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SHIP-INDUCED SEDIMENT TRANSPORT IN COASTAL WATERWAYS (SeST)

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SUMMARY

The question of the extent to which the residual sediment transport in estuaries is influenced by the passage of ever larger vessels has repeatedly been discussed during the last decade. In the context of the natural (tidal) transport of sediment and suspended matter in coastal waterways and the increased sedimentation in port basins and marinas along the estuaries following a series of extension measures. Measurements carried out in "still" water illustrated not only the available options but also the limitations of the various measurement techniques for recording the increased sediment concentration which is induced in the water column by sailing vessels. The use of redundant measurement techniques permits a scientifically confirmed evaluation and provides initial insights into the magnitude of the increased ship-induced sediment concentration in coastal waterways depending on the passing vessels.

1 INTRODUCTION

In the context of the natural (tidal) transport of sediment and suspended matter in coastal waterways and the increased sedimentation in port basins and marinas along the estuaries following a series of extension measures. The question of the extent to which this residual sediment transport is influenced by the passage of ever larger vessels has repeatedly been discussed during the last decade.
Research in the literature showed that on the one hand, studies of ship-induced sediment transport have been carried out to investigate the resuspension or erosion of shore zones due to ship-induced wave systems in inland waterways and coastal waters (e.g. [12], [5], [11]) and enable the ship-induced increase in suspended matter in the cross section of the water body to be estimated by integration in relation to naturally induced values (e.g. [4]). However, the majority of such works have been concerned with the passage of pusher craft, coasters, smaller ships and recreational craft in inland waterways and rivers (e.g. [10], [1]). Furthermore, simple analytical approaches have been developed, mathematical models used and compared (e.g. [6]) and existing approaches called into question on the basis of new numerical models and field measurements, for example with respect to the impacts of propeller wash (e.g. [15]).
As container ships continue to increase in size and new plans are devised to adapt the fairways of coastal waterways for container shipping, the recognition that ship-induced sediment transport contributes to the sediment regime of tidal estuaries takes on growing importance.
Whether or not this increased vessel size could also have a tangible influence on the sediment transport regime of tidal estuaries is explained and debated in the following with reference to preliminary basic measurements carried out in the KIEL CANAL in the framework of the BAW's R&D project on ship-induced sediment transport (SeST).

The interaction between the sailing ship and the coastal waterway, and in particular with ship-induced suspended sediments, is not considered further in this work because the sediment concentration in the water column is relatively low compared to fluid mud and therefore no significant interactions are anticipated. Additional comprehensive studies of the ship dynamics of ultra large vessels in coastal waterways of limited width and depth are being undertaken by the BAW on behalf of the German Federal Waterways and Shipping Administration (WSV) (currently e.g. [13]).

2 THE SeST RESEARCH PROJECT

The main overarching objectives of the BAW's ongoing research project on coastal waterways, which was launched in 2011, are to record basic information on ship-induced sediment transport (SeST), to differentiate this information spatially and according to processes, to develop empirical-analytical approaches for estimating SeST in coastal waterways in the near field, the far field and the shore zone and to determine SeST as a proportion of the total volume transported in a tidal estuary.

Figure 1 illustrates this spatial and process-oriented differentiation by dividing sediment transport between the near field (approximately two ship widths), the far field (transition from the fairway to shallow water) and the bank zone.

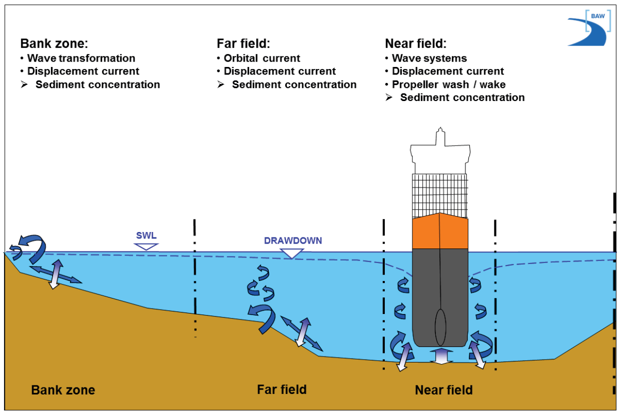

Figure 1. Diagrammatic view of ship-induced sediment loading differentiated spatially and according to processes.

