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Implications of Freshwater Discharge on Estuarine Sediment Dynamics

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ABSTRACT: Freshwater discharge is known to have significant impact on both the location of the estuarine turbidity maximum (ETM) and on the intensity of the upstream transport (tidal pumping) of suspended particulate matter (SPM). Periods of persistently low discharge can cause an accumulation of SPM and maximum sedimentation rates in the upper part of the estuary. In this study we investigate how turbidity (proxy for SPM concentration), change rate in bathymetry (proxy for sedimentation rates) and freshwater discharge are related to each other. The study area is the upper part of the Elbe River Estuary, Germany. It is one of the most important waterways for waterborne cargo transport in Europe and connects the North Sea with the Port of Hamburg. The exact location of the study area is a major dredging site, where mainly fine sediments deposit. Here a sediment trap is maintained since 2008, accompanied by a comprehensive monitoring. Hence, it is for the first time possible to investigate the sediment dynamics in very much detail and based on multi-annual time series. Low freshwater discharge causes higher sedimentation rates. In periods of persistently low freshwater discharge, lasting several weeks to months, turbidity is continuously increasing. However, no correlation between turbidity and sedimentation rate could be found. This contradiction disappears, once turbidity is understood solely as measure for the amount of SPM that is potentially available in the water column and therefore can deposit on the river bottom. It is other factors, e.g. current velocity, water temperature and the properties of the SPM material that determine the proportion of the freshly accumulated material that will deposit on river bottom for the longer term and will continue to consolidate.

Keywords: Estuary, Sediment dynamics, Turbidity, Suspended particulate matter, Freshwater discharge

1 INTRODUCTION

The Elbe River Estuary is one of the most important waterways for waterborne cargo transport in Europe. It connects the North Sea with the Port of Hamburg located about 100 km inlands. To maintain the required water depths for commercial navigation vessels in estuarine waterways several million cubic meters of sediments have to be dredged per year.

Freshwater discharge (hereinafter often referred to as 'discharge' only) is known to have significant impact on both the location of the estuarine turbidity maximum (ETM) and on the intensity of the upstream transport (tidal pumping) of suspended particulate matter (SPM) (e.g. GKSS, 2007; BAW, 2012). Periods of persistently low discharge can cause an accumulation of SPM and maximum sedimentation rates in the upper part of the Elbe River Estuary. As a consequence dredging volumes sharply increase.

This study sets its focus on the sediment dynamics in the upper part of the Elbe River Estuary. The study area is the river section next to the city of Wedel, which is situated some kilometers downstream of the Port of Hamburg. This river section is one of the major dredging sites in the Elbe River Estuary, where mainly fine sediments (silt with a significant amount of fine sand) deposit (Figure 1).

