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Research on groundwater flow and transport problems at the Universität Stuttgart

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ABSTRACT: The groundwater research activities at the Institut für Wasserbau of the Universität Stuttgart are described. Numerical methods as well as laboratory and field measurements are used for the development of transport models and exploration techniques and their applications to problems of groundwater protection.

1 INTRODUCTION

The groundwater research program at the Institut für Wasserbau of the Universität Stuttgart has grown in the last decade in a continuous interplay of fundamental research and work on applied problems. The program is financed primarily by the Deutsche Forschungsgemeinschaft and by the Environmental Ministry of the State of Baden-Württemberg and supplemented by contract work for municipalities, water authorities and industry.

The general aim of our work is to contribute to the development of the scientific basis and the methods necessary for an effective and long-range environmental protection, and also to contribute to the transfer of new research results into the practise of water resources management. The complexity of the problems demands necessarily interdisciplinary cooperation, and our work is greatly enhanced by international collaboration with several partner institutions.

2 RESEARCH GOALS

Large scale deterioration of groundwater quality due to human activities has been observed in all industrial countries. With respect to the usage of groundwater for drinking water supply, problems have been encountered with significant changes of groundwater temperatures, with industrial contaminations primarily by chlorinated hydrocarbons, and with agricultural effects mainly by nitrates. Other substances have to be considered in connection with contaminated sites and old waste deposits. In all these cases, water management is faced with problems which require a quantitative description and prediction of transport processes in groundwater. Therefore, modelling and monitoring concepts are developed which are oriented directly towards the demands of practical applications. The research program implies the following elements:

- development of calculation methods for flow and transport,
- development of new measurement and exploration technologies,
- testing in laboratory experiments and field studies,
- application for exploration, management and cleanup concepts.

Under the heading "modelling of large-scale heat and mass transport in groundwater", the Deutsche Forschungsgemeinschaft (DFG) has installed an interdisciplinary research group involving, in addition to our institute, the Institut für Bodenkunde und Standortslehre of the Universität Hohenheim and the Engler-Bunte-Institut of the Universität Karlsruhe (Kobus, 1987). This research group has been funded since 1984 as an element of the DFG program "Contaminants in groundwater". The program of the research group concentrates on three typical classes of substances resp. properties: transport of heat, of chlorinated hydrocarbons, and of nitrates.

The research program has been initiated because so far transport models - in contrast to numerical flow models - had not yet been developed into a tool which could be applied routinely. One major reason is the discrepancy between the requirements for input data of transport models and the usually very limited field data available. Therefore, the program addresses the following questions:

- improvement of the description of macrodispersion caused by geological

inhomogeneities;
- development of transport models with extended adsorption and reaction terms for consideration of non-equilibrium conditions and of several interacting substances;
- development of nitrogen balance models for the unsaturated zone;
- identification of the main parameters of natural denitrification;
- analysis of the uncertainty of model results for given field data and stochastic interpretation as a requirement for the correct application of models;
- improvement of measurement and probing techniques.

The fundamental research is accompanied by several case studies with intensive field measurements, which are used to check the model developments with respect to applicability, compatibility with the available data and prognostic power in practical application.

In the course of the program development, a "test site water and soil" has been installed in 1987 on the Horkheimer Insel, which is described in Kobus (1988). This test site is funded by the State of Baden-Württemberg in its "Project Water-Waste-Soil (PWAB)" and is operated by our institute in close cooperation with the Institut für Bodenkunde und Standortslehre and the Institut für Pflanzenbau of the Universität Hohenheim, the Institut für Radiochemie at the Kernforschungszentrum Karlsruhe and the Institut für Informatik of the Universität Stuttgart. The main research topics are:
- development of measurement, exploration and monitoring methods for soil and groundwater protection,
- the development of natural groundwater quality as a function of the chemical processes in the unsaturated zone,
- short- and long-term changes of soil and groundwater quality due to agricultural activities, particularly agrochemicals,
- development of a distributed data bank system for storage, administration, preservation and flexible presentation of results of long-term measurement data.

