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TRANSPORT PROCESSES IN RIVERS INVESTIGATED BY TRACER EXPERIMENTS

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ABSTRACT In advanced research of hydrology, tracer experiments are reliable tools for the evaluation of natural data. Described for the river Rhine calibration and verification of an one-dimensional alarm model by such data allows prediction results of high accuracy.

INTRODUCTION

In addition to continuously high-levels pollution, accidental spills are the greatest ecological and economic danger for rivers. Spills may be caused by industrial or road/river accidents (e.g. barges). In such cases, downstream water supply companies and other water users need to be informed of the pollutant wave.

Generally, the knowledge of transport processes in both large and small rivers are of increasing importance concerning the prediction of the pollutant distribution in aquatic systems. In principal, there are two approaches to calculate the transport of solutes in rivers. One is the more classical calculation based on exact river morphological input data and the other is the calculation based on estimation of transport parameters such as travel time and dispersion coefficients.

Since exact morphological data are often unavailable, the parameter estimation technique is more promising. In both cases, tracer experiments are needed to calibrate and verify the calculation. Tracer experiments play a decisive role in the model development. Therefore, special measurement equipment is necessary. In the studies described in this paper, two transport models based on one-dimensional dispersion equation are presented. The application of two- or three-dimensional transport models in the frame of Alarm Models is not plausible, because high-speed computations are required.

The focus of this paper is the calibration and verification of solute transport models using experimental tracer methods. The modeling and field work were conducted on the River Rhine in Europe.

METHODS

To develop "Alarm Models" based on solute transport processes, one-dimensional transport models are necessary (Fig.1). Within this frame the calibration and verification of the models by field data are of great importance. Often, the calibration is a weak step in the model development. Using experimental tracer techniques, the calibration problem can be solved satisfactory.

To investigate the solute transport in rivers, artificial tracers have to be applied. These tracers have characteristics that fulfill important requirements. For example, the tracers should be easily detected, have a conservative behavior, and be non toxic.

The tracer methodology is advanced in most parts of hydrology, but not all problems are solved. Specific problems of the application of tracers to surface water investigations include the photosensitivity of dyes, such as fluorescence tracers, and recovery efficiency and related correction techniques for tracer losses. Downstream from pollutant spills a spectral overlying of the tracer fluorescence with other fluorescence or the decomposition of the tracer material can be given. Therefore, advanced analytic methods must be used.

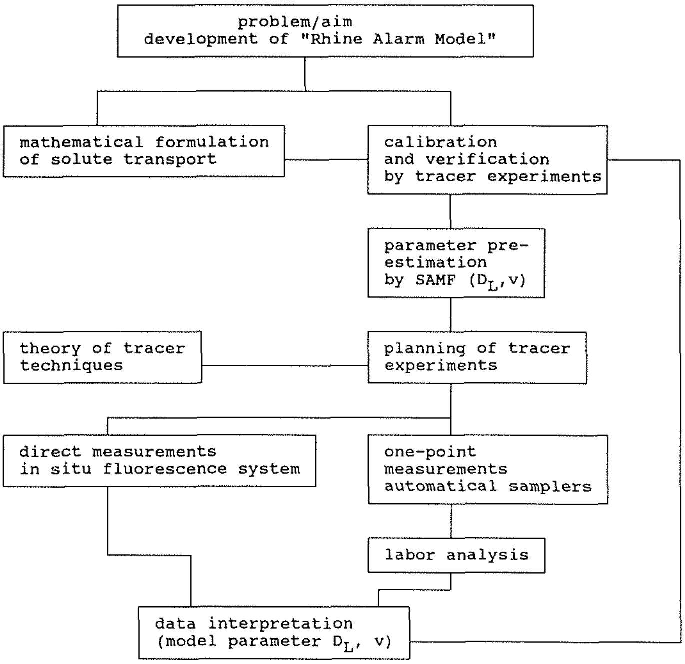


FIG. 1 Analysis flow chart for the Rhine Alarm Model.

