STUDIES OF TRACER TRANSPORT IN THE RIVER ELBE

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ABSTRACT

Accidental river pollution is a severe hazard to all rivers. To mitigate the consequences of a possible contamination of the river Elbe the contaminant transport model ALAMO (alarm model Elbe) was developed. This dead-zone-model (DZM) was calibrated and verified by nine dye experiments. The experimental set-up comprises measurements with in-situ and ex-situ fluorometers and fluorescence spectrometers. The experiments were carried out for a wide range of discharge conditions of the river. In order to account for different discharges the model coefficients of longitudinal dispersion and lateral exchange were parameterized by a power-law relationship depending on the river geometry. A comparison of the experimentally determined tracer concentration curves with those derived with ALAMO gave good agreement. The error of the time of travel, the width and the asymmetry of the tracer cloud amounts to 8 %, 10 % and 12 % at a maximum.

1. INTRODUCTION

The European Water Directive 2000/60/EC (article 11 (3) l) (European Parliament 2000) requires measures to reduce the impact of accidental pollution incidents for each river basin district. Therefore the International Commission for the Protection of the River Elbe (IKSE), working group H - Accidental River Pollution, worked out the International Alarm Plan Elbe (2004).

The Alarm Plan Elbe regulates the messaging in case of accidental river pollution including the forecast of the contaminant transport. This forecast of the contaminant transport is based on the numerical model ALAMO, i.e. alarm model Elbe (Mai et al. 2006). ALAMO was developed by the German Federal Institute of Hydrology in cooperation with the Leichtweiss Institute and the Czech institutes Povodi Labe, CHMU and VUV. The model covers the whole stretch of the not tidally influenced river Elbe. Figure 1 gives a sketch of the model area with the Czech part from Jaromer to Schöna and the German part from Schöna to Geesthacht. The model covers a total length of 900 km.

The basic idea of the model ALAMO was given by Taylor (1953) describing the dispersion of contaminants along the river. This concept of ALAMO was extended by Hays et al. (1966) to account for the exchange of contaminants between the main stream of the river and the still water zones at the river banks. For the calibration of the model ALAMO nine dye studies were carried out from 1997 to 2005. Both, modeling concept and dye studies, are described in the following.

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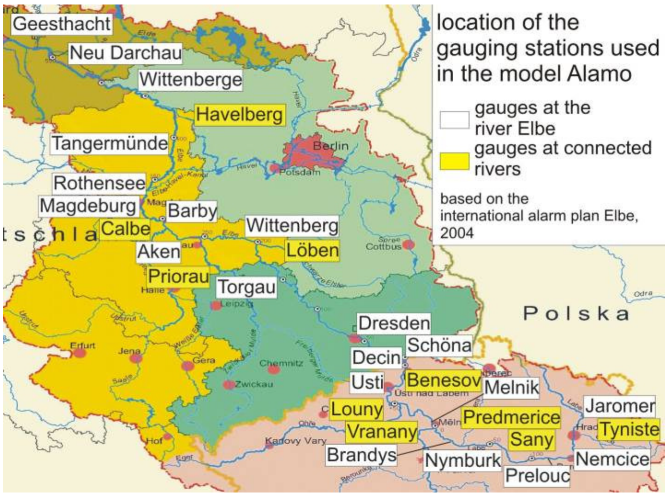

Figure 1 River Elbe form Jaromer to Geesthacht - extend of the model Alamo.

2. MODELING CONCEPT

ALAMO includes the physical processes of advection, dispersion, diffusion in the main stream, the exchange between the main stream and the still water zone, as well as the degradation of pollutants in main stream and still water zones. These processes are described by the following fundamental set of differential equation

$$\frac{\partial c}{\partial t} = -v \frac{\partial c}{\partial x} + D_L \frac{\partial^2 c}{\partial x^2} - \varepsilon D_S (c - s) - k c \tag{1}$$

$$\frac{\partial s}{\partial t} = D_s (c - s) - k s \tag{2}$$

with the contaminant concentration in the main stream c and in the still water zone s, the flow velocity in the main stream v, the coefficient of decay k, the relative area of the dead-water zone ε, the longitudinal dispersion coefficient D_L, and the exchange coefficient D_S between main stream and dead-water zone. The set of coupled differential equations is solved using the Rosenbrock-Wanner method as given by Rentrop and Steinebach (1997).