3 DEVELOPMENT OF NUMERICAL FLOW AND TRANSPORT MODELS

3.1 Objectives

The flow and transport models developed in this program are intended for use as planning tools and decision aids in
- planning for groundwater resources management, such as design of new water wells,
- prognosis of the likely future effects of groundwater contaminations,
- planning and design of safeguarding and cleanup measures.

In order to develop criteria for the assessment of transport models as quantitative tools, it is necessary to specify
- which modelling methods can be used appriopratel y for which questions in groundwater protection,
- which prototype data are required in which density and quality for various levels of model complexity,
- which measurement methods with which quality are available,
- which expectations can be held as to the accuracy of model calculation results,
- in which ratio the measuring and modelling effort stands to the reliability of the results,
- and finally, in which cases model calculations cannot give useful answers.

For the numerical work, the institute has available a number of work stations and PC's as well as a direct connection to the supercomputer CRAY 2 of the university. The model development is carried out in various parallel projects.

3.2 Hydrodynamic dispersion in aquifers

Fundamental research is carried out on dispersive processes in natural aquifers, considering geological structures and inhomogeneities. Various parametric descriptions are used in numerical transport models and verified against an extended database from systematic laboratory experiments. Current results from this project are described in the paper by G. Schäfer and H. Kobus at this symposium. The goal of the project is an improved description of macrodispersive transport in numerical groundwater models.

3.3 Numerical modelling of heat transport and heat budget in aquifers

A multilayer horizontally two-dimensional numerical model has been developed and verified for forecasting the development of large-scale temperature anomalies in time and space. It was investigated in how far the multilayer approach allows an adequate description of the vertical heat fluxes and hence of the time development of temperature fields in space. Particular attention was given to the problem of collecting suitable data in nature (see section 5.1) and to their interpretation in the model. After extended verification on various field cases, the model has been documented and is described in Söll (1988).

3.4 Numerical modelling of large scale transport of contaminants in aquifers with consideration of adsorption and chemical reactions

In this project, a two-dimensional model for processes in the saturated zone is developed, which can be applied to horizontal- as well as vertical-plane configurations. The various modules of the system contain stepwise options for

- adsorption equilibrium,
- adsorption under non-equilibrium conditions,
- several chemically interacting substances.

By means of several case studies it is investigated to which approximation the modelling of the transport of substances under field conditions is possible. Prerequisite for model identification is a good knowledge of both the contaminant source term and the reactive behaviour of the contaminant. For the modelling of nitrate transport, these questions are investigated in parallel research projects by the Institut für Bodenkunde und Standortslehre of the Universität Hohenheim and by the Engler-Bunte-Institut of the Universität Karlsruhe, with the results of all projects being fed into the model. Various results from these studies are described in the paper of B. Huwe and R. van der Ploeg, the contribution of M. Rödelsperger and the presentation of W. Kinzelbach, W. Schäfer and J. Herzer at this symposium.

3.5 Numerical modelling (3D) of the borehole and its nearfield in an aquifer

A three-dimensional flow and transport model is developed which describes the nearfield processes in the vicinity of a borehole, including the influence of the flow and pressure distribution within the borehole due to pumping or probing actions. This model is verified by laboratory measurements on the test setup for borehole hydraulics (see section 4.2) and subsequently applied for sensitivity analyses and the interpretation of field measurements. Current results from this project are described in the paper by V. Kaleris at this symposium.

3.6 Verification of simulation models for transport of pesticides in soils

Three selected onedimensional models for the transport of pesticides are examined and validated by means of application to various percolation test series in laboratory columns. The laboratory tests are performed by the Biologische Bundesanstalt in Braunschweig.

4 DEVELOPMENT OF NEW MEASUREMENT AND EXPLORATION TECHNIQUES IN LABORATORY AND FIELD

4.1 Objectives

For experimental work, the infrastructure of the Institut für Wasserbau with laboratory, workshops, instrumentation and electronics laboratory is available. The groundwater laboratory includes facilities for determination of soil properties on undisturbed and disturbed probes and a number of test facilities filled with various materials, which can be operated under well-defined hydraulic conditions for various investigations. The experiments are useful for:

- visualisation for a better understanding of physical processes in aquifers,
- development and testing of new measurement and exploration techniques,
- systematic investigation of flow processes and of the transport behaviour of various substances in aquifers,
- testing of in-situ cleanup methods under controlled boundary conditions.

