NETHERLANDS JOURNAL OF AQUATIC ECOLOGY 29 (3-4) 217-227 (1995)

APERIODIC VARIATIONS OF THE TURBIDITY MAXIMA OF TWO GERMAN COASTAL PLAIN ESTUARIES

I. GRABEMANN[1], J. KAPPENBERG[1] and G. KRAUSE[2]

KEYWORDS: SPM dynamics; estuarine turbidity maximum; location of the turbidity maximum; aperiodic river floods; Elbe; Weser.

ABSTRACT

Suspended particulate matter dynamics in estuaries can be split into more or less regular and periodic phenomena dominated by the tide and aperiodic events like river spates which have lasting effects on the suspended matter distribution. The catchment areas of the estuaries of both the River Elbe and R. Weser (Germany) are subject to almost the same meteorological conditions. But the mean freshwater runoff of R. Elbe is about twice the mean R. Weser runoff. In the turbidity maxima of both estuaries, suspended matter dynamics are dominated by the tide most of the year. The turbidity maxima are associated with the low salinity regions, and the locations of both the mixing zones and turbidity maxima depend on runoff. In both estuaries, mixing zone and turbidity maximum react almost immediately and simultaneously on strong increases of runoff. During river floods no turbidity maxima can be observed in the inner estuaries. With decreasing runoff after a river flood the re-establishment of the turbidity maximum lags behind the return of the mixing zone. The restoration of the turbidity maximum to its normal magnitude lasts for months. For the 7 river floods presented here the restoration period varied from 1 to 6 months for the Weser and from 5 to 7 months for the Elbe estuary.

INTRODUCTION

Suspended particulate matter (SPM) dynamics in estuaries can be split into two modes. More or less regular and periodic phenomena are associated with the action of the tide. On the other hand, river spates or storm surges result in specific events. River floods bring about large and lasting changes to estuarine suspended matter characteristics. This effects especially the turbidity maximum, a dynamic feature (*e.g.* DYER, 1988), in which particles are accumulated and may undergo many cycles of erosion, resuspension and sedimentation. Pools of bed-source fine sediment can be formed in prolonged periods of low runoff (*e.g.* UNCLES and STEPHENS, 1993). As heavy metals and organic trace compounds are adsorbed onto SPM, the residence time of SPM is of great importance. River floods are considered to be effective mechanisms for flushing of SPM being caught in the turbidity maximum to the outer estuary and probably to the adjacent coastal area (NICHOLS, 1977; CASTINGS and ALLEN, 1981; AVOINE, 1986; SCHUBEL and PRITCHARD, 1986; VALE *et al.*, 1993; GRABEMANN and KRAUSE, 1994; UNCLES *et al.*, 1994).

In this paper we will investigate (1) variations of the location of the turbidity maximum depending on runoff, and (2) characteristics of the response of the turbidity maximum to river floods with respect to time scales of flushing-away and restoration. Long sequences of measurements of SPM are required for this kind of analysis. Suitable data sets are available for the Elbe and Weser estuaries (Fig. 1), neighbouring coastal plain estuaries with well-developed turbidity maxima at the German coast of the North Sea.

DATA BASE

Time series of salinity, temperature, optical transmission and current velocity were recorded at the platforms P1 and P2 (Fig. 1), 5 m below the water surface in the turbidity maximum region of the Elbe estuary since 1989 with a resolution of some minutes. Similar measurements were performed at Blexen (BL, Fig. 1) 1 m above the bottom in the Weser estuary since 1983 with long gaps. Additionally, longitudinal transects and cross-sectional measurements with vertical resolution were undertaken during a few episodes on Elbe (KAPPENBERG *et al.*, 1996) and Weser (GRABEMANN and KRAUSE, 1989, 1994; RIETHMÜLLER *et al.*, 1988). By such campaigns the representativity of the long-term measuring sites (P1, P2, BL) was investigated. The instrument packages as well as the procedures for estimating SPM concentrations from turbidity measurements on Elbe and Weser are described in FANGER *et al.* (1990) and GRABEMANN and KRAUSE (1989), respectively. The observations on both rivers were performed independently of each other. For this reason, the relative positions of the fixed observation sites with respect to the mean location of the turbidity maximum are different.

Near-surface longitudinal transect measurements of salinity and turbidity with an interval of usually one to two months are available from Water Authorities (Arbeitsgemeinschaft für die Reinhaltung der Elbe, Senator für Umweltschutz und Stadtentwicklung Bremen, Staatliches Amt für Wasser und Abfall Brake) for the Elbe (upstream of km 747) and Weser estuaries (upstream of km 80) for several years.

MORPHOLOGY AND HYDROGRAPHY

The Elbe and Weser estuaries (Fig. 1) between their last weirs and seaward limits (defined as the regions where salinity shows only small intratidal and annual variations) have similar lengths: 160 km and 120 km, respectively. Both estuaries are shipping channels to the harbours of Hamburg and Bremen, respectively, and often dredged to maintain a required navigational depth of 13 to 25 m and 9 to 15 m below chart datum in the fairways. The outer parts of both estuaries are funnel-shaped within the Wadden Sea area. The tides of both estuaries are semi-diurnal. They have similar mean tidal ranges and tidal range variations between spring and neap tides at Cuxhaven (Elbe: mean 3 m, spring 3.5 m, neap 2.5 m) and Bremerhaven (Weser: mean 3.5 m,