The conceptual model of transient, ship-induced flow and turbulence development, including the influence of the propeller, is presented as a side view in Figure 2.

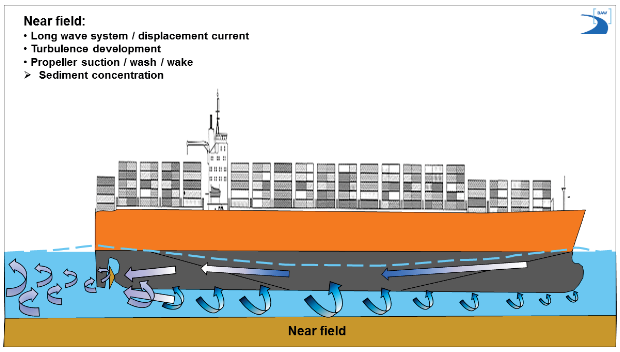

Figure 2. Schematic model showing the development of transient, ship-induced turbulence and flow in a ship's near field (vertical exaggeration)

Owing to the interdependence of the tidal and ship-induced physical processes which influence ship-induced sediment transport (SeST) in a coastal waterway, measurements carried out in the field are essential in order to gain an insight into the relevant interactions. SeST measurements in the near and far fields as well as in the bank zone are required for a holistic view.

The methodological structure of the BAW research project is shown in the diagram below (Figure 3), which groups the various sub-projects on the top level (planning, recording, evaluation and implementation) together with their respective work packages. Some of the work packages under the recording and analysis sub-projects are processed concurrently.

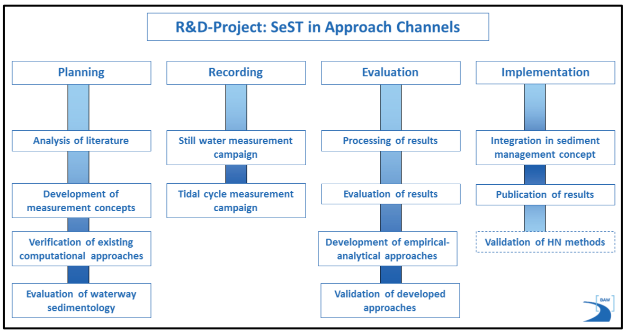

Figure 3. Diagram of the realisation concept for the BAW SeST R&D project

The first measurements were required to be carried out under controlled conditions in "still water", for instance in the KIEL CANAL, with a minimum of "background noise"; after verifying the measurement techniques in this way, the next step was to embark on more measurement campaigns under tidal conditions.

The near-field analyses of passing vessels were intended to provide detailed insights into the physical processes both of the water flowing around these vessels and of ship-induced sediment transport, to enable the influence of the displacement flow, propeller wash and the wake, for example, to be determined. To permit a complete description of ship-induced sediment transport in a cross profile, it was necessary to simultaneously record SeST in the far field as well as in the bank zone.

Various measurement techniques such as ADCP/PDT from Aqua Vision, a cooperation partner in the Netherlands, backed up by sample collection and a few other systems including an Innomar SES2000 supported by the NIAH at HafenCity University Hamburg (HCU), a project partner, as well as single probes (turbidity, flow, water level) needed to be tested and their suitability established for the task at hand.

The results of the hydrodynamics measurements and the measurements of ship-induced sediment transport in each zone then had to be analysed according to processes, formulated as empirical-analytical approaches and assessed with regard to their accuracy and limits of applicability.