The parameters v, ε, D_S and D_L of the differential equations (1) and (2) are parameterized with the river discharge measured at the gauges given in Figure 1, i.e.

$$\varepsilon = a_\varepsilon \cdot Q^{b_\varepsilon} \tag{3}$$

$$v = a_v \cdot Q^{b_v} \tag{4}$$

$$D_L = a_L \cdot Q^{b_L} \tag{5}$$

$$D_S = a_S \cdot Q^{b_S} \tag{6}$$

with the tunable coefficients a and b for each of the parameters.

The determination of the coefficients a_v and b_v is based on the results obtained from one-dimensional numerical modeling described by Drewes et al. (2001) while the determination of the coefficients a_L, b_L, a_S, b_S, a_ε and b_ε is carried out using tracer experiments as described in the following chapter. For the longitudinal dispersion coefficient D_L and the exchange coefficient D_S the parameterization is given in Figure 2. Both coefficients increase with increasing river discharge. Besides of the river discharge the coefficients are influenced by the geometric properties of a river section. An increase in the longitudinal dispersion coefficient and a decrease in the lateral exchange coefficient are found for increasing river width as well as for increasing river curvature. As found also in laboratory experiments by Weitbrecht (2004), a decrease in the distance of groins or an increase of the length of groins lead to a decrease of the lateral exchange coefficient D_S.

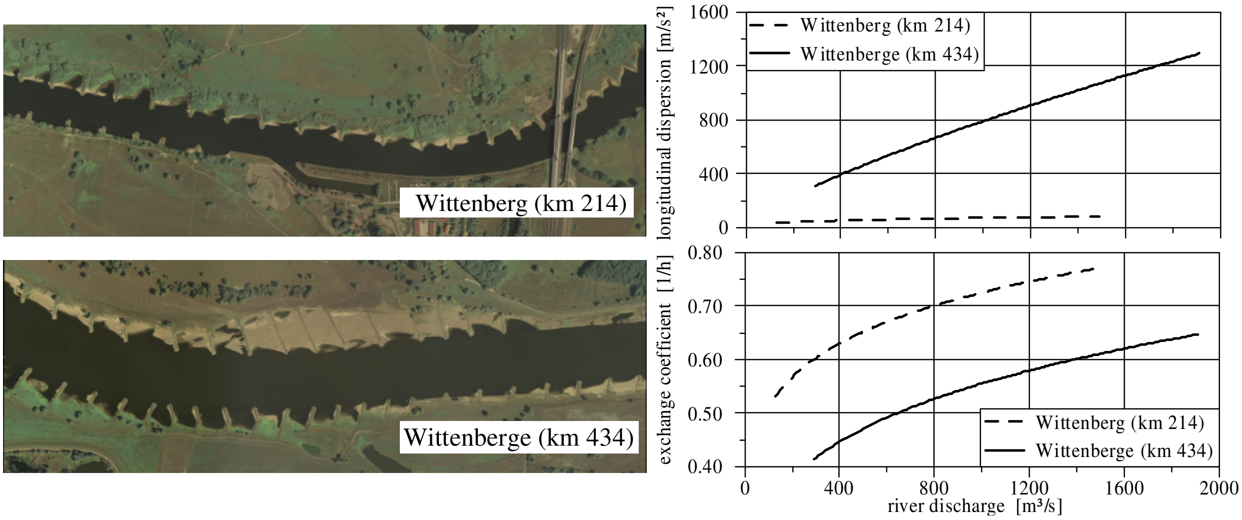

Figure 2 Influence of the river discharge on the longitudinal dispersion coefficient (top right) and the lateral exchange coefficient (bottom right) for two different locations at the river Elbe (left).