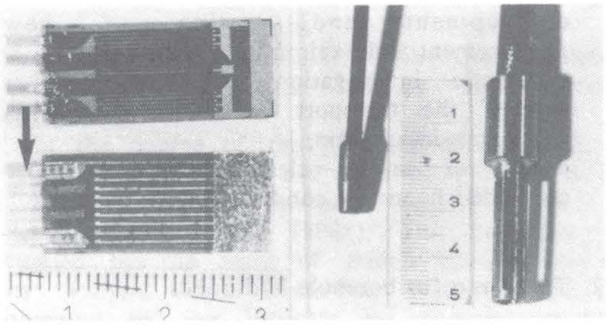
4.2 Test setup for borehole hydraulics

A large-scale test setup containing an aquifer volume of 55 m^3 is available for experiments on exploration techniques (figure 1). It contains an original four-inch borehole with a total depth of 4.5 meters. Tests are performed to explore the influence of borehole installation, borehole measurement techniques and probing techniques upon the determination and interpretation of groundwater data. For the purpose of improving the methods for determination of mass transport rates in aquifers, the influence of pumping rates, pumping duration, and probing techniques upon the probing results is investigated under controlled boundary conditions. Recent results from these investigations are described in the paper by B. Barczewski and P. Marschall at this symposium.

Fig.1 Test facility for borehole hydraulics

4.3 New sensors for groundwater measurement

For the determination of permeability profiles, new sensors for borehole dilution measurements on the basis of an in-situ light-fibre fluorometer are developed, which can also be applied directly in tracer tests. Also, a flowmeter for exact measurements of very small vertical velocities in boreholes has been developed on the basis of a thermosensor (see figure 2). Furthermore, an improved measurement and evaluation technique for a modified slug test is being developed. All these developments are aimed at a better grasp of the geohydraulic conditions at the borehole.



Thermal sensor for measuring very small vertical velocities in boreholes

Light fibre fluorometer probe for in-situ measurement of tracer concentrations

Fig.2 New sensors

The applicability of the various methods is being tested under varying field conditions by means of supplementing field measurements. For this purpose, two specially equipped vans are available (figure 3), which are instrumented for borehole measurements, pumping tests and groundwater probing.

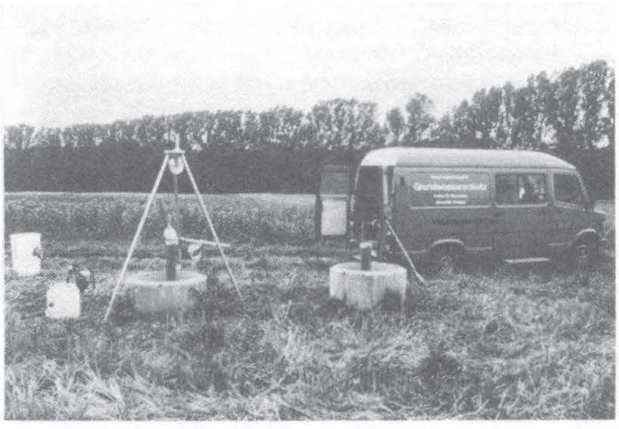


Fig.3 Instrumented car for field measurements

4.4 Dispersion experiments

Systematic experiments on dispersion are being conducted at a test stand of 14 m in length, which contains an articifially structured model aquifer made up of 81 individual elements of varying, well defined structure with layers and local inhomogenities. The experiments provide a better understanding of dispersion processes induced by geological layers or inhomogenities. The longitudal dispersion is seen to be a combined effect of differential convection and transverse dispersion. The systematic experiments provide a database for verification of various multiparameter dispersion models (see section 3.2).

In another configuration, the spreading and dispersion of injected water with a temperature difference has been investigated (Mehlhorn, 1982). Figure 4 shows a borehole injection of heated water into a uniform, homogenous aquifer with a cross flow. One can clearly see the nearfield effects of the buoyancy of the injected water, which cause a pronounced variation of the outflow distribution and a marked upward tendency due to buoyancy effects.

