D-4-1

GROUNDWATER POLLUTION CONTROL - A CHALLENGE TO HYDRAULIC RESEARCH

Helmut E. Kobus
Institut für Wasserbau, Universität Stuttgart, Germany

ABSTRACT: Groundwater constitutes a major natural resource for drinking water supply. The serious deterioration of groundwater quality observed in all industrialized and densely populated countries can be considered as an unspectacular, but ubiquitous "man-caused environmental disaster". Groundwater management has to match the increasing demands of drinking water supply (and other uses) with the constraints of the natural groundwater system with respect to both quantity and quality. In this paper, groundwater pollution problems are described and strategic considerations with respect to groundwater protection and subsurface remediation are illustrated by several examples. It is shown that the way towards adequate engineering solutions for sustainable development of groundwater resources still poses many challenges to hydraulic research /5/.

1. GROUNDWATER, A MAJOR RESOURCE FOR DRINKING WATER SUPPLY

In many parts of the world, groundwater constitutes a major natural resource for drinking water supply. Because of its purity and pleasant taste, natural groundwater is considered to be the best water for human consumption. Groundwater systems are naturally well protected against contamination, partly due to the filtration effect of the covering layers, and partly to the purification potential of the aquifer strata.

In Germany, about 72% of the public water supply stems from groundwater. The overall demand of 4 to 5 billion m^3 per year amounts to only about 2% of the hydrological cycle and hence poses no quantitative problems due to the favourable hydrological conditions. However, during the last two decades a continuing degradation of groundwater quality due to anthropogenic causes has been observed and has brought to our attention that groundwater resources, like surface waters, need protection and remediation efforts in order to maintain their quality. The detection of large scale groundwater contaminations by chlorides, chlorinated hydrocarbons and nitrates showed the new dimension of the problems, which have to be dealt with at regional rather than only local scale.

A contamination potential for groundwater results from nearly any activity of our industrial societies. Pollutant sources may be roughly classified as:

- infiltration from surface waters (rivers, lakes, reservoirs),
- diffuse area sources (rainfall-infiltration, deposition, agricultural sources of nitrates and pesticides, leaking sewage canals),
- local sources of industrial contaminants (industrial sites, deposits, spills and accidents).

It is only recently that numerous headlines in the media have sharpened public awareness of the problems affecting groundwater. Industrial sites and disused waste dumps have caused pollution of the groundwater to an extent which still remains to be determined. In Germany, about 135,000 suspect areas are registered as potential hazards to groundwater, many of which are in need of remediation. In addition, annually 1,500 to 1,800 accidents during storage and handling of substances hazardous to water are recorded. The subsequent contamination of the subsoil adds up to hundreds and thousands of m^3. Considering the concentration levels found in the polluted soil and comparing it to drinking water standards, dilution factors of 10^6 to 10^{10} are not unusual. This makes evident why local pollution can result in degradation of the groundwater over large areas and times.

When assessing groundwater pollution, the time factor is of vital importance /2/. Due to the very low rate at which groundwater moves, its reaction to contamination is very slow, and many years or decades can pass from the time at which pollution occurs to its "discovery" in the raw water reaching a water supply well. Therefore, degradation of groundwater is a long term problem which can only be rectified at great expense and over correspondingly long time periods. Hence, groundwater protection is posing significant new tasks for the water industry. These embrace preventive measures for avoiding pollution as well as techniques for the observation and assessment of groundwater quality, methods for predicting the future transport and fate of pollutants as well as designing and optimizing remediation schemes for polluted aquifers. These tasks are linked to an ever growing demand for quantitative predictions of the transport and spreading of contaminants in aquifer systems.