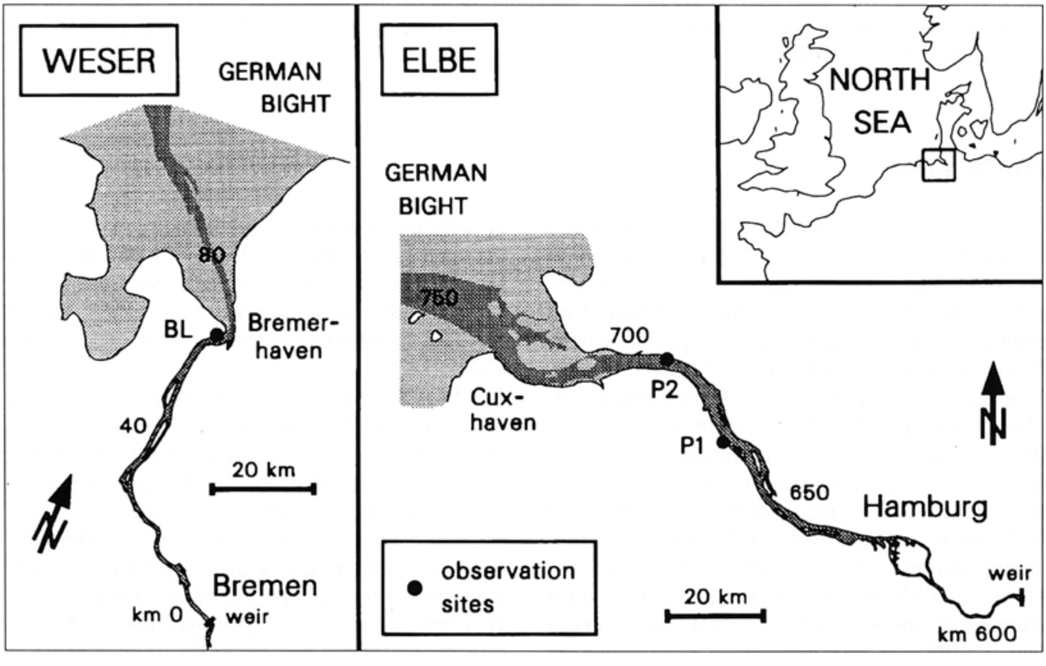

Fig. 1. Maps of the estuaries of Elbe and Weser. The shown official kilometer scales for Elbe and Weser start at the confluence of Elbe and Moldau and at a bridge in Bremen, respectively. The measuring sites Blexen (BL, Weser) and platforms 1 and 2 (P1, P2, Elbe) are indicated.

spring 4.0 m, neap 3.0 m). Both estuaries are hypersynchronous. In the Weser estuary the mean tidal range increases upstream to about 4 m at the weir in Bremen.

The catchment areas of R. Elbe and R. Weser are subject to almost the same meteorological conditions and their freshwater runoffs are correlated. But because of its larger catchment area the long-term mean discharge of R. Elbe (722 m^3s^{-1}, during 1926-1984, determined 45 km upstream of the weir) is about twice the long-term mean discharge of R. Weser (324 m^3s^{-1}, during 1941-1984, determined 30 km upstream of the weir). Long-term averages of the annual minimum and maximum flow rates ($\bar{Q}_{min}$ and $\bar{Q}_{max}$) of R. Elbe and R. Weser are 279 and 119 m^3s^{-1} and 1880 and 1180 m^3s^{-1}, respectively. Long-term mean SPM concentrations are about 40 g m^{-3} in the R. Elbe and in the R. Weser. Daily values can be greater than 200 g m^{-3} (Deutsche Gewässerkundliche Jahrbücher, Elbe (Neu Darchau, Hitzacker), Weser (Intschede),1984).

THE TURBIDITY MAXIMA AND THEIR LOCATION

Both estuaries exhibit strong turbidity maxima in which SPM dynamics are dominated by the tide for most of the year. Cyclic deposition, resuspension and transport of material by tidal currents are the most important short-time processes within these regions. They are resulting in significant SPM concentration peaks during ebb and flood tide (GRABEMANN and KRAUSE, 1989, 1994; KAPPENBERG *et al.*, 1996). In the Elbe estuary, the water with the turbidity maximum contains about $80x10^6$ kg SPM extending over a distance of some 30 km. In the Weser estuary, this distance is 15-20 km, and the content $20\text{-}40x10^6$ kg. In both cases SPM concentrations in deeper layers of the fairway can exceed the mean riverine values by factor up to 40.

The turbidity maxima are always associated with the low salinity regions, but regions of increased turbidity can be found further upstream. The locations of turbidity maximum and mixing zone depend on the freshwater discharge. With increasing discharge turbidity maximum and mixing zone move down-estuary. Fig. 2 presents near-surface locations of the turbidity maxima and mixing zones. The variations in location at a particular discharge depend mainly on the runoff history. In both estuaries, the location-sensitivity to fluctuations decreases with increasing discharge. For flow rates greater than 1200 m^3s^{-1} in the Elbe estuary, there is almost no further downstream movement of the turbidity maximum. The empirical relationships for the near-surface positions of mixing zone (position of the S=2 (x_{S2}) or S=3 (x_{S3}) isohaline) and turbidity maximum (centre of gravity (x_{TM})) in kilometer (official kilometer scale) are for the Elbe (Q = 200 - 1800 m^3s^{-1}):

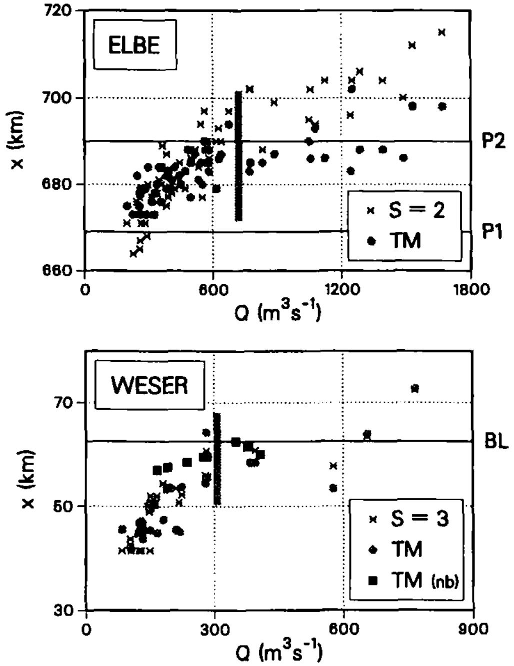

Fig. 2. Correlations of river discharge Q and the near-surface locations of both turbidity maximum (TM, center of gravity) and mixing zone for well developed ebb currents for Elbe and Weser. The locations of the mixing zones are represented by the locations of the S=2 and S=3 isohalines, respectively. The vertical grey bars depict the mean near-surface longitudinal extent of the respective turbidity maxima for mean runoffs. TM (nb) represents near-bottom location of the turbidity maximum. Near-surface data are from the Water Authorities: Arbeitsgemeinschaft zur Reinhaltung der Elbe (Elbe) and Staatliches Amt für Wasser und Abfall Brake (Weser).