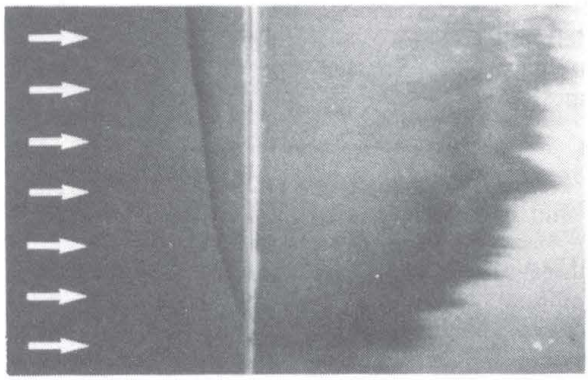


Fig.4 Dispersion experiment: borehole injection of heated water into a uniform, homogeneous aquifer with a cross flow

4.5 Hydraulic cleanup techniques experiments

For the simulation of hydraulic cleanup techniques under various boundary conditions, a test setup has been used which is shown in figure 5 (Herr, 1985). It allows contamination injections in various parts and experiments with cleanup wells at various locations for variable cross-flow conditions. Furthermore, a large number of column setups and small visualisation models is available.

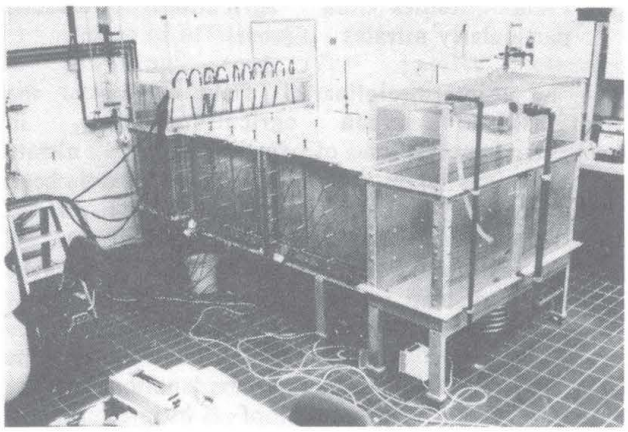


Fig.5 Basic experiments on the efficiency of hydraulic cleanup methods

4.6 Field test site Horkheimer Insel

The field test site "water and soil" at the Horkheimer Insel encompasses an area of about 2 ha and contains at present 30 multilevel groundwater observation wells, a specially equipped lysimeter with an undisturbed soil monolit of 1.6 m in diameter and 1.6 m in depth, a weather station and a great number of tensiometer and suction probe arrays. At the test site, geophysical methods (geoelectrics, seismic methods, borehole geophysics), hydraulic methods (pumping and injection tests) and tracer tests as well as various types of probing techniques are being tested. An example of the newly developed techniques is described in the presentation by G. Teutsch and T. Ptak at this symposium. The densely equipped arrangement at the test site allows the comparative investigation of groundwater exploration techniques under well-known natural conditions. Figure 6 gives an impression of the arrangement of the various installations at the Horkheim field test site.

5 CASE STUDIES

5.1 Test areas for heat transport investigations

In the Emmental in Switzerland, under the auspices of the Wasser- und Energiewirtschaftsamt Bern, several intensive field measurement campaigns have been conducted on the development of the temperature anomaly due to a local cold-water injection through a borehole, and on the large scale effects due to infiltration of river water along the Emme. These case studies have been used to test and validate the heat-transport models developed in our program. The results as given in Söll (1988) show that the models allow a sufficiently accurate calculation of the