3. DYE STUDIES

Although first steps to use the geometric properties of a river section for a parameterization of the coefficients of longitudinal dispersion and lateral exchange based on results of laboratory experiments were undertaken, in-situ dye studies are still essential. For the calibration of ALAMO nine dye studies were carried out so far.

Table 1 Tracer experiments for the calibration and verification of ALAMO.

Date	location of input	station [km]	mass of tracer [kg]	Discharge Q [m³/s]	mean low water [m³/s]	mean high water [m³/s]	Reference
29/11/99	Němčice	-249,2	2,0	16	12	309	Dostál et al. (2000)
02/05/05	Němčice	-249,2	8,0	52	12	309	
26/04/99	Mělník	-104,8	24,0	255	76	1324	Dostál et al. (1999)
30/11/97	Ústí	-37,0	12,1	130	91	1430	Dostál et al. (1998)
15/07/97	Schmilka	4,1	33,5	330	102	1480	Hanisch et al. (1997)
29/03/01	Schmilka	4,1	75,8	912	102	1480	Hanisch et al. (2004)
06/10/04	Mauken	184,5	20,0	136	114	1380	
11/10/99	Elster	200,4	26,0	160	130	1490	Hanisch et al. (2004)
27/10/98	Elster	200,4	26,4	265	130	1490	Hanisch et al. (2004)

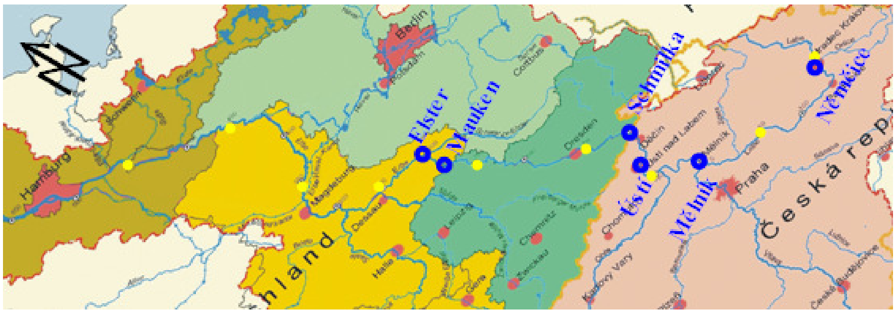

Figure 3 Locations of dye input along the river Elbe.

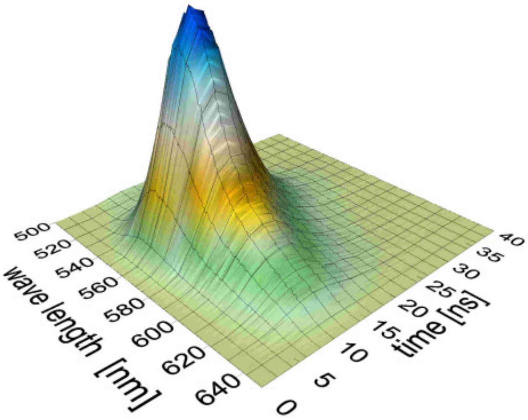

Figure 4 Fluorescence spectrum of the tracer Red Dye (measured with the laser fluorescence spectrometer OPTIMOS)

Figure 5 Input of the tracer Red Dye near Němčice, Czech Republic

Table 1 characterizes the tracer experiments by the conditions of river discharge prevailing during the experiment, the mass of dye and the location of its discharge (see Figure 3). For the experiments the non eco-toxic tracer Red Dye (Sulforhodamine G) was used. The fluorescence spectrum of Red Dye is given in Figure 4. The spectrum is single peaked with a maximum for the wavelength of 554 nm. In case of pulsed excitation the half-life period of the fluorescence intensity equals approximately 7 ns.