3 MEASUREMENTS IN THE KIEL CANAL

The measurements in "still water" without any "background noise" due to flow-related turbidity were carried out in the KIEL CANAL, which links the North Sea to the Baltic, at approximately km 18 not far from the Hochdonn viaduct [7]. The sediment at the bottom of this canal section is comprised of about 75% fine to medium sand (62 < µm < 500), which could be suspended as a result of passing vessels.

The measurement configuration in cooperation with the Waterways and Shipping Office (WSA) Brunsbüttel and Aqua Vision is summarised in Figure 4 and consists of the following individual components:

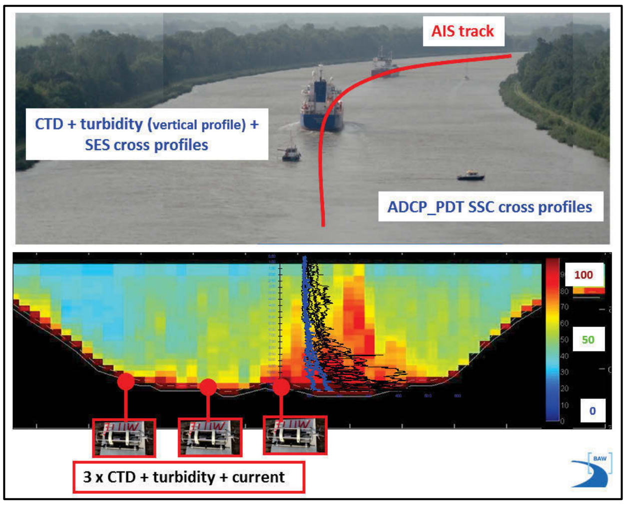

Figure 4. Measurement configuration for recording ship-induced sediment transport in the "still water" of the KIEL CANAL

- Three autonomous CTD, OBS turbidity and VECTOR flow probes installed near the bottom of the cross profile as a stationary, continuous measurement system.
- Ship-based ADCP/PDT cross profile measurements before and after the passage of vessels ([2]).

- Ship-based profiles in the wake with lowered CTD and OBS turbidity probes.
- Ship-based SES cross profiles for analysing the acoustic signal in the wake.
- AIS for detecting passing vessels and determining their ship parameters.

Stationary measurements were performed during the period from 17 to 25 September 2012 at the three points near the bottom for 506 passing vessels (both convoys and single vessels).

In addition, 79 passing vessels were recorded by means of ship-based measurements during the period from 18 to 20 September 2012; 161 profiles with lowered probes (CTD + SSC) and 175 SES cross profiles (acoustic signature) were measured on these three days while measurements for a further 523 ADCP/PDT cross profiles (SSC + v) were conducted and documented.

4 EVALUATION OF THE RESULTS

The various systems used for the measurements are presented in the following for selected events, which are representative of the large number of passing vessels recorded. After discussing the results and analysing their fitness, the suitability of each system for future recordings of ship-induced sediment transport is assessed.

4.1 SHIP-BASED MEASUREMENTS

4.1 (a) Profile measurements in the wake with lowered probes

Profiles were calculated in the wake of passing vessels using a ship-based system of lowered CTD and OBS turbidity probes, in order to measure the vertical distribution of ship-induced turbidity.
Figure 5 shows five time-dependent profile measurements in the wake of a feeder ship. Turbidity concentrations between 150 and 300 g/m^3 were measured at a water depth h of approximately 10 m as a function of time.

