Process-oriented Concepts for Adaptive Water Resource Management

Implications for Urban Hydrogeology

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Thesis parts

Part I

Integrated Methods and Scenario Development in Urban Groundwater Management, and Protection during Tunnel Road Construction

A Case Study of Urban Hydrogeology in the City of Basel, Switzerland

Epting J, Huggenberger P, Rauber M (2008)

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Part II

Integrated Methods for Urban Groundwater Management Considering Subsurface Heterogeneity

Epting J, Huggenberger P, Regli C, Spoljaric N, Kirchhofer R (2008)

In: Quantitative Information Fusion for Hydrological Sciences. Cai X, Jim Yeh TC (Eds.) 2008, Springer Series: Studies in Computational Intelligence; X, Vol. 79, 218 p.

Part III

Groundwater Protection in Urban Areas Incorporating Adaptive Groundwater Monitoring and Management

Epting J, Regli C, Huggenberger P (2007)

In: Adaptive and Integrated Water Management, Coping with Complexity and Uncertainty. Pahl-Wostl C, Kabat P, Möltgen J (eds) 2008, Springer; XIV, 440 p.

Part IV

A Concept for Integrated Investigations of Karst Phenomena in Urban Environments

Epting J, Huggenberger P, Glur L (2009)

Submitted to Engineering Geology

Part V

Integrating Field and Numerical Modeling Methods for Applied Urban Karst Hydrogeology

Epting J, Romanov D, Huggenberger P, Kaufmann G (2009)

Submitted to Hydrology and Earth System Sciences

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Integrating Field and Numerical Modeling Methods for Applied Urban Karst Hydrogeology

Executive Summary

The present thesis illustrates process-oriented methods for water resource monitoring, management and protection. The methods have been applied and tested for specific questions arising in the context of urban hydrogeology within selected areas in the region of Basel, Switzerland. The results contribute to an integrated perception of surface and subsurface water resources in urban areas. Although the topics of the investigations may differ in terms of objectives and scales, the concept and methods are characteristic for many hydrogeologic problems in urban environments. The basic principles of adaptive groundwater management include the identification of the current profiles of groundwater systems. The methods applied facilitate the evaluation of the sum of impacts and their interaction in time and space with changing hydrological, operational, technical and even geological boundary conditions.

The thesis consists of five parts (Parts I-V), including this executive summary, an introduction, a general summary together with the discussion of results and conclusions. Each part represents an already published or submitted scientific article. The investigations address a variety of site-specific questions arising from different scales in the context of urban hydrogeology. All parts deal with impacts of engineering projects and infrastructure development on surface and groundwater systems.

Part I illustrates that, with the aid of groundwater modeling, the dynamics of the groundwater flow regime under changing spatial and temporal constraints could be simulated and evaluated successfully during the various project phases of a tunnel highway construction. The results allowed to optimize groundwater monitoring, management and protection and to progressively evaluate different engineering proposals.

The methods presented in Part II exemplify quantitative data fusion for urban hydrogeology as a practical tool for subsurface characterization. The applied techniques allow integrating different type and quality data into groundwater models and to quantify the effect of groundwater flow budgets and velocities in individual sedimentary structures. Obviously, groundwater flow in heterogeneous media occurs largely through interconnected highly permeable sedimentary structures.

In Part III process-oriented approaches for adaptive groundwater management in urban areas is illustrated by selected examples in the region of the city of Basel. The concept focuses on the influence of various water engineering projects on the future development of water resources and associated flow regimes. Further emphasis is on the transient character of river-groundwater interaction and the revision of existing protection concepts.

Part IV and V illustrate the results of a project dealing with urban infrastructure maintenance and development at a smaller scale. Subsidence of a river dam and an adjacent highway, both constructed on gypsum-containing rock, required remedial construction measures. This case study presents comprehensive research within a gypsum karst site. Next to universal measurements and monitoring technologies, investigative methods with predictive character are developed that allow long-term predictions on the future evolution of the system and on further

subsidence. This part further illustrates that the proposed concept and methods can be used for the setup of monitoring networks and the development of adaptive water management tools on the one hand, but also can be applied for basic research on the development of gypsum karst systems on the other hand. The various investigative methods for karst aquifer characterization complement each other and allow the interpretation of short-term impacts and long-term developments.

The scientific achievements of this thesis include: (1) the implementation of a concept for adaptive and integrated water resource management; (2) the demonstration of integrating different methods and tools for process-oriented investigations in urban areas (monitoring, modeling, hydrogeophysics, etc.); (3) the fusion of qualitative and quantitative geological and hydrological information of different quality to describe aquifer heterogeneity; (4) the revision of existing protection concepts and approaches for risk assessment; (5) the application of karst evolution modeling based on genuine field data; (6) novel iterative approaches for the setup and combination of groundwater and karst evolution modeling techniques; (7) methods applied to characterize short-term impacts and long-term development of flow regimes in karst areas and (8) suggestions for monitoring strategies, including the development of tools that can be used for prediction in urban hydrogeology.

1 Introduction

1.1 Motivation

Water resources in urban areas are under increasing pressure: According to the European Environmental Agency about 70 % of the European population lives in urban areas, which cover in total about 25 % of the total territory (EEA 1999). With over 40 % of the water supply of Western and Eastern Europe and the Mediterranean region coming from urban aquifers, efficient and cost-effective management tools for this resource are essential to maintain the quality of life and to ensure that water is available for future generations (Eiswirth et al. 2003; 2004). Sustainable use of water resources and protection and conservation of their quality are hence a key issue of European environmental policy and an enormous challenge for European research (Prokop 2003). Sustainability describes the rates of use for a resource that are considered appropriate for the current generation's benefit offset by preserving the viability of the same resource for future generations (WCED 1987).

Urbanization comes along with increasing pressures on water resources and may lead to conflicts between users in the future. The main effects of urban development are changes in recharge and groundwater levels, (Lerner et al. 1990; Ku et al. 1992; Foster & Morris 1994; Carmon et al. 1997) and in water quality (Nazari et al. 1993; Eiswirth & Hötzl 1994; Lawrence et al. 1996; Lerner 1996). The impact of the functions on water resources can be described as "pressures". Pressures are the agents that potentially stress the environment. They fall into three main categories (EEA 1999): (1) emission of chemicals, waste and radiation, (2) use of environmental resources and (3) area of land used. Foster et al. (1998) and Burke et al. (1999) identify two main urban water resource objectives, namely: (1) to improve the sustainability of resource exploitation in and around cities by avoiding irreversible degradation of aquifer systems and (2) to use available resources more efficiently, avoiding anarchy in their exploitation and in land contaminant discharge. The demands on resources include the objectives of society, as well as ecological, environmental and hydrological integrity (Loucks and Gladwell 1999). Therefore, the principle of resource protection is based on conservation as well as prevention and reduction of contaminant release into the environment.

The need for upgrading and developing transportation infrastructures in urban areas often requires construction measures under difficult geotechnical and hydrogeological conditions, while maintaining the entire operation of city life. Often infrastructure development and associated changes in land-use consider only the benefits of an improved infrastructure, and planning largely takes the pragmatic form of engineering for short-term economic objectives. As a consequence, water resources are under increasing pressure, especially in urban areas. They are subject to ongoing adaptations under changing boundary conditions.

In Switzerland many local drinking water supplies are subject to time variant risks concerning groundwater quality. The flood events in 2006 and 2007 and a recent ecological investigation on natural diversity clearly demonstrate that sustainable surface and groundwater management concepts should not exclusively focus on the drinking water supplies. Such concepts should also consider ecological integrity, regional scale hydrological and hydrogeological processes and fluxes across the main system boundaries. Furthermore, it should account for uncertainties derived from incomplete knowledge. This requires the application of adaptive management optimization strategies. Such strategies incorporate a coordinated iterative process of selecting and testing hypothesis of responses to management interventions. Risk assessment for water pollution, reservoir depletion, flood protection in relation to climate change and river restoration, etc. has to be carried out in regard to current and future conflicts amongst stakeholders. In order to meet these goals, the combination of results from basic research focusing on process understanding and practical applications of efficient Adaptive Water Management (AWM) is necessary. These concepts also facilitate strategies for reorientation of current groundwater and surface water management practices. Successful application of the developed methods and forward-looking strategies are the scientific basis for decision-making by government and administration.

Although legal frameworks for water protection as well as water policy, have continuously been adjusted in the last decades, considerable damage to water resources still occurs. Previous studies only concentrated on potential mitigation of various impacts (the term “mitigation” encompasses a broad range of measures that might reduce or compensate the effects of environmental damage; National Research Council 1992). There are several reasons for this: (1) more attention is paid to purely technological problems concerning water management rather than to issues dealing with sustainable water use; (2) water protection and engineering projects were planned under outdated legal frameworks and would not be approved today. More restrictive laws, as well as changed perceptions and policy concerning water resources now apply; (3) realization of water protection is still oriented mainly towards documentation of changes in the flow regime and water quality, whereas less attention is paid to the prediction of future demands and to the management of water resources; and (4) until now, the impacts of engineering measures on water systems were only regarded as solitary and limited events. However, examinations of the interactions between the impacts and other activities as well as changing boundary conditions were not attempted. Existing legal frameworks for water protection usually focus on the local monitoring of a set of given parameters rather than on the understanding of the fundamental processes and long-term changes. Therefore, the implementation of sustainability concepts during engineering projects is a key objective of urban hydrogeology. Such concepts should include innovative approaches that take into account the complexity of the system and facilitate the adequate quantification of the site-specific aspects, as well as of the consequences of cumulative effects on a larger scale.

1.2 Approach

To meet the challenges of a sustainable development of water resources, it is necessary to develop and implement integrated and adaptive water management in urban areas (Adaptive Water Management (AWM), Integrated Water Resource Management (IWRM)). This requires innovative approaches that take into account the full complexity of the systems to be managed (Pahl-Wostl 2006). The basic principles of these approaches, including water resource monitoring and modeling, are already established (Eiswirth et al. 2003; Fatta et al. 2002; Pahl-Wostl et al. 2005). However, these concepts have rarely been successfully applied in urban planning. Many innovative technologies proposed for groundwater management, including groundwater modeling and scenario development are confronted with enormous implementation barriers. Confidence in their success is often low, and conventional and more expensive technologies are preferred (Prokop 2003).

For the development of AWM and IWRM it is essential to know the demands and potentials of individual water resources and to be able to predict the cumulative effects of numerous possible impacts. This can be accomplished by the setup of efficient monitoring and modeling systems together with the identification of relevant indicators. Based on extended knowledge of the dynamics of water resources, scenarios can be formulated that account for future demands and facilitate early detection of destabilization of natural processes. Currently, the knowledge of the complex interference between natural and anthropogenic impacts on hydrological and hydrogeological processes and systems is incomplete. Water protection strategies in urban areas are mainly oriented towards requirements of particular sectors, e.g. protection zones for pumping wells. Extending current protection concepts with process-oriented approaches can enhance sustainable development of water resources. Therefore, the knowledge of the composition of water quality, including an adequate consideration of variable hydrologic, operational and technical boundary conditions is of great importance. To accomplish this, it is necessary to develop instruments that facilitate the adequate quantification of the consequences resulting from cumulative effects of numerous decisions concerning flow regimes and water quality.

The purpose of this thesis is to develop concepts and tools that allow understanding and predicting the cumulative effects of the numerous single impacts to water resource systems during and after engineering projects in the region of Basel, Switzerland (Fig. 1). Often, infrastructure development and associated alterations in land use only consider the benefits for the improved infrastructure itself and planning largely takes the pragmatic form of engineering for short-term economic objectives. This often leads to adverse effects on flow regimes with respect to quantity and quality of water resources. Furthermore, such impacts on flow regimes and water resources are often only recognized after several years. The term “flow regime” thereby includes all flow patterns, velocities and budgets for a defined region in a temporal context. To develop concepts and methods for sustainable water use in urban areas, environmental impact assessments not only have to include above-ground impairments such as ground motions with effects on existing buildings and infrastructures, as well as noise exposure and air pollution, but also the negative impacts on flow regimes.

