INVESTIGATION OF MATERIAL TRANSPORT AND LOAD IN TIDAL RIVERS

H.-U. Fanger, H. Kuhn, W. Michaelis, A. Müller and R. Riethmüller

Institut für Physik, GKSS Research Centre, Geesthacht, F.R.G.

ABSTRACT

The transport of suspended particulate matter and of heavy metals in tidal rivers is of both ecological and economic relevance. But temporal variabilities and spatial heterogeneities considerably complicate its quantitative treatment by numerical simulation and the acquisition of representative field data for systematic investigations. As a contribution to the potential solution of this problem, a methodology has been developed at the GKSS Research Centre which combines theoretical and experimental techniques in an effective way. A novel measuring system on board a ship allows the fast determination of hydrographic parameters, and water samples are taken in parallel from different depths. Various analytical techniques are applied for quantitative trace-element detection. The experimental data are used as boundary conditions in hydrodynamic and transport model calculations. In the paper, the experimental equipment, techniques, and numerical models are described. Some results of first promising investigations are presented: Lateral distribution of water transport, tidal variation of vertical turbidity profiles, settling velocities, cumulative transport of suspended matter and heavy metals, dissolved and particulate heavy-metal contents and, in part, their tidal variations.

KEYWORDS

Elbe river; suspended matter; heavy metals; transport; settling; attenuation (optical); numerical models; trace-element analysis; moving boat technique.

INTRODUCTION

Our hitherto existing knowledge on pollutant discharge of rivers into the sea, about ecological trends in selected areas of tidal rivers, and on sedimentation processes in tidal harbours and fairways (involving the deposition of heavy metals and organic compounds) is rather poor and, certainly, not quantitative. Reasons for this deficiency are the complex flow conditions in tidal rivers, combined with interactions of salty and fresh water, settling and resuspension of solid matter, and chemical as well as biological processes with sediment and suspended matter in water. A better understanding of these phenomena and therefrom derived prognostic capabilities would be of great ecological and economic importance.

As a contribution to the potential solution of these problems, a methodology has been developed at the GKSS Research Centre which combines, in an effective way, both theoretical and experimental techniques. In brief, it comprises hydrographic measurements, based in part on the moving-boat concept, water sampling, trace-element analysis and the application of mathematical simulation models using the experimental data as boundary conditions.

The main object of investigations is the Lower Elbe River extending from a lock at Geesthacht - 40 km upstream Hamburg - to the 130 km far-off river mouth at the North Sea. Since it is hardly practicable to study the total Lower Elbe including most heterogeneous parts such as limnic regions, harbours, mixing zones, and sea-water mouth by one single experiment, the strategic concept pursued is the step-by-step sectional inflow-outflow balancing (German acronym: BILEX).
Fig. 1.
Cantilever at the bow of the measuring boat 'Ludwig Prandtl'. It supports the sensors for horizontal hydrographic profiling.

Fig. 2.
Extended CTD probe for vertical profiling. The extension consists of ultrasonic current meters (left-hand) with auxiliary sensors for inclination and earth magnetic field, an oxygen sensor and an optical-attenuation sensor.

Fig. 3.
Vector scheme relating to current metering from a moving boat. Quantities measured are the angle $\phi$ between boat axis ($x$) and north (gyroscope), the bottom-related velocity $V_{sch}$ (Doppler-shift of radio signals between boat and land stations A and B) and the relative current speed $V_{rel}$ (ultrasonic sensors).
The two confining cross-sections of a river section are considered as open boundaries the transport parameters of which have to be determined, as far as possible, synchronously for at least one tidal period. With the data thus obtained time-dependent cross-sectional averages of current speed, suspended matter and heavy metal concentrations are taken as input boundary conditions for model calculations. Since the boundaries are not independent of each other, they can be used to cross-check the consistency of experimental data, numerical constants, and theoretical assumptions. In order to construct complete flow fields which might be interesting for the simulation of plumes, the experimental data of the open boundaries can also be used, in adequate local resolution across the river, as input data for a depth averaged (2-D) model at this institute.