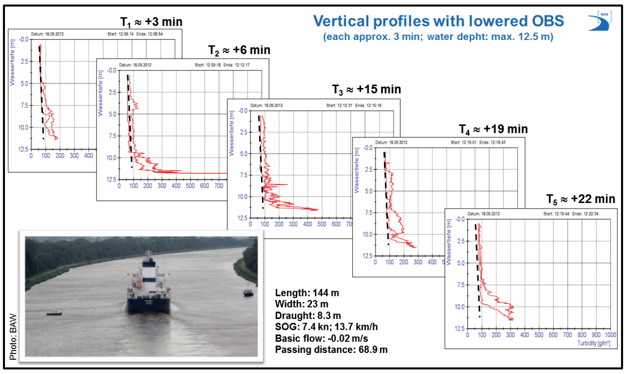

Figure 5. Vertical turbidity profiles in the wake of a passing vessel in the KIEL CANAL as a function of time

However, these values can only be taken as a guide to the time-dependent vertical turbidity distribution because even experienced shipmasters were unable to keep the measurement vessels stationary in a particular position owing to the strong flows and turbulences in the wake. The original idea of an unequivocal spatial assignment of the vertical profile to cross profile and stationary point measurements could therefore no longer be realised, which is why a more detailed evaluation and "blending" with the results of the stationary measurements near the bottom were dispensed with.

This ship-based measurement technique was considered to be unsuitable for scientifically confirmed data analyses – and hence also for further measurement campaigns, especially in the tidal estuary – owing to the insufficient positioning stability in the wake of a ship.

4.1 (b) SES cross profile measurements

As an alternative to profiles with lowered CTD/OBS probes for recording the vertical turbidity distribution, cross profile measurements were carried out using an Innomar SES2000 system (sediment echo sounder or sub-bottom profiler), to enable the ship-induced acoustic signature in the wake to be recorded and subjected to a qualitative analysis. Initial experience with this system was gained on the Lower Elbe as well as in the KIEL CANAL with assistance from the Hydrographic Laboratory and the NIAH at HCU Hamburg [3].

Figure 6 shows the acoustic signature in the wake immediately after the passing of a vessel and at various intervals as an example of SES measurements in the wake. It is interesting to note the "rising" hydroacoustic signals as a function of time, which is an indication of air bubbles and eddies in the wake but says nothing about sinking, ship-induced suspended sediment.

It is presently impossible to separate these acoustic signatures according to individual influences (air ingress, eddies and suspended sediment); complex research projects by specialists in acoustics will consequently be necessary in future.

Selected SES cross profiles were post-processed in order to assess the quality of the ADCP/PDT results.

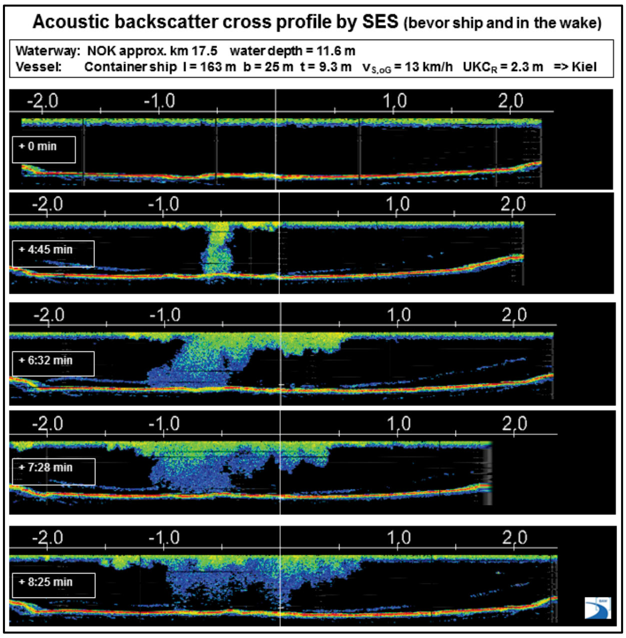

Figure 6. SES cross profile measurements for detecting the acoustic signature in the wake of a feeder ship in the KIEL CANAL as a function of time

4.1 (c) ADCP/PDT cross profile measurements

Wide-area recording of the vertical suspended sediment concentration in the water column using a ship-based Aqua Vision ADCP/PDT (Acoustic Doppler Current Profiler / Plume Detection Tool) is a tried and tested acoustic technique in tidal waters (e.g. [8], [14]). The ship carrying out the measurements crosses the waterway from one bank to the other at a speed as constant as possible. The acoustic backscatter signals recorded by the ADCP/PDT allow conclusions to be drawn regarding the sediment concentration in the individual depth cells. Calibration with the suspended matter samples taken from the water column during the measurement campaign is necessary for this purpose. A second ADCP, inclined 20°, was used to record the sediment concentration close to the bottom. The measurements were conducted with the ADCP/PDT parametrised for depth cells with a vertical extent of 0.5 m. Hence, sediment concentration information was obtained for 22 depth cells in the KIEL CANAL, which has a water depth of about 11 m.

