2009). Note that the measurements were not taken at the same tidal phase.

The locations of the mixing zone and the ETM are also influenced by mean sea-level. In a climate change sensitivity study HOLZWARTH et al. (2011) found an upstream shift of the mixing zone of more than 3 km for an increase of 80 cm in mean sea level and a related upstream shift of the ETM by the same order of magnitude.

3 Materials and methods

3.1 Measurements

The German Waterways and Shipping Administration of the Federal Government (WSA Bremerhaven) is conducting long-term near-surface time series measurements of turbidity which started in 2002 with one station. Since 2011, nine stations have been in operation. Furthermore, in the late 1990s, in 2002 and 2003, time series measurements of turbidity together with salinity and current velocity were undertaken simultaneously in two to three water depths at three to six locations along the estuary over a period of a few weeks with low, mean and high river discharge. For each station, the mean, the 5 % and 95 % percentile turbidity were calculated for chosen river discharge intervals. Based on these station data along the estuary longitudinal transects were derived and subsequently normalized by mean discharge conditions. The extensions of the ETM were estimated from these transects using a threshold normalized turbidity of 0.6. The data analysis was divided into near-surface measurements (for the years 2008-2012 at 8-9 stations, MES_Surf in Fig. 7) and near-bottom measurements (for the years before 2003, MES_Depth in Fig. 7).

3.2 Numerical modelling system

The transport of suspended sediments in the Weser estuary was simulated with the coupled modelling system UnTRIM-SediMorph. The hydrodynamic model UnTRIM (CASULLI and ZANOLLI 2005) uses a finite volume-finite difference method which solves the momentum und transport equations on a horizontally unstructured grid. It was set-up three-dimensionally with a median spatial resolution increasing from about 180 m in the outer estuary to 60 m in the inner parts and a vertically constant resolution of 1 m.

The hydrodynamic model is coupled to the sediment transport module SediMorph, which has been developed at BAW (BAW 2005). Sediment transport is treated for individual size fractions with a given mode of transport either as suspended load or bed load. In this study, suspended sediments are modelled using three different size classes (fine, medium and coarse silt); bed load transport is split into four fractions (fine, medium and coarse sand and gravel). The size of these fractions was chosen according to the Udden-Wentworth scale. Density and porosity are taken to be constant at 2,650 kg/m³ and 40 %, respectively. Sediments with a diameter larger than gravel, e.g. boulders, are included as gravel and sediments finer than fine silt are included as fine silt. Based on the spatially variable sediment distribution, characteristic values such as the mean grain size are calculated to derive a sediment grain-related roughness. Account is also taken of the form roughness of small scale bed features. SediMorph calculates sediment deposition-erosion and bedload transport based on the bed shear stress obtained from near bed velocity and roughness. Changes in bottom evolution are not taken into account.

The model topography represents the year 2002 in order to be compatible with available measurements to force the model. As the lower Weser estuary is maintained at a given minimum depth and laterally fixed, the changes compared to 2014 are small. However, no account is taken of morphological changes in the outer estuary. The observed composition of sediments at the bed is represented by the seven different sediment fractions described above.

The model is set-up as a process study but realistic forcing is applied. Wind stress at the surface was obtained from the operational German National Meteorological Service (DWD) weather forecast model (COSMO/LM, e.g. DOMS et al. 2002). At the lateral open sea boundaries, water levels from a BAW measurement campaign in 2002 are prescribed. River discharge was included based on daily averages of measurements at the Intschede station about 30.5 km upstream of the tidal barrier (data provided by the Federal Waterways and Shipping Administration). While the model does include salt transport, it does not take heat transport into account. A model validation (BAW 2009) has been successfully performed. The representation of water levels is close to observed values, the mean error of water level amplitude and phase at the individual gauge stations in the Weser estuary is between -15 cm and +12 cm and -23 minutes and +5 minutes respectively.

4 Results and discussion

In the following, SPM dynamics on intratidal, spring-neap and seasonal (changes in river discharge) time scales based on recent measurements and results from numerical simulations are presented and compared with published findings.