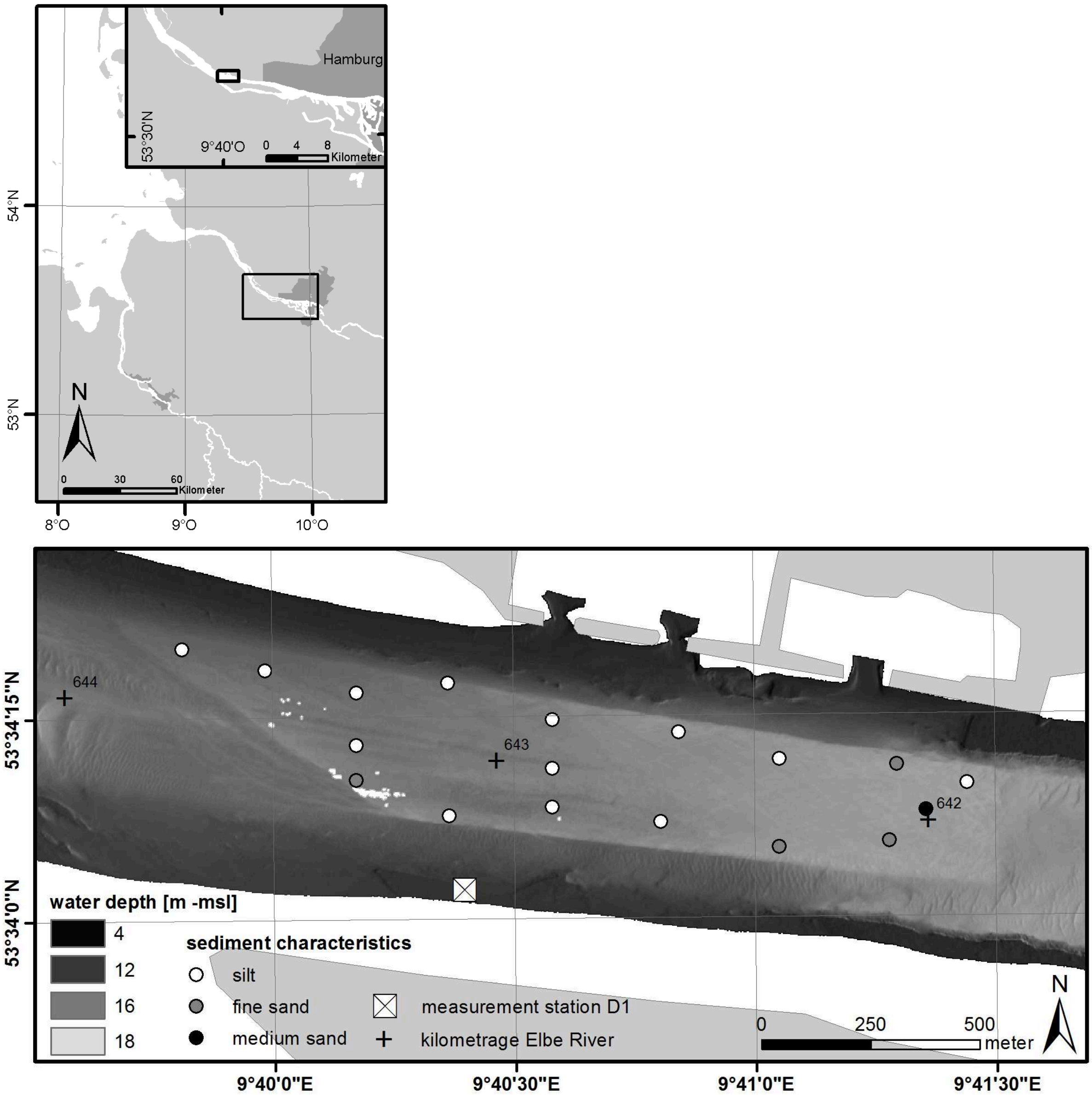

Figure 1. Study area and location of the sediment trap in upper part of the Elbe River Estuary, Germany.

In the study area a sediment trap is maintained since 2008. It is a basin about 2 km long (Elbe km 642 - 644), 2 m deep and it spans the whole roughly 300 meter-wide navigation channel. From 2008 – 2011 there was a comprehensive monitoring (refer to BfG, 2012). Hence, it is for the first time possible to investigate the impact relation between freshwater discharge and sediment dynamics in very much detail and based on multi-annual time series.

2 DATA AND MEASUREMENT METHODS

Starting in 2005 continuous records of single point measurements of turbidity, flow velocities and directions are available at several locations along the River Elbe Estuary. For a description of this monitoring network the reader can refer to Strömich (2011). In this study we use the records of turbidity taken at the measurement station D1 (Figure 1). The optical backscatter sensors are deployed at two water depths, about 1.5 m above the river bottom and 1.5 m below water surface independent of the tide. Until 2010 station D1 was equipped with an Aanderaa RCM9 multi-sensor measuring platform. Today station D1 is equipped with a modernized Aanderaa platform called Seaguard, including a Seapoint optical backscatter sensor.

Within the sediment trap sedimentation patterns were monitored every two weeks using a multi-beam echo sounder. This hydrographical mapping generated a continuous record of change rates in bathymetry within the sediment trap. For further information such as technical specifications and the methods used to analyze the hydrographical data the reader can refer to BfG (2012).

Time series of freshwater discharge are available for the gauging station at Neu Darchau (Elbe-km 536.44), which is located 50 km upstream of the tidal weir near Geesthacht. For the data analysis we use the daily values taken at 5 a.m.. The hydrological main values for Neu Darchau are 708 m³/s for average discharge (MQ), 272 m³/s for average low discharge (MNQ) and 2040 m³/s for average high discharge (MHQ). The lowest discharge ever recorded was 128 m³/s in 1904 (all data taken from the web-based information platform Undine; refer to undine.bafg.de).