METHODOLOGY

Equipment and Techniques

For the experimental investigation of transport phenomena in tidal waters or estuaries, a special measuring system, called HYDRA, has been developed and composed at GKSS. Due to its high measuring speed and sampling rate, it is particularly suited for continuous measurements from a moving boat in fixed horizons or for vertical profiling on defined locations. The main components (Nehlsen et al., 1981; Michaelis, 1983) of the system are:

- the measuring boat Ludwig Prandtl (Schmidt et al., 1983) (length 23 m, beam 6 m) as support for the equipment and the operating team
- a cantilever at the bow of the boat (see Fig. 1) bearing sensors for measuring horizontal currents (two components), temperature, conductivity, optical attenuation, oxygen, and water depths (echo sounder)
- a vertical profiler (see Fig. 2) essentially equipped with the same sensors; depth is derived from a pressure sensor
- a radio-positioning device for the precise determination of the vessel's position and velocity
- and a micro-processor system for acquisition and storage of data and for quick-look surveys.

In addition, there are available Niskin-type water samplers (5 l, 12 l, 30 l) attachable to the vertical profiler, an infrared detector for water surface temperatures, a radiometric density gauge lowerable into muddy bottom layers (Fanger et al., 1985), an Owen-tube (Owen et al., 1976) for measuring 'in situ' settling velocities of suspended matter, and a gravity corer for sediment analysis. The determination of current speed from the moving boat (Nehlsen et al., 1981) has been realized by combination of a highly resolving radio-positioning system (communicating with land-based stations) and a reliable, high-precision ultrasonic current meter. The vessel's gyroscope is taken as reference for the direction of the current measured. The principle of the moving-boat method has been sketched in Fig. 3. Suspended matter concentration profiles are derived from continuous light attenuation measurements with repeated calibration by sampling and 0.45 μm filtration. An example for results obtained with the cantilever measuring device of HYDRA at an Elbe cross-section near the isle Lühesand is given in Fig. 4. The diagram of Fig. 5 shows distributions of velocity, salinity and optical attenuation as determined by the vertical profiler close to the Elbe river mouth (Neufeld).

Fig. 4. Diagram of measured horizontal profiles at the isle Lühesand versus distance λ from the right-hand Elbe River bank. From top to bottom: temperature T, current velocity v, oxygen concentration, and specific conductivity C* normalized to 20 °C.
To ensure precision and accuracy in the trace-element determinations, several analytical methods are applied: neutron activation analysis (NAA), total reflection X-ray fluorescence analysis (TXRF or TRFA), inductively coupled optical emission spectroscopy (ICP), atomic absorption spectrometry (AAS), and anodic stripping voltammetry (ASV). TXRF is a rather new technique, but has proven to be particularly economical and efficient (Knoth et al., 1978). An example for analytical results for lead and arsenic in suspended matter from Elbe water samples near Heilingen is presented in Fig. 6. The bars indicate the estimated analytical errors at a 95% confidence level; from the good agreement of independent results from different methods it may be concluded that the systematic errors are also quite small. It has to be pointed out that the analyses are performed after the campaigns in the labs of the research centre. Since the heavy-metal traces are determined separately for particulate matter and liquid phase, the water samples are filtered on ship-board immediately and frozen afterwards to avoid further precipitation and alteration.

Numerical models

To simulate transport processes in tidal rivers and estuaries numerical models of different degrees of complexity have been (or are being) developed at the GKSS Research Centre:

(i) a cross-section averaged model
(ii) a depth averaged model
(iii) a three-dimensional model.

All models are time dependent but can also be used for stationary problems. They are derived, basically, from the conservation equations for mass, momentum, energy, and water constituents (e.g. dissolved and suspended matter, trace elements, etc). Some terms in the model equations have as yet to be parameterized by empirical relationships which are based on field observations and special measurements. Therefore, numerical modelling is done in close connection with the experimental investigations at the GKSS Research Centre, in order to verify the model assumptions, to adjust the model parameters, and to get realistic boundary values.

Although it is most desirable to simulate the phenomena in tidal rivers by consideration of time dependence and all three spatial dimensions, 3-D models are as yet, in general, not used for practical purposes but rather for special investigations. This is mainly due to several difficulties:

(i) the lack of sufficient input data from field measurements, (ii) the problem of proper calibration, (iii) the necessity of additional parameterization, and (iv) limitations in computer capacity and/or computer speed.

Fig. 5.
Experimentally determined vertical profiles of current velocity \( v \), optical attenuation and salinity versus distance, measured in the brackish water region of the Elbe River.