$$x_{S2} = 573\ Q^{0.029}$$

$$x_{TM} = 630\ Q^{0.013}$$

for the Weser (Q = 100 - 900 m^3s^{-1}):

$$x_{S3} = 16\ Q^{0.215}$$

$$x_{TM} = 20\ Q^{0.176}$$

The near-surface locations can differ from the near-bottom locations (see *e.g.* RIETHMÜLLER *et al.*, 1988, Figs. 3 and 4), but there are too few longitudinal transects with vertical resolution to determine the position of the turbidity maximum in different water layers as a function of the discharge. For the Weser estuary, there exist at least a few observations of the locations of the near-bottom turbidity maximum for river discharges between 150 and 450 m^3s^{-1}. They seem to be slightly down-estuary from the near-surface positions.

EFFECTS OF RIVER FLOODS

In Fig. 2 locations of the turbidity maxima in Elbe and Weser are given for river discharges smaller than $\bar{Q}_{max}$. Freshwater flow rates exceeding 0.85 $\bar{Q}_{max}$ are defined as river floods. In general, the near-surface longitudinal transect measurements show no pronounced turbidity maxima in the inner parts of both estuaries in times of high river discharges or river floods. These findings are confirmed by the long-term measurements at the sites P1 (Elbe) and BL (Weser) which are situated in or close to the respective turbidity maximum zone under 'normal' discharge conditions. During river spates only freshwater, low SPM concentrations, and absence of significant intratidal variations of SPM, indicating that no turbidity maximum zone is present, are observed at these sites.

The time scales for the reaction of the turbidity maximum zone to the extent of river floods are different. Fig. 3 displays the rapid decrease of SPM concentration and salinity at strongly increasing river discharge for site P1, which is situated in the centre of the Elbe turbidity maximum zone for low runoff (Fig. 2). Turbidity maximum and mixing zone leave the observation area (the inner estuary) without almost any delay within a few days. This time interval depends on how fast the discharge increases. The subsequent period of slowly increasing SPM concentrations lasts for about half a year after the peak of the spate.

The longitudinal transect measurements have an interval of one to two months. As this interval might be similar to the reaction time of the turbidity maximum to flooding events, only the long-term measurements at fixed sites with intervals of minutes will be used for the following analysis.

Before investigating the effects of events, first normal conditions will be defined. Empirical relationships between river discharge, salinity and SPM concentration are derived for the long-term observation sites. Fig. 4 presents correlations between river discharge and maximum intratidal SPM concentration and salinity for BL. The heavy curves

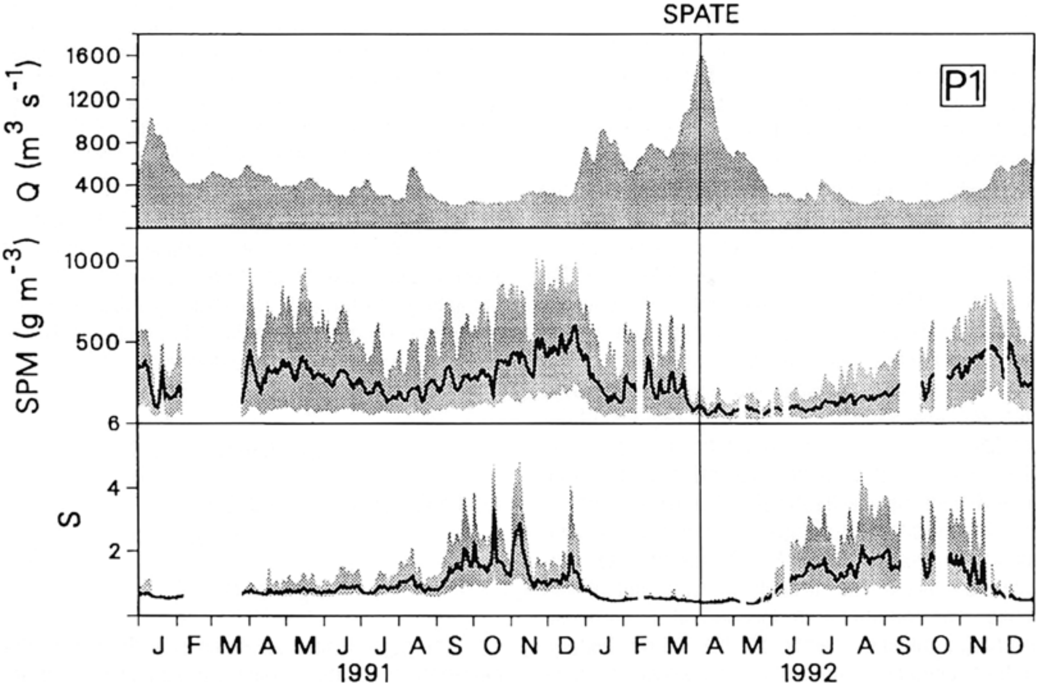

Fig. 3. Seasonal variation of daily mean discharge (Q), and minimum, mean and maximum intratidal SPM concentration and salinity (S; ‰) for site P1 in the Elbe.