2. TRANSPORT OF POLLUTANTS IN THE SUBSURFACE

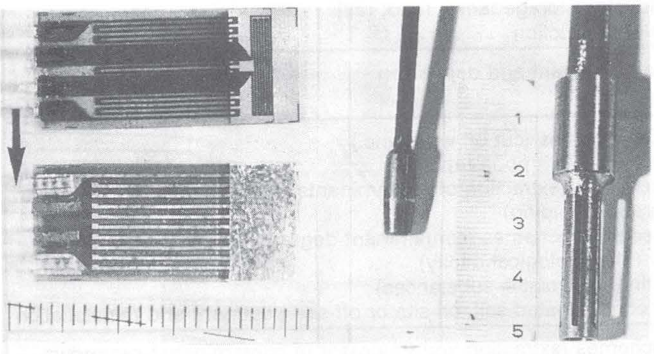
The transport of pollutants in groundwater is mainly determined by the geological structure of the aquifer, its permeability and the hydrological conditions /4/. As local geological characteristics can vary drastically and the hydrological conditions are prone to marked fluctuations, the pattern of pollutant transport can differ widely according to the time and place of the incident. This fact greatly complicates predictions, particularly because the regional geological structure and the hydraulic parameters of the aquifer are usually only vaguely known, and more detailed knowledge can only be gained by measurements which are comparatively expensive and time-consuming. The installation of groundwater observation wells by itself represents a disturbance of the natural aquifer, and it can only provide information at one given location, from which the areal distribution then has to be extrapolated. As compared to surface water sytems, the investigation of aquifers and groundwater circulation systems requires therefore a much bigger effort of exploration, and numerical modelling of flow and heat and pollutant transport in aquifers is a complex task.

Numerical transport models are based on the differential mass flux equation with consideration of convective transport, diffusion and dispersion as well as adsorption to the soil matrix and mass changes due to chemical reactions or processes of microbiological decomposition /3, 6/.

Water-soluble contaminants are primarily transported convectively. The flow field can be calculated provided adequate data on the hydraulic and hydrologic parameters of the aquifer are to hand. The determination of these parameters from available data (model calibration and validation) is the main issue in practical calculations of groundwater flows. Whereas predictions of integral parameters such as discharge or groundwater tables are relatively insensitive to local variations in permeability, these variations may be essential for describing transport processes. The pollutants transported convectively simultaneously experience dispersive mixing. This is due to molecular diffusion, pore-scale dependent dispersion and macroscale dispersive effects caused by the inhomogeneous geological structure of the aquifer. The combination of these effects leads to a pronounced dependence of the dispersion coefficient with the scale of the contamination plume. All of these various mixing effects must be taken into account in any realistic attempt at modelling contaminant transport.

The interaction between pollutants and the solid matrix exerts a strong influence on transport. Adsorption produces a delay in contaminant travel (chromatography effect). When modelling, it is important to distinguish between "fast" and "slow" adsorption (in comparison to the flow). In the former case, adsorption equilibrium is reached instantaneously, whereas for slow adsorption processes the kinetics of the process must be taken into account. The aquifer parameters governing adsorption (such as organic carbon content) must be known or estimated for proper consideration of adsorption effects in transport models.

Consideration of chemical reactions and microbiological decay ranges from including a simple first-order reaction term in the mass balance equation to complex systems of coupled equations for all reactands involved in the process. The reaction parameters must also be known (or assumed) in each case for the groundwater aquifer under study.



Thermal sensor for measuring very small vertical velocities in boreholes

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

Fig. 1: *New groundwater sensors*

The application of groundwater transport models places clearly increased demands on exploration technology. New methods are required which will allow collection of detailed data on the hydrogeological and transport parameters and new sampling techniques for determining local concentrations and eliminating inherent equipment errors. As an example, some newly developed sensors are shown in Fig 1. New measurement techniques matching the data requirements of numerical models are of vital importance for proper model validation, which is always complicated by the large number of parameters for which adequate knowledge is not to hand. The elucidation of material transport processes in aquifers therefore represents a major interdisciplinary task /6/.

3. STRATEGIES FOR GROUNDWATER POLLUTION CONTROL

The planning of remediation schemes requires for each contamination case sufficient knowledge in the following areas /2/:

- aquifer and hydrogeologic parameters,
- groundwater flow (including the effects of imposed hydraulic schemes),

- transport parameters of the contaminants,
- extent and characteristics of contamination source,
- knowledge of the effects of possible remediation technologies,
- criteria for assessing the need for remediation: this involves both the definition of remediation goals as well as the prognosis of the time development of the contamination without and with remediation scheme.

The requirements for exploration of the contaminated site are correspondingly high and exceed by far the usual frame for groundwater explorations.

Because of the multitude of contamination causes and of contaminants as well as of the hydrogeological and hydrological site conditions, no standard solutions for groundwater contamination problems can be formulated. Nevertheless, overall guideance is provided by two basis premises:
- prevention is better (and much cheaper) than remediation, and
- groundwater remediation has priority in comparison to merely securing a safe drinking water supply.