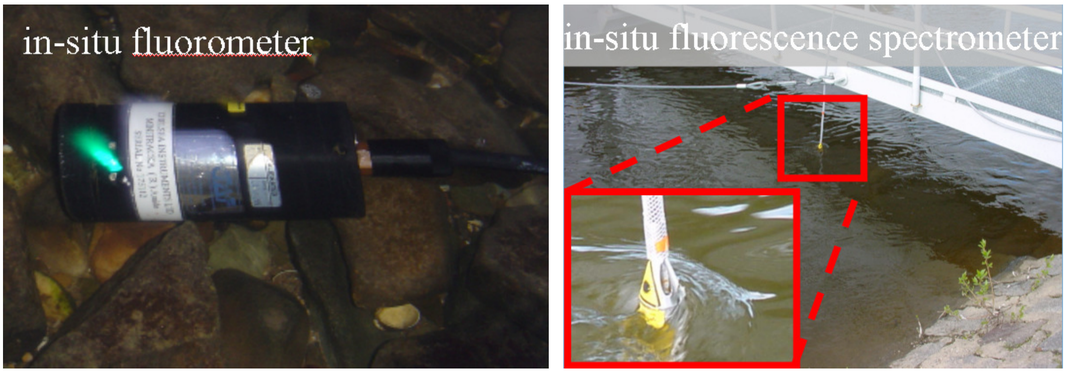

Figure 6 In-Situ measurements of dye concentration.

Figure 7 Sampling and ex-situ quantification of dye concentration.

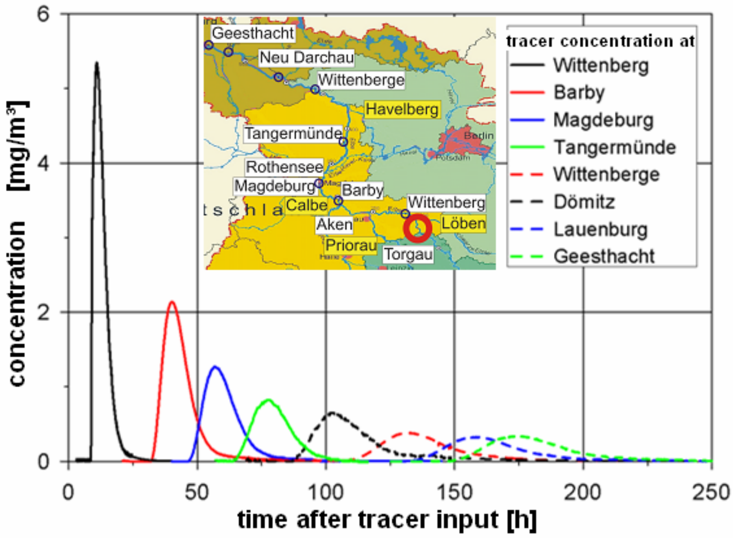

Figure 8 Time-series of tracer concentration at eight locations downstream of Mauken in 2004.

To enhance mixing in the main stream right at the location of tracer input the dye was discharged from a boat traveling across the river (Figure 5). The dye concentration in the mainstream and in the still water zones downstream of the location of tracer input is measured using in-situ fluorometers and fluorescence spectrometers (Figure 6). The measurements were supplemented by automatic sampling and ex-situ fluorescence spectroscopy (Figure 7).

Using spectrometers it was possible to account for a varying background fluorescence in the water body caused by organic matter. However only very little deviations of the tracer concentrations derived by fluorometers or by fluorescence spectrometers are found. An example of the time concentration curves is given in Figure 8. For the given experiment the tracer cloud travels about 2.5 km/h (see also Figure 10). Due to dispersion and storage of tracer in the still water zones the peak concentration of the tracer cloud decreases, while its width and asymmetry increases (see also Figure 11 and 12).