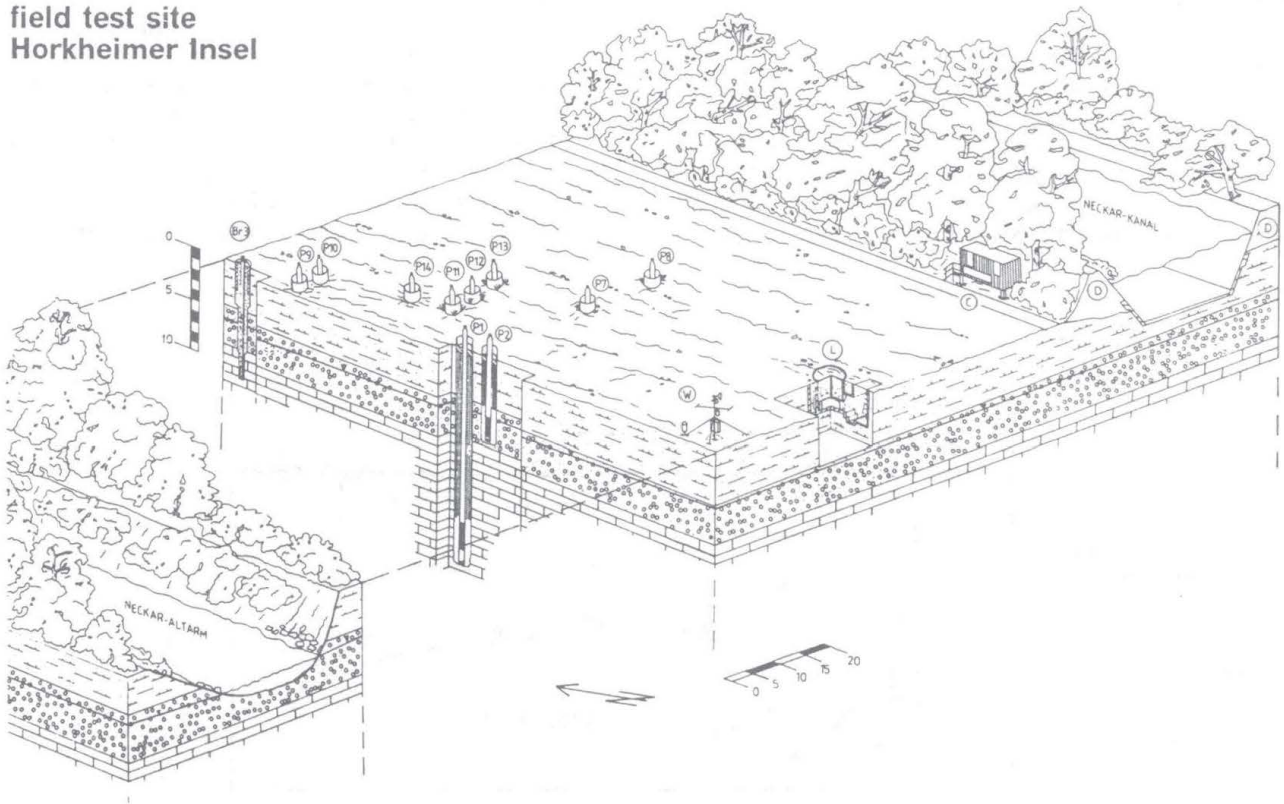


Fig.6 Installations at the Horkheim field test site

underground heat balance in order to predict temperature changes due to local injections.

5.2 Case studies of industrial contaminations by chlorinated hydrocarbons

In collaboration with a number of other research institutes and state agencies, several case studies about the behaviour of chlorinated hydrocarbons have been performed, in which the flow and transport models served the purpose of a systematic and integrating presentation of all available information. The experiences from these joint investigations are contained in MELUF Baden-Württemberg (1983).

The numerical transport models are used here to answer the following questions:

- assessment of the potential danger for drinking water supplies from known contaminations by chlorinated hydrocarbons,
- planning tool for measurement strategies for observation of the development with time of contaminations (also, for unknown sources, back tracking in space and time to the contamination source),
- planning tool for the conception of hydraulic defense- and cleanup measures,
- estimation of the efficiency and duration of cleanup measures and development of optimal cleanup strategies.

A recent example is presented in the contribution of C. Kauffmann and W. Kinzelbach to this symposium.

New investigations about hydraulic cleanup measures include methods of ventilation of soil-air, as is being used successfully in many cases. Present research concerned with the development of calculation methods to optimize such cleanup arrangements is described in the paper by J. Croisé, W. Kinzelbach and J. Schmolke at this symposium.