Fig. 6.
Lead and arsenic contents in suspended matter of water samples taken at different locations and depths across the Elbe River at the isle Lühesand. Results are of different analytical methods, as indicated inside the diagrams: the error bars represent 2\( \sigma \)-values.
A depth averaged model, MOHNA, utilizing the hydrodynamical numerical procedure of Hansen (1956) has been developed at GKSS (Nehlsen et al., 1982) and successfully applied for the construction of flow fields from experimentally determined boundary data. The agreement between those results and the data of GKSS measurements between the confining river cross-sections in regions of the Elbe and Weser River was quite satisfactory (Michaelis et al., 1985). This model, completed by equations considering the transport of conservative constituents or heat, was also used for the simulation of the thermal plume from a nuclear power plant at the Weser River (Häuser et al., 1981).

Of most practical relevance for the simulation of transport processes, up to now, is the one-dimensional model FLUSS (Fiedler et al., 1981). The cross-sectional averaged velocity can in this model be calculated by the set of 'St. Venant equations', i.e. equations describing the conservation of mass and momentum (including terms like bottom friction and wind stress), or by the cubature method. The latter is, in most cases, sufficient to predict the time-dependent velocity for transport calculations because the tide gauges in the Lower Elbe or Lower Weser, respectively, are located close enough to interpolate their tidal curves linearly.

In the three additional equations describing the transport of suspended matter and heavy metals, for the longitudinal transport coefficient, the deposition velocity and the resuspension flux, special parameterizations and empirical constants are used (Michaelis et al., 1985). For the results of FLUSS calculations presented in the following, flocculation, remobilization, adsorption or other chemical exchange processes have not been considered, more because of gaps in the physical understanding and experimental data than due to the numerical model capabilities.

RESULTS OF INVESTIGATIONS

Water flow

Accurate current velocities are essential prerequisites for correct long-term predictions of amount and direction of transported water constituents. From data of the first 'balancing' experiment in the Elbe River near the isle Lühesand, BILEX '82, the tidal net transport of water through one cross-section has been computed, considering the water depth and the current velocities measured by HYDRA.

The data had been taken hourly over the period of one tide along one cross-section. Since the tidal net value was only about 5 % of the total amount of water transported in both directions, high accuracy of the measurements was required. The lateral distribution of the water net transport, shown in Fig. 7, exhibits a sizeable asymmetry. Its direction is downstream (as expected), but only over two thirds of the river width, whereas it is opposite at the Hetlinger river side. This effect might be due to the curvature of the Elbe in this region and shows up one of the problems connected with transport calculations based on measurements at one single point. The integral over the river width yields a water discharge of 355 ± 65 m³/s which is in good agreement with data permanently registered by other institutions upstream the tidal regime (ARGE Elbe, 1982).

The measured current velocities have also been used to test numerical model calculations. As mentioned above, in the one-dimensional transport model cross-section averaged velocities are generated by a cubature method using both velocity data measured at another cross-section and tidal curves from river gauges. The full curve in Fig. 8 shows the computation results over one tide. The agreement with the measurement data (crosses in the figure) indicates that the cubature method works very well in this river region. The dotted curve in this figure represents the cumulative water transport through this cross-section. It shows that the residual transport is directed upstream, which is due to an exceptionally strong flood stream at the tide chosen (and which differs from the tide considered in Fig. 7).
To test the two-dimensional, depth integrated model, current velocities have been measured in alternating runs along both confining cross-sections and across the river area between. The model calculations have been performed on a 50 m x 50 m x-y grid (see Fig. 9) where the x-axis corresponds approximately to the main current direction and the cross-section represent the open boundaries. Continuous current boundary values at each time step have been created by a time interpolation with spline functions. The computed current velocities inside the area of computation have been compared to the data measured there. The result of one arbitrary run revealing good agreement is also given in Fig. 9. Averaged over all runs performed during one tidal cycle, the x-components of the current velocity agree within 7 cm/s and the y-components within 8 cm/s, locally.