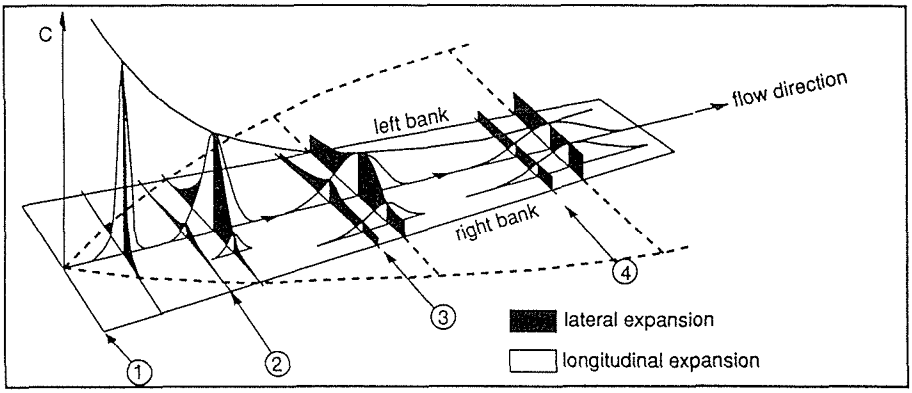


FIG. 2 Transport processes in rivers (modified from Hubbard et al., 1989).

The dispersion processes are combined with a decrease in maximum concentration. Fig. 2 shows the dynamic processes of dispersion in rivers. The distribution of the tracer in all directions follows the slug injection into the channel (point 1). The vertical distribution indicates that the dispersion is complete after 1 km of transport (point 1 to 2), followed by the lateral dispersion, which is complete only after 50 to 100 km of transport from the injection point (point 3 to 4) in large rivers like the Rhine River. The only continuing process is the longitudinal dispersion (point 4). Here the reduction to one-dimensional modeling provides a correct simulation of dispersion.

In contrast, one-dimensional transport models require a homogeneous distribution of tracer concentration at each cross section. Consequently, if the homogeneous distribution exists then only one measurement at each observation station is necessary. However, uniform tracer concentrations do not occur across the river for 50 to 100 km downstream of the injection point. Furthermore, a homogeneous distribution can be disrupted by large tributary inflows. For these cases, special measuring equipment is necessary.

After the mathematical modeling of solute transport, the tracer requirements for model calibration and verification can be formulated. Measurement techniques, generally, must be selected or developed to meet individual model requirements.

To plan a tracer experiment, the tracer break-through times (travel times) at every observation point in the river will be calculated initially with the model. The model, in turn, requires estimates of the parameter mean flow velocity and the longitudinal dispersion coefficient for this calculation.

The coordination of staff and materials for the field data collection depends on the results of this estimation. Before tracer injection takes place, careful planning to provide a time table for measurements, laboratory analysis, and data interpretation is necessary.

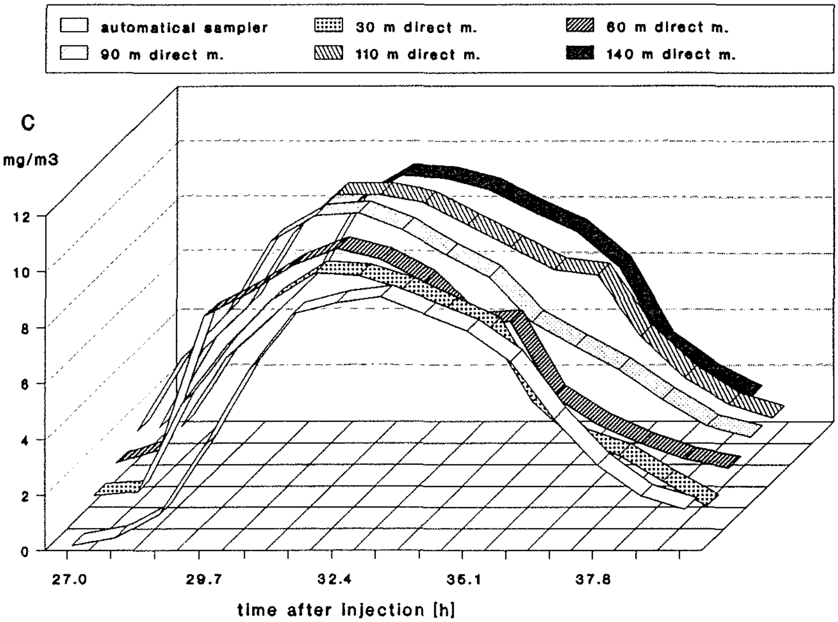


FIG. 3 Comparison between one and multiple point data. Automatical sampler = one point data; direct m. = multiple point data.

TRACER EXPERIMENTS

Under the condition of homogeneous distribution of tracer concentration at the measuring cross section, the on- dimensional approach is valuable. Automatic samplers were used to collect point samples from measurement sites. The samplers can be programmed to collect 20 water samples before it is serviced and at intervals ranging from 2 min to 24 h, which can provide excellent coverage for defining the tracer break-through curves.