3 IMPLICATIONS OF FRESHWATER DISCHARGE ON TURBIDITY

With decreasing freshwater discharge the ETM moves up-estuary thus leading to higher SPM concentrations in the study area. The relation between turbidity and discharge is depicted in Figure 2, separated according to tidal phase (flood / ebb tide) and water depth (near water surface / near river bottom).

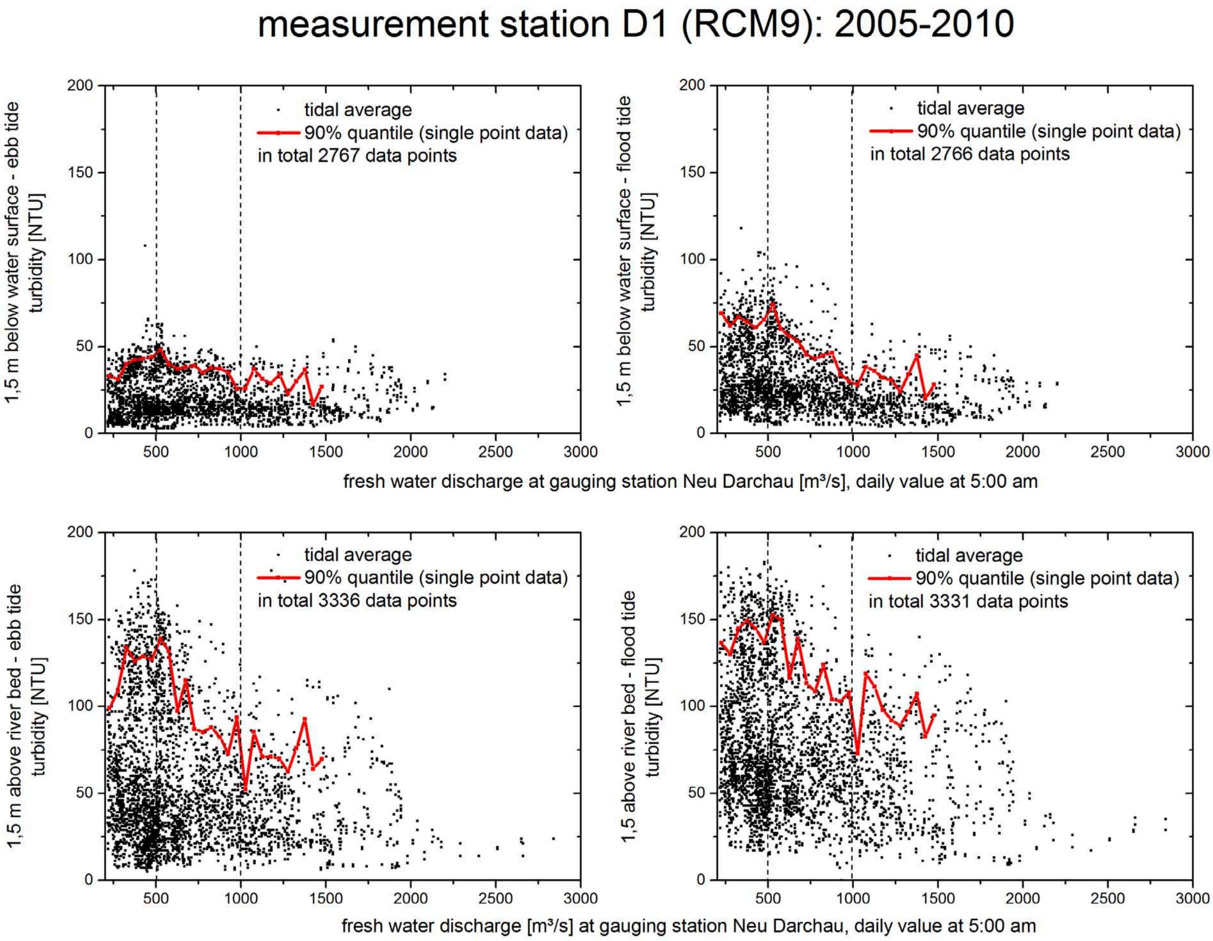

Figure 2: Relation between turbidity (station D1, Elbe-km 643) and freshwater discharge (gauging station Neu Darchau), years 2005-2010.

On first examination there is high level of variability included in the data. However, taking the 90% quantile as a reference for orientation[1], turbidity generally increases with lower discharge. This is the same for flood and ebb tide and for both measurement levels. Turbidity is highest on the bottom level and during flood tide.