These premises provide a clear priority for the sequence of possible actions for groundwater protection. In Fig. 2, a roughly schematized listing of such actions is given. Of first priority, preventive measures for avoiding groundwater contamination are to be considered, but these often conflict with other priorities of society and industry on land use. The field of remediation technologies has been subject to rapid technological developments in recent years. General experiences so far indicate that remediation of the contamination source is extremely difficult and costly and in many cases technically impossible, whereas control and removal of contaminant plumes appears more promising (see examples in section 4).

Preventive schemes (avoiding contaminant inputs)	• delineation of wellhead protection areas with restriction on land use • restrictions of appliction of water-hazardous substances • regulations for handling and transport of water-relevant hazardous substances (industry, storage tanks, road, rail) • prohibition of production
Immediate actions in accidental spills (minimizing contaminant inputs)	• soil removal, treatment and deposition
Retaining and remediation schemes at the contamination source (prevention of contaminant spreading)	• geotechnical schemes (cut off walls, etc.) • chemical schemes (immobilization) • hydraulic schemes (extraction of contaminants in phase and/or in solution by flushing and pumping) • in-situ remediation schemes (contaminant degradation by chemical reaction and/or microbiological decay) • soil air venting (for volatile substances) • removal of contaminated soil, on-site or off-site treatment and reinstallation
Remediation of contaminant plumes	• hydraulic schemes (extraction and treatment of contaminated groundwater), possibly combined with chemical or microbiological schemes
Hydraulic defensive schemes in the vicinity of waterworks	• optimization of pumping schemes and selective use of individual wells (only effective in partially contaminated aquifers)
Technical schemes for maintaining drinking water supply	• water treatment technology for extracted raw water • addition of unpolluted water from other sources • use of other water supply systems (regional instead of local water supply)

Fig. 2: *Groundwater pollution control schemes (listing in order of strategic priorities)*

In case of diffuse pollution sources such as nitrates or pesticides from agriculture, one can only resort to the long term removal of the source and also to defensive hydraulic schemes at the waterworks in those cases in which only a partial segment of the aquifer is contaminated (Fig. 3). As a last resort, technical methods to upgrade the raw water quality to drinking water standards can be provided at the waterworks, if all other efforts fail.

4. SOME EXAMPLES OF GROUNDWATER REMEDIATION SCHEMES

Groundwater remediation schemes aim at removal of the contaminants. Among a number of alternatives, hydraulic schemes are most frequently applied /1/. These involve hydraulic wells which pump contaminated water or also collect contaminants in phase (Fig. 4). Naturally, such a scheme will be the more effective the earlier and the closer to the contamination source it is applied, before the large scale transport has provided a strong spreading and reduction of contaminant concentrations. The pumped water has to be treated (e.g. for the case of chlorinated hydrocarbons (CHC) either by a stripping system with air or by an adsorption system with activated carbon) and afterwards is discharged either into surface water, into a sewage system or else reinfiltrated into the groundwater to maintain a zero water balance. If the reinfiltration is provided upstream of the extraction, a subsurface recirculation zone ("remediation island") is formed, which is hydraulically separated from the surrounding groundwater system.

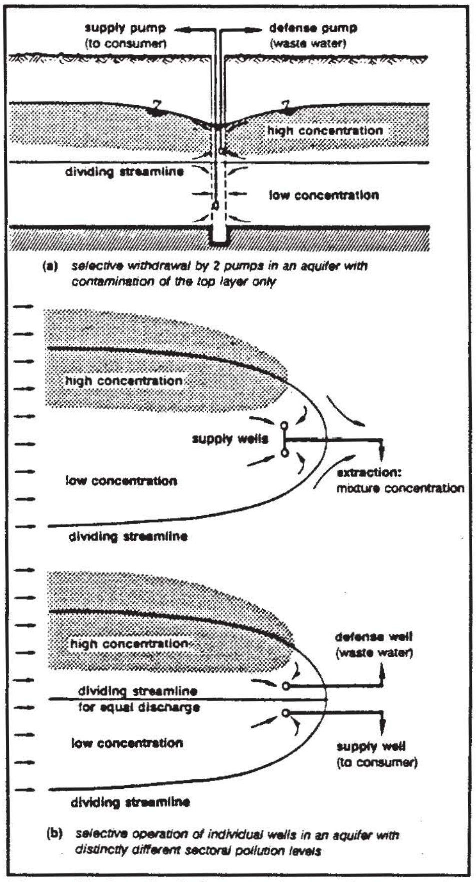


Fig. 3: *Hydraulic defense schemes for extraction from a partially contaminated aquifer*