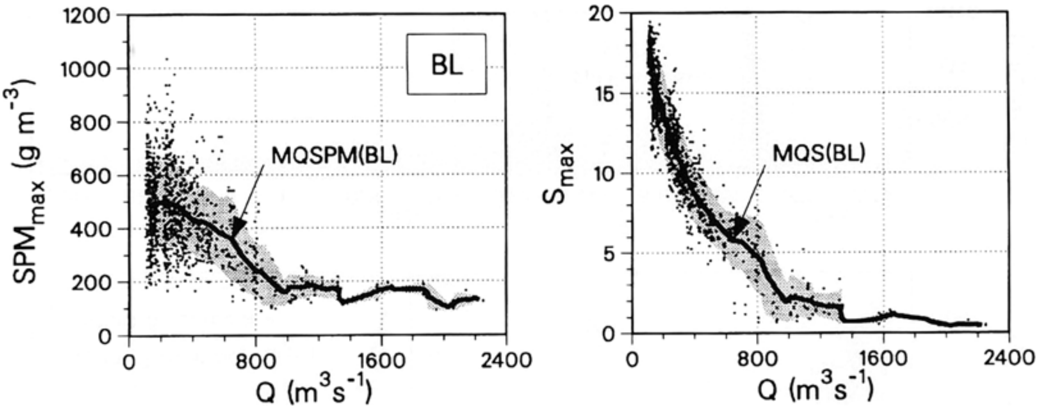

Fig. 4. Correlations between river discharge Q, maximum intratidal SPM concentration (SPM_{max}) and salinity (S_{max}; ‰) for site BL (Weser). The thick black lines MQSPM (BL) and MQS (BL) represent the empirical relationships, and the shaded areas the standard deviations.

represent running averages for discharge intervals of 200 m^3s^{-1} with a step of 50 m^3s^{-1}. These empirical relationships have been established on the basis of about 1000 tidal cycles for the Weser and 2500 tidal cycles for the Elbe. They include a wide variety of spring-neap cycles and river discharges. At a particular discharge the concentrations fluctuate strongly due to the history of the discharge and variations within the fortnightly cycle. Maximum intratidal SPM concentrations at spring tides can exceed those at neap tides by factor up to 2 in both estuaries (GRABEMANN and KRAUSE, 1989, Fig. 9; KAPPENBERG *et al.*, 1996).

At site BL in the Weser, large intratidal SPM concentrations occur only for Q <1000 m^3s^{-1}. At greater discharge riverine conditions prevail with absence of sea salt. When BL is close to the centre of the Weser turbidity maximum zone (250<Q<500 m^3s^{-1}, Fig. 2), the value of MQSPM(BL) is 450 to 500 g m^{-3}. This concentration denoted SPMC(BL) is defined as that value to which the concentration in the centre of the Weser turbidity maximum zone has to be restored after a flooding event. This value indicates the mean or 'normal' magnitude, but the SPM concentration of the turbidity maximum can be higher.

The sites P1 and P2 are close to the landward and central part, respectively, of the Elbe turbidity maximum zone for mean runoff (Fig. 2). Large SPM concentrations at P1 occur only for Q <1200 m^3s^{-1}. When P1 is located close to the central part of the turbidity maximum zone (Q<400 m^3s^{-1}), SPMC(P1) is about 500 g m^{-3} (Fig. 6).

Our time series measurements contain only 2 river floods for the Elbe and 5 for the Weser. For the following analyses, the reaction of mixing zone and turbidity maximum during a receding river flood will be split in a sequence of time lags.

For the Weser, Fig. 5 illustrates SPM and salinity variations with strongly increasing runoff leading to flood conditions (1.9 $\bar{Q}_{max}$) in winter 1986/87 and for a receding river flood (1.4 $\bar{Q}_{max}$) in spring 1987. No SPM data is available between the two events. The maximum intratidal salinity shows almost no hysteresis. The salinity values are similar for given discharge and nearly independent of the discharge history and vary around MQS(BL). In contrast, the maximum intratidal SPM concentrations show a hysteresis in which the concentrations are close to the upper limit of the empirical relationship for increasing runoff and close to the lower limit and therefore smaller than MQSPM(BL) for decreasing runoff after a river flood.

During the peaks of the spates, the SPM concentrations reach a temporary maximum due to an increase of fluvial SPM influx. Generally during the rising phases of river floods, an increase of fluvial SPM can also be detected at stations located upstream of the weir. Additionally, the peak in spring 1987 coincided with spring tide.

It took only about a week of strongly increasing flow rate from about 300 to 2200 m^3s^{-1} for flushing the turbidity maximum from its usual position between km 45 and 70 towards the outer estuary and probably the adjacent coastal area (the concentration decreases from about SPMC(BL) to 150 g m^{-3}). The mixing zone moved down-estuary at the same time. Due to lack of data for the outer estuary, the fate of the turbidity maximum and SPM content during river flood peaks is unknown.

During the receding river flood in April 1987 the mixing zone moved upstream almost immedia-