The fact that the waterway was traversed several times shows how the concentration of ship-induced suspended sediment changes over time in the cross section of the water body. The measurements and evaluations for the investigations of the KIEL CANAL described here were undertaken by the Dutch firm Aqua Vision BV on behalf of the BAW in [2].

Cross profile measurements were carried out in the narrowest possible time frame immediately after each vessel had passed, in order to estimate the ship-induced sediment concentration in the water column as a function of time. The graphs in Figure 7 summarise the ship-induced acoustic backscatter signals, converted to give the sediment concentration, obtained with the ADCP/PDT cross profile measurements in the wake of the vessel from the first journey (T_1 = 0 min) up to the time T_5 = +7.0 min.

Based on the experience with SES measurements in connection with the acoustic signature comprised of air bubbles, eddies and sediment concentration in the wake, the cross profile measurements at the times T_1 = 0 min, T_2 = +1.1 min and T_3 = +4.0 min were not evaluated because it is impossible to separate the backscatter owing to sediment concentration. The concentration values can only be estimated as of T_4 = +5.5 min and T_5 = 7.0 min, since a vertical concentration distribution which increases towards the bottom is only clearly discernible when these intervals are reached (Figure 7). It is obvious for this reason that acoustic measurement techniques are not adequate on their own for recording ship-induced sediment transport in the near field of a vessel, because it is not currently possible to record the maximum ship-induced sediment concentration in the cross profile of a waterway after a vessel has passed.

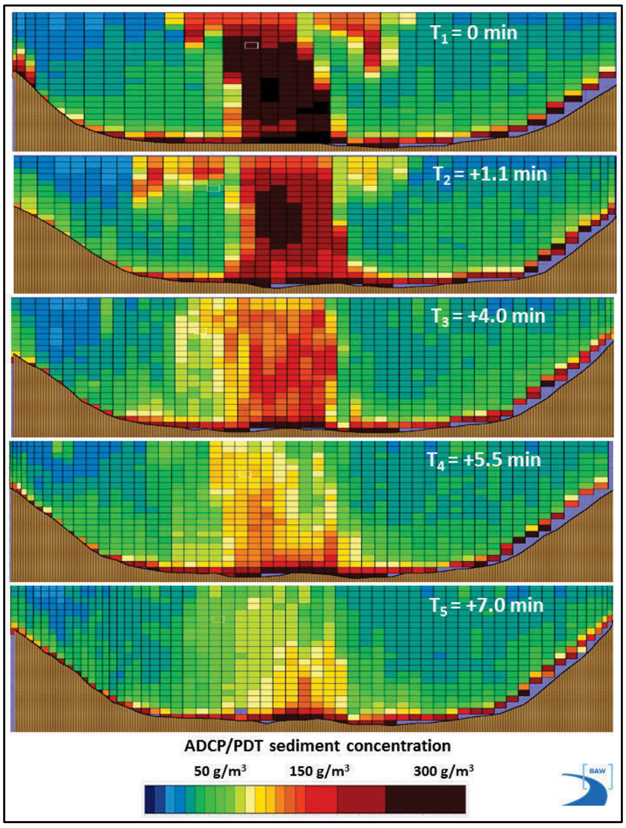

Figure 7. Ship-induced acoustic backscatter signals obtained with the ADCP/PDT cross profile measurements in the wake of a feeder ship as a result of air ingress, eddies and sediment concentration (converted to SSC according [2])

Two individual SES and ADCP/PDT profiles are compared in the following in order to evaluate the results of the acoustic methods; they serve to illustrate why it is problematic to employ these measurement techniques for investigations in a ship's near field (Figure 8). The information on passing vessels is included as a guide (top part of the diagram with the positions of the stationary measuring instruments; red, green and blue lines).