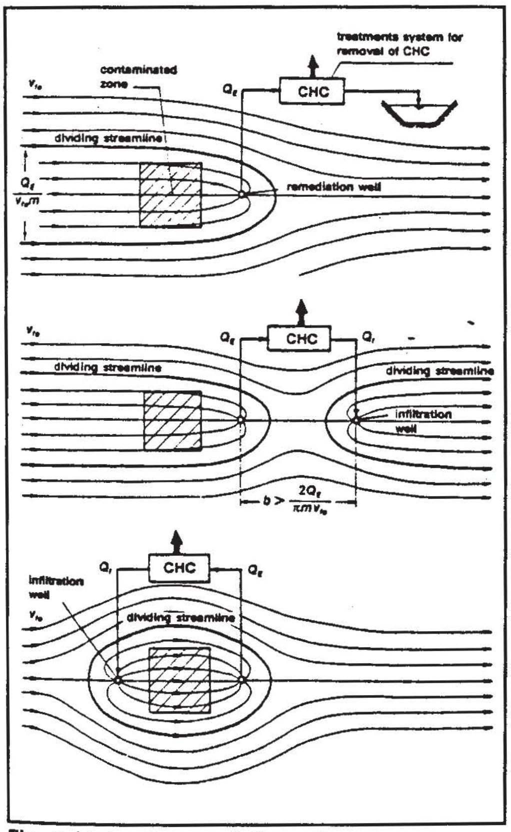


Fig. 4: *Hydraulic remediation schemes*

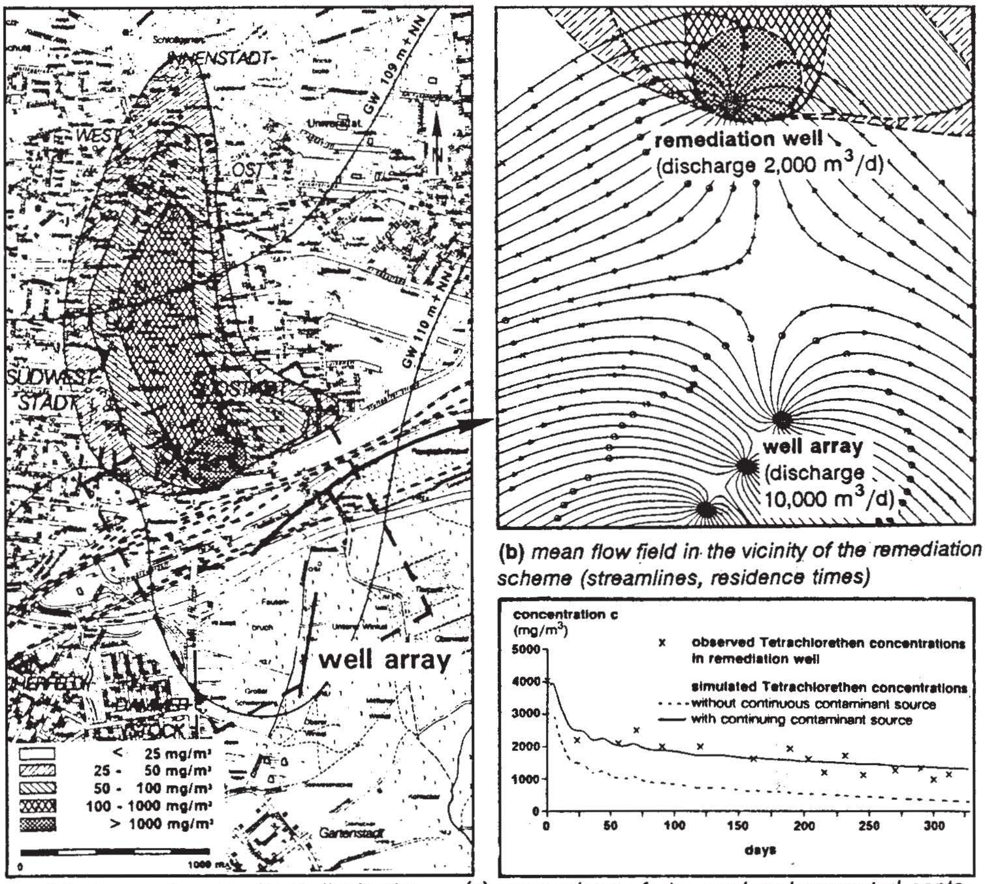
The goal to remove the contaminant mass completely and with a minimum effort contains two conditions:

- the subsurface contamination must be contained entirely in the withdrawal reach of the remediation well, and
- in order to be economical, the remediation should be achieved with a minimum of pumped water volume.