4.1 Intratidal variability

On the shortest time scale considered here, suspended sediments are transported within the tidal cycle. On this intratidal time scale, strong variability of SPM is due to the deposition of material over slack waters, subsequent resuspension and depletion of temporarily-formed and spatially-limited deposits during the following ebb or flood, and subsequent transport by tidal currents. This periodic deposition of suspended sediments has been shown in great detail by RIETHMÜLLER et al. (1988) for low river discharge in a specific region of the Weser estuary. GRABEMANN and KRAUSE (1989) have found that this cyclic behaviour is typical for other river discharge conditions also. This cyclic behaviour is also reproduced in the numerical simulations and illustrated for two tidal cycles in Fig. 3. For the chosen river discharge of about 300 m³/s, the simulated ETM is centred around km 64.

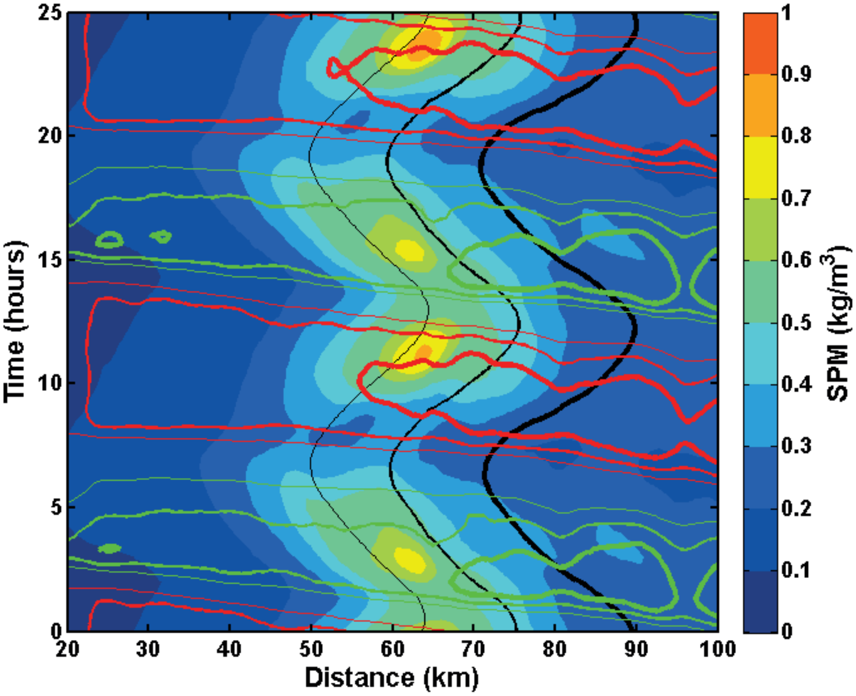

Figure 3: Spatial and temporal distribution of SPM concentrations (colour scale), salinity and current velocities (isolines) based on model results. Salinities of 2, 10 and 20 are shown as black isolines, where higher salinities are represented by thicker lines. Flood and ebb current velocities are shown as green and red isolines, respectively. An increase in line thickness represents an increase of current velocity (0.5 m/s, 0.75 m/s and 1.0 m/s, respectively).

The simulations confirm that the region with increased SPM concentrations moves with the low salinity region of the mixing zone (Fig. 3). High SPM concentrations are commonly located between the 2 and 10 PSU isohalines. The coupling of mixing zone and ETM is consistent with conceptual mechanisms proposed to explain the ETM formation.

BURCHARD und BAUMERT (1998) investigated the relative importance of different mechanisms in a numerical process study for a schematic estuary. They found that gravitational circulation and tidal pumping are the main processes responsible for the formation of the ETM. Moreover, there are also other important baroclinic processes. During ebb tide the fresh river water lies on top of more salty sea water which inhibits vertical mixing whereas during flood tide the water column is destabilized and there is an increase in vertical mixing (e.g. LANG et al. 1989). The term for this process, strain induced periodic stratification (SIPS), was coined by SIMPSON et al. 1990. Changes in vertical mixing efficiency ("tidal mixing asymmetry") during times of stratification can lead to more efficient upstream transport when sediment is transported further up in the water column compared to less efficient downstream transport when turbulence is damped by salinity stratification (JAY und MUSIAK 1994).