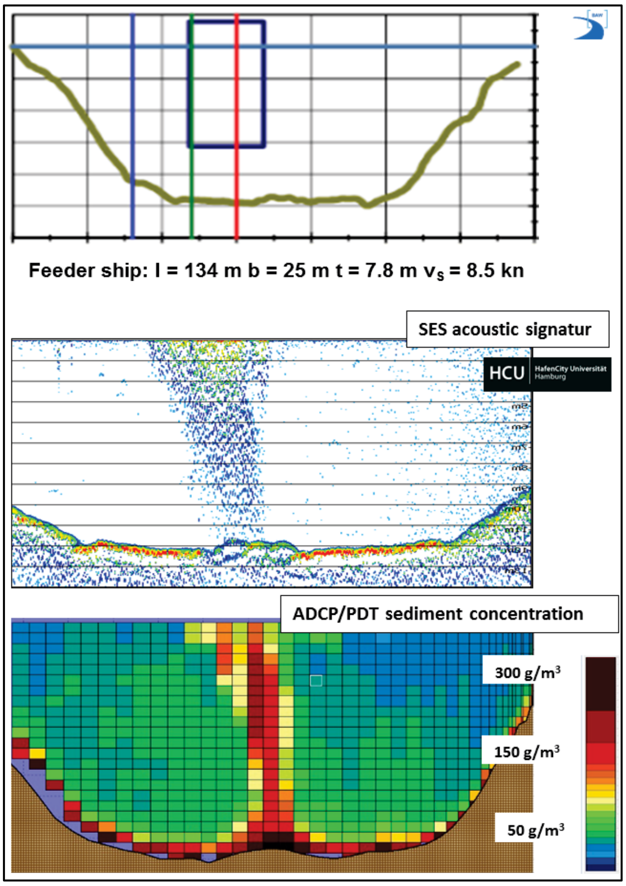

Figure 8. Comparison and evaluation of ship-induced acoustic backscatter signals for a passing feeder ship – interpretation of air ingress, turbulence and sediment concentration (example)

To enable the magnitude of the ship-induced sediment concentration and the corresponding dry matter in the measurement cross section to be estimated in spite of the many scientific reservations, the time intervals $T_4 = +5.5$ min and $T_5 = +7.0$ min were evaluated in relation to the "basic turbidity" previously recorded at the time $T_0 = -12$ min (Figure 9).

Based on the ADCP/PDT measurements at km 18 in the KIEL CANAL (bottom material: fine to medium sand 62 < µm < 500), the total dry matter in the measured cross profile is SeSS = +28 kg/m approximately 5 minutes after the passing of a large feeder ship or SeSS = +20 kg/m after 7 minutes.

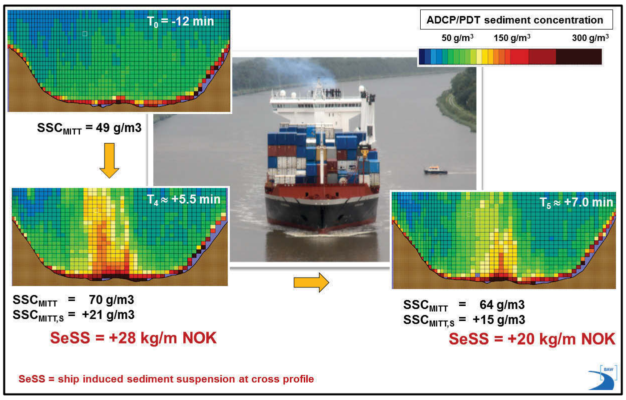

Figure 9. Estimated ship-induced suspended sediment (SeSS) as a function of time in the measurement cross section based on ADCP/PDT measurements of a passing feeder ship in the KIEL CANAL (according [2])