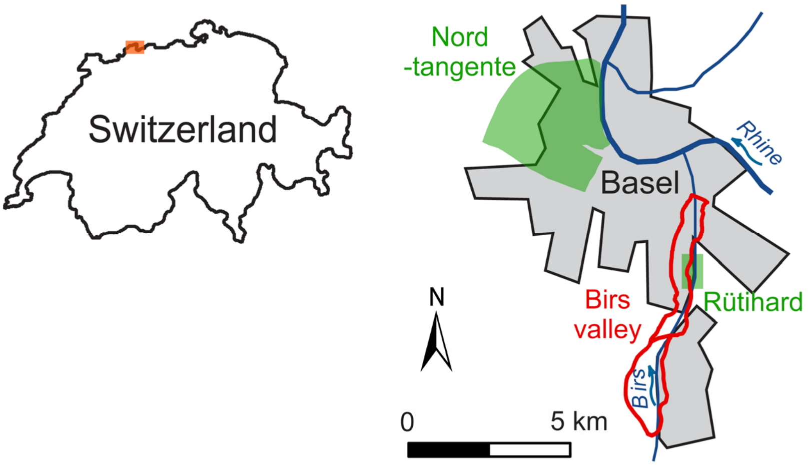

Fig. 1 Investigation areas in the region of Basel

1.3 Concept

The following concept was applied, with project-specific modifications, throughout the various project parts of the thesis (Fig. 2).

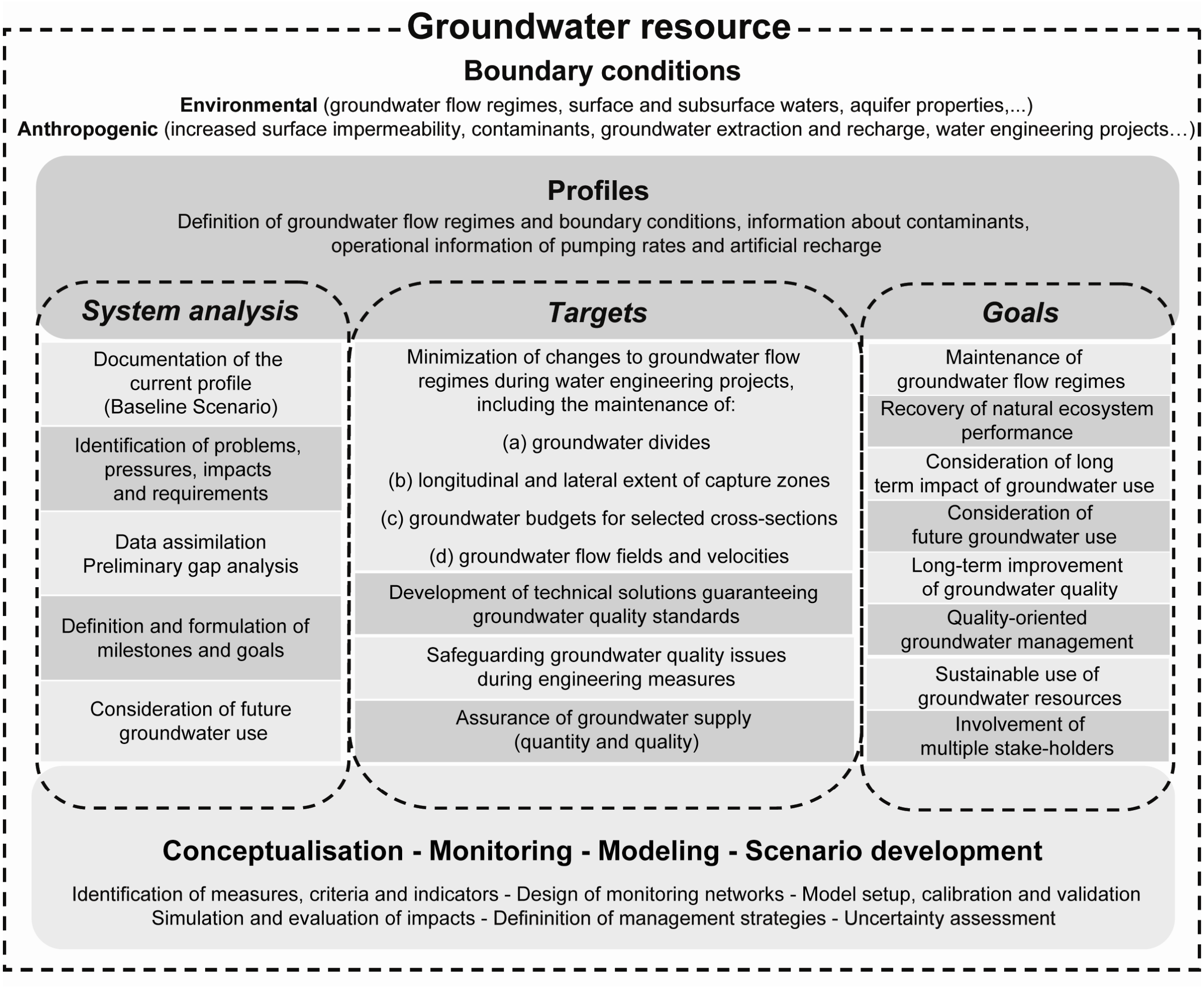

Fig. 2 Conceptual approach for practical urban hydrogeological applications

The concept proposed for practical urban hydrogeological applications in the context of regional urban landscape development consists of the following iterative procedure:

(1) Delineation of the investigation area, including an inventory of all relevant environmental and anthropogenic/geotechnical ***boundary conditions*** for the specific area of the engineering project, as well as adjacent zones of possible interferences or negative impacts.

(2) Definition of system ***profiles*** that describe the system before, during and after the completion of engineering projects. These profiles include an inventory of the boundary conditions and the multiple impacts on flow regimes at specified times, whereas the concluding profile should comprise the general goals for the future system development desired. Such profiles allow decision-makers to see the impact of past and present modification patterns of the system. Generally, system changes are validated and referred to a natural state. However, because of the multitude of anthropogenic processes in urban areas, this is difficult or even impossible. Therefore, the primarily defined system profile of the initial state before the beginning of

engineering projects is usually chosen as a reference.

(3) ***System analysis***. This comprises the documentation of the current system profile and the stationary or non-stationary processes. This also includes the identification of problems, pressures, impacts and requirements, data assimilation and preliminary gap analysis and the definition of specific targets that lead to overall goals for particular water resources and a desired long-term development.

(4) ***Targets*** are defined at relevant scales and include: (a) the minimization of qualitative or quantitative changes to water resources during engineering projects. This may include the maintenance of the courses of groundwater divides, the longitudinal and lateral extent of capture zones, the dimensions of water budgets for selected cross-sections as well as flow fields and velocities; (b) the development of technical solutions that guarantee sustainable development of surface and subsurface waters and (c) the assurance of continuous water supply, regarding quantitative and qualitative aspects. As the individual targets may interfere with each other and, in combination, may not necessarily lead to a desired overall goal, techniques that facilitate the comparison of interferences have to be applied. This can be accomplished by scenario development and the implementation of equivalence and acceptance criteria (Bedford 1996). Equivalence and acceptance criteria include: (1) the evaluation of simulated water budgets and velocities through defined regions, local and regional, during engineering measures and after their completion; (2) the assurance of a continuous local and regional water supply; (3) the possibility of additional water use in the region in the future; (4) the overall development of water quality throughout the engineering measures and (5) the technical feasibility of current and future engineering measures related to cost and safety requirements.

(5) Finally, ***goals*** for a sustainable development of surface and subsurface water resources are formulated. These goals guide mitigation strategies and refer to defined standards, i.e. natural composition of water or quality standards defined by existing regulations. They also establish a standard upon which individual decisions are based. Goals with respect to flow regimes at the regional scale should be based on the knowledge of physical properties governing the system. General goals are: (a) maintenance of flow regimes; (b) recovery of natural ecosystem function; (c) consideration of long-term impacts of geotechnical measures; (d) consideration of future water use; (e) long-term improvement of water quality and (f) quality-oriented water management. Whereas goals focus on a long-term sustainable development after the completion of engineering projects, targets center on surface and subsurface water protection and geotechnical issues during engineering measures. Both targets and goals may have to be modified as perceptions change in time.

The concept (***Conceptualization***) also incorporates the different information obtained from geological, hydrogeological and engineering investigations as well as the determination of the relevant parameters and indicators. This is accomplished by combining instruments that facilitate the adequate identification of the influences of the various single impacts on the complete system. The core elements of this adaptive procedure include the ***integration and combination of different investigative tools*** such as the design of extensive monitoring systems (e.g. hydrometrical and geophysical) and numerical groundwater and karst evolution modeling. The tools developed allow the relevant processes to be monitored and can be used for prediction. Together with the ***development of scenarios,*** possible future impacts and remedial strategies can be defined and evaluated.

For each specific project the concept and the investigation methods must be adapted to the questions addressed. Therefore, at the beginning of projects the following key questions have to be addressed: (a) Which are the determining hydrological and hydrogeological processes as well as geotechnical boundary conditions to be considered in the investigation areas? (b) Which indicators allow characterizing flow regimes and predicting vulnerability of water resources and infrastructures? (c) Which are the main anthropogenic and naturally caused impacts and risks of water resources and infrastructures and what is their frequency? (d) How far can water management and monitoring systems be optimized with respect to the temporal and spatial transient character of risks and vulnerability? (e) What are the effects of environmental (urbanization and climate change) change to water resources and their management?

In a next step the following issues should be addressed: (a) Are the existing data sufficient to answer the relevant questions and which concepts can be set up with the data? (b) Which additional data and experiments could improve predictions and allow hypothesis-testing? (c) How could data acquisition and experiment design be optimized? Consequently, data acquisition and the realization of specific experiments for hypothesis-testing is an iterative procedure.

In urban areas, large amounts of geological and hydrological data are generally available but spread over different institutions. Often, these data are difficult to localize and their preparation for specific questions time-consuming. Therefore, the setup of geological and hydrological databases can significantly contribute to questions arising in the context of urban hydrogeology. During the last two decades, a comprehensive geological database was set up for north-western Switzerland (GeoData, Kirchhofer 2006). This considerably supported the investigations. It comprises a systematic data collection, an analysis of drill-core data and an assessment of metadata from geological and hydrological reports. GeoData can be linked to a Geographic Information System (GIS) to provide, together with groundwater head and further hydrological data, a unique data source. This is suitable for empirical studies and hypothesis-testing in the field of quantitative information related to urban hydrological questions.

1.4 Thesis Organization

The thesis consists of five parts (Parts I-V), each representing an already published or submitted scientific article. The investigations address several site-specific questions arising from different scales in the context of urban hydrogeology. All parts deal with water management and protection issues in the region of Basel, Switzerland and focus on impacts of engineering projects and infrastructure development on surface and groundwater systems. Additionally, they are interrelated by: (1) adaptive water management and monitoring; (2) river-groundwater interaction processes considering different spatiotemporal scales and (3) development of quality-oriented water monitoring strategies with predictive character. While, for the area in north-western Basel, river water infiltrations can be a major part of overall water budgets, especially during flood events, the area south-east of Basel illustrates a special case of river-groundwater interaction in the vicinity of a river dam.