The design and optimization of a hydraulic remediation scheme according to these criteria with respect to the number and placement of the remediation wells and their respective pumping rates requires knowledge of the transport behaviour of the contaminant in the aquifer system. Therefore, the design and optimization of hydraulic remediation technologies requires application of numerical flow and transport models.

One example for a remediation scheme for chlorinated hydrocarbons (CHC) is shown in Fig. 5 /2/. The contamination case dates back to World War II damages. About 40 years after the date of the damage, the contamination has been discovered and explored as is shown on the left hand side. By the natural groundwater flow, the contaminant plume has moved in a northerly direction and did not reach the waterworks in the south. As a hydraulic remediation scheme, contaminated groundwater is being pumped directly at the contamination source site.

The flow field as it has been changed by the remediation well is shown on the right hand side in the form of stream lines and mean travel times. The marks on the stream lines indicate the travel times (in steps of one year) which a fluid element needs until it reaches the remediation well. If the known contaminant concentrations in the aquifer and the flow field are used to calculate the expected concentrations in the remediation well (lower right), it can be seen that the observed concentrations are consistently higher. This indicates that in the vicinity of the source there still must exist contamination in phase, which, while being depleted, acts as a continuous additional source.



(a) *observed contaminant distribution*

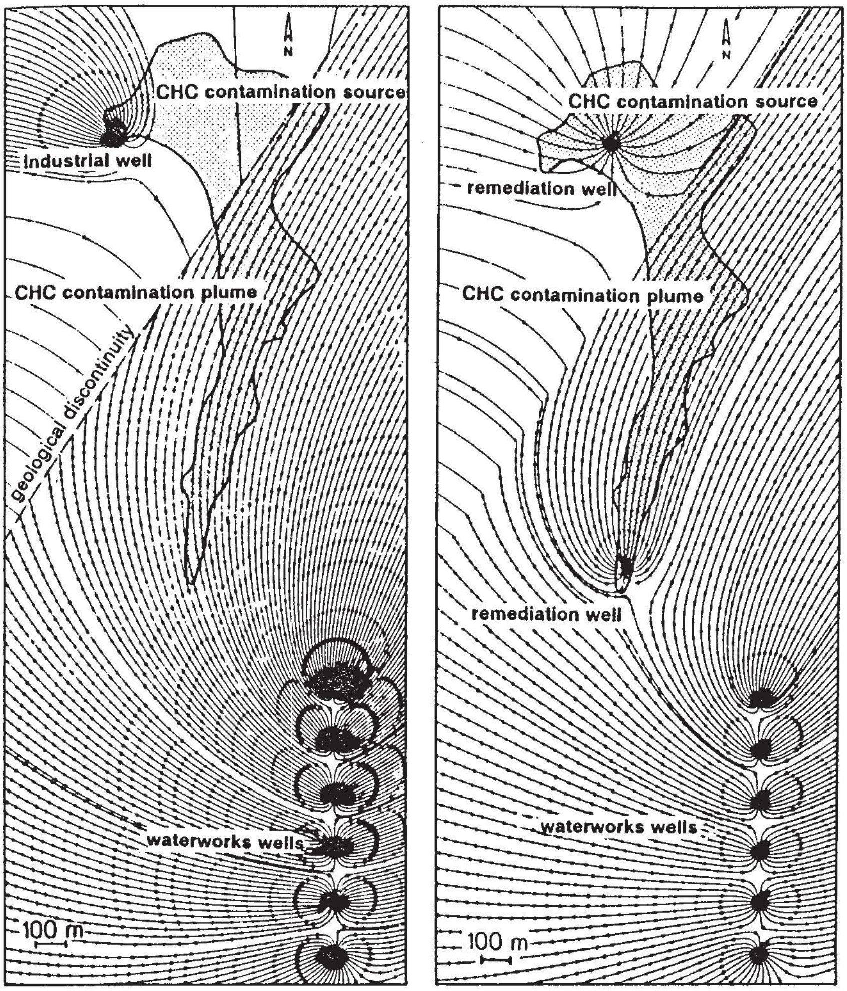
(b) *mean flow field in the vicinity of the remediation scheme (streamlines, residence times)*