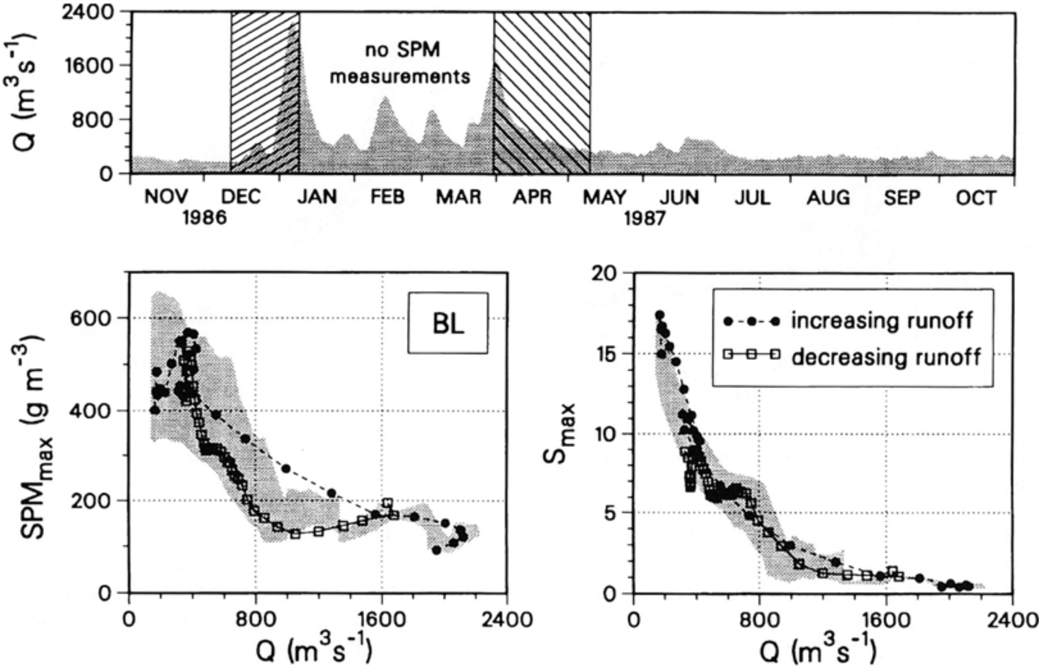

Fig. 5. Time series of the river discharge Q for 1986 and 1987 (upper panel) together with correlations between discharge and maximum intratidal SPM concentration (SPM_{max}) and salinity (S_{max}) (lower panels) for station BL in the Weser estuary. The shaded areas in the lower panels present the empirical relationships with standard deviations as in Fig. 4. The black dots and squares give the values (5-day-running-averages) for increasing and decreasing discharge, respectively, during the runoff events marked by the hatched areas in the upper panel.

tely (almost no hysteresis in the relationship between discharge and salinity) but the time for restoration of the former SPM concentration was much longer. If there was any time lag t_1 (see also Fig. 7) between river discharge peak and return of the mixing zone, this lag was small *i.e.* in the order of a few days. The landward margin of the mixing zone returned to site BL when the discharge fell below 1000 m^3s^{-1}. Former investigations (GRABEMANN and KRAUSE, 1994) showed that after this event a turbidity maximum zone was present in the low salinity region when the discharge decreased below 800 m^3s^{-1}, but located seaward from its usual position. It took about 2 weeks after the peak of this spate (time lag t_2) until the turbidity maximum was re-established in its usual position of the low salinity region. Afterwards, turbidity maximum zone and mixing zone moved further simultaneously as the river discharge diminished.

At the spate peak of about 1700 m^3s^{-1} the SPM concentration at BL was about 180 g m^{-3}. It needed about 1 month until the value fluctuated around MQSPM(BL). Within this month the river discharge decreased slowly to about 400 m^3s^{-1}. For this discharge the site BL is normally located in the center of the turbidity maximum region and MQSPM(BL) coincides with SPMC(BL). Therefore, the time span t_3 for restoring the turbidity maximum to its normal magnitude was about 1 month for this event.

For an other episode of high runoff (about $\bar{Q}_{max}$) in 1983, t_3 was up to half a year. However, the effect of a small intermediate event (700 m^3s^{-1}) is unknown. For the event in spring 1988 (1.5 $\bar{Q}_{max}$) t_3 was also about 6 months. In 1994 after a sequence of 4 discharge peaks larger than $\bar{Q}_{max}$, t_3 was about 2 months after the last peak. The last two values of t_3 are uncertain due to long gaps in the time series of SPM and salinity. A flow rate of about 1000 m^3s^{-1} (0.85 $\bar{Q}_{max}$) in winter 1988/89 seemed to move the turbidity maximum only some 10 km down-estuary. Returning with decreasing runoff, the SPM concentration of the turbidity maximum had its normal value.

For the Elbe estuary it was possible to observe the impact of a runoff event on the turbidity maximum at site P1 in 1992 (Fig. 6, see also Fig. 3). Salinity had been below 1 at P1 since December 1991, so that at the beginning of the high-lighted episode on March 1, the site was already in the freshwater region of the estuary. There was already

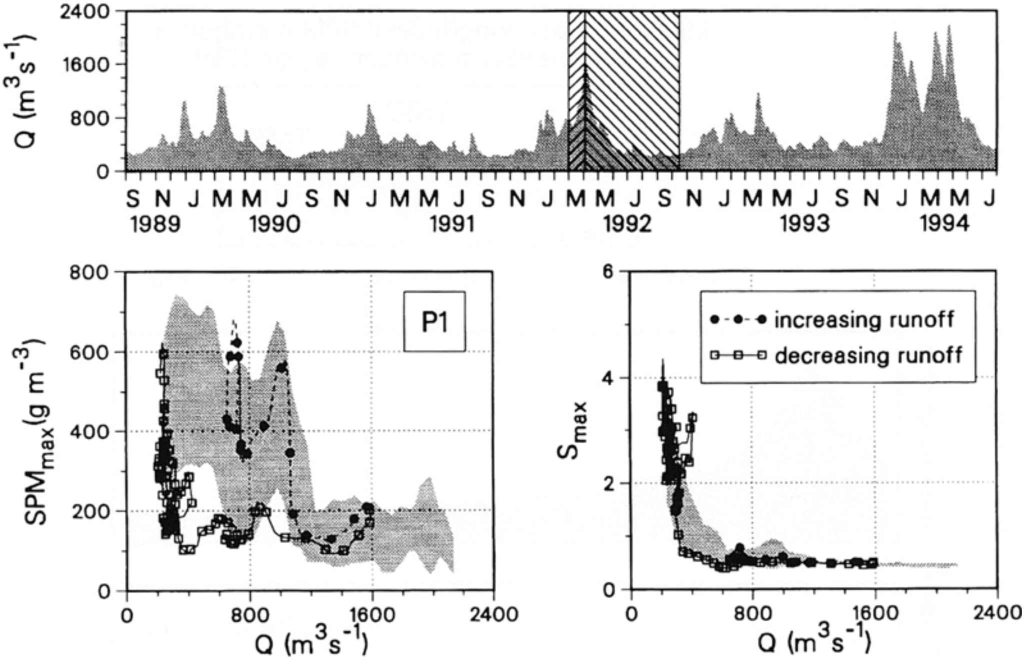

Fig. 6. As in Fig. 5 for station P1 in the Elbe estuary in 1992.