Furthermore, the data exhibit two significant breakpoints (indicated in Figure 2 by the vertical lines). A first breakpoint can be found at a discharge of around 1000 m³/s. When discharge falls below this point, turbidity starts to increase. This is because of the ETM moving into the study area. Following the 90% quantile turbidity shows an increasing trend until the second breakpoint, located at a discharge of around 500 m³/s. Beyond this second point the 90% quantile for turbidity remains relatively constant. Independently of the absolute minimum discharge the ETM reaches its most upstream limit around Elbe-km

[1] The 90 % quantile was not calculated for turbidity data taken at any discharge greater than 1500 m³/s. This is due to the sharply decreasing number of data points available for periods of very high discharge.

630. This is shown by a long-time data set for SPM concentrations presented by GKSS (2007). Reaching back to 1979 water probes (to determine SPM concentrations) were taken several times a year by a helicopter on a full longitudinal profile starting from the German Bight (Elbe-km 750) and then going upstream to the tidal limit at Weir Geesthacht (Elbe-km 585,9).

Freshwater discharge is not the only factor of influence. There are others that can be significantly associated with the actual level of turbidity. It is their interaction that causes the overall variability included in the turbidity records (see Figure 2). For example, in a full spring/neap cycle SPM concentrations are relatively higher during spring than during neap tide (GKSS, 2007). Furthermore, there are seasonal differences in water temperature (viscosity, settling velocity of individual grains) and in the properties of the SPM (grain size, organic content, flocculation). The relocation of dredged material some kilometers upstream of the study area[2] may also have an effect on turbidity. Another factor, on which this study is going to focus in the subsequent paragraph is the development of turbidity during periods of persistently low fresh-water discharge.

4 DEVELOPMENT OF TURBIDITY IN PERIODS OF PERSISTENTLY LOW FRESHWATER DISCHARGE

Since 2005 continuous records of turbidity are available for station D1. The records include several periods of persistently low freshwater discharge. For the analyses 500 m³/s was selected as threshold discharge that defines start and end of each period. From observations in the port area of Hamburg sedimentation rates and dredging amounts are known to rapidly increase once the discharge constantly remains below this value of 500 m³/s. Furthermore, we could confirm this value by our analysis results (Figure 3). Table 1 gives an overview of all 12 periods from 2005 until 2013 with a minimum duration of more than four weeks; in the following referred to as periods #1 to #12. Period #5 in 2008 was the longest with a total duration of 183 days. At the same time this period was the most extreme in terms of the mean (324 m³/s) and minimum (215 m³/s) discharge.

Table 1. Periods of persistently low freshwater discharge (2005-2013), threshold value Q = 500 m ³/s

period	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
year	2005	2005	2006/07	2007	2008	2009	2009	2011	2011	2012	2012	2013
start	06.06	13.10	26.11	21.04	03.06	18.05	03.08	07.05	07.11	17.05	28.07	20.08
end	26.08	22.12	11.01	15.08	03.12	24.06	04.11	25.07	11.12	10.07	05.12	13.10
duration	81	69	46	116	183	37	93	79	34	54	130	54
mean Q	422	379	410	416	324	454	341	419	419	371	371	445
min Q	265	323	365	293	215	372	215	318	366	282	266	339

Figure 3 shows for the periods #1 to #12 (see Table 1) the temporal development of turbidity for station D1, measured 1.5 m above the river bottom. The temporal resolution of the raw data is 5 minutes. In Figure 3 all data is averaged over tidal phases and depicted separately for flood and ebb tide. On all x-axes the position x = 0 indicates the start of each period. The conditions of turbidity in advance to each period are depicted for the duration of a complete spring neap cycle (x-values < 0 on all x-axes).

Trends in turbidity were analyzed by linear regression. A variance analysis was performed to determine the significance of the trend (see the p-values). Much of the variance can be explained by the influence of the spring neap cycle at a frequency of around 28 tidal phases.

Please note the change of optical sensors in 2010 (see chapter 2) which caused a sudden 'technical' increase of levels of turbidity. Although both sensors use NTU (Nephelometric Turbidity Unit) to measure turbidity, the absolute values are not comparable to each other. In other words, there was no sudden increase in the overall turbidity conditions after 2010!