Parts I and II: "Nordtangente"

The investigations for Part I and II were performed in the north-western area of the city of Basel (Fig. 1). Open space in urban areas is very rare and new infrastructure is increasingly constructed in the subsurface under difficult geotechnical and hydrogeological conditions (other examples include: "Big Dig", a major highway in Boston, USA (Altshuler and Luberoff 2003); and infrastructure constructions in central Berlin, Germany (Hufschmied 2006)). Strategies are discussed to understand and predict the cumulative effects of the numerous single impacts on groundwater resources during a major suburban development project at a regional scale. Subsurface constructions can result in significant changes in groundwater quality and dynamics of both local and regional groundwater flow regimes (Foster 2001). While some changes only temporarily affect urban groundwater systems during construction, others are permanent, like the reduction of cross-sectional groundwater flow and aquifer-storage capacities. Together with various sources of groundwater pollution observed in urban environments, subsurface construction may interfere with a previously balanced urban-groundwater flow regime. Within the investigated area pressures on urban water resources include (1) extensive industrial groundwater use, (2) vast areas formerly contaminated by industrial wastes and (3) major changes in the groundwater flow regime during some construction phases of a tunnel road. With respect to these impacts, particular focus was placed on determining the data required to understand changes affecting groundwater flow and transport. Integrated multidisciplinary approaches were chosen to predict, mitigate or prevent environmental problems, as well as to ensure groundwater supply throughout construction.

Part I is a case study for applied urban hydrogeology and introduces ***"Integrated Methods and Scenario Development for Urban Groundwater Management and Protection during Tunnel Road Construction"***. Investigations include the setup of a groundwater management system with the following two main elements: (1) an extensive groundwater monitoring system for groundwater levels and quality; and (2) a high-resolution numerical groundwater model combined with scenario development.

Part II "Integrated Methods for Urban Groundwater Management Considering Subsurface Heterogeneity" applies to a part of the investigation area already presented in Part I. This study compares groundwater modeling results from integrating large-scale zoning of aquifer parameters, derived from pumping tests, with aquifer properties related to sedimentary heterogeneities. Investigations include the integration of geological and hydrological data resulting in a groundwater management system comprising: (1) extensive groundwater monitoring; (2) development of a database application facilitating lithofacies-based interpretation of drill-core data; (3) geostatistical analyses of the aquifer's heterogeneity and simulations of hydraulic parameter distributions and; (4) regional and local high-resolution groundwater modeling. The combination of techniques presented in Part II exemplifies the fusion of qualitative and quantitative geological and hydrological information of different quality.

Part III: "Birs valley"

Part III is a contribution for the CAIWA (Conference on Adaptive and Integrative Water Management) conference 2007 in Basel. It is an outline on ***"Groundwater Protection in Urban Areas Incorporating Adaptive Groundwater Monitoring and Management"***. This study investigates water systems and their usage related to interference during flood events and water engineering activities along rivers in the region of Basel (Fig. 1). In the context of river training for flood protection, a multitude of river engineering measures are currently planned in Europe. Water engineering measures along rivers have to be accomplished to mitigate the impact of hazardous flood events and the conservation and recovery of natural functions of water systems. Therefore, such projects have to incorporate qualitative, quantitative and ecological groundwater protection issues. The development goals for natural or near-natural rivers (sufficient space for rivers, sufficient discharge and reasonable water quality; BUWAL 2004) thus have to be coordinated with those of groundwater protection. Based on the experience gained from hazardous flood events in the last twenty years, most countries have acquired a more comprehensive view of rivers. This includes the consideration of processes at the catchment scale as well as ecological aspects. Multiple interests concerning water use and protection challenge the intentions of water engineering and water protection schemes that can only be solved by simultaneously considering all interests. Investigations focus on: (1) river-groundwater interaction, (2) quality-oriented groundwater monitoring and (3) adaptive groundwater management. The results help to better understand and to predict the cumulative effects of the numerous single impacts on water resources during flood protection and river restoration. In addition, strategies are discussed in the Basel area on a regional scale.

Parts IV and V: "Rütihard"

The investigations of ***Parts IV and V*** were performed southeast of Basel (Fig. 1). Infrastructures in karst regions, especially in gypsum, are prone to subsidence. This can cause severe problems, especially in urban areas. The case study documents the integration of various investigative methods related to an engineering project and the upgrade of a subsiding highway located next to a river dam. Surface and groundwater monitoring during engineering projects usually is restricted to satisfy the needs and constraints of existing laws and regulations with respect to surface and groundwater quality issues during construction measures. Comprehensive research within gypsum karst sites is rare. This case study presents a combination of data analysis and field experiments with modeling techniques. Results allow describing the hydrogeologic settings and the long-term hydrogeological evolution of the gypsum karst. At the beginning of the project, system knowledge was limited to purely conceptual models and sparse accurate groundwater observation data. In order to predict further subsidence and to plan appropriate measures, it was necessary to understand the current stage of the hydrogeologic flow regime as well as the subsidence mechanism and its development over time. The development of instruments that can be used for prediction requires the design of surface and groundwater monitoring systems, goal-oriented field campaigns and selected modeling strategies in order to investigate the locally specific relevant processes.

Part IV comprises ***"A Concept for Integrated Investigations of Karst Phenomena in Urban Environments - Merging Geophysical and Hydrometrical Investigations with 3D Hydrogeological Modeling for Applied Urban Hydrogeology within a Gypsum Karst Area"***. Here, investigation methods included high-resolution 3D hydrogeological modeling and the integration of geological (outcrops, lithostratigraphic information of boreholes), hydrometrical (extensive groundwater monitoring, dye tracer tests) and hydrogeophysical (Electrical Resistivity Tomography, ERT) field data of different quality.

Part V ***"Integrating Field and Numerical Modeling Methods for Applied Urban Karst Hydrogeology"***. While the characterization and modeling of flow in heterogeneous and fractured media has been intensively investigated, there are no well-developed long-term hydrogeological research sites for gypsum karst. Similar systems for monitoring the evolution of karst phenomena are rare. An approach is presented merging high resolution 3D hydrogeologic modeling with 2D karstevolution modeling. The different modeling techniques capture various aspects of the hydrologic processes and were employed by independent modeling teams. This allowed to cross-check estimated parameters and to continuously evaluate and interpret results of both approaches separately.

Part I

Integrated Methods and Scenario Development for Urban Groundwater Management, and Protection During Tunnel Road Construction

A Case Study of Urban Hydrogeology in the City of Basel, Switzerland

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Integrated Methods and Scenario Development for Urban Groundwater Management, and Protection during Tunnel Road Construction

A Case Study of Urban Hydrogeology in the City of Basel, Switzerland

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In the northwestern area of Basel, Switzerland, a tunnel highway connects the French highway A35 (Mulhouse-Basel) with the Swiss A2 (Basel-Gotthard-Milano). The subsurface highway construction was associated with significant impacts on the urban groundwater system. Parts of this area were formerly contaminated by industrial wastes, and groundwater resources are extensively used by industry. During some construction phases, considerable groundwater drawdown was necessary, leading to major changes in the groundwater flow regime. Sufficient groundwater supply for industrial users and possible groundwater pollution due to interactions with contaminated areas had to be taken into account.

A groundwater management system is presented, comprising extensive groundwater monitoring, high-resolution numerical groundwater modeling, and the development and evaluation of different scenarios. This integrated approach facilitated the evaluation of the sum of impacts, and their interaction in time and space with changing hydrological boundary conditions. For all project phases, changes of the groundwater system had to be evaluated in terms of the various goals and requirements. Although the results of this study are case-specific, the overall conceptual approach and methodologies applied may be directly transferred to other urban areas.

Keywords: Urban groundwater, Groundwater management, Groundwater protection, Subsurface infrastructure development, Switzerland

1 Introduction

Groundwater in urban areas is under increasing pressure. According to the European Environmental Agency, about 70% of the European population lives in urban areas, which cover in total about 25% of the total territory (EEA 1999). With over 40% of the water supply of Western and Eastern Europe and the Mediterranean region coming from urban aquifers, efficient and cost-effective management tools for this resource are essential to maintain the quality of life and ensure that water is available for use by future generations (Eiswirth et al. 2003, 2004). Sustainable use of soil and groundwater resources and protection and conservation of their quality are hence a key issue of European environmental policy and an enormous challenge for European research (Prokop 2003).

As a result, in recent years, urban hydrogeology has emerged as a specialized area of research. While the basics of groundwater as a science are well established, the specific aspects of groundwater in urban environments have only recently been recognized (Vázquez-Suñé et al. 2005). This resulted in the foundation of the Commission on Groundwater in Urban Areas in 1993 by the International Association of Hydrogeologists (IAH), as well as initiation of projects like AISUWRS (Assessing and Improving Sustainability of Urban Water Resources and Systems; Eiswirth et al. 2003; Wolf et al. 2006) and NeWater (New Methods for Adaptive Water Management under Uncertainty; Pahl-Wostl et al. 2005). In addition, the number of international congresses and workshops (Chilton et al. 1997; Ellis 1999; SGH 2006) and the number of publications and books on urban groundwater and its sustainable use continuously increase (e.g. Lerner 1996, 2003; Eyles 1997; Gossell et al. 1999; Aldrick et al. 1999; Foster 2001; Eiswirth 2001; Howard and Israfilov 2002; Vázquez-Suñé et al. 2005; Howard 2006).

The challenge to develop and implement integrated and adaptive water management requires innovative approaches that take into account the full complexity of the systems to be managed (Pahl-Wostl 2006). The basic principles of these approaches, including groundwater monitoring and modeling, are already established (Eiswirth et al. 2003; Fatta et al. 2002; Pahl-Wostlet al. 2005). However, their application in urban planning processes has rarely been accomplished.

The purpose of this report is to discuss strategies and to understand and predict the cumulative effects of the numerous single impacts to groundwater resources during a major suburban development project at the regional scale of the city of Basel (Fig. 1). Often, infrastructure development and associated alterations in land use only consider the benefits for the improved infrastructure itself and planning largely takes the pragmatic form of engineering for short-term economic objectives. This often leads to adverse effects on groundwater flow regimes with respect to quantity and quality of water resources. The term “groundwater flow regime” thereby includes all groundwater flow patterns, velocities and budgets for a defined region in a temporal context. To develop concepts and methods for sustainable groundwater use in urban areas, environmental impact assessments not only have to include above-ground impairments such as ground motions with effects on existing buildings and infrastructures, as well as noise exposure and air pollution, but also the negative impacts on groundwater flow regimes.

This study illustrates selected examples, focusing on a construction phase that is associated with considerable changes to the groundwater flow regime resulting in the turnaround of flow lines and shift of groundwater divides.

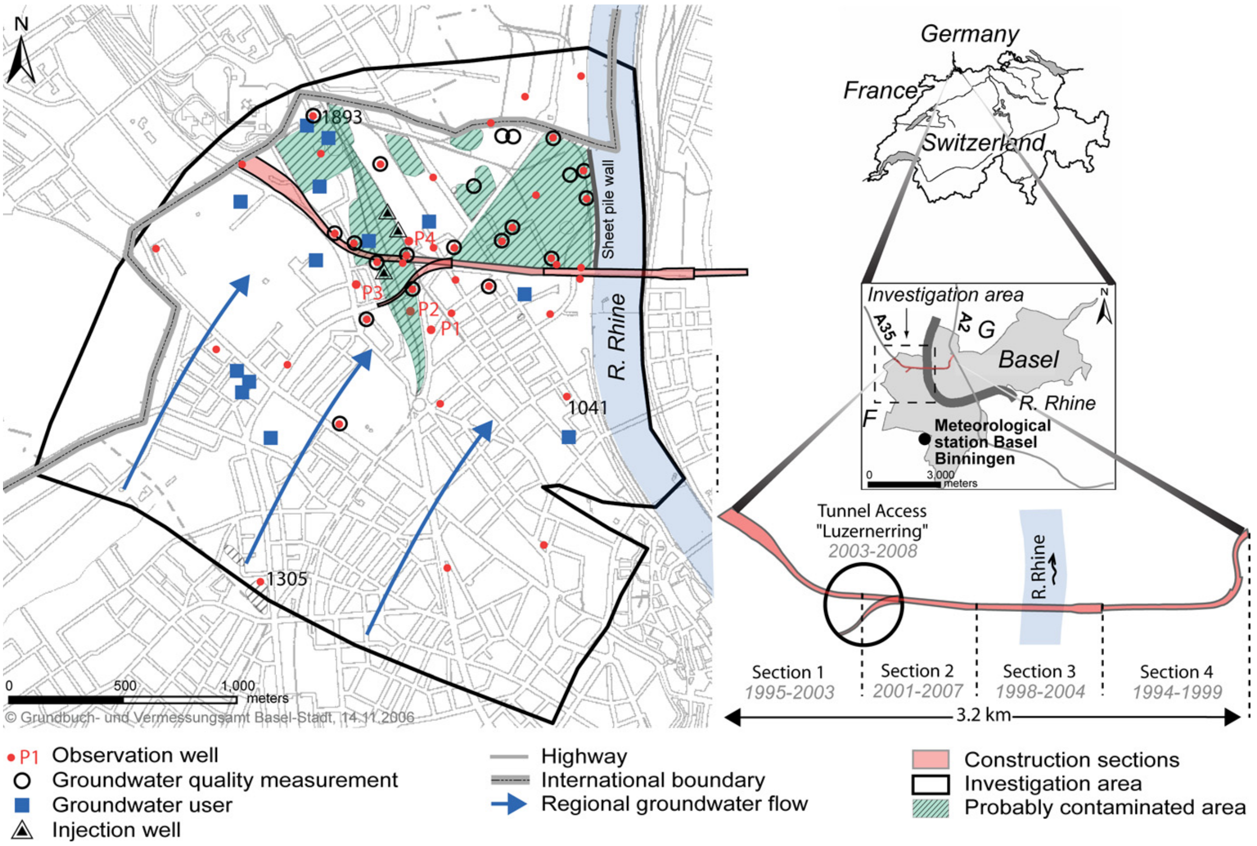


Fig. 1 Investigation area in Basel, northwestern Switzerland, bordering France (F) and Germany (G). Note that the highway tunnel runs at an angle of approximately 60° (counterclockwise) to the regional groundwater flow. In the middle of the right-hand column, the years are given within which each section of the construction was completed