4. VERIFICATION OF NUMERICAL MODELLING

The tracer experiments, listed in Table 1, were recalculated with ALAMO. The model results were analyzed at the locations of the measuring devices deployed during the experiments. Figure 9 shows a comparison of the measured time-concentration curves and those predicted by ALAMO. Both, measured and modeled results, agree quite well. This is also found when analyzing the time of travel as well as the width and asymmetry of the tracer cloud.

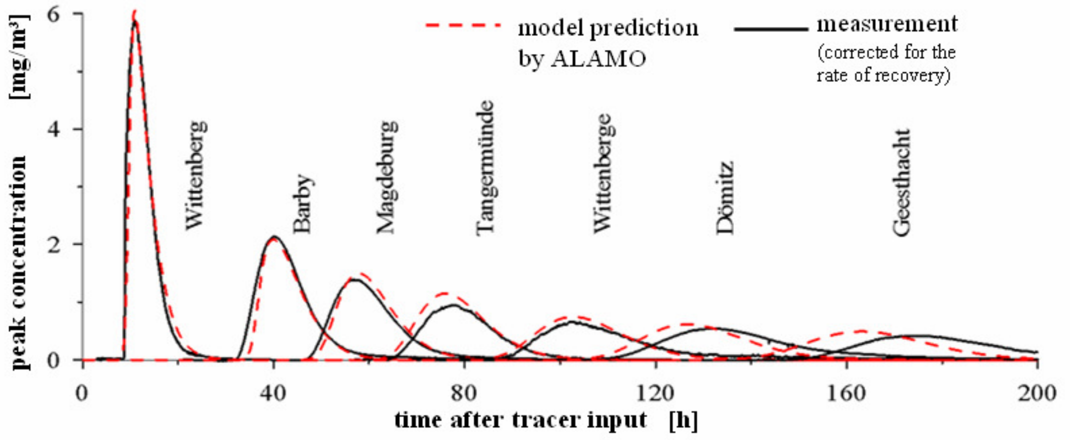

Figure 9 Comparison of measured time-concentration curves with those acquired from ALAMO.

The time of travel, which is related to the time t_p of the peak tracer concentration, is given in Figure 10. The general trend is approximated correctly by ALAMO. This is a sign of a good parameterization of the flow velocity (see eq. 4). The maximum deviation of measured and modeled time of travel amounts to less than 10 hours, i.e. less than 10 %. The time of travel increases linearly with the distance from the location of tracer input.

The width of the tracer cloud, which relates to the time lack between the end and the beginning of tracer passage, i.e. $\Delta t = t_e - t_b$, is given in Figure 11. Right after the tracer input the width of the tracer cloud increases strongly. However with an increasing time of travel the increase of the width becomes smaller. The maximum deviation between modeled and measured width is equal to 3 hours, i.e. the deviation is less than 10 %. This indicates an adequate parameterization of the longitudinal dispersion coefficient (see eq. 5).

The asymmetry of the tracer cloud, being defined as the ratio of the time with decreasing and the time with increasing tracer concentrations, i.e. $\Delta t_e / \Delta t_b = (t_e - t_p) / (t_e - t_b)$, is given in Figure 12.

The general dependence of the asymmetry of the tracer cloud on the location along the river is met indicating the quality of the parameterization of the lateral exchange coefficient (see eq. 6).