During periods of persistently low freshwater discharge (threshold level 500 m³/s) turbidity shows an increasing trend (at a 99% level of significance); this is for all except three periods. Among these exceptional periods the linearized trend was either positive but of less significance for the ebb tide (period #10, p-value 0,018 for ebb tide), significantly negative (decreasing turbidity in period #4) or not significant (period #1). The further conclusions from Figure 3 are:

[2] Relocation site Neßsand (Elbe-km 637), used from November until March by the Hamburg Port Authority for the relocation of dredged material.

- During flood tide turbidity is constantly higher than during ebb tide. There are only a few data with equal or higher turbidity during ebb tide (e.g. periods #8 and #10). This observation is in line with the conclusion of other investigations that there is a net upstream transport of fine sediments into the upper part of the estuary (e.g. BAW, 2013; BfG, 2012).
- Looking at the turbidity for flood and ebb tide there is a good coherence between both time series.
- Despite of very long periods of up to 183 days included in the data records, in none of these periods any maximum level of turbidity could be reached. It can therefore be assumed that a continued accumulation of SPM took place in the project area.
- In most periods a time lag between discharge and turbidity of about 20 to 30 tidal phases (flood/ebb) exists. Turbidity does not start to increase at position x = 0 (discharge falls below threshold value Q = 500 m³/s); instead it starts to increase at any position between x = 20 or x = 30. Such behavior can be interpreted as system inertia in relation to changes in freshwater discharge.
- The strength of the subsequent accumulation (expressed by the gradient of the linearized trend) is independent of the initial turbidity level. It is the actual amount of SPM included in the ETM further downstream that is crucial to determine the potential strength of the subsequent accumulation of SPM in the project area. This amount depends on the preliminary (freshwater) hydrological regime.
- For example, the absence of a significant trend in period #1 can be explained by two consecutive flood events in March (peak flow Q = 1867 m³/s) and April (peak flow Q = 2291 m³/s). It can be assumed that substantial amounts of SPM were removed from the ETM and exported into the German Bight resulting in very low SPM concentrations afterwards. The low concentrations are confirmed by the previously mentioned SPM monitoring on a longitudinal profile, documented in GKSS (2007). Thus, immediately afterwards during period #1 less SPM was available in the ETM that could accumulate further upstream in the project area.
- This should also be the case for period #8. There is a positive and significant trend, however, it is much smoother in comparison to all trends of the other periods. In this case the preliminary (freshwater) hydrological regime was characterized by a long period of run-off that was high starting in March 2010 and lasting until February 2010. The data taken on the longitudinal profile show again low SPM concentrations (see GKSS 2007, time series is updated on http://www.coast.gkss.de/staff/kappenberg/).
- Period #4 is exceptional because of the decline of turbidity. So far, no explanation for this observation can be given.