2 Settings

2.1 Geography and hydrogeology

Basel, located in northwestern Switzerland, borders both Germany and France. The River Rhine enters Basel from the east and changes its course towards a northern direction within the city (Fig. 1). The highway construction sections outlined in this report are located in the northwestern part of Basel to the west of the Rhine. The shallow unconfined aquifer mainly consists of late Pleistocene gravel deposited by the Rhine. The gravel deposits, interbedded with fine-grained, flood plain sediments result in variable hydraulic conductivity within the aquifer. The thickness of the aquifer, ranging between 15 and 35 m, is underlain by an aquiclude composed of Oligocene mud to clay rich sediments. The general slope and the main directions of the regional groundwater flow are S–N and E–W. Ancient abandoned channels cut into the pre-Quaternary bedrock surface and result in the steep slope of the aquiclude topography (Fig. 2; Table 1).

Figure 3 shows three examples of hydrographs that characterize the regional hydrological settings. The hydro-graph of observation well 1305 (Fig. 3a) illustrates the regional trend of the groundwater flow regime. This hydrograph is not influenced by groundwater use and shows a slow response to recharge from precipitation. By contrast, water-level fluctuations in observation well 1893 (Fig. 3b) show periodic water-level changes related to nearby industrial groundwater use while the water-level fluctuations in observation well 1041 (Fig. 3c) next to the Rhine correspond to the river-level fluctuations. This demonstrates that river–groundwater interactions along the Rhine are an important element of the regional groundwater-flow regime. The water-table fluctuations are phase-delayed and have reduced amplitude in response to the river-level fluctuations. Depending on hydrologic constraints, the river acts both as a receiving ("gaining") and an infiltrating ("losing") stream. Seasonal river-head fluctuations are moderate, as well as those observed in the observation wells close to the river, and are in the order of 1m.

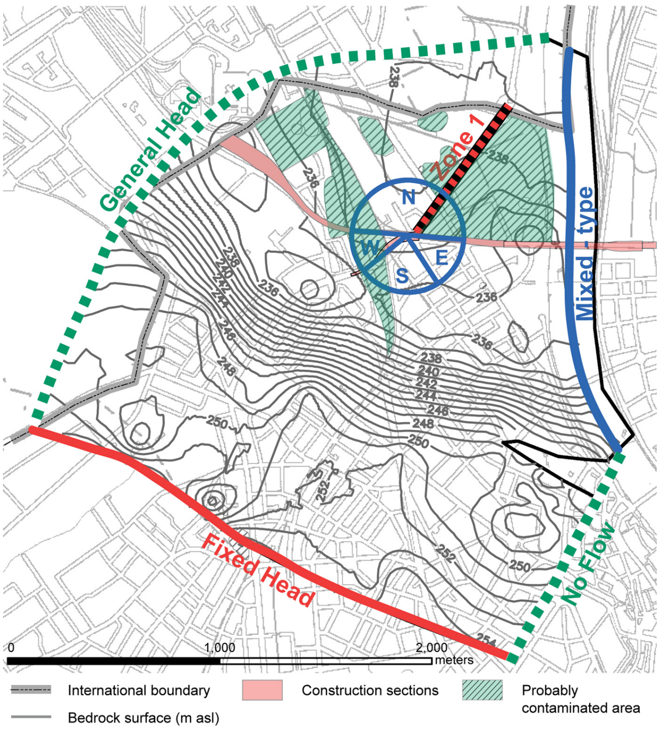


Fig. 2 Bedrock surface and boundary conditions used for the numerical groundwater model. Groundwater budgets were calculated across all model boundaries. Additionally, groundwater budgets for zone 1 and the inflow budgets, from different directions (symbolized by the pie diagram), to the drained construction site were evaluated (Table 1). The industrial subregion, called zone 1, is characteristic for the total flow rate through the northern industrial area

Table 1 Total rates (in ls^{-1}) of extraction and injection as well as water budgets (in l ls^{-1}) across model boundaries, zone 1 and the inflow budgets, from different directions, to the drained construction (see Fig. 1 for locations of wells and Fig. 2 for locations of zones for water budgets)

		Wells		Inflow budgets to the construction site				Model boundaries					Zone 1
		Extraction	Recharge	East	South	West	North	South	West		R. Rhine		
									In	Out	In	Out	
A	Situation March 2003	70.3	3.5	6.3	13.2	9.4	14.4	105.1	No flow	No flow	3.5	65.5	12.8
B	Situation February 2006 (maximum drawdown)	142.8	46.9	29.9	35.9	43.3	6.9	77.5	52	51.6	11.2	25.4	4.1
C	Scenario February 2006 (without injection)	123.8	1.6	27.2	33.5	30.6	5.8	77.1	40.7	62.8	10.4	28	2.4
D	Future state	48.3	3.5	9.6	10.3	6.6	13.5	104.9	No flow	No flow	3.1	75.7	9.5

Flows are considered "in" if they are entering a subregion

The long-term average for yearly precipitation is 788 mm, measured during the 30-year period 1961–1990 at the Binningen meteorological station (Fig. 1). Urbanization has led to an increase in impermeable surfaces, thereby causing a reduction in direct groundwater recharge and generation of additional surface runoff from precipitation. As a result, a large spatial and temporal variability in recharge rates over short distances can be observed. For the region of

Basel, current studies indicate that natural monthly groundwater recharge from precipitation range from 5 to 45 mm for non-sealed surfaces and from 2 to 25 mm for areas with a high degree of surface sealing (Huggenberger et al. 2006).

At the beginning of the 1900s, to stabilize the river bank for harbor facilities, a sheet pile wall, approximately 500 m long and 20 m deep, was driven down to the bottom of the aquifer on the western river bank north of the main course of the tunnel road (Fig. 1). It acts as a low-permeability barrier and reduces locally the interaction between river and groundwater. Regionally, it forces the groundwater to flow either south or north of this wall, thereby creating an area of low-flow velocity near the sheet pile wall, and an E–W groundwater divide running behind the wall. Since the position of this groundwater divide shifted during the different construction phases, it provides a key indicator for changes in the northern groundwater flow regime.

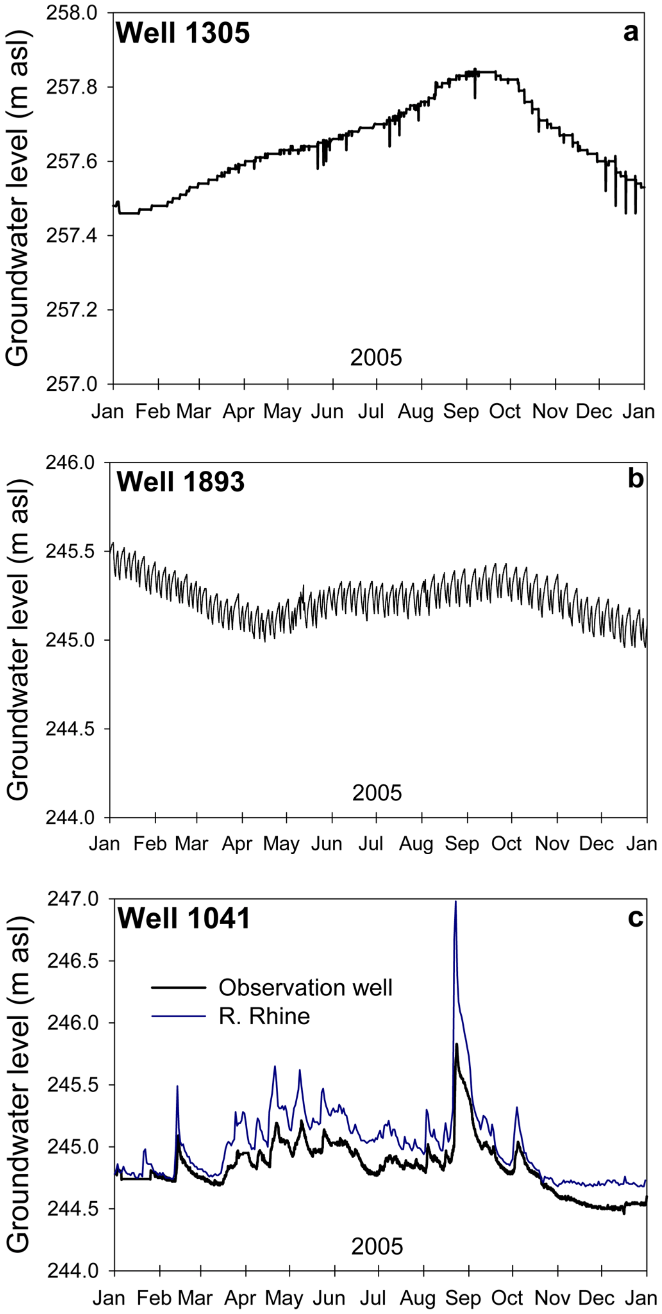


Fig. 3 Examples of hydrographs that characterize the regional hydrological settings for the year 2005: **a** well 1305, **b** well 1893, **c** well 1041 (see Fig. 1 for locations of observation wells)

2.2 Urban infrastructure development

Open space in urban areas is very rare and new infrastructure is increasingly constructed in the subsurface under difficult geotechnical and hydrogeological conditions (other examples include: "Big Dig", a major highway in Boston, USA (Altshuler and Luberoff 2003); and infrastructure constructions in central Berlin, Germany (Hufschmied 2006). In particular, tunnel construction in nonconsolidated rocks and below the water table can lead to a higher risk of subsidence. To maintain city life and safety standards on the construction site, geotechnical measures such as cement injections for subsurface stabilization are commonly used.

Subsurface constructions can result in significant changes in groundwater quality and dynamics of both local and regional groundwater flow regimes. While some changes only temporarily affect urban groundwater systems during construction others are permanent, like the reduction of cross-sectional groundwater flow and aquifer-storage capacities. Together with various sources of groundwater pollution observed in urban environments, subsurface construction may interfere with a previously balanced urban-groundwater flow regime.

The subsurface highway construction highlighted in this report is 3.2 km long and connects the French highway A35 (Mulhouse–Basel) with the Swiss A2 (Basel–Gotthard–Milano). It is divided into four sections, of which about 87% are tunnel constructions; the remaining 13% consist of the bridge across the Rhine and the various tunnel entrances (Fig. 1).