some variation in runoff before the event, which is also reflected in the SPM curve. P1 was located in the landward part of the turbidity maximum zone and the concentration varied around MQSPM(P1). At a critical flow rate of some 1000 m^{3}s^{-1} SPM concentrations rapidly decreased during an interval of 3 days. During the time of maximum runoff, SPM concentrations were already increasing again because it coincided with spring tide. As in the case of the Weser, the SPM concentrations were near the upper limit of the empirical relationship MQSOM (P1) during increasing runoff and could be found near the lower limit during decreasing runoff. Low salinity occurred again in June. As P1 was situated in the freshwater region upstream of the mixing zone for about half a year, no statements are possible for t_1. The time span t_2 for re-establishment of the turbidity maximum within its usual part of the mixing zone has not been determined for the Elbe. The method for finding t_2 which had been applied to the Weser (GRABEMANN and KRAUSE, 1994) is not easily applicable to the Elbe. From August 1992 the site P1 was close to the centre of the turbidity maximum zone for discharges of about 200 m^{3}s^{-1} (Fig. 2), but the SPM concentrations were lower than the MQSPM(P1) level. SPMC(P1) was not reached before October 1992. Then, the concentration fluctuated again around SPMC(P1) and t_3 was about 7 months. No effects of the event could be observed at the site P2 20 km downstream of P1, which was monitored since April 1. This lack of effect is also confirmed by the data from the monthly longitudinal transects. The peak discharge during the event was only 0.85 $\overline{Q}_{max}$ and the turbidity maximum was not flushed to the outer estuary but only transported some 20 km downstream. As to whether the turbidity maximum is flushed to the sea during an event of greater magnitude could not be determined from the measuremens at P1 during the second recorded event in winter and spring 1993/94. The seaward station P2 was out of operation by the end of 1993. The time series of SPM and salinity at P1 resembled those of 1992 and t_3 was also in the same range (5 months), although the river discharge exceeded 2000 m^{3}s^{-1} (1.1 $\overline{Q}_{max}$) at three times during the first 4 months in 1994.

Concerning a receding river flood, different effects correlated with re-establishment of a turbidity maximum in the vicinity of its mean position and the restoration of its SPM concentration have to be distinguished (Fig. 7). It is assumed that the SPM concentration within the turbidity maximum region increases from the landward part (TML) towards a central region (TMC) and decreases again towards the sea (TMS). In both estuaries the turbidity maximum zone is usually associated with the low salinity