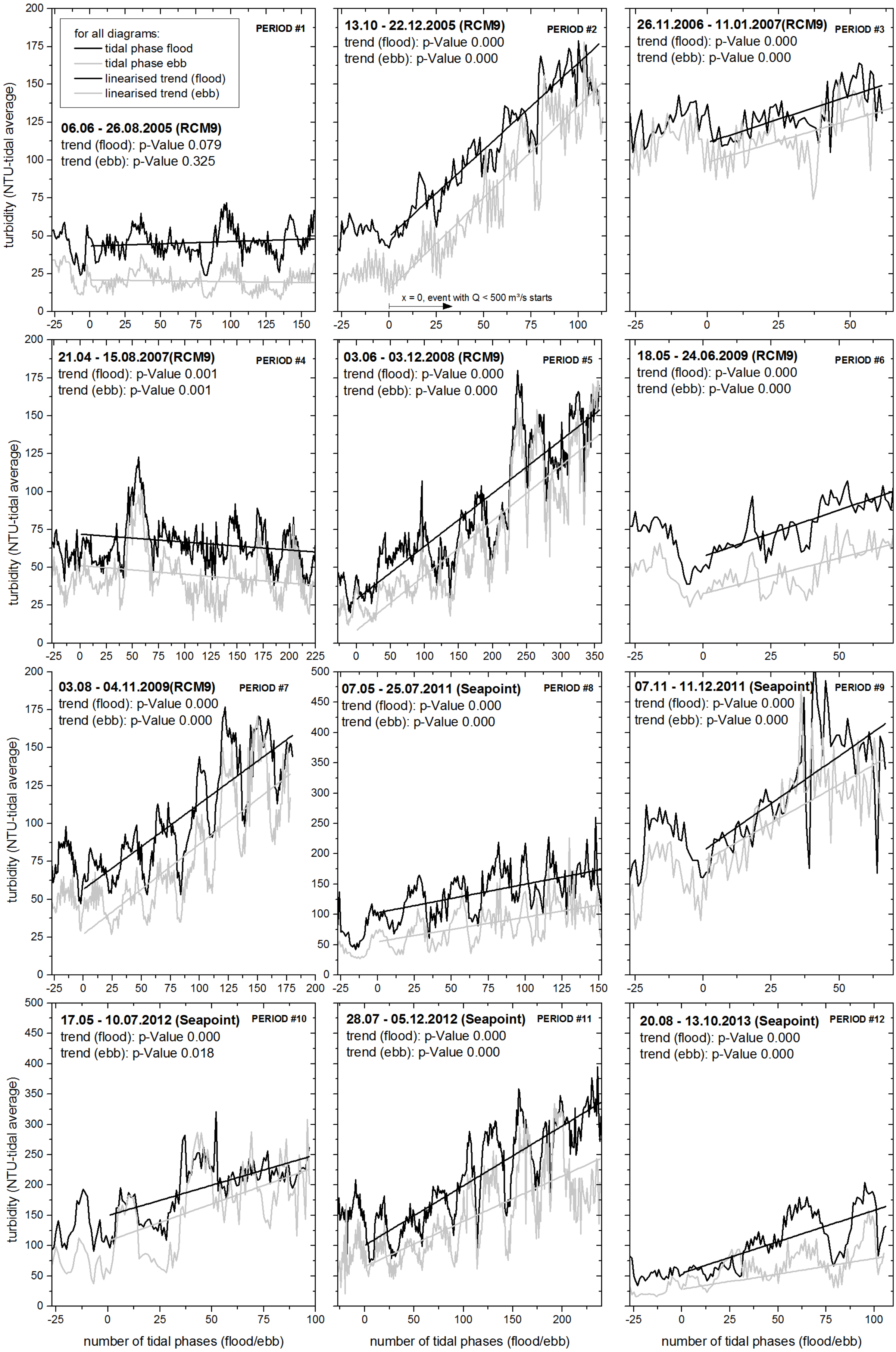

Figure 3. Measurement station D1 (Elbe-km 643), development of turbidity (1.5 m above river bottom) during periods of persistently low freshwater discharge.

5 SEDIMENTATION RATES IN PERIODS OF PERSISTENTLY LOW FRESH-WATER DISCHARGE

Figure 4 depicts the average rate of change in bathymetry within the sediment trap. This time series is based on the multi-beam echo sounding every two weeks. At times of maintenance dredging no soundings were carried out. In Figure 4 these periods are indicated by a background in very light grey. For an explanation of the black and dark grey bars in this time series refer to the caption of Figure 4.