The overall route planning and final decision for the realization of the tunnel highway connection was completed some 30 years ago. Therefore, it was not possible to conduct investigation studies comparing various courses for the realization of the tunnel and to evaluate solutions with minimal impact to the groundwater flow regime. At that time, studies only concentrated on potential mitigation of various impacts. The term "mitigation" encompasses a broad range of measures that might reduce or compensate the effects of environmental damage (National Research Council 1992).

Construction started in 1994 and the whole highway project will be completed by the end of 2008 (Fig. 1). The progressive shift of the construction sites, requiring different drainage systems, affected the groundwater flow regime throughout construction. Depending on the excavation technique applied, complexity of the groundwater drainage varied and was realized either as open sump drainage, the dewatering of residual groundwater in areas enclosed, or a combination of both methods (Fig. 4). Open sump drainages are generally associated with major changes in groundwater flow regimes. By contrast, for the dewatering of residual groundwater in areas enclosed, additional technical measures have to be employed (cement injections for subsurface stabilization, sheet pile walls and slide pales). They will, after completion of the construction works, irreversibly degrade the aquifer. During the construction of the highway access and exit roads to the main tunnel, called "Tunnel Luzernerring" (Figs. 1, 2, 4, 5 and 6), a combination of both drainage systems with groundwater extractions up to approximately 140 ls^{-1} (October 2003 to May 2007) was chosen. The exit road crosses below the main tunnel road and is thus the deepest part of the entire construction requiring maximum drawdown. Once the construction is completed, connectivity of the groundwater will be enhanced by technical measures such as the installation of highly permeable culverts as well as drawing sheet pile walls and slide pales.

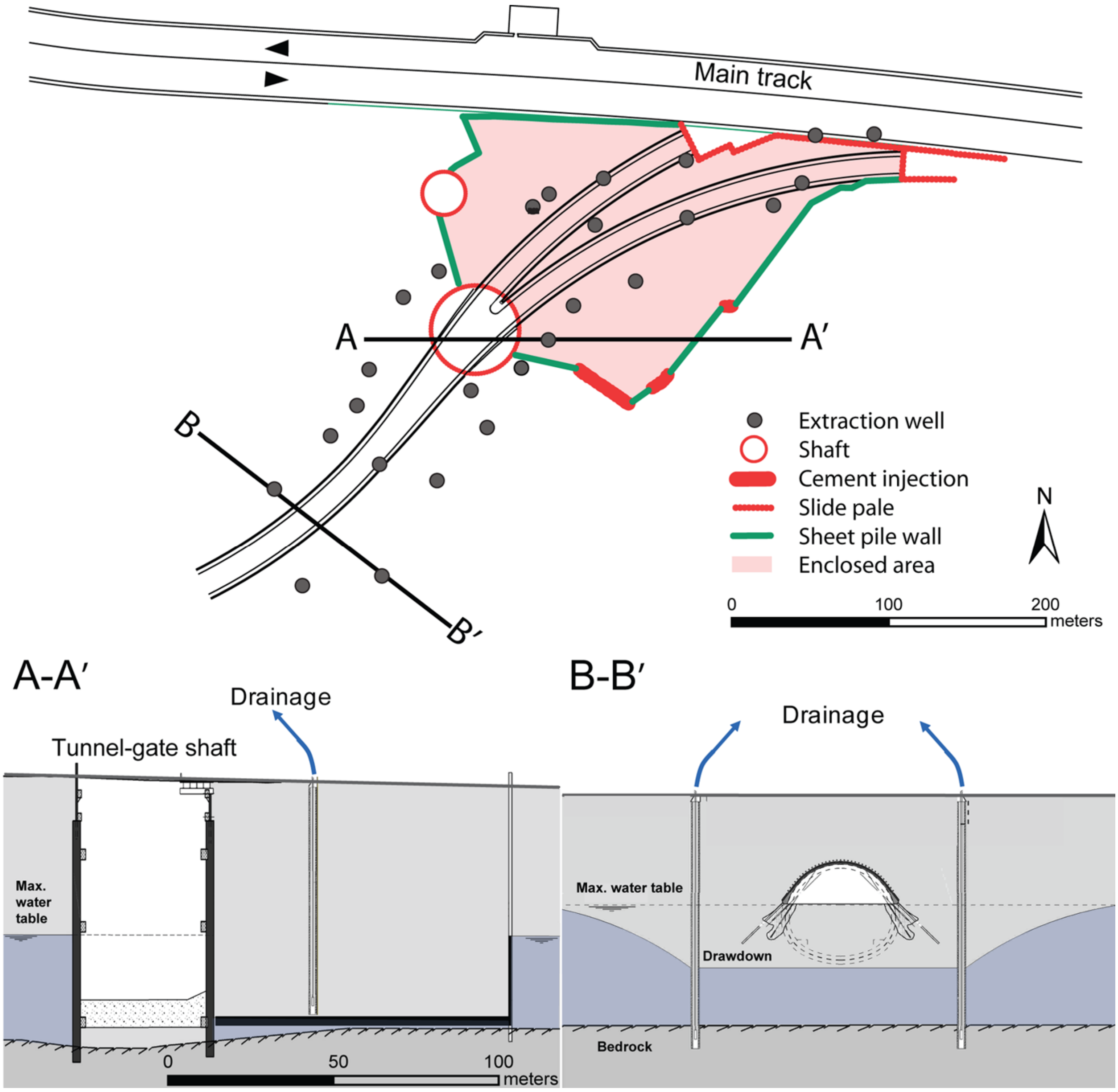


Fig. 4 Illustration of different drainage systems employed. Cross section A–A′: dewatering of residual groundwater in areas enclosed; cross section B–B′: open sump drainage

2.3 Industrial groundwater use

In the investigation area, groundwater resources are extensively used by industry for processing or cooling (Fig. 1). A total of 13 industrial wells are operated in the vicinity of the construction site. The average amount of groundwater extracted from the aquifer is about 30 ls^{-1},and approximately 3.5 ls^{-1} are injected back into the aquifer.

The significant drawdown during single construction phases on the one hand and the injection of groundwater with potentially elevated temperatures on the other hand could lead to supply shortages. In this case, the construction site owner would be responsible for an alternative supply, leading to a significant financial burden. Therefore, it is advisable to develop alternative supply strategies for processing water in advance. For this purpose, negotiations with all relevant users were conducted to determine the individual quantitative and qualitative requirements.

Users of groundwater for cooling purposes could be supplied by lower quality groundwater from the construction site. Nevertheless, temperature limits must be observed.

Fig. 5 Tunnel-gate shaft (see Fig. 4, section A–A′). The shaft reaches down to the bedrock

2.4 Contaminated areas

Since Basel turned into a major industrial centre for the chemical and pharmaceutical industry in the nineteenth century, vast areas have been or are likely to be contaminated (Fig. 1). Contaminants mainly include residues and solvents from the color industry, like BTEX/MTBE (benzene, toluene, ethylbenzene, xylenes/methyl tertiary butyl ether), volatile organic compounds, chlorinated compounds and their metabolites, as well as metals. In addition, other abandoned sites of small enterprises and numerous contaminated areas on adjacent French territory lie close to the construction site. As environmental problems generally do not stop at national boundaries, this obviously requires conceptual and cross-national investigations of the groundwater system.

Changes in the groundwater flow regime caused by groundwater drawdown during individual construction phases may lead to a reversal of flow lines and can induce serious water-quality deterioration (Foster 2001). As a result, contaminated areas may suddenly lie in the capture zones of the industrial groundwater users or within the groundwater drainage area of the construction site.

Fig. 6 From the tunnel-gate shaft the highway access and exit roads to the main tunnel are excavated using the “micropale” mining technique

2.5 Legal framework

Although legal frameworks for groundwater protection as well as groundwater policy strategies have continuously been adjusted in the last decades (e.g. quantitative conservation of groundwater resources, Art. 43, last revision of the GSchG (1991); approval of subsurface constructions, Art. 32, last revision of the GSchV (1998), drainage of subsurface constructions, Art. 44, last revision of the GSchV (1998)), considerable damage to groundwater flow regimes still occurs. There are several reasons for this. Firstly, more attention is paid to purely technological and constructional problems concerning groundwater management during construction rather than to issues dealing with sustainable groundwater use or possible interferences with historically polluted industrial areas. Secondly, some projects undertaken under outdated legal frameworks, i.e. some 30 years ago, would not be approved today because more restrictive laws pertaining to groundwater, as well as changed perceptions and policy concerning groundwater and its sustainable use, now apply. Thirdly, groundwater protection in urban areas is still focused mainly towards documentation of changes in groundwater quality and the groundwater flow regime like maintaining local flow capacities and preventing a significant lowering of the water table. Less attention is paid to the prediction of future demands and to the management of groundwater resources. Fourthly, until now, the impacts of various groundwater users were only regarded as solitary limited impacts and examinations of the interactions between them and other aspects such as possible interactions with former industrial sites, were not attempted.

Therefore, the maintenance of a relevant specific groundwater flow regime together with new legislation frameworks, handling pollution of historically industrial areas, must be seen in a broader context. Under present regulations, any disturbance of the ordinary groundwater flow regime, including changes of flow direction and potential mobilization of contaminants, would have consequences with respect to responsibilities of the parties involved. This would include financing evaluations and implementations of remedial measures. Furthermore, additional contracts between the city of Basel and individual groundwater users assure the latter of an agreed amount of groundwater extraction. Likewise, in case of supply shortages caused by the drainage on the construction site, the party responsible for disturbing the initial status would have to come up with alternative supply solutions.

3 Conceptual approach and methodology

In the following sections, the conceptual approach and the methodology of this study, consisting of the various elements of the groundwater management system, are described.

3.1 Conceptual approach

Primarily, the area of investigation was delineated encompassing an inventory of all relevant boundaries characterizing the regional groundwater flow regime as well as all possible impacts to it before the beginning of the construction (Fig. 7). In the next step, the hydrogeological boundary conditions and impacts were identified that may be subject to changes during the tunnel construction.

Within these defined boundaries, goals for a sustainable development are formulated. These goals guide mitigation strategies and refer to defined standards, i.e. natural composition of groundwater or quality standards defined by existing regulations. They also establish a standard against which individual decisions are made. Goals with respect to the groundwater flow regime at the regional scale should be based on knowledge of the physical properties governing the system. The general goals at the regional scale are: (1) minimization of changes of the groundwater flow regime, including the maintenance of the courses of regional and local groundwater divides, dimensions of groundwater budgets, and groundwater flow velocities; (2) consideration of additional future groundwater use; and (3) long-term improvement of groundwater quality, with main focus on former industrial sites. At the local scale, in the vicinity of the construction site, goals should focus on: (1) minimization of backwater effects behind parts of the construction extending below the water table; and (2) prevention of the development of stagnating groundwater zones close to construction elements, extending below the water table. These elements can act as a barrier to groundwater flow and would reduce the storage volume of the aquifer.

In order to attain these goals, a definition of profiles is required that describe the groundwater system before, during and after the completion of the construction works. These profiles include an inventory of the hydrogeological boundary conditions and the multiple impacts on the groundwater flow regime at specified times. Based on this information, it is possible to identify and to describe an initial profile of the system, as well as to define desirable profiles for the individual construction phases and for the status after the completion of the tunnel road. The concluding profile comprises the general goals for the future development of the groundwater flow regime and groundwater quality. Some impacts will only temporarily affect the system during the construction of the tunnel road, like groundwater extractions and injection on the construction site as well as drawable sheet pile walls and slide pales. Other impacts will be permanent, like parts of the tunnel construction extending below the water table, permanent sheet pile walls, pales and cement injections for subsurface stabilization. Permanent impacts will change aquifer properties in a virtually irreversible way leading to an altered profile of the initial system. The profiles should allow decision makers to see past and present modification patterns of the aquifer system.

In order to achieve the system profiles desired, methods have to be developed together with the definition of specific targets (Fig. 7). Whereas goals focus on a sustainable development for specific groundwater areas and a desired long-term development of urban groundwater resources after project completion, targets also comprise groundwater protection issues during the development of the individual construction sections.