Transport of suspended matter

The transport of suspended matter (s.m.) in tidal rivers is complicated by the settling of particles around slack water and vice versa by the erosion of sediments at strong currents. The settling behaviour is strongly influenced by conglomeration which seems to depend on various not too well known parameters. Thus, rather than analyzing grain-size distributions, it appears being more useful to determine in situ or at least immediately after sampling, the settling velocity \( w \) of flocs. This has been done under different tidal conditions in the brackish water region of the Elbe River, both with in-situ and laboratory experiments (Puls, 1985). The observed \( w \)-values (median velocity) range from 0.003 cm/s to 0.3 cm/s and seem to grow with increasing concentration \( c \) of the suspended sediment (see Fig. 10). This may be expected since the collision probability of s.m. particles and, therefore, the formation of large flocs increases with the particle concentration. A regression analysis yields a quadratic dependence of \( w \) on \( c \). No dependence on salinity and current velocity has been found so far.

For the modelling of sediment transport, the vertical distribution of suspended matter has to be known. In an experiment performed in the brackish water region of the Elbe at a fixed location, vertical profiles of current velocity, salinity and the optical attenuation coefficient which, in first order, is proportional to the s.m. concentration (Ohm, 1985), were recorded over a period of two tides. The tidal evolution of the optical attenuation profiles is shown in Fig. 11. The s.m. concentration is minimum at the beginning of the ebb stream and increases during the ebb period rather homogeneously from bottom through surface.

---

**Fig. 8.** Calculated tidal curves of cross-section averaged current speed (solid line) and cumulative water transport (dotted line). For details see text.

**Fig. 9.** Two-dimensional modelling grid over an Elbe-River area with diagonal measuring boat route (upper part) and the assigned calculated as well as measured components of current speed (lower part). The distance is in x-direction (river axis).
Around slack tide ebb, steep vertical gradients indicate the settling of particles or, respectively, after the concentration minimum just at slack water their resuspension at flood currents of sufficient strength. The profiles taken at strong ebb and flood currents have been fitted to vertical steady-state distributions assuming (i) a constant and (ii) a parabolically $z$-dependent vertical eddy diffusion coefficient $A_z$. The vertically averaged values $A_z$ obtained with (i) and (ii) are similar and yield values around 150 cm$^2$/s (Riethmüller, 1985).

The one-dimensional numerical transport model was tested with data collected during BILEX '82. Cross-section means of the s.m. concentration were obtained from four samples collected alternating each hour at both boundaries of the Elbe river section at Lühesand. Current velocities derived from the cubature method described above. The data have been interpolated in time using spline functions. The values of the upstream cross-section have been used as inflow boundary-conditions. On the downstream cross-section, computation and measurement results have been compared to test the model. The result at one cross-section - for the same tide as in Fig. 8 - is shown in Fig. 12. The model calculations are in good agreement with the measurements.

On the other hand, since the distance between the two boundaries is only about 1 km and the cross-section means built out of four samples contain some error, it is not possible to draw strict conclusions on the correctness of the empirical relationships assumed in the model.
The net transport of suspended matter through this cross-section can be seen in the accumulative s.m. transport curve shown in Fig. 13. It amounts to \(1.6 \times 10^6\) t and is, in contradiction to the 'normal' conditions, directed upstream in accordance with the water net transport (see Fig. 8) at this special tide.

Transport of heavy metals

In the literature, a great number of papers deal with investigations on suspended matter and heavy metal load in the Elbe river (Vollbrecht, 1980; Duinker et al., 1982; Tent, 1983; ARGE Elbe, 1979/1980). This work differs from others and earlier ones by the intention to obtain a representative description of the underlying dynamic processes which requires a high sampling density in space and time as well as an adequate coordination with hydrographic measurements and modelling.

As examples, further results from the above-mentioned BILEX '82 experiment will be given; for full details, see Michaelis et al. (1985). Nearly 200 water samples, taken during three complete but not consecutive tidal periods have been analyzed, separately for filtrates and residues. The fact that sampling was performed on several days turned out to be advantageous for reducing the risk of wrong conclusions from fortuitous phenomena and for recognizing systematic trends.