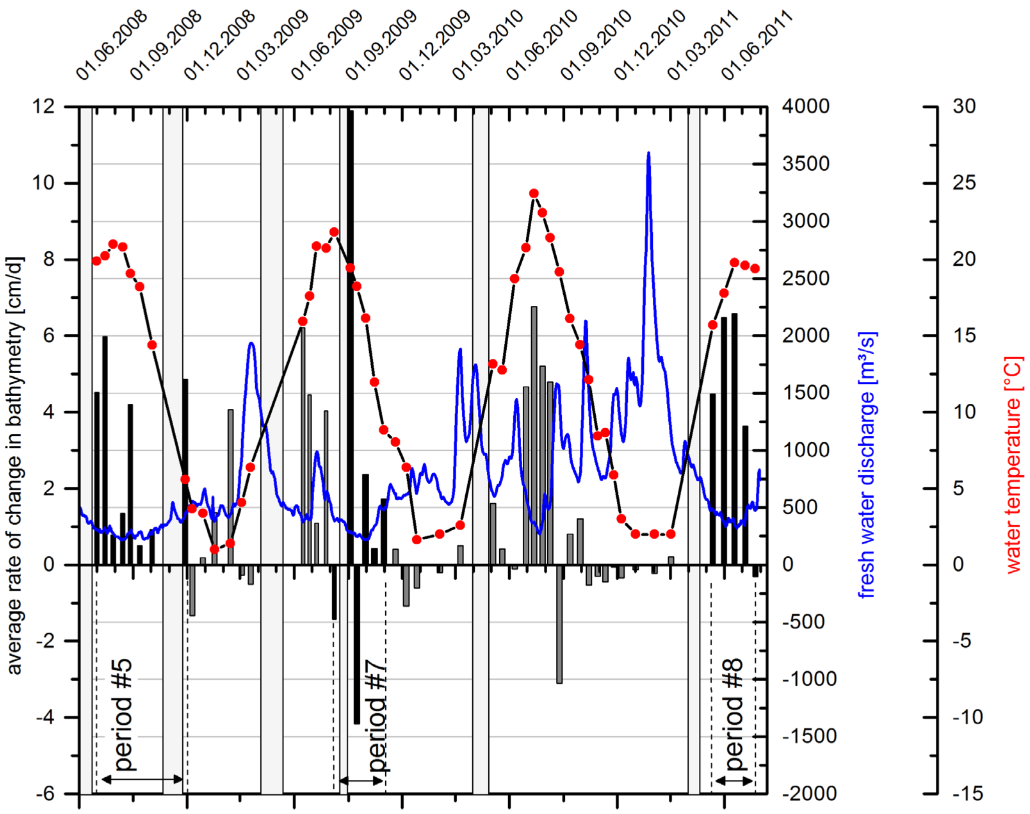

Figure 4. Sediment trap (Elbe km 642 – 644). Development of the average change in bathymetry (adopted from Winterscheid et al., 2011), bars that fall within periods of persistently low freshwater discharge are highlighted in black, otherwise shown in dark grey. Periods of maintenance dredging are indicated by a background in very light grey.

Figure 4 clearly shows an interrelation between freshwater discharge and average rate of change in bathymetry (or sedimentation rates). Persistently low discharges cause higher sedimentation rates. Thus, the mean elevation of the river bottom can increase in the magnitude of several centimeters per day. High water temperatures might also foster this effect (Winterscheid et al., 2011).

Conversely in periods of high discharge only little changes of the bed height or even a decrease of the bed height can be observed. Especially in winter and early spring seasons the absolute values of change are small. Sediment samples at that time were showing a river bottom that was continuously covered by a layer of medium sand at least several centimeters thick. Hence, the net sedimentation rate was about near zero at that time (BfG, 2012). On the other hand it is remarkable to recognize that summer periods, strongly favoring a net increase of the bed height, can generate extremely "negative" change rates or greatly abrupt changes between two subsequent change rates. This abrupt, extremely non-linear system behavior is suggested to be the consequence of the complex interaction between the partial processes of sedimentation, erosion and consolidation (Winterscheid et al., 2011).

In the following we investigate how increasing turbidity (and therefore increasing SPM concentrations) can affect the average rate of change in bathymetry (Figure 4). For this we have a closer look at the temporal overlap of this time series of change rates during periods of persistently low discharge, namely periods #5, #7 and #8[3] (see Figure 4 and the respective bars highlighted in black).

Referring back to Figure 3 the development of turbidity shows a characteristic pattern that is roughly composed of a linear trend (for periods #5, #7 and #8 the trend is positive) and a periodic fluctuation of the single values compared to the trend. The time series of average rates of change in bathymetry (see Figure 4) shows fluctuations as well. High change rates are followed by small or even negative change

[3] period #6 was at the same time as maintenance dredging took place; no multi-beam echo soundings were taken.

rates. But this fluctuation is different to the one for turbidity. It is of major importance, there is no positive trend. The change rates which occur at the beginning of each period are greater than those rates occurring in the final phase of the period, in face of conditions of turbidity that have reached maximum values (cf. positive trends in Figure 4). To conclude, no direct correlation between turbidity and average rate of change in bathymetry could be found. This becomes evident in Figure 5a, in which the average rates of change (taken from Figure 4) are plotted against the corresponding averaged turbidity at station D1. The data show no correlation. This is different in Figure 5b which shows that high rates of change correlate quite well with situations of low discharge; apart from those data points with negative change rates of about less than 1 cm/d.