4.2 STATIONARY MEASUREMENTS

The time series for the water level, the standard deviation σ of the individual flow components, the turbulent energy derived from this where TKE = ½ $(\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2)$ and the turbidity measured near the bottom are shown below as representative of the stationary measurements conducted at three points in the cross section of the KIEL CANAL (Figure 10). The values were recorded during the passage of a feeder ship with a length $l_{oa} = 155$ m, a width b = 25 m and a draught t = 7.8 m, which navigated through the water at a speed $v_S = 8.5$ kn and a passing distance from the bank L = 59 m (ship sailing in the middle, north measuring point = red line).

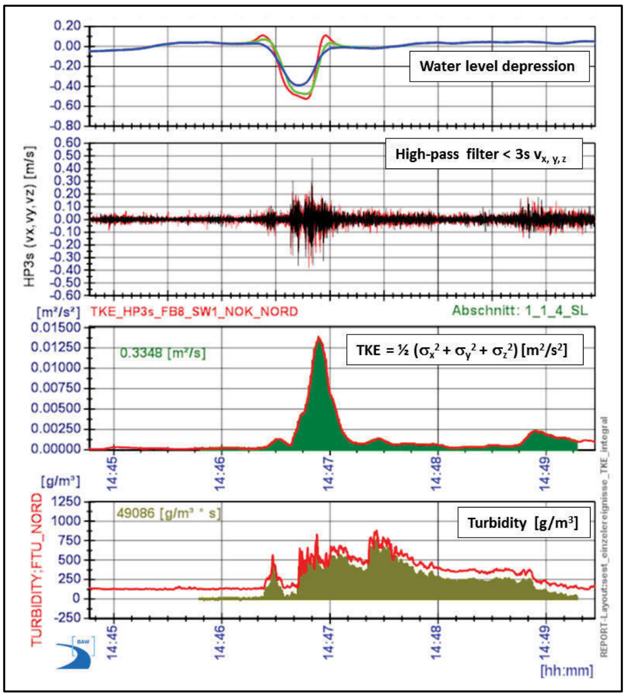

Figure 10. Change in the water level, flow components, derived TKE and turbidity near the bottom for a feeder ship passing approximately in the middle

These time series enable the change in the water level at the three stationary points to be unequivocally assigned along with the ship-induced standard deviation of the flow and hence also the TKE.

It was not possible to assign characteristic turbidity profiles unequivocally either to selected parameters of the passing vessels (length, width, draught, speed, course) or the TKE during the initial evaluations because the influencing parameters – even in a canal – proved to be far more complex than was originally assumed.

The integral of the offset-corrected turbidity time series over a period of about 3.5 minutes yielded approximately 49 kg/m^3·s of suspended dry matter near the bottom (converted from nephelometric turbidity units (NTU) with a factor of 1.6).

A preliminary detailed analysis of the ship-induced turbidity near to the bottom was undertaken in order to determine the dependence on the draught. The time series for the turbidity measurements of 59 passing vessels sailing roughly in the middle were selected for this purpose; the median was subsequently determined, separated according to the draught $t < 6.1$ m $\leq t$ and plotted in Figure 11.

The separation of the median into two typical draught classes for the KIEL CANAL ($t < 6.1$ m $\leq t$) clearly illustrates the influence of the draught both on the change in ship-induced turbidity over time and on the maximum turbidity value. It is conceivable that the ship-induced suspended particle diameter of the bottom material also has an effect on this draught-dependent turbidity characteristic, and this will be the object of a further investigation to be carried out with the Research Institute for Water and Environment (fwu), a project partner at the University of Siegen [9].