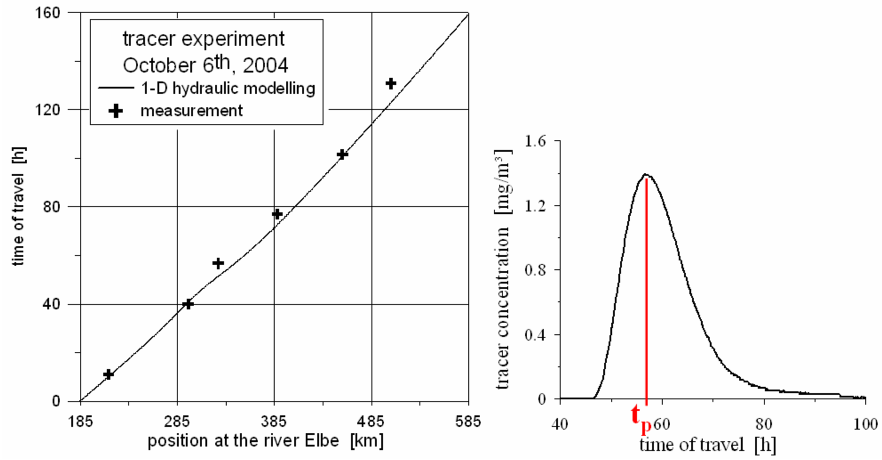

Figure 10 Traveling time of the tracer cloud – measurement vs. ALAMO.

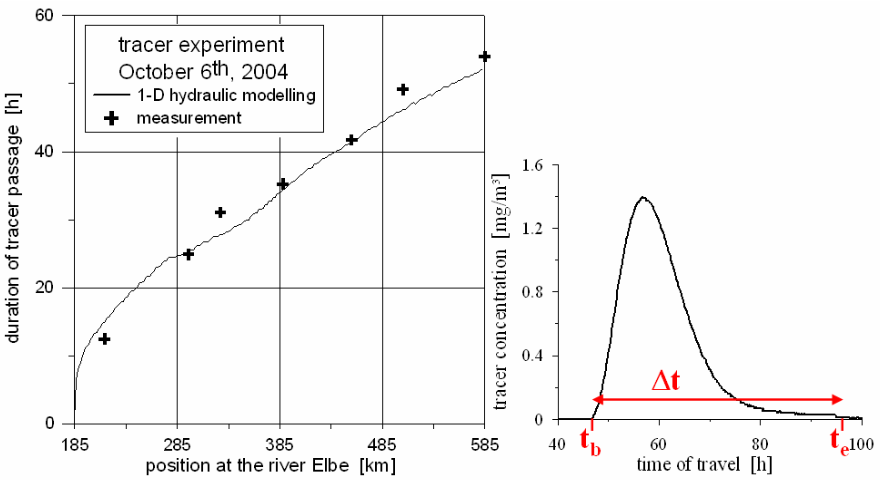

Figure 11 Width of the tracer cloud – measurement vs. ALAMO.

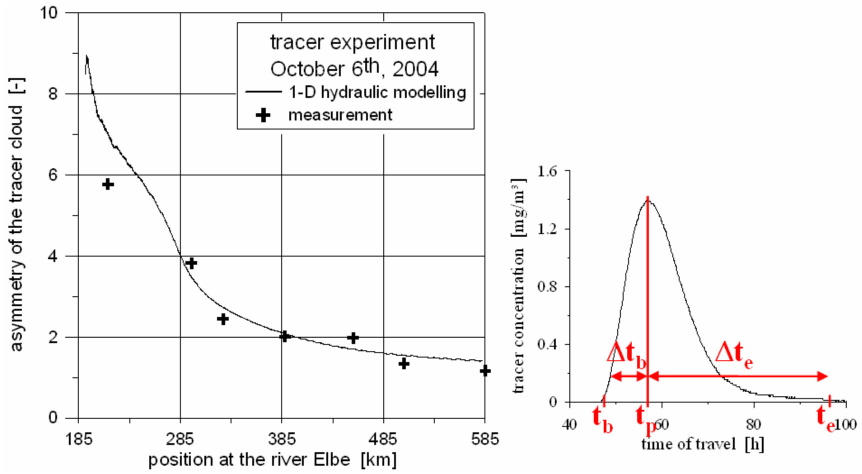

Figure 12 Asymmetry of the tracer cloud – measurement vs. ALAMO.