Simulated high SPM concentrations exceed 800 g/m³, which is consistent with observations (e.g. Fig. 2). During slack water the SPM concentration is reduced and suspended sediments are consequently deposited to the ground and eroded again during the following onset of higher current velocities and are then transported up- or downstream. The sediment concentration at one location therefore describes the sum of SPM advected from distant sources and locally eroded material as discussed in detail in GRABEMANN and KRAUSE (1989) based on measurements and in LANG et al. (1989) based on model results.

For average discharge conditions the ETM stretch of the Weser shows ebb dominance in current velocities evident both in measurements and modelling results (Fig. 4). Peak velocities are consistently higher during ebb tide compared to flood tide. For station Nordenham (Fig. 4, upper panel) modelled and measured current velocities match rather well; for station Rechtenfleth (Fig. 4, lower panel) modelled current velocities are consistently higher but show a comparable structure for flood and ebb tide.

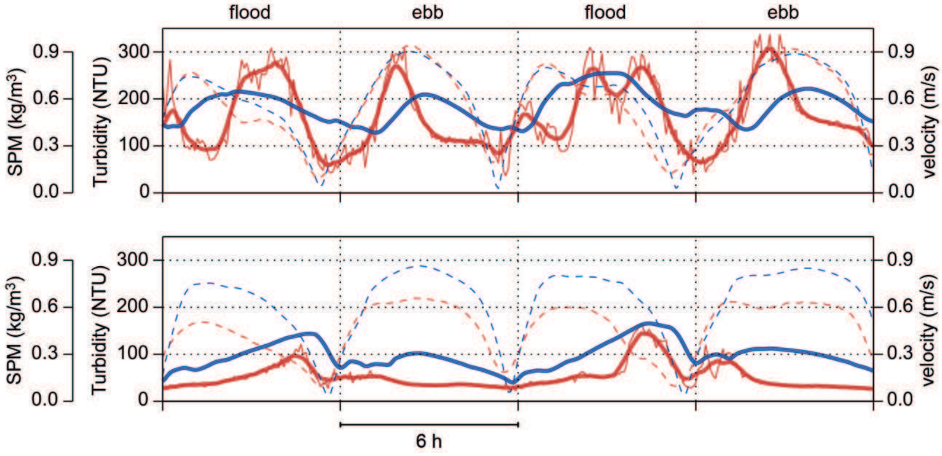

Figure 4: Time series of near-bottom modelled SPM concentration (solid blue line), modelled current velocity (dashed blue line), measured velocity (dashed red line) and measured turbidity (red) at stations Nordenham (km 55.8, upper panel) and Rechtenfleth (km 46.5, lower panel). The thin and thick red lines present the measured turbidity with and without small-scale variability, respectively.

Depending on the position of an observation point in relation to the ETM this leads to different characteristic patterns in SPM time series, as shown in Fig. 4. For average discharge conditions the station Nordenham is near the centre of the ETM (upper panel) and the station Rechtenfleth is near its landward margin (lower panel). In the centre of the ETM (Fig. 4, upper panel), the SPM concentration increases in phase with the current velocity. The signal during flood tide shows a characteristic bimodal form, especially in the measurements. The first peak is probably due to the erosion of local sediment sources and the second peak to advected material which was resuspended further downstream. During ebb tide, material is resuspended with increasing velocity and transported downstream. At the position further upstream (Fig. 4, lower panel), the SPM concentration peak sets in later during flood tide, probably presenting SPM advected from downstream, and early during ebb tide, probably presenting local erosion of sediments which are subsequently transported downstream. This is consistent with the cyclic deposition and erosion behaviour referred to above. A diurnal inequality of the SPM in the ETM exists but is generally not very strong.

Results from simulations and measurements may differ in detail, but they are consistent in the description of the characteristics of SPM concentrations. High flood tide and high ebb tide SPM values are comparable but the duration of high values is longer during flood tide than during ebb tide. This can be seen in the measurements as well as in the simulations. Thus, residual upstream transport of SPM can be expected due to higher sediment concentrations transported over a longer time during flood than during ebb tide.

The comparison of modelled and observed SPM concentration and turbidity shows a similar overall structure but the variability on shorter time scales is underestimated in the model. In nature sediments settle in the water column rapidly by e.g. flocculation and resuspension of flocs and this may lead to the highly variable behaviour observed. The model partly takes into account the effects of flocculation and the breaking up of flocs by treating the settling velocity of sediments as dependent on concentration and shear stress as proposed by MALCHEREK (1995). Yet, the observed variability of SPM concentration could not be fully reached.