Fig. 14 represents a survey on the partition of some heavy metals into particulate matter (> 0.45 \(\mu m\)) and liquid phase, as found with the analysis of the BILEX '82 samples. The weakly shadowed regions in the columns indicate the range of variation between the phases. Evidently, the concentrations of heavy metal loads carried by suspended matter vary considerably. Only iron and lead are almost quantitatively bound to s.m. In this diagram, no distinction has been made due to tidal alterations of s.m. concentration or dependences of depth (grain size gradation) and local bottom structures. When classified due to these criteria (Michaelis et al., 1985; Michaelis, 1983) the data seem to indicate the existence of two main groups of heavy metals: (i) Fe, As, Zn, Hg, and Pb, also with exceptions - Ti and V, reveal a rather uniform behaviour with respect to tidal phases and location, and are, therefore, directly accessible to transport calculations. The results of model FLUSS computations for the concentrations and cumulative transports of Pb, As, Zn, and Fe are shown in Fig. 12 and Fig. 13, respectively, the meaning of which has been discussed above. The average concentrations of the elements in this group (referred to dry substance s.m.) are Fe 40 mg/g, As 40 \(\mu g/g\), Zn 550 \(\mu g/g\), Hg 2.5 \(\mu g/g\), Pb 105 \(\mu g/g\), Ti 3 \(\mu g/g\), and V 100 \(\mu g/g\). The corresponding values, as far as determined, for the dissolved phase are: Fe 30 \(\mu g/l\), As 6 \(\mu g/l\), Zn 14 \(\mu g/l\), V 2.7 \(\mu g/l\). For mercury potential trends are hidden in somewhat greater analytical errors.

(ii) The results for Cr, Ni and, possibly, Cd suggest a surprisingly pronounced time dependence of the load with minima at the phases of slack water and, partly, strong local inhomogeneities. Ni and Cr, showing a strong correlation, seem to be bound to particles of a size class that participate in settling and resuspension during the tidal cycle.
A special behaviour has been found with manganese where sorption/desorption and the known stages of oxidation with different degrees of solubility seem to be of great influence. The element has maximum filtrate concentration of up to 400 µg/l at slack tide ebb, whereas at high tide the content is partly below the detection limit of the TXRF method applied (µg/l). The assumption that this effect is strongly influenced by the oxygen content in water is quite well supported by the records of the oxygen sensor of the ship-borne measuring system HYDRA. Fig. 15 clearly reveals the anti-correlation between oxygen and manganese versus time or tidal phase, at least for the river axis and one river side (Hetlingen). The tidal dependence can be understood having in mind that the measuring site is rather close to the upstream located city of Hamburg, i.e. there is a pronounced negative downstream gradient of oxygen causing an O₂ increase during flood stream. For the river side Lühesand, the oxygen level seems to be constant at a comparatively high level so that the tidal dependence of the dissolved manganese might have to be interpreted by lateral mixing of Mn(II) during low tide.

It may be pointed out that the absolute variation of conductivity is too small to accept that the unambiguous negative correlation of manganese and conductivity, shown in Fig. 15, might represent a causal relationship.

**Fig. 14.** Partition of some heavy metals into particulate matter and liquid phase, as found with the analysis of nearly 200 water samples from the Elbe River at Lühesand in August 1982.

**Fig. 15.** Tidal variation of the dissolved manganese concentration, oxygen concentration and conductivity at three locations across the Elbe River at Lühesand.
CONCLUSIONS

A concept for the investigation of transport of water and water constituents in tidal rivers, the corresponding techniques and simulation models have been described in this paper, and some results of first investigations in the Elbe River were presented. The latter seem to prove that measuring system, sampling strategy and analytical methods are well suited to yield useful field data of sufficient precision and accuracy to be taken as input boundary conditions for model computations and for model verification. Calculated currents in the river area investigated and calculated (cross-averaged) concentrations and transports of suspended matter and heavy metals agree, so far, quite well with the experimental data, although the extent of the river section was somewhat small for a critical test of the parametrization and empirical constants assumed in the models. Therefore, the measuring basis has to be enlarged in subsequent experiments. In order to obtain long term trends from studies of this kind, the experiments have to be repeated at identical sites but under different meteorological and discharge conditions, and the temporal interpolation should be performed with the aid of permanent measuring and sampling stations at sites being representative for the cross-section of interest.

ACKNOWLEDGEMENT

We would like to thank the members of the analytical groups and the coworkers of the hydrographic measuring team and of the modelling group for their careful work which was the basis of the results presented in this paper.

REFERENCES

Puls, W., Kuehl, H. (1985). Settling velocities of mud flocs: measurement in the field and in the laboratory. EUROMECH 192, Int. Conf. on Transport of Suspended Solids in Open Channels, Munich/Neubiberg.