5. CONCLUSION

The applicability of the model ALAMO for the prediction of pollutant transport in the river Elbe has been shown by comparison with tracer experiments. It is possible to model dispersion using Taylor's concept. The exchange between main stream and still water zones is modeled adequately using the dead-zone concept of Hays et al. It is proofed that the geometry of the river strongly influences the processes of longitudinal dispersion and lateral exchange. It is planned to use information on river geometry for the parameterization of dispersion and lateral exchange. However dye studies will be still necessary for verification.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the cooperative work with the International Commission for the Protection of the River Elbe (IKSE) and the very good collaboration with the Czech institutions Povodi Labe, CHMU and VUV as well as the Leichtweiss Institute, Germany.

Special thanks are addressed to the colleagues at the local waterways and shipping offices (WSA) in Dresden, Magdeburg and Lauenburg who helped to carry out the tracer experiments in 2004.

REFERENCES

Dostál K., Koza V., Rederer L. (1998) "Tracer experiment in the river Elbe (original in Czech: Zpráva o testovacím pocusu na Labi)", report, Povodi Labe, Hradec Králové, Czech Republic.

Dostál K., Koza V., Rederer L. (1999) "2nd Tracer experiment in the river Elbe (original in Czech: Zpráva o 2. testovacím pocusu na Labi)", report, Povodi Labe, Hradec Králové, Czech Republic.

Dostál K., Koza V., Rederer L. (2000) "3rd Tracer experiment in the river Elbe (original in Czech: Zpráva o 3. testovacím pocusu na Labi)", report, Povodi Labe, Hradec Králové, Czech Republic.

Drewes, U., Ettmer, B. Mende, M. (2001) "Hydraulic calculations of the river Elbe from Nemcice to the German-Czech border (original in German: Hydraulische Berechnungen von Nemcice bis zur deutsch-tschechischen Grenze)", report, Leichtweiss Institute, no. 869, Braunschweig.

European Parliament and the Council of the European Union (2000) "Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy (short title: EU Water Framework Directive (WFD))", Official Journal of the European Communities, L327/1.

Hanisch H.-H., Dostál K., Trejtnar K., Vosika S., Specht F.-J., Eidner R. (1998) "Tracer experiments in the river Elbe (original in German: Traceruntersuchungen in der Elbe)", Proc. of the 8th Seminar on inland water protection (original German title: Magdeburger Gewässerschutzseminar), Magdeburg, Germany, pp 29-32.

Hanisch, H.H., Mende, M., Ettmer, B. (2002) "Operational Prediction of Contaminant Transport with the Alarm Model Elbe" (in German), 10th Seminar on Water Protection, Magdeburg, Teubner, Stuttgart, Germany, pp. 337-338.

Hanisch, H., Dostál, K., Rederer, L., Specht, F.-J., Mende, M., Stahl, K. (2004) "Tracer experiments in the river Elbe (original in German: Tracerversuche Elbe)", report, German Federal Institute of Hydrology, Koblenz, Germany.

Hays, J.R., Krenkel, P.A., Schnelle, K.B. (1966) Mass Transport Mechanisms in Open-Channel Flow, Technical Report 8, Vanderbilt University, Nashvilee Tennessee.

IKSE (International commission for the protection of the river Elbe) (2004) “International alarm plan of the river Elbe (original in German: Internationaler Warn- und Alarmplan Elbe)”, report, Magdeburg, Germany, pp. 1-23.

Mai, S., Lippert, D. and Barjenbruch, U. (2006) “Operational Modeling of Contaminant Transport in the River Elbe”, Proc. of the 7th Int. Conf on Hydroinformatics, Nice, France, Vol. 1, pp. 16-23.

Rentrop, P., Steinebach, G. (1997) “Model and numerical techniques for the alarm system of river Rhine”, Surveys on Mathematics for Industry, Vol. 6, pp. 245-265.

Taylor, G.I: (1953), “Dispersion of Soluble Matter in Solvent Flowing Slowly Through a Tube”, Proc. R. Soc. London, Ser. A 219, pp. 186-203.

Weitbrecht, V. (2004) “Influence of dead-water zones on the dispersive mass transport in rivers”, Universitätsverlag Karlsruhe, Germany.