4.2 Spring-neap variability

Tidal variations in the Weser estuary are dominated by semi-diurnal components (M_2, S_2). At the tide gauge station "Alte Weser" (km 115), for example, the mean tidal range is about 2.9 m with a pronounced spring-neap difference of about 70 cm. The variation of the tidal range within a spring-neap-cycle leads to changes in current velocity and thus in bed shear stress. During spring tides higher bed shear stresses are expected and result in higher sediment concentrations (e.g. LANG et al. 1989).

As an example for the effect of an increase in tidal range two different time spans within the simulations are compared (Fig. 5). In order to minimize small-scale effects the model results are spatially averaged over the width of the navigational channel. The difference in tidal range between the two time spans is about 40 cm, which is roughly half the maximum spring-neap tide difference at station "Alte Weser". The mean water level is also increased by about 20 cm.

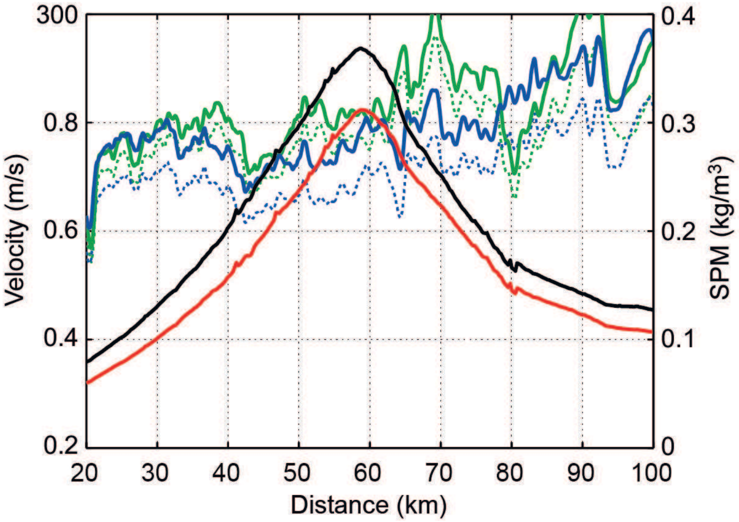

Figure 5: Transects of mean SPM concentrations for a situation with high (black line) and low (red line) tidal range, flood current velocities for high (solid blue line) and low tidal range (dashed blue line) and ebb current velocities for high (solid green line) and low tidal range (dashed green line). Current velocities are averages over ebb or flood tide.

The increase in tidal range (+11 %, average over km 20 - 100) leads to increased mean current velocities, flood velocities are affected more strongly (+13 %) than ebb velocities (+7 %) in this case. Due to higher current velocities mean SPM concentrations increase by about 20 %, thus the region with higher SPM concentrations is extended further up- and downstream. Taking into account that the spring-neap variability of the tidal range can be up to 70 cm at station “Alte Weser” at the mouth of the estuary, the variability of the SPM concentration can be expected to be higher than 20 %.

This assumption is corroborated by time series measurements at e.g. an individual location in the upstream part of the ETM (Fig. 6). In the simulations tidally averaged SPM concentrations are about 50 % higher during spring tide than during neap tide for the averaging time spans in Fig. 6. Similarly, tidally averaged measured turbidity is about 35 % higher during spring tides. For intratidal maximum SPM concentrations (turbidities) spring tide values exceed neap tide values by a factor of about 2 which is consistent with results given in GRABEMANN and KRAUSE 2001.

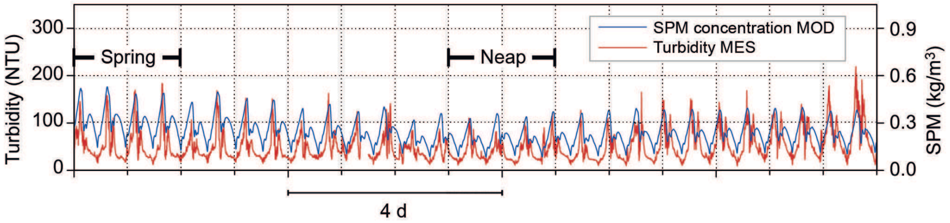

Figure 6: Time series of near-bottom measured turbidity (MES, red) and modelled SPM concentration (MOD, blue) at station Rechtenfleth (km 46.5). Averaging time spans for spring and neap times are shown by bars.