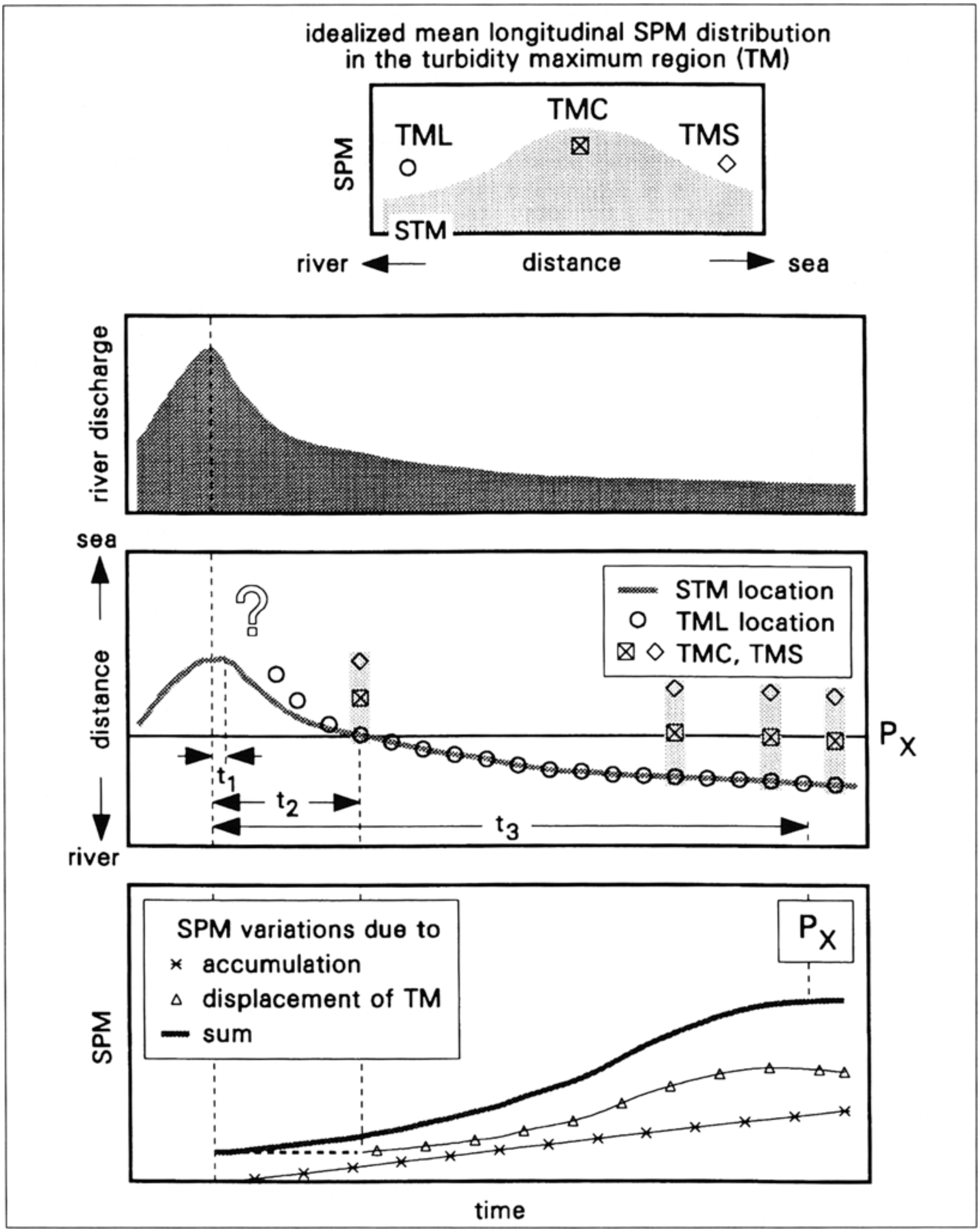

Fig. 7. Schematic diagrams to illustrate the sequence of assumed effects during a receding river flood (all parameters refer to tidal averages). TML, TMC and TMS denote the landward, central and seaward part of the idealized tidally averaged turbidity maximum region, respectively, and STM depicts a specific isohaline. The upstream movements of STM and TML are presented in relation to river discharge. The vertical grey bars in the time/space diagram depict exemplarily the mean turbidity maximum region with TML, TMC and TMS. For a site PX the additive SPM variations due to superposition of displacement of the turbidity maximum and the long-term accumulation of SPM are shown. The symbols t_1, t_2 and t_3 indicate time lags for return of the mixing zone, re-establishment of the turbidity maximum in its usual position within the mixing zone and restoration period, respectivily. The question mark denotes the uncertain fate of the turbidity maximum during the peak discharge.

region. The landward margin of the turbidity maximum and a specific isohaline (STM) are assumed to react on runoff changes in the same way (in the Elbe, parts of the turbidity maximum zone can occur upstream of the mixing zone in the freshwater region and STM is assumed to be close to TMC). After a flooding event, STM moves up-estuary with decreasing river discharge with a small time lag t_1 (only estimated for the Weser) of a few days. Due to lack of observations we do not know whether a turbidity maximum exists in the outer estuary and to which extent the SPM may have been flushed to the sea and dispersed over the large tidal flats. We do know that some time after the peak of a river flood, a turbidity maximum occurs again in the more upstream parts of both estuaries. As shown by GRABEMANN and KRAUSE (1994) for the Weser it takes a time t_2 (about 2 weeks for the event in 1987) until the turbidity maximum has regained its usual location within the low salinity region of the mixing zone (TML coincides with STM). This turbidity maximum has a lower content of SPM, which is either old material which has not been dispersed or newly accumulated material. With decreasing runoff (1) the turbidity maximum region moves further up-estuary (simultaneously with the mixing zone) and (2) the SPM content of the turbidity maximum increases due to accumulation processes associated with the dynamics in the turbidity maximum region. The superposition of these two effects can be observed as an increase of the SPM concentration at a fixed position P_X (*e.g.* for BL or P1) during the restoration period t_3. Time t_3 varies between 1 and 7 months and depends on the history of the river discharge which determines the displacement of the turbidity maximum, on the shape of the turbidity maximum region and on the input of SPM. As t_3 only describes the restoration up to a normal SPM content, afterwards a further increase of SPM is possible.

In Fig. 7 SPM accumulation in the turbidity maximum region was assumed to be a linear function of time since no theoretical background exists for the real functional relationship. Material accumulated in the turbidity maximum region may enter this region either landward (river), seaward or laterally from mud banks.

Within the restoration period t_3 of about 6 months after the flooding event in the Weser in 1983, the river transported a similar amount of material as within the period t_3 of about 1 month after the event in spring 1987 (about 300 x 10^6 kg). The riverine transports within the rising phase of the respective event preceding t_3 have been included. These data show only that in 1987 one of the possible sources supplied more material for accumulation in a shorter time span than in 1983. Especially the fluvial SPM transports during the rising phases of river floods seem to be important. In general, it is unknown which percentage of the turbidity maximum SPM is of riverine origin.

Upstream movement of marine material beyond the freshwater/saltwater interface has been detected in both the Elbe and Weser estuaries (IRION *et al.*, 1987; SCHUCHARDT and SCHIRMER, 1990; VOLLMER *et al.*, 1990), but the percentage of the turbidity maximum SPM of marine origin is also uncertain.

Part of the fluvial and the marine SPM load will be deposited in the estuary (harbour areas, banks, fairway, *etc.*) and dredging activities further complicate estimations of mass balances.

Insight into the origin of the SPM of the turbidity maximum can be got from VOLLMER *et al.* (1990) who analysed a flooding event of about 1800 m^3s^{-1} (about $\bar{Q}_{max}$) in the R. Elbe in June 1986. Before and during the event the SPM in the inner estuary (upstream of the turbidity maximum) consisted of high percentages of riverine material. During the 5 to 6 months of approximately mean discharge following the event the composition of the SPM became more marine. This was derived from the increase of the smectite/kaolinite ratio about 35 km upstream of site P1. From this data it seems likely that a high percentage of the material for the restoration of the turbidity maximum after an event is of marine origin. During the sequence of high runoffs at the beginning of 1987, the smectite/kaolinite ratio decreased again, indicating that riverine material entered the inner estuary.

SUMMARY AND CONCLUSIONS

Within the turbidity maximum regions, SPM dynamics in Weser and Elbe are dominated by the tide most of the year. SPM concentrations increase and decrease as a function of the semi-diurnal tidal cycle modified by the spring-neap cycle. The daily riverine SPM inputs are small compared to the amount of SPM within the turbidity maxima, and the SPM concentrations within the turbidity maxima reflect mainly tidally induced resuspension from the bed and sedimentation. Aperiodic river floods bring about large changes to estuarine suspended matter characteristics. They seem to be effective mechanisms for flushing SPM and harmful substances to the outer estuaries and the adjacent coastal areas.

Uncertainties exist regarding the fate of the turbidity maximum during high river discharge and the re-establishment of SPM concentrations after a river flood.

Because river floods do not occur every year, relevant observations on SPM are scarce. Based on our case studies for the Elbe and Weser estuaries we can only provide some rough estimates on time scales relating to river discharge, mixing zone and turbidity maximum.

During the rising phase of a runoff event, mixing zone and turbidity maximum leave their usual positions almost simultaneously and without delay. The further fate of the turbidity maxima and their SPM is unknown. Long-term or dedicated observations in the outer estuaries and adjacent coastal area are necessary to investigate what happens to the material including its pollutant load. During a receding river flood the re-establishment of the turbidity maximum lags behind the return of the mixing zone. Even if the turbidity maximum is in its usual position within the mixing zone it can take up to half a year until the turbidity maximum is restored to its normal magnitude.