Targets within the previously delineated boundaries had to be defined at relevant scales and include, at the regional scale, firstly, minimization of changes to the groundwater flow regime during construction phases. This includes the maintenance of (1) the courses of regional and local groundwater divides, (2) the course and width of capture zones of the drainage on the construction site and of the industrial groundwater users, (3) the dimensions of groundwater budgets and (4) groundwater flow lines and velocities. Other targets also included are assured supply of groundwater (quantity and quality) for industrial users; and safeguarding groundwater-quality issues during tunnel construction. Targets at the local scale include: (1) technical solutions guaranteeing predefined lowered water tables during single project phases, including the adherence to safety standards on the construction site; (2) the minimization of groundwater inflow to the construction site drainages from contaminated or probably contaminated areas; (3) the documentation of contaminant mobilizations and groundwater velocities in areas that are contaminated; and (4) the minimization of backwater effects behind parts of the construction extending below the water table and the prevention of the development of stagnating groundwater in this area.

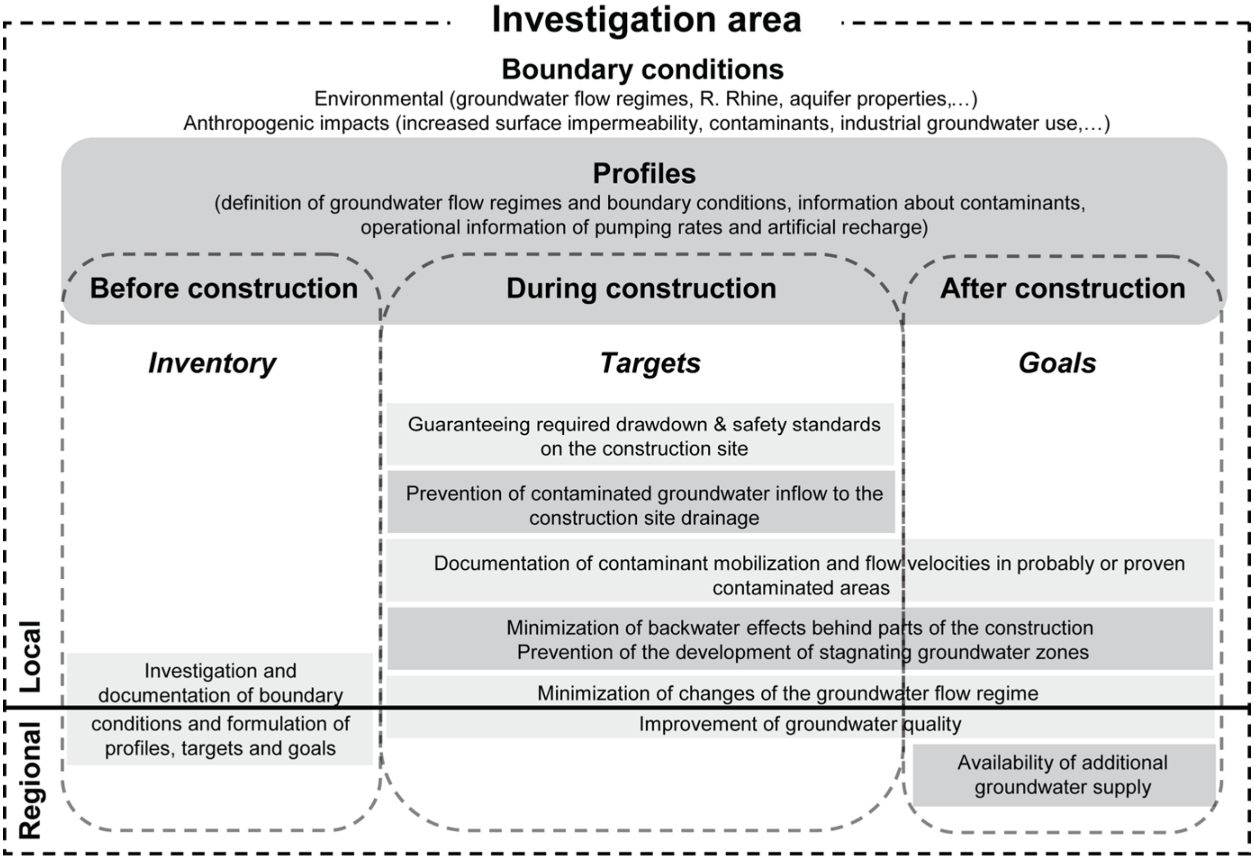
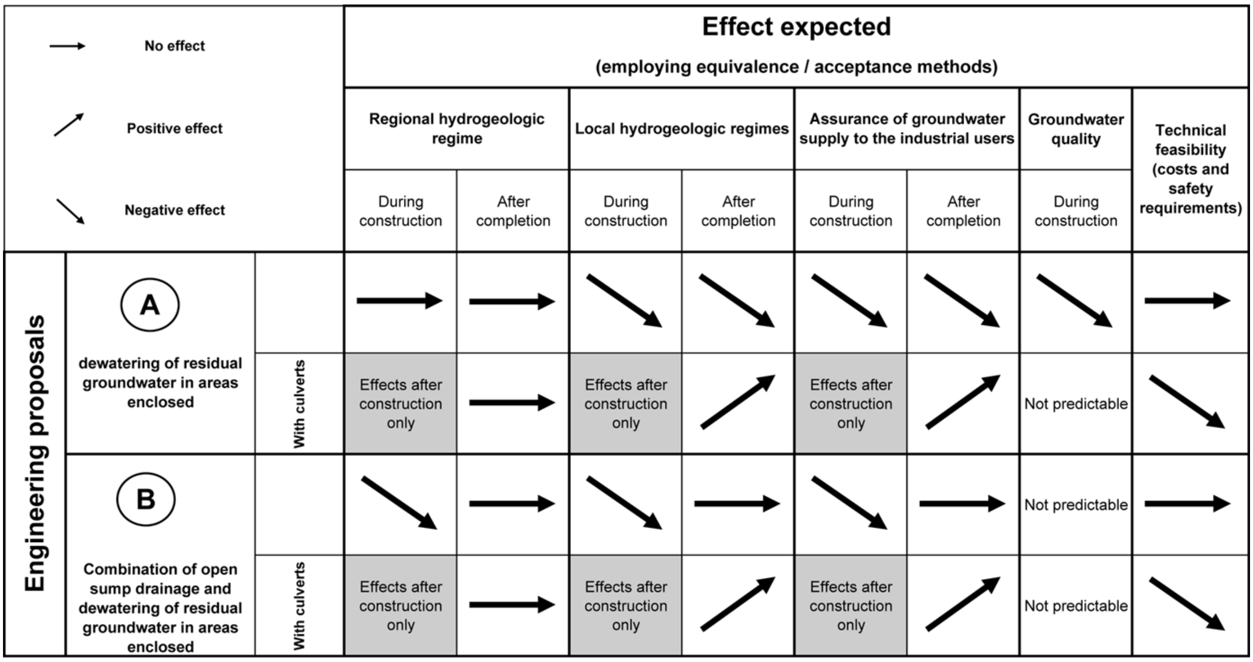


Fig. 7 Conceptual approach

As the individual targets may interfere with each other and, together, may not necessarily lead to a desired overall goal, techniques that facilitate the comparison of interferences had to be applied. This was accomplished by the development of scenarios and the implementation of equivalence and acceptance criteria (Fig. 8, Bedford 1996). They assess the technical benefits of the different engineering projects, the supply situation for industrial groundwater users, the development of the groundwater flow regime and the improvement of overall groundwater quality.

Given the multitude of anthropogenic processes occurring in urban areas, it is difficult or even impossible to make comparative studies with system profiles describing a potentially uninfluenced natural environment. Therefore, for reference, the previously defined system profile of the initial state before the beginning of the major construction phase was chosen. Comparative studies between this initial profile and the corresponding profiles of different proposals submitted for the various construction phases were carried out. Together with equivalence and acceptance criteria, these profiles and their impact on the groundwater flow regime and groundwater quality can be compared and evaluated (Fig. 8). Equivalence and acceptance criteria include: (1) the evaluation of simulated water budgets and velocities through defined regions, local and regional, during construction and after completion of the tunnel road; (2) the assurance of groundwater supply to the industrial groundwater users, during construction and after completion of the tunnel road; (3) the possibility for future groundwater use in the region, after completion of the tunnel road; (4) the overall development of groundwater quality, during construction of the tunnel road and (5) the technical feasibility of the engineering proposal, concerning cost and safety requirements.



→ No effect

↗ Positive effect

↘ Negative effect

Effect expected

(employing equivalence / acceptance methods)

Engineering proposals			Regional hydrogeologic regime		Local hydrogeologic regimes		Assurance of groundwater supply to the industrial users		Groundwater quality	Technical feasibility (costs and safety requirements)
			During construction	After completion	During construction	After completion	During construction	After completion	During construction	
	A dewatering of residual groundwater in areas enclosed		→	→	↘	↘	↘	↘	↘	→
		With culverts	Effects after construction only	→	Effects after construction only	↗	Effects after construction only	↗	Not predictable	↘
	B Combination of open sump drainage and dewatering of residual groundwater in areas enclosed		↘	→	↘	→	↘	→	Not predictable	→
		With culverts	Effects after construction only	→	Effects after construction only	↗	Effects after construction only	↗	Not predictable	↘

Fig. 8 The effects expected from two different engineering proposals (A and B) during construction and after completion, employing equivalence and acceptance criteria

3.2 Methodology

Additional to the identification of significant factors in urban hydrological cycles, methodologies to quantify and control these factors must be developed and applied (Vázquez-Suñé et al. 2005). In order to achieve this, a groundwater management system was set up with the following two main elements: (1) an extensive groundwater monitoring system for groundwater levels and quality; and (2) a high-resolution numerical groundwater model combined with scenario development. Besides a simple documentation of changes in groundwater quantity and quality, the goal of the management system is to detect undesired developments in advance. Throughout the entire progress on the various construction sections, the groundwater management system is continuously adapted and all recently obtained data (e.g. pumping test data) are incorporated (Fig. 9). Data management and visualization is accomplished with a database and a geographic information system (ArcMap).

Groundwater monitoring

The network comprises 44 observation wells instrumented by automated water-level loggers for continuous measurement of the hydraulic head. The hydrographs of this observation network are analyzed monthly. A total of 21 observation wells are sampled regularly for groundwater-quality measurements. Seven observation wells are sampled quarterly and 14 half-yearly (Fig. 1). Furthermore, the extracted water for industrial groundwater use and for settling tanks on the construction sites is sampled at regular intervals. Quality measurements include, among others, physical parameters (temperature, electrical conductivity (EC), pH-value, oxygen content, turbidity/color and odor), organic sum parameters (dissolved organic carbon (DOC), halogenated organic compounds (AOX)), major ions, BTEX/MTBE, volatile organic compounds, chlorinated compounds and their metabolites, as well as metals.