Overall, significant differences between spring and neap tides exist in the Weser estuary. Different effects on flood and ebb tide velocities suggest changes in sediment dynamics, i.e. the flood to ebb ratio may change. This needs to be kept in mind, when planning or interpreting measurements or trying to obtain representative model results based on just a few tides.

4.3 River discharge-related variability

On longer time scales the redistribution of sediments in the system becomes important. Redistribution of sediments is the result of natural processes, such as tide induced residual upstream transport or the flushing of fines from the estuary during flood events, as well as of anthropogenic impacts, such as the dredging and disposal of sediments from the main navigation channel. Changes in ETM position related to river discharge are shown in Fig. 7.

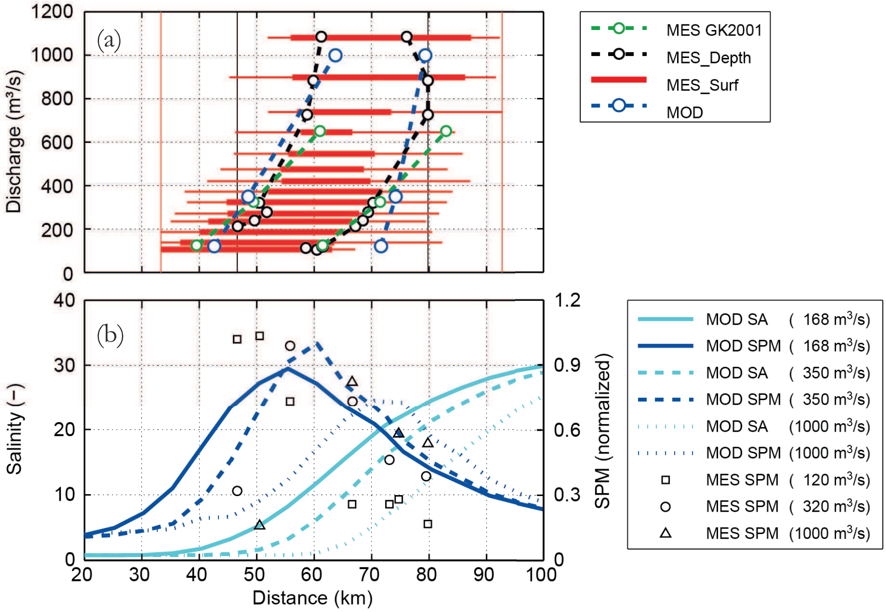

Figure 7: (a) ETM position for different river discharge conditions as obtained from turbidity measurements (MES GK2001: Results from GRABEMANN and KRAUSE (2001), MES_Depth: based on near-bottom data (see section 3.1), MES_Surf: based on long-term near-surface monitoring data (see section 3.1)) and modelling results (MOD). Although error bars are only shown for MES_Surf based on 5 % and 95 % percentiles of measured turbidity; the other measurements and model results have similar uncertainties. The red and black vertical lines denote the up- and downstream limits of the near-surface and near-bottom measurements, respectively. (b) Tidally averaged salinity and SPM concentration from model results MOD (lines) and measurements MES (symbols). The vertical axis for SPM was normalized by medium river discharge conditions.

The ETM is shifted downstream for increasing river discharge. During low discharge the ETM occurs at about km 40 to 60, during high discharge it is more than 20 km further downstream. The shift of the ETM closely reflects the shift of the FSI. The close coupling of FSI and ETM seen for the intratidal variability (Fig. 3) is also seen here (Fig. 7b). The impact of changes in river discharge depends on the hydrological condition. Under conditions with low river discharge the same change has a larger effect than under conditions with high river discharge. Thus the system is more sensitive to river discharge variations during times of low discharge showing a non-linear behaviour of ETM transition.