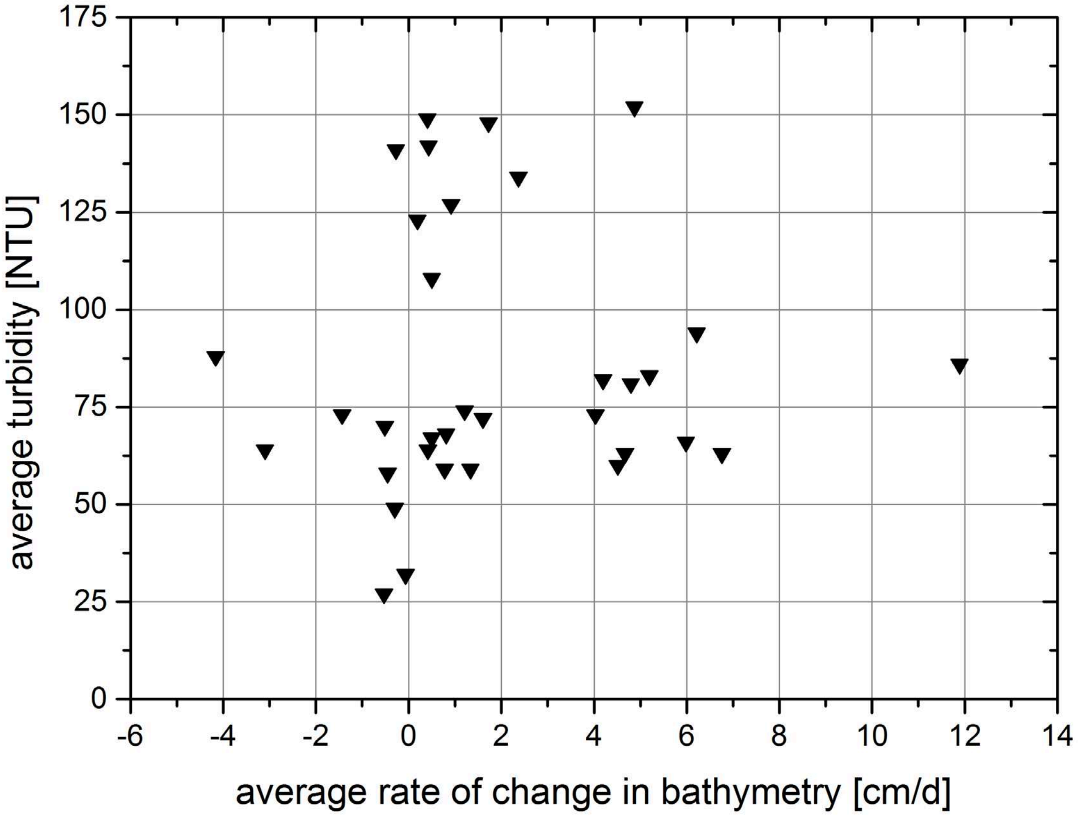

Figure 5: Interrelation between rate of change in bathymetry with turbidity (on the left - Figure 5a) and with freshwater discharge (on the right - Figure 5b).

6 DISCUSSION AND CONCLUDING REMARKS

At first glance the previous findings might appear contradictory: On the one hand low freshwater discharge intensifies the upstream transport of SPM (tidal pumping). As a result, amounts of SPM are accumulating in the upper part of the Elbe River Estuary and sedimentation rates as well as dredging volumes increase. On the other hand no direct correlation between turbidity data and the rate of change in bathymetry could be found in the study area.

This contradiction disappears once turbidity is understood as measure for the amount of material that is potentially available in the water column (SPM concentration), and therefore can deposit on the river bottom. However, other factors determine the proportion of the freshly accumulated material that will deposit on the river bottom for the longer term and will continue to consolidate. These ‘other factors’ are e.g. current velocities, water temperatures and the properties of the SPM material, and these are independent of the actual SPM concentration. The current velocity is known to strongly depend on freshwater discharge, e.g. downstream of Hamburg the ebb current velocity is enhanced and the flood current velocity is reduced if the discharge increases (BAW, 2012).

The rate of change in bathymetry must be understood as an integral unit composed of deposition, erosion and consolidation of sediments; and this explains why there is no direct correlation with turbidity. The exact proportions of deposition, erosion and consolidation are variable in time and unknown. Solely the total change in bathymetry is known from the hydrographical mapping. Considerable research efforts are needed at the level of the process dynamics. Its partial processes can be roughly structured into the following categories: (1) sinking behavior of the individual grain and of flocs, (2) interaction current and river bottom, (3) soil mechanism, (4) physical and chemical processes at the particle-particle level (microscale) and (5) biological processes.

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