To calibrate and verify one and more dimensional transport models, the flow and transport processes have to be known in detail. Multiple point measurements are used to control one-point concentration data (see Fig.3), to solve special problems of transport processes, and to control the boundary conditions for the optimization of a tracer experiment. Therefore, high spatial and temporal resolution concentration data are required to define the tracer break-through curves. Special equipment for multiple point measurements at a sampling site was developed. The multiple point measurement equipment consists of an *in situ* fluorescence system connected to a laptop computer. The *in situ* fluorescence instrument system not only determines and records dye concentration, but also measures and records temperature and depth, and the boats position using a laser distance instrument (Fig.4).

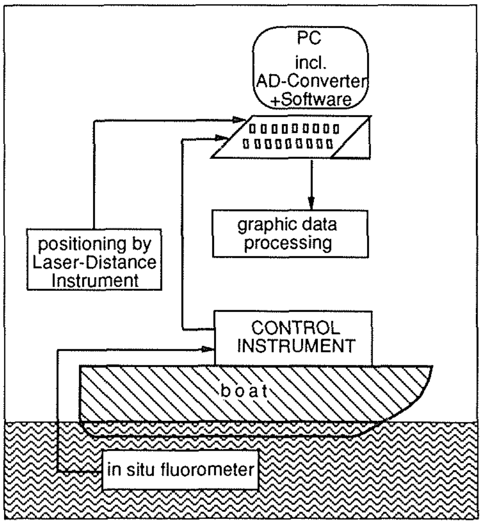


FIG. 4 The direct measurement system.

CALIBRATION AND VERIFICATION OF THE RHINE ALARM MODEL

The Rhine Alarm Model was developed to predict rapid transport, as in cases of accidental spills, and this information wa combined with a minimum deviation between measured and calculated travel times. The basic approach of this model is given by the one-dimensional convection-dispersion equation and its solution for a slug injection by Taylor (1954). To account for differences in the morphology along the river, the river was divided into sections and subsections (Fig.5). Sections are characterized by constant discharges, and subsections are characterized by constant flow velocities (Spreafico & Leibundgut, 1989).

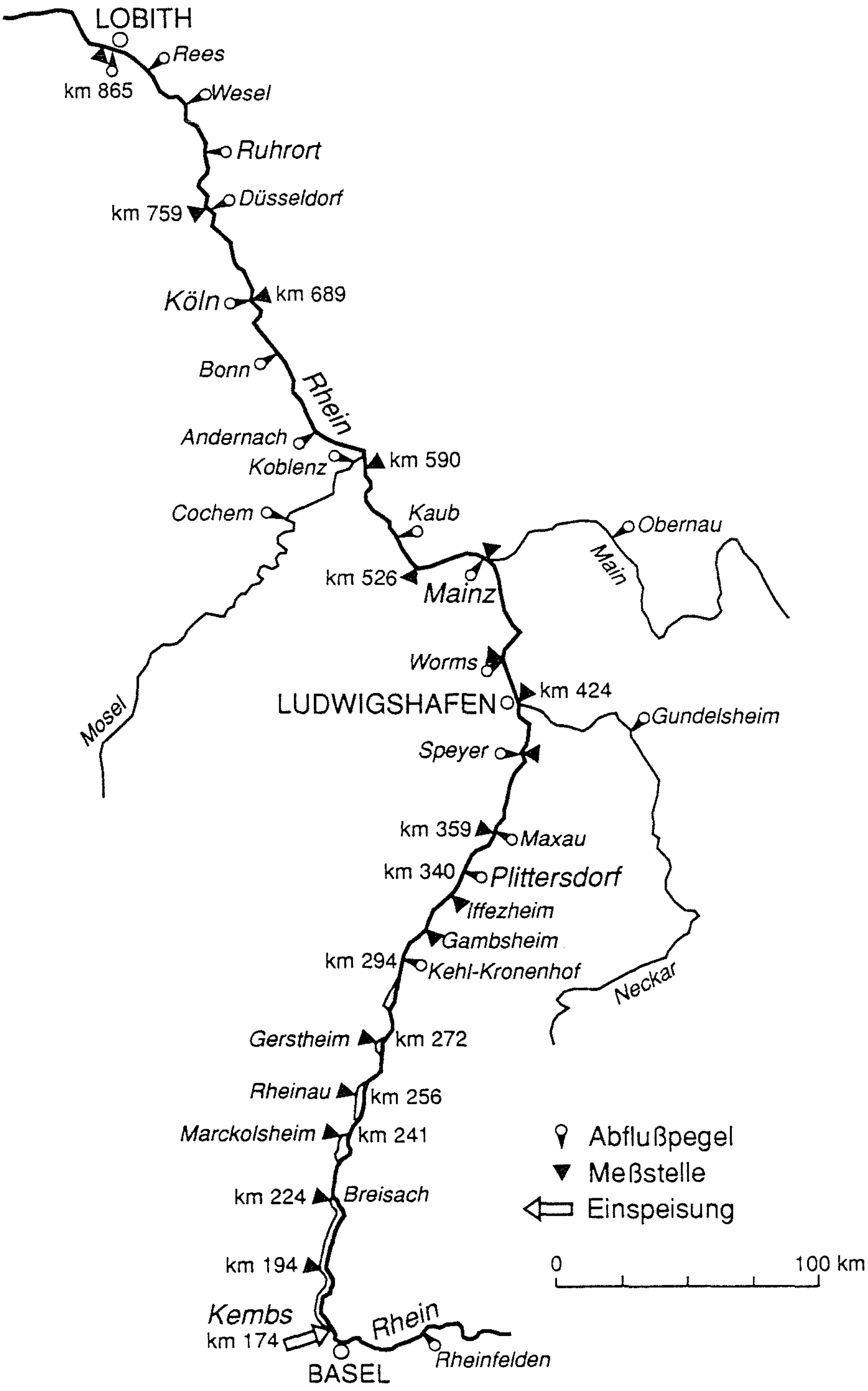
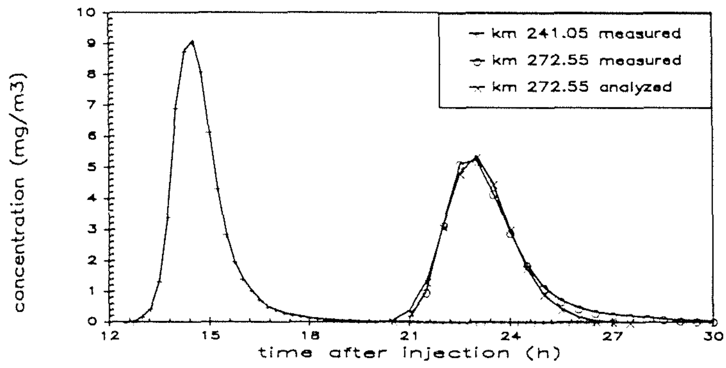