The near-bottom positions of the ETM (MES_Depth) generally corroborate the previous findings of GRABEMANN und KRAUSE (2001) with respect to changes of ETM position and its longitudinal extension with varying river discharge (Fig. 7a). MES_Depth suggests slightly less sensitivity of the ETM for high discharges. The positions based on the near surface long-term measurements of turbidity (MES_Surf) which comprise more river discharge conditions are in general comparable to the near-bottom ETM positions, but seem to be somewhat more extended upstream and have a larger longitudinal extent. The positions based on the measurements are likely biased by the vertical structure of the ETM. The region with highest near-bottom SPM (turbidity) in the longitudinal section is not necessarily the region with highest near-surface SPM (e.g. see Fig. 2). Near-surface and near-bottom measurements do not cover the same time span thus different forcing conditions (e.g. meteorological situations, river discharges) are covered, which may further complicate a direct comparison of ETM positions derived from different data sets.

In order to compare measurements with modelling results the ETM position was determined from the modelled SPM concentrations (Fig. 7b). A threshold SPM concentration of 0.6 was taken to determine the location of the ETM. The numerical modelling results show similar results as the measurements concerning the ETM position (MES and MOD in Fig. 7a). The upstream limit of the ETM for low and high river discharge is at about the same position along the river axis. The non-linear response of ETM transition to changes in river discharge is less pronounced in the model. The downstream limit of the ETM is further downstream in the model for low river discharge conditions.

The SPM concentration in the ETM can only be roughly compared between actual modelled SPM concentration (averaged over the width of the navigational channel) and measured turbidity as representative for SPM concentration (depth average at one location) (Fig. 7b). Even though the ETM positions and SPM concentrations are similar in simulations and measurements, they differ in details.

The model considers only the chosen quasi-stationary discharge conditions but omits transitions between different discharge conditions. The measurement data shown in Fig. 7b were analysed for specific discharge classes. In the measurements these classes contain the transitions between different discharge and environmental conditions. The interpretation is consequently restricted. The most frequent position of the ETM can be expected to be between km 45 and km 70 when considering that the river discharge is between 100 m^3/s and 400 m^3/s over 75 % of the time. This most frequent ETM position covers the mud stretch of the Weser found between km 55 and km 66.

Measurements indicate that river floods may have a longer lasting impact (GRABEMANN und KRAUSE 2001). SPM concentrations in the ETM after river floods (> 1,100 m^3/s) are in some cases reduced and subsequently increase in the course of the following months thus indicating changes in local sediment sources. Account is not taken of the observed effects of high river discharges in terms of changes in the sediment inventory at the bed, such as changes in the amount of fine sediments. These effects should, however, be considered in following studies.

5 Summary and conclusions

The variability of the ETM on intratidal, spring-neap and river discharge-related (seasonal) time scales has been shown based on modelling results and measurements. The previously proposed description of suspended sediment transport within the ETM as a cyclic process (GRABEMANN and KRAUSE 1989, LANG et al. 1989) has been corroborated here. The intratidal ETM movement appears to be tightly coupled to the movement of the FSI for a given river discharge condition. On a fortnightly time scale a pronounced spring-neap variability of SPM concentration exists which modulates SPM concentrations. The increase of SPM concentration is almost uniform over the ETM region and the ETM can consequently be seen as extended further up- and downstream. On seasonal time scales the ETM will be strongly affected by changes in river discharge, which shifts the ETM together with the low salinity region of the mixing zone along the estuary depending on the discharge condition.

The determination of the position of the ETM from turbidity measurements appears to be reliable. However, the inference of SPM concentrations from turbidities is still limited by a number of uncertainties. The correlation of measured turbidity and SPM is not necessarily constant in time as assumed here, but may vary due to e.g. biological influences (e.g. phytoplankton). Moreover, it is assumed that measured tidal mean values for the two to three samples in a specific cross-section can be averaged to obtain average tidal mean SPM concentration for this cross-section. The numerical model delivers a more complete set of information on the sediment distribution, but is influenced by the model parameters chosen, such as the sediment fractions modelled and the choice of settling velocities.

Despite the uncertainties, the similarity between model and measurements on the different time spans considered here yields some confidence in the approaches taken. Thus, we are confident that the numerical model will allow more detailed simulations in the future in order to identify relevant processes further. As this study was focused on chosen quasi-stationary different river discharge conditions, the transition between different states will be a question of further research.