(c) *comparison of observed and computed contaminant concentrations in the remediation well*

Fig. 5: *CHC remediation scheme Karlsruhe, Rüppurrer Strasse /2/*

Another example illustrating the optimization of a larger CHC-remediation scheme is shown in Fig. 6 /1, 2, 3/. In this case, a rather longspread contaminant plume has been discovered (obviously many years after the spill) with its source in an industrial area. The regional groundwater flow field is governed by the prevailing geological conditions and by the operation of a series of wells for a public water supply plant, as well as an industrial well near the contamination source.

If such a contamination is to be remediated, several hydraulic configurations can be considered. The minimal configuration consists in placing a single remediation well at the tip of the contaminant plume and another one at the center of the contamination source and operating both for very long time periods. The resulting flow field is shown in Fig. 6. on the right hand side. As an alternative, a large number of simultaneously activated remediation wells can be considered, which requires higher investment costs, but offers the advantage that the duration of the remediation scheme can be drastically reduced. If the overall water balance is to be maintained, then contaminated water extracted from the plume can be reinfiltrated after treatment in the adjacent aquifer. This leads to a further acceleration of the remediation. However, it also requires an increased effort in



(a) *observed contaminant plume and flow field before remediation*

(b) *flow field with remediation wells at the contamination source and at the plume tip*

Fig. 6: *Remediation scheme for an industrial CHC-contamination /1/*

treatment technology because of the high quality requirements for the reinfiltrated water. Fig. 7 shows several possible hydraulic configurations in comparison. The decision for the optimal remediation strategy can be based on such hydraulic calculations and comparative predictions according to financial, operational and regulatory considerations.

5. DESIGN REQUIREMENTS AND RESEARCH NEEDS

The above examples show but a few elementary aspects of the great scientific and technical challenges posed by the problems of groundwater pollution control. So far, practical methods of calculation are available only for handling relatively simple transport problems in groundwater: for prediction of space-time changes of non-reactive substances, or those subject to "simple" reactions (fast adsorption, first order decay), if adequate field data are to hand. These methods are employed for a number of different purposes: for optimising exploration programs, for groundwater management planning and operation of water supply systems, for forecasting the impact of groundwater contamination and assessing potential hazards and, last but not least, for planning protective and remediation measures in order to achieve optimum success and cost effectiveness.

In order to develop sound design procedures and safe and reliable engineering technology, much research and development is still needed

- to improve our methods of exploring and characterizing aquifer hydraulic parameters and contaminant distributions,
- to improve our understanding of contaminant transport processes in aquifers and to develop adequate flow and transport models for predictive purposes,
- to understand and optimize existing remediation technologies and also to develop new technologies for groundwater remediation: in particular for controlling the contamination source either by removal or by fixation /7/.

In all of these areas, considerable research efforts are underway in many parts of the world, including the Universität Stuttgart. The Stuttgart research program strikes at a balance between experimental laboratory work, numerical modelling work and field exploration techniques. A future focus will concentrate on experi-