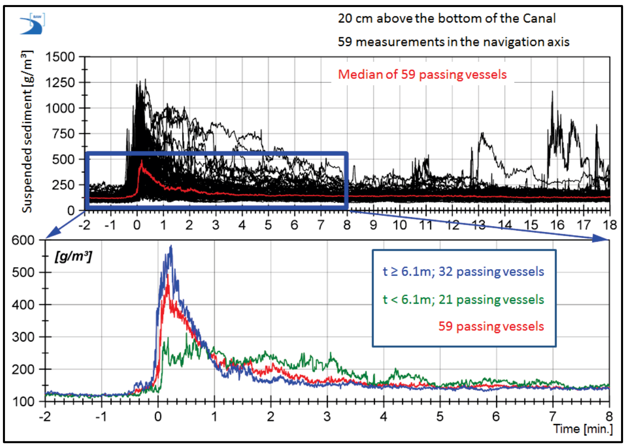

Figure 11. Classification of turbidity measurements near the bottom according to the draught in the KIEL CANAL (59 passing vessels sailing in the middle)

The representative measurements described here and the first evaluations raised a whole series of broader questions concerning the way the processes are understood as well as the interactions between passing ships and ship-induced turbidity characteristics; these issues will be dealt with subsequently in the framework of the SeST research project with fwu, the BAW's university research partner.

5 CONCLUSIONS AND NEXT STEPS

The first measurements carried out in "still" water – in this case in the KIEL CANAL – within the BAW's SeST R&D project illustrated not only the available options but also the limitations of the various measurement techniques for recording the increased sediment concentration which is induced in the water column by sailing vessels. When analysing the acoustic backscatter signals in the wake of these vessels, it is necessary to separate the portions attributable firstly to propeller-induced turbulences and air bubbles, for example, and secondly to the increased sediment concentration and to then consider their possible mutual interactions. The use of redundant measurement techniques permits a scientifically confirmed evaluation and provides initial insights into the magnitude of the increased ship-induced sediment concentration in coastal waterways depending on the passing vessels.

In accordance with the realisation concept for the SeST R&D project, further measurements were conducted in the tidal Elbe estuary in autumn 2015. In addition to the six stationary measuring points near the bottom shown in Figure 12, ADCP/PDT cross profiles were undertaken at the main measurement cross section – in spite of the known scientific drawbacks described above – in order to estimate the magnitude of the ship-induced sediment concentration in relation to natural (tidal) sediment transport.

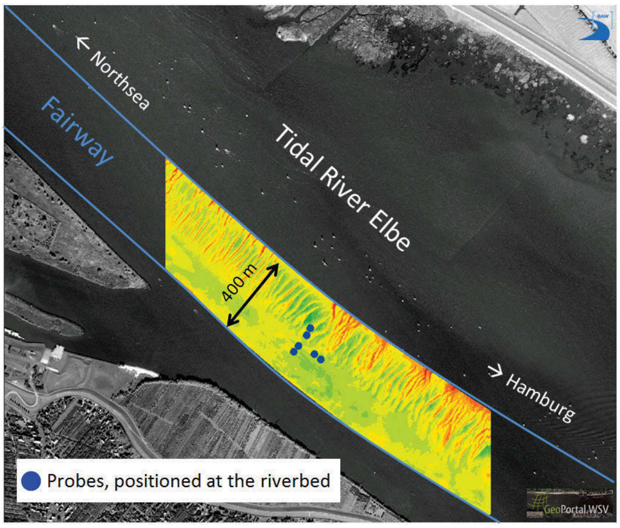

Figure 12. Positions of the stationary measurement probes installed near the bottom of the tidal Elbe at Lühesand (seawards from Hamburg) for recording ship-induced sediment transport and relating it to the natural sediment regime

In accordance with the realisation concept, the various approaches for estimating ship-induced sediment transport developed together with fwu, the BAW's research partner, will be validated based on the results of the stationary measurements conducted in the tidal Elbe as a starting point for further research work on this complex topic.

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7 AUTHORS' BIOGRAPHIES

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