5.3 Field studies on agricultural impacts, particularly nitrates

In an interdisciplinary field study, the relationship between agricultural use, in particular application of fertilisers, and nitrate concentrations in groundwater have been investigated quantitatively since 1984. Field measurements are performed in collaboration of several institutions as is schematized in figure 7, in two test areas located in Bruchsal-Karlsdorf-Neuthard and in Lobdengau. The results and the model calculations for nitrate balances give a quantitative explanation of the causes and processes of nitrate input, transport and denitrification. A recent summary of the results is contained in H. Kobus and L. Zilliox (1988).

The developed models are useful for the following questions:

- identification of the catchment area of the individual wells of water supply plants and of travel times involved,
- prognosis of nitrate inputs into the groundwater as a function of agricultural activities, soil properties and climatic conditions,
- identification of the parameters involved in denitrification in the soil and in the groundwater,
- prognosis of the effects of changes in the nitrate inputs upon the nitrate concentrations in the water supply wells (such as reduced input because of reduced fertilizer application, or increased input by changing from grassland to agriculture),
- planning tool for measurement strategies in order to observe the long-term development and the effects of countermeasures,
- planning tool for the conception of hydraulic countermeasures in cases where there are significant differences in nitrate concentrations of the groundwater

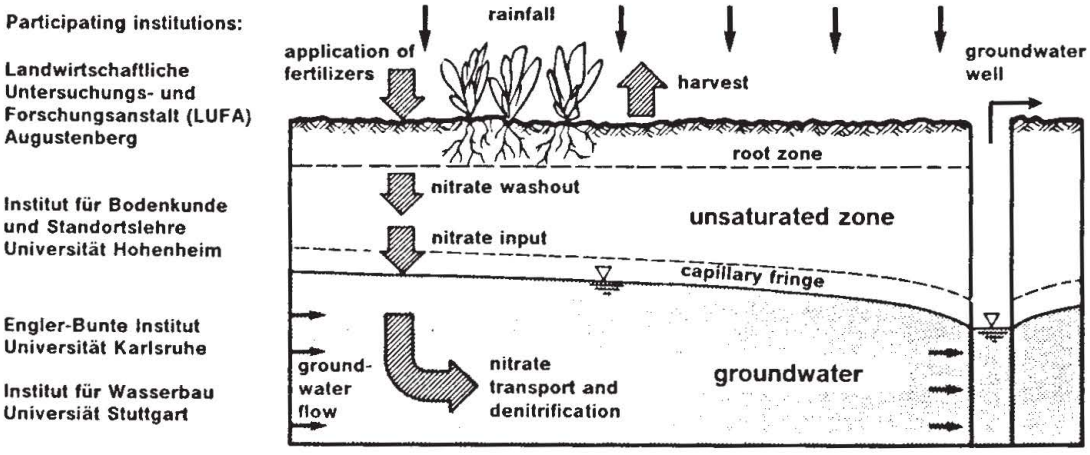


Fig.7 Case studies on nitrates in groundwater: participating institutions

(arrangement of wells, pumping rates, degree of efficiency),
- planning tool for in-situ cleanup techniques.

At the Horkheim test site, the influence of agricultural activities upon the groundwater quality is being investigated more generally, including the effects of application of agrochemicals and the effects of various agricultural techniques. These investigations aim at a comparison of two agricultural cells operated under standard agricultural conditions in one case and under "groundwater-friendly" conditions in the other. The aim is to see whether an improvement on the resulting groundwater quality can be achieved without a marked loss to the agricultural productivity, or else to quantify these effects.

6 CLOSING REMARKS

The research program described here is supplemented by a number of applied investigations for water supply agencies and communities, which concern the planning of new water supplies with consideration of water quality aspects as well as assessment and design of cleanup techniques. Considerable efforts are connected with a state-wide cleanup program on old contaminated sites and waste deposits. In this connection, further research will focus on local-scale and on multiphase flow problems. It is envisioned to enlarge the experimental facilities considerably for systematic and interdisciplinary investigations of such problems in the future.

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