Due to the larger catchment and storage area, river floods in the Elbe are less frequent than in the Weser. Lasting effects on position and dimension of the turbidity maxima in Elbe and Weser seem to be caused by flooding events with peak values exceeding $\bar{Q}_{max}$. Nevertheless, the effects of peaks are uncertain when they occur in close sequence, but the general frequency of peaks exceeding $\bar{Q}_{max}$ is only 13 and 18 in the Elbe and Weser, respectively, within the 15-years-period from 1980 to 1994. In 3 cases, a number N of these peaks succeeded each other (Elbe: N=2, 3, 3; Weser: N=3, 3, 4).

ACKNOWLEDGEMENT

The authors are indebted to all colleagues of GKSS Forschungszentrum Geesthacht GmbH and Alfred Wegener Institut für Polar- und Meeresforschung for their helpful contributions and great efforts with the field measurements. The Senator für Umweltschutz und Stadtentwicklung Bremen and the Staatliches Amt für Wasser und Abfall Brake made available the near-surface longitudinal transect measurements of SPM and salinity.

REFERENCES

Arbeitsgemeinschaft für die Reinhaltung der Elbe (ARGE Elbe), Wassergütedaten der Elbe von Schnackenburg bis zur See. Zahlentafeln 1988-1992. Wassergütestelle Elbe, Hamburg.

AVOINE, J., 1986. Sediment exchanges between the Seine estuary and its adjacent shelf. J. Geol. Soc., 144: 135-148.

DEUTSCHES GEWÄSSERKUNDLICHES JAHRBUCH, Weser- und Emsgebiet, Abflußjahr 1984. Niedersächsisches Landesamt für Wasserwirtschaft, Hildesheim.

DEUTSCHES GEWÄSSERKUNDLICHES JAHRBUCH, Unteres Elbegebiet, Abfluſljahr 1984. Freie und Hansestadt Hamburg, Behörde für Wirtschaft, Verkehr und Landwirtschaft, Strom- und Hafenbau, Hamburg.

CASTING, P. and G.P. ALLEN, 1981. Mechanisms controlling seaward escape of suspended sediment from the Gironde: a macrotidal estuary in France. Mar. Geol., 40: 101-118.

DYER, K.R., 1988. Fine sediment particle transport in estuaries. In: J. Dronkers and W. van Leussen, Eds., Physical processes in estuaries. Springer Verlag, Berlin: p. 295-310.

FANGER, H.-U., J. KAPPENBERG, H. KUHN, U. MAIXNER and D. MILFERSTAEDT, 1990. The hydrographic measuring system HYDRA. In: W. Michaelis, Ed., Estuarine water quality management. Springer Verlag, Berlin: p. 211-216.

GRABEMANN, I. and G. KRAUSE, 1989. Transport processes of suspended matter derived from time series in a tidal estuary. J. Geophys. Res., 94(C10): 14373-14380.

GRABEMANN, I. and G. KRAUSE, 1994. Suspended matter fluxes in the turbidity maximum of the Weser Estuary. In: K.R. Dyer and J.R. Orth, Eds., Changes in Fluxes in Estuaries. Olsen and Olsen, Fredensborg: p. 23-28.

IRION, G., F. WUNDERLICH and E. SCHWEDHELM, 1987. Transport of clay minerals and anthropogenic compounds into the German Bight and the provenance of fine-grained sediments SE of Helgoland. J. Geol. Soc., 144: 236-240.

KAPPENBERG, J., G. SCHYMURA, H. KUHN and H.-U, FANGER, 1996. Spring-neap variations of suspended sediment concentrations and transport in the turbidity maximum of the Elbe Estuary. Arch. Hydrobiol. Spec. Iss. Adv. Limnol., 47: 323-332.

NICHOLS, M.M., 1977. Response and recovery of an estuary following a river flood. J. Sediment. Petrol., 47: 1171-1186.

RIETHMÜLLER, R., H.-U. FANGER, I. GRABEMANN, H.L. KRASEMANN, K. OHM, J. BÖNING, L.J.R. NEUAMNN, G. LANG, M. MARKOFSKY and R. SCHUBERT, 1988. Hydrographic measurements in the turbidity zone of the Weser estuary. In: J. Dronkers and W. van Leussen, Eds., Physical processes in estuaries. Springer Verlag, Berlin: p. 332-346.

SCHUBEL, J.R. and D.W. PRITCHARD, 1986. Response of the Upper Chesapeake Bay to variations in discharge of the Susquehanna River. Estuaries, 9: 236-249.

SCHUCHARDT, B. and M. SCHIRMER, 1990. Diatom frustules as natural tracers to determine the origin suspended matter in the Weser estuary. Environm. Technol., 11: 853-858.

UNCLES, R.J. and J.A. STEPHENS, 1993. The freshwater-saltwater interface and its relationship to the turbidity maximum in the Tamar Estuary, UK. Estuaries, 16: 126-141.

UNCLES, R.J., M.L. BARTON and J.A. STEPHENS, 1994. Seasonal variability of fine-sediment concentrations in the turbidity maximum region of the Tamar Estuary. Est. Coast. Shelf Sci., 38: 19-39.

VALE, C., C. CORTESAO, O. CASTRO and A.M. FERREIRA, 1993. Suspended-sediment response to pulses in river flow and semidiurnal and fortnightly tidal variations in a mesotidal estuary. Mar. Chem., 43: 21-31.

VOLLMER, M., B. HUDEC, H.-D. KNAUTH and E. SCHWEDHELM, 1990. Seasonal variations of mineralogical composition and heavy metal contamination of suspended matter in the River Elbe Estuary. In: W. Michaelis, Ed., Estuarine Water Quality Management. Springer Verlag, Berlin: p. 153-158.

Addresses of the authors:

[1] GKSS Forschungszentrum, Postfach 1160, D-21494 Geesthacht, Germany.
[2] Alfred-Wegener-Institut für Polar- und Meeresforschung, Postfach 120161, D-27515 Bremerhaven, Germany.