FIG. 5 Injection and observation points in the River Rhine.



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longitudinal dispersion coefficient:  76.0 m²/s
mean transport velocity:              0.80 m/s
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FIG. 6 SAMF input tracer curves and analized transport parameters.

TABLE 1 Deviations between measured and calculated travel times for the tracer experiment in June 1991.

Observation point	Rhine-km	T_m [h]	T_c [h]	T_d [%]
Injection	174.1			
Speyer	400.0	54.25	55.77	-2.8
Bad Honnef	640.0	107.25	110.44	-3.0
Duesseldorf	759.6	129.25	134.21	-3.8
Bimmen	865.0	153.25	159.35	-4.0
Hagenstein	946.5	185.25	191.96	-3.3

T_m = measured travel times
T_c = calculated travel times
T_d = travel time deviations

The recent version of the model contains both a proportionality constant, α, derived from the definition of the longitudinal dispersion coefficient, and a stagnant zone factor, ß, which accounts for the influence of stagnant zones. With these two parameters, calibration and verification of the Rhine Alarm Model was possible. The parameters were calibrated for each subsection. Input data for the calibration included the longitudinal dispersion coefficients and the mean transport velocities, which were computed from the measured break-through curves by the model SAMF (Fig. 6).

SAMF is an one-dimensional transport model developed for the analysis of tracer experiments. The analysis of the measured break-through curves is performed using the moment method and a non-linear least squares fitting procedure. The calibrated Rhine Alarm Model was verified by comparing calculated and measured concentration distributions from additional tracer experiments.

Between 1988 and 1992, 10 tracer experiments were conducted which covered about 1500 km of the Rhine River and its tributaries. Calibrated and verified by these tracer experiments, the recent version of the Rhine Alarm Model allows the prediction of travel times and concentration distribution with standard errors of less than 4% (Table1).

CONCLUSIONS

The prediction results obtained after calibration and verification of the one-dimensional Rhine Alarm Model emphasize the lack of comparable methods to tracer experiments for the investigation of transport parameters in rivers and control values estimated by transport models.

One-dimensional modeling, which was required to estimate short-term travel times typical of accidental spills, and the one point measurement technique are simple and reasonably reliable tools to be considered for estimating the distribution of solutes in large rivers. Complex processes, for example in dead zones or downstream from the confluence of two rivers, have to be investigated by direct measurements and described by two-dimensional transport models. But if improved or modified for these specific problems of transport studies in rivers, tracer experiments will remain the reliable technique for investigations in natural systems.

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