Two practical aspects of this study merit a brief mention. Firstly, the use of long-term measurements at the gauge stations to obtain the position of the ETM has been shown to be feasible, but is subject to large uncertainties. These uncertainties are expected to derive from strong natural variability, limitations of the analysis method and data limitations (e.g. device specific measurement accuracy). Currently turbidity can only be measured permanently at the edge of the fairway due to the requirements for safety and ease of navigation in restricted waterways. This limitation may be overcome in the future when plans of the WSA Bremerhaven to employ a Horizontal Acoustic Doppler Current Profiler (H-ADCP) have become operational. Secondly, even though the location of the ETM is highly variable on each of the different time scales considered here, a certain predictability exists. This may provide a useful element for a better description of the suspended sediment dynamics in the ETM and thus may contribute to the optimisation of sediment management in the Weser estuary.

6 Acknowledgements

The authors thank the German Waterways and Shipping Administration of the Federal Government (WSA Bremerhaven) for providing hydrodynamic and turbidity measurements. Assistance with graphics from B. Gardeike and W. Appel are gratefully acknowledged.

7 References

AQUA VISION BV: Suspended sediment measurements in the Weser, June 2009. Technical report. Aqua Vision BV, 2009.

BAW: Modellvalidierung UnTrim / SediMorph - Hydrodynamik und Schwebstofftransports des Jade – Weser – Ästuars. Bundesanstalt für Wasserbau, 93 p., 2009. from http://www.baw.de/downloads/wasserbau/mathematische_verfahren/Validierungsstudien/Modellvalidierung_Weser-GM_UnTRIM2007_v1.3.pdf

BAW: Mathematical module SediMorph – Validation document, Bundesanstalt für Wasserbau, 77 p., 2005. from http://www.baw.de/downloads/wasserbau/mathematische_verfahren/pdf/vd-sedimorph.pdf

BURCHARD, H. and BAUMERT, H.: The Formation of Estuarine Turbidity Maxima Due to Density Effects in the Salt Wedge. A Hydrodynamic Process Study. In: Journal of Physical Oceanography, Vol. 28, 309-321, 1998.

CASULLI, V. and ZANOLLI, P.: High resolution methods for multidimensional advection–diffusion problems in free-surface hydrodynamics. In: Ocean Modelling, Vol. 10, 1-2, 137-151, doi: 10.1016/j.ocemod.2004.06.007, 2005.

DE NIJS, M.A.J.; WINTERWERP, J.C. and PIETRZAK, J.D.: On harbour siltation in the fresh-salt water mixing region. In: Continental Shelf Research, Vol. 29, 1, 175-193, doi: 10.1016/j.csr.2008.01.019, 2009.

DEUTSCHES GEWÄSSERKUNDLICHES JAHRBUCH: Weser und Emsgebiet 2010. 1.11.2009 - 31.12.2010. Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz, 301 p., 2013.

DIECKMANN, R.: Morphologische Strukturen im Weserästuars. In: Deutsche Gewässerkundliche Mitteilungen, Vol. 33, 3/4, 104-112, 1989.

DOMS, G.; STEPPELER, J. and ADRIAN, G.: Das Lokal-Modell LM. In: promet, Vol. 27, 3/4, 123-128, 2002.

DYER, K.R.: Estuaries: a physical introduction. John Wiley and Sons, 1997.

FESTA, J.F. and HANSEN, D.V.: Turbidity maxima in partially mixed estuaries: A two-dimensional numerical model. In: Estuarine and Coastal Marine Science, Vol. 7, 4, 347-359, doi: 10.1016/0302-3524(78)90087-7, 1978.

GRABEMANN, I. and KRAUSE, G.: Transport processes of suspended matter derived from time series in a tidal estuary. In: Journal of Geophysical Research, Vol. 94, C10, 14373, doi: 10.1029/JC094iC10p14373, 1989.

GRABEMANN, I. and KRAUSE, G.: On Different Time Scales of Suspended Matter Dynamics in the Weser Estuary. In: Estuaries, Vol. 24, 5, 688, doi: 10.2307/1352877, 2001.

HOLZWARTH, I.; SCHULTE-RENTROP, A. and HESSER, F.: Auswirkungen klimabedingter Änderungen auf das Strömungs- und Transportverhalten deutscher Nordseeästuare. In: HAFENTECHNISCHE GESELLSCHAFT E.V. (ed.): Vorträge HTG-Kongress 2011. Würzburg, 275-282, 2011.