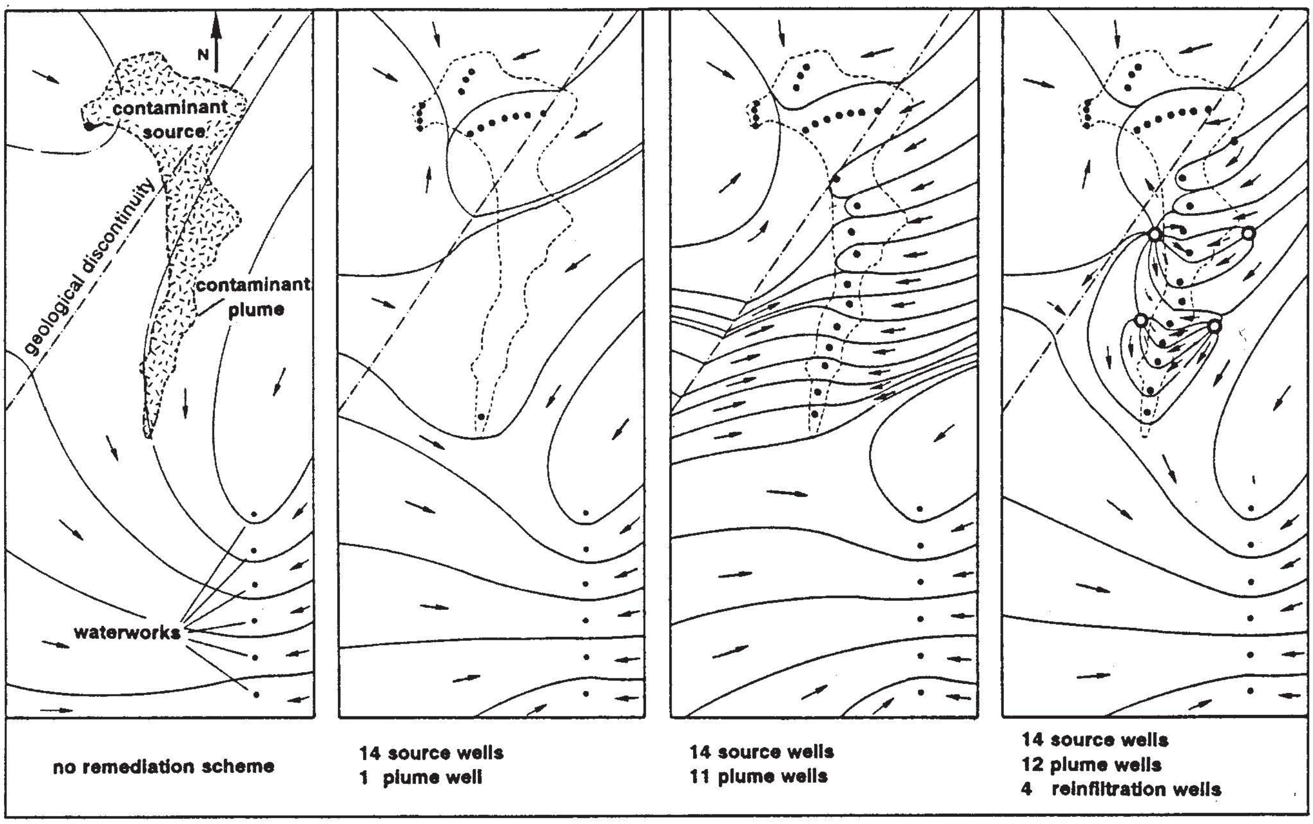


Fig. 7: *Various strategies for hydraulic remediation of the industrial CHC contamination of Fig. 6*

mental investigations at technical scale under controlled laboratory conditions for the development and improvement of remediation technologies.

REFERENCES

/1/ Herr, M.: "Grundlagen der hydraulischen Sanierung verunreinigter Porengrundwasserleiter", Mitteilungsheft Nr. 63, Institut für Wasserbau, Universität Stuttgart, 1986

/2/ Kobus, H.: "Grundwasserbelastungen, Sanierungsbeispiele und Schutzmaßnahmen", Die Geowissenschaften 6. Jahrgang, Nov. 1988

/3/ Kobus, H; Kinzelbach W. (Eds.): "Contaminant Transport in Groundwater", Proceedings, IAHR Symposium Stuttgart 1989, Balkema-Verlag Rotterdam, 1989

/4/ Kobus, H.: "On the Track of Soil Pollutants, Transport Processes in Ground Water"; german research, Reports of the DFG, N°3/1990

/5/ IAHR (1991): "Hydraulic and the Environment: Matching Hydraulics and Ecology in Water Systems", Extra issue, Journal of Hydraulic Research, Vol. 29, 1991

/6/ Kobus, H. (Ed.): "Schadstoffe im Grundwasser I: Wärme- und Schadstofftransport im Grundwasser", DFG-Forschungsbericht, VCH-Verlag, Weinheim, 1992

/7/ Cherry, J.A.: "Pump-and-Treat: Processes and Limitations", NWWA Conference on Aquifer Restoration: Pump-and-Treat and the Alternatives, 30.9.-2.10.1992, Las Vegas, USA