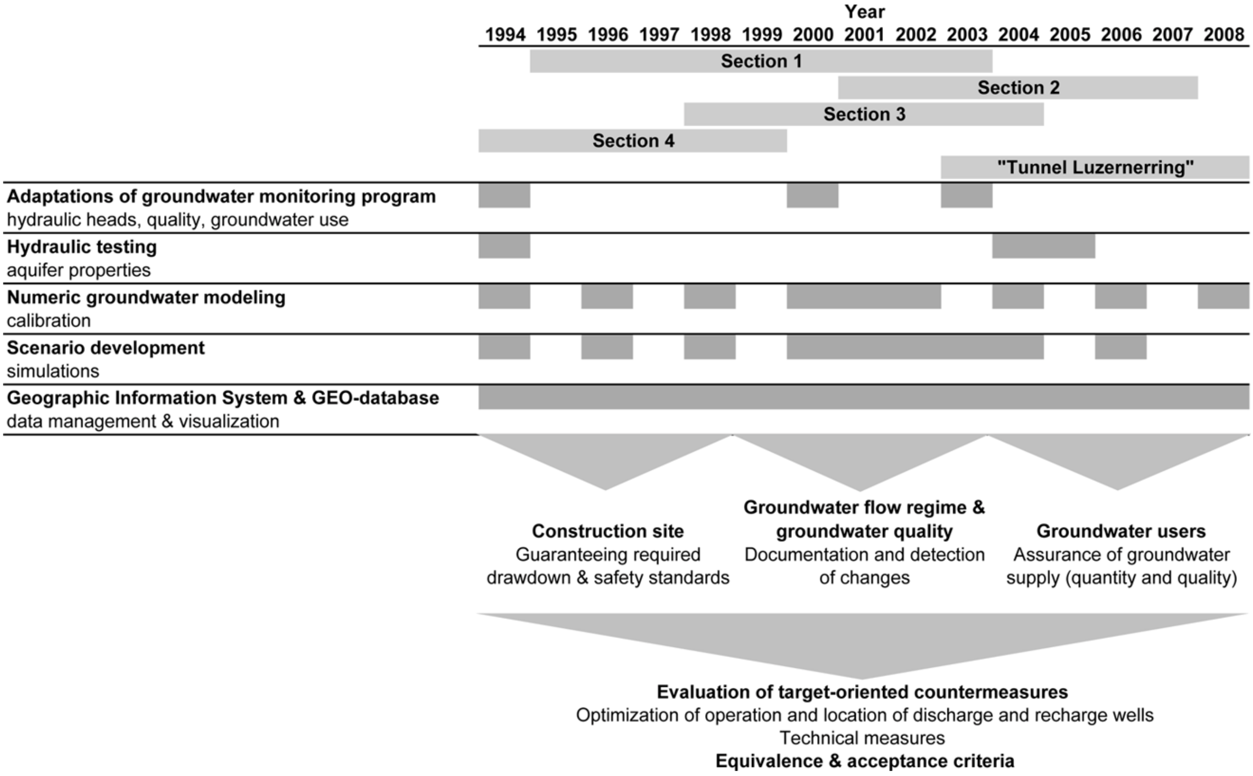


Fig. 9 Tools employed for groundwater management during progressive construction phases

In total, 26 extraction wells and three injection wells were installed to achieve the required drawdown of the water table (Figs. 1 and 4). Wells close to each other are combined into groups and the extracted groundwater is discharged to nine settling tanks. There, the physical parameters are monitored on a daily basis. At moments of change, the pumping rates are controlled by ultrasonic flow measurement, and the discharge monitoring in the settling tanks is calibrated. Part of the extracted groundwater is injected back into the aquifer in three injection wells at distances 150−250 m from the construction site. The remaining amount of extracted groundwater is channeled to the Rhine.

In addition to long-term strategies in groundwater monitoring, short-term monitoring programs were set up during drawdown tests. These adapted programs encompass the installation of supplementary observation wells, the set up of high-frequency measurement intervals, and more detailed programs to analyze the groundwater chemistry.

The monitoring program was adapted to the progress of the various construction sections, to the current groundwater management requirements and to the results obtained from groundwater modeling. Interpretation of the changes observed in groundwater-quality measurements together with the modeling results allowed optimizing the localization of new observation wells. New observation wells consequently were localized (1) in the inflow of the construction site drainage and nearby groundwater users; (2) between the construction site drainage and contaminated areas; and (3) on the model boundary.

Hydraulic testing

Prior to starting the project, a series of hydraulic tests was performed. In most cases, the results could only demonstrate that the required drawdown would be achieved. Unfortunately, there was neither a documentation of the relationship of drawdown versus time nor a further analysis of aquifer parameters. Furthermore, the test results are not reproducible. Based on these tests, the values taken for hydraulic conductivity range from 1E4 ms^{-1} to 5E-3 ms^{-1}.

A 14-day pumping tests was conducted in order to ensure that the required maximum drawdown for the Tunnel Luzernerring construction phase can be achieved with the number of extraction wells as predicted. As a result, the groundwater drainage for this drawdown was accomplished with 13 wells dewatering the residual groundwater in the area enclosed by sheet pile walls and with 13 wells outside the enclosed area by open sump drainage (Fig. 4). Under the actual hydrological constraints, the required groundwater drawdown was achieved with a drainage rate of approximately 100 ls^{-1}. Some 50 ls^{-1} of the extracted groundwater was injected back into the aquifer using three injection wells. Simultaneously, eleven extraction wells of the remaining construction sites as well as nine extraction wells and one injection well of the industrial groundwater users were active.

Figure 10 shows, next to cumulative rates of groundwater extraction and injection, the hydrographs of four observation wells in the vicinity of the construction site. Whereas groundwater drawdown in observation wells P1 and P2 south of the construction site is distinctive, the response of the hydrograph in P3 is only small. The hydrograph in P4 clearly shows the effect of nearby groundwater injection.

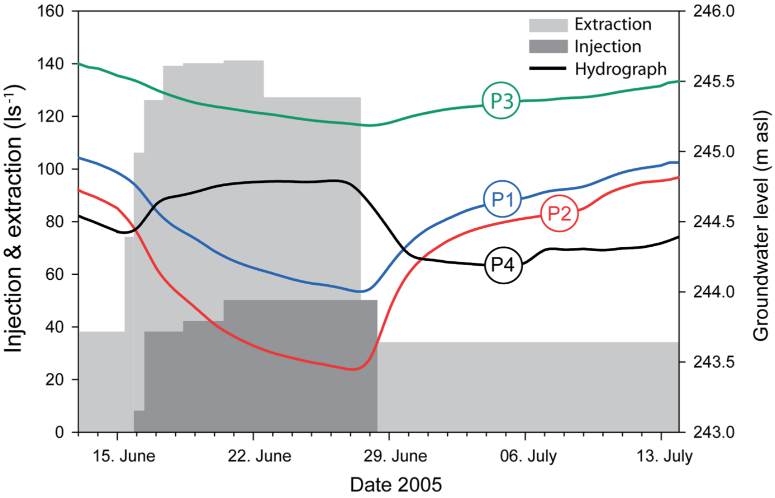


Fig. 10 Cumulative rates of groundwater extraction and injection as well as hydrographs of four observation wells (P1-P4) in the vicinity of the construction site during a 14-day pumping test (see Fig. 1 for locations of observation and injection wells)

The test was analyzed using the software AQTESOLV integrating transient data from multiple observation, extraction, and injection wells and considering the region as a homogeneous, anisotropic medium. For the calculation of the aquifer parameters, the Neumann's analytical solution for unsteady flow to a partially penetrating well in an unconfined aquifer was chosen

(Neumann 1974). For the specific storage value, the Moench's analytical solution was chosen (Moench 1997). This solution assumes unsteady flow to a partially penetrating large-diameter well in an unconfined aquifer. The large-scale hydraulic conductivity resulted in an average value of 1.28E-3 ms^{-1}. The calculation of the transmissivity of the alluvial aquifer arrived at a value of 1.67E-2 m^2s^{-1}. Calculation of the specific yield resulted in 0.1 and of the specific storage in 7.69E-5 m^{-1}. These additional results of aquifer parameters were used to evaluate and to validate hydraulic parameters for the groundwater model.

3.3 Groundwater modeling and scenario development

Regarding selection and setup of an appropriate groundwater model, it is important to ensure that the chosen model and desired resolution are capable of answering relevant questions simultaneously. When applying groundwater models, one of the key requirements is high-quality, site-specific data (National Research Council 1990). Before setting up a groundwater model, groundwater budgets and boundary conditions - the main components of a groundwater system - must be identified and analyzed.

For groundwater flow simulations, the three-dimensional finite difference code MODFLOW (Harbaugh et al. 2000) was employed in combination with the graphical user interface Processing Modflow (Chiang 2005). Most simulations were modeled steady state; the conducted pumping tests were modeled transient.

The groundwater model was continuously adapted, finally covering an area of 2,720 m×2,860 m (about 8km^2; Fig. 1). The spatial discretisation resulted in cell sizes varying between 5 m×5 m (near the construction site) and 30 m×30 m in a total of 132,500 cells. An approach with four horizontal layers was chosen to vertically integrate the construction. Construction itself was integrated either as inactive cells or as horizontal flow barriers with defined hydraulic permeability. Locations with cement injections were incorporated as horizontal flow barriers (Fig. 4). During construction, progressive adjustments were made. The surface of the aquifer base (interpolated from the information of more than 400 boreholes), and the distribution of horizontal hydraulic conductivity zones (see section Hydraulic testing) was based on different type and quality data sets available from the geological database administered by the Applied and Environmental Geology Group at the University of Basel. Since the southern part of the model area has a broad steep slope in the aquifer base without any detailed geological information, hydraulic conductivity had to be calibrated. A 10:1 ratio between horizontal and vertical hydraulic conductivity was chosen. Based on a 1-day test measurement of groundwater levels (Wagner et al. 2001) model boundary conditions are of the first type (fixed head) along the southern side, and of the third mixed type (leakage) along the Rhine. Hydraulic conductance of the riverbed was set at 5.0E-5 m^2s^{-1}. The western and northern boundaries were initially specified as no flow. Pumping tests preceding the major drawdown phases indicated that this boundary is more complex. Finally, this boundary was considered as general head, leading to a groundwater outflow south of the steep slope and an inflow north of it (Fig. 2).

A total of 48 extraction wells were integrated, i.e. nine production wells and one injection well for industrial groundwater use, 35 wells extracting groundwater along the various construction sections as well as three injection wells. The hydraulic head was continuously monitored in a total of 44 observation wells. As a routine procedure, the groundwater model was calibrated at least biannually, by updating the boundary conditions and adjusting the permeability of sheet pile walls. With the calibrated groundwater model, possible scenarios were developed. Scenarios were grouped into five types: (1) comparison of engineering projects; (2) simulation of important project phases in advance; (3) optimization of groundwater management strategies; (4) investigation of changing hydrological constraints; and (5) worst-case scenarios.

4 Results

The application of the conceptual approach and the methodology of the groundwater management system are illustrated by the following examples: (1) scenario development and application of equivalence and acceptance criteria; and (2) groundwater modeling results and scenario development for the construction phase requiring the maximum drawdown as well as the development of the groundwater flow regime after completion of the tunnel road.

All results are being compared with the calibrated initial state in March 2003 before the major construction phase. Furthermore, the various model calculations and developed scenarios are compared and validated by means of groundwater budgets through defined regions (Fig. 2; Table 1), the course of well capture zones as well as the description of simulated hydraulic heads, flow paths and velocities (particle tracking).

4.1 Scenario development and application of equivalence and acceptance criteria

In the following, examples for the five scenario types are summarized (see section Groundwater modeling and scenario development).

Scenario type 1

Various engineering proposals were compared by using scenario development together with the application of equivalence and acceptance criteria. Some parts of the construction remaining below the water table after completion are associated with irreversible disturbances and impede groundwater exchange. Permeability and backwater behind parts of the construction after completion was evaluated for the various proposals. This approach helped to compare different proposals with respect to feasibility and impact on the groundwater flow regime during construction and after completion of the tunnel road.

Figure 8 illustrates the procedure using the method to compare and validate two different proposals. The first engineering proposal for the Tunnel Luzernerring construction section suggests drainage only by dewatering of residual groundwater in the area enclosed by sheet pile walls. This proposal includes increased cement injections as well as the use of additional slide pale walls. The second proposal suggests drainage by a combination of open sump drainage and the dewatering of residual groundwater in the area enclosed (Fig. 4). For both proposals the application of culverts after completion of the tunnel road were also simulated. Additional culverts crossing under the construction, particularly required for the first proposal, would lead to a cost increase.