IRION, G.; WUNDERLICH, F. and SCHWEDHELM, E.: Transport of clay minerals and anthropogenic compounds into the German Bight and the provenance of fine-grained sediments SE of Helgoland. In: Journal of the Geological Society, Vol. 144, 153-160, 1987.

JAY, D.A. and MUSIAK, J.D.: Particle trapping in estuarine tidal flows. In: Journal of Geophysical Research, Vol. 99, C10, 20445, doi: 10.1029/94JC00971, 1994.

LANG, G.: Zur Schwebstoffdynamik von Trübungszonen in Ästuarien. Universität Hannover, Hannover, Institut für Strömungsmechanik und Elektron. Rechnen im Bauwesen, 113 p., 1990.

LANG, G.; SCHUBERT, R.; MARKOFSKY, M.; FANGER, H.-U.; GRABEMANN, I.; KRASEMANN, H.L.; NEUMANN, L.J.R. and RIETHMÜLLER, R.: Data interpretation and numerical modeling of the Mud and Suspended Sediment Experiment 1985. In: Journal of Geophysical Research, Vol. 94, C10, 14381, doi: 10.1029/JC094iC10p14381, 1989.

LANGE, D.; MÜLLER, H.; PIECHOTTA, F. and SCHUBERT, R.: The Weser Estuary. In: KURATORIUM FÜR FORSCHUNG IM KÜSTENINGENIEURWESEN (ed.): Die Küste. Archiv für Forschung und Technik an der Nord- und Ostsee. Heide i. Holstein, 275-287, 2008.

MALCHEREK, A.: Mathematische Modellierung von Strömungen und Stofftransporten in Ästuaren. PhD thesis. Universität Hannover, Hannover, Institut für Strömungsmechanik und Elektron. Rechnen im Bauwesen, 203 p., 1995.

OFFICER, C. B.: Physical dynamics of estuarine suspended sediments. In: Marine Geology, Vol. 40, 1-2, 1-14, doi: 10.1016/0025-3227(81)90039-6, 1981.

RIETHMÜLLER, R.; FANGER, H.-U.; GRABEMANN, I.; KRASEMANN, H.L.; OHM, K.; BÖNING, J.; NEUMANN, L.J.R.; LANG, G.; MARKOFSKY, M. and SCHUBERT, R.: Hydrographic Measurements in the Turbidity Zone of the Weser Estuary. In: DRONKERS, J. and LEUSSEN, W. (eds.): Physical Processes in Estuaries. Berlin, Heidelberg, 332-344, doi: 10.1007/978-3-642-73691-9_18, 1988.

SCHROTTKE, K.; BECKER, M.; BARTHOLOMÄ, A.; FLEMMING, B.W. and HEBBELN, D.: Fluid mud dynamics in the Weser estuary turbidity zone tracked by high-resolution side-scan sonar and parametric sub-bottom profiler. In: Geo-Marine Letters, Vol. 26, 3, 185-198, doi: 10.1007/s00367-006-0027-1, 2006.

SEIFFERT, R.; HESSER, F.B.; SCHULTE-RENTROP, A. and SEIß, G.: Potential effects of climate change on the brackish water zone in German estuaries. In: HINKELMANN, R.-P., LIONG, Y., SAVIC, D., NASERMOADDELI, M.H., DAEMRICH, K.-F., FRÖHLE, P. and JACOB, D. (eds.): Understanding Changing Climate and Environment and Finding Solutions. Hamburg, 2012.

SIMPSON, J.H.; BROWN, J.; MATTHEWS, J. and ALLEN, G.: Tidal Straining, Density Currents, and Stirring in the Control of Estuarine Stratification. In: Estuaries, Vol. 13, 2, 125, doi: 10.2307/1351581, 1990.

TALKE, S.A.; SWART, H.E. DE and SCHUTTELAARS, H.M.: Feedback between residual circulations and sediment distribution in highly turbid estuaries: An analytical model. In: Continental Shelf Research, Vol. 29, 1, 119-135, doi: 10.1016/j.csr.2007.09.002, 2009.

WELLERSHAUS, S.: Die Trübungswolke im Weser-Ästuar. In: Deutsche Gewässerkundliche Mitteilungen, 26, 1982.