While the first proposal would influence the local groundwater flow regime during construction but also after completion, the second one has a considerable influence on both the regional and local groundwater flow regime only during construction. The groundwater supply to industrial users in the vicinity of the construction site may be affected during construction for both engineering proposals. An appreciation of all factors gave preference to the second engineering proposal. This project had the advantage that additional measures would not be necessary. Critical sections such as Tunnel Luzernerring, where parts of the construction almost reach down to the bedrock and the risk for subsidence during construction is the highest, were enclosed by sheet pile walls and cement injections. Outside the enclosed area, where only shallow drawdown is required, open sump drainage was employed. The combination of the two drainage methods ensured the safety standards required on the construction site. Moreover, it better fulfilled the requirements of a sustainable development of the groundwater flow regime after completion.

Scenario type 2

Important project phases were simulated in advance. Therefore, the arrangement and required number of extraction and injection wells was evaluated for the various construction phases. The optimum arrangement of injection wells was determined resulting in a minimum change of the local groundwater flow regime in the vicinity of certain industrial groundwater users and the northern industrial area (Fig. 1).

Scenario type 3

Different groundwater management strategies were compared. This helped evaluating the localization and operation of extraction and particularly injection wells; localization and dimension of culverts, sheet pile walls and slide pales; localization of additional observation wells; and prediction of additional groundwater use in the future.

After completion of the project, the performance of technical measures will be reviewed. Technical measures that enhance groundwater exchange beyond the construction period include the installation of culverts, sheet pile walls and slide pales. However, previous modeling suggests the effect of culverts to be rather small. The successful implementation of these measures will eventually reveal the degree to which the initial profile can be restored. Throughout the project, the results of the groundwater model allowed evaluation of the optimal localization of additional observation wells. For the prediction of additional groundwater use in the future, wells with a defined extraction rate of 20 ls^{-1} either north or south of the tunnel road were simulated (see the following).

Scenario type 4

Furthermore, changing hydrological constraints were investigated. Seasonal changes of groundwater recharge and levels were simulated by lifting or lowering the hydraulic head at the southern model boundary, resulting in changing inflow rates. Flood and low-water events were simulated by adjusting the water level of the River Rhine. Data for these simulations were obtained from long-time records of groundwater and river level monitoring.

Scenario type 5

Finally, worst-case scenarios were simulated. They concentrate on incidents caused by the mobilization of contaminants. One possible incident could occur if the drainage on the construction site drew contaminated groundwater. In case defined limits were exceeded, the extracted groundwater could not be discharged into rivers or injected back to the aquifer. Considering the worst of all cases, extracted groundwater could not even be discharged to the sewage system and would have to be pre-processed. Furthermore, for all scenarios, inaccuracies in supplied data were also taken into consideration.

4.2 Groundwater modeling and scenario development during maximum drawdown

Figure 11 illustrates the results from model calibrations in March 2003 and February 2006 (see also Fig. 12a,b). For all model runs, divergence of calculated and observed hydraulic heads is highest for observation wells located on the broad steep slope in the southern part of the model area and is in the order of 1 m (see Figs. 1 and 2). However, the divergence for the remaining hydraulic heads averages 0.2 m.

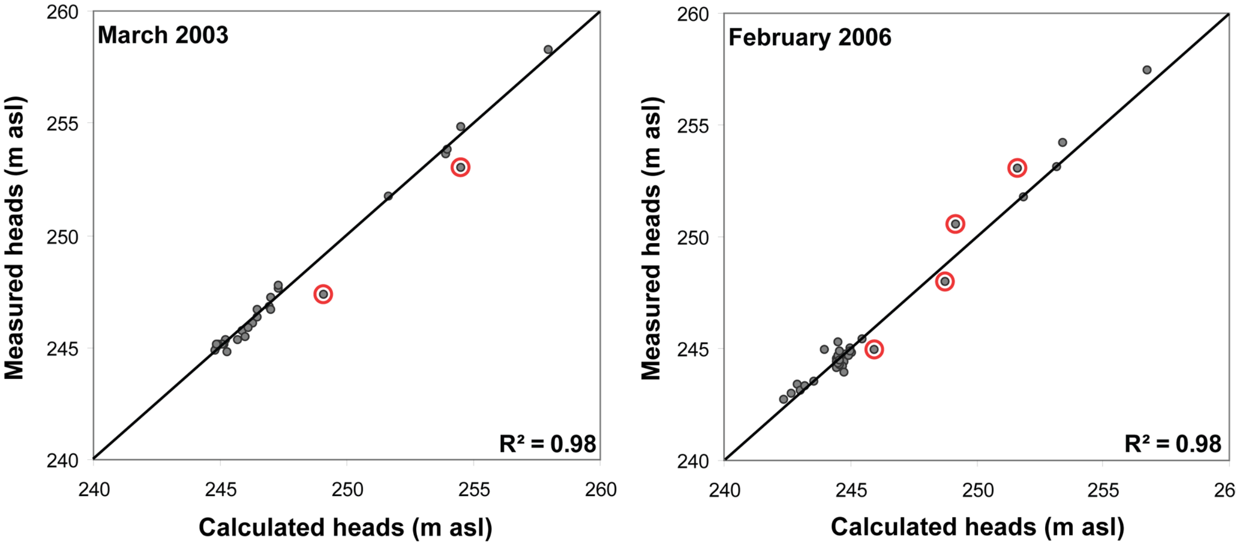


Fig. 11 Results from model calibrations for the situation in March 2003 and February 2006 (see Fig. 12a,b). Those observation wells that are located in the southern part of the model area on the broad steep slope are highlighted (see Figs. 1 and 2)

Regional groundwater flow regime

Below, an outline of the groundwater budgets and ranges calculated across model boundaries for all scenarios are briefly summarized (Figs. 2, 12a–d and Table 1). The main model inflow occurs across the southern model boundary characterizing the natural groundwater flow regime with inflow-rates ranging between 77 and 105 ls^{-1}. The Rhine acts both as a receiving and an infiltrating stream. Groundwater exfiltrating into the Rhine is estimated to range from 25 to 86 ls^{-1} and infiltration ranges from 3 to 11 ls^{-1}. Beyond the western model boundary, a groundwater outflow south of the steep bedrock slope ranging between 51 and 63 ls^{-1} and an inflow to the north ranging between 40 and 52 ls^{-1} was calculated.

The calculated contour map of the hydraulic heads in March 2003 shows a main direction of the regional groundwater flow from south to north and from west to east (Fig. 12a). During this time, the extraction rates of the construction site drainages amounted to only 42 ls^{-1}. Including industrial users, extraction rates result in a total of 70 ls^{-1} and injection rates of about 3.5 ls^{-1}. A steep gradient of the hydraulic heads in the middle of the model area can be observed. This coincides with the steep slope of the bedrock surface in this area (Fig. 2). By contrast, a comparatively low hydraulic gradient in the northern industrial area occurs. The course of particle tracks illustrates the capture zones of the various industrial groundwater users and of the construction site drainage.

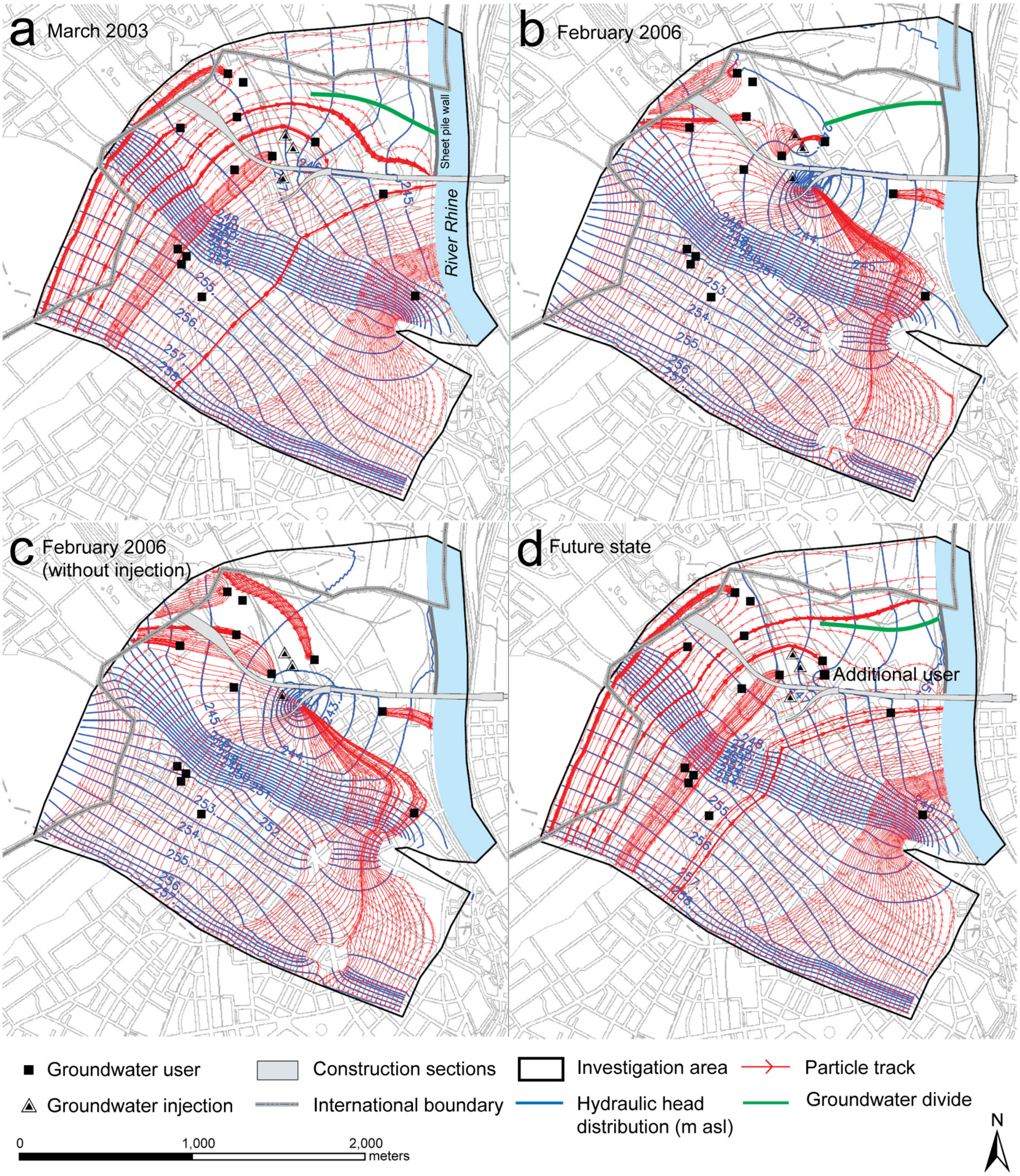


Fig. 12 Visualization of hydraulic head distributions (0.5 m resolution) and flow paths illustrated by particle tracks (distance between two arrow heads indicates 50 day travel time) for four modeled situations: a March 2003, b February 2006, c February 2006 (without injection), and d future state. Whereas the results for and derive from model calibrations, those for and are based on simulated scenarios

During the construction of subsurface freeway access and exit roads to Tunnel Luzernerring (see section Urban infrastructure development), maximum drawdown is required with extraction rates up to 143 ls^{-1} and injection rates of 47 ls^{-1} (including operations of industrial users). Figure 12b shows the course of the hydraulic heads and particle tracks during the pumping test. The drawdown around the construction site is observable up to a distance of 500 m. Regions influenced are predominantly within the southern model area. As one would expect, the open-sump drainage induces a far wider-ranging drawdown compared to the dewatering of residual groundwater in the area enclosed by sheet pile walls. Extraction rates previously calculated correspond well with values measured during the pumping test. The distribution and the performance of the three injection wells were confirmed. Modeling results and hydraulic heads measured show that the supply of groundwater for industrial groundwater users in the vicinity of the construction site is assured. Moreover, the change of the local groundwater flow regime of the northern industrial area is minimized. Due to the groundwater injection, the hydraulic gradient remains low in this area. Model simulations of high hydraulic heads and a flood event in the Rhine result in increased inflow rates across the southern model boundary amounting to 119 ls^{-1} and Rhine infiltration rates of up to 133 ls^{-1}. This results in an increase of groundwater extraction rates on the construction site of about 15 ls^{-1}. In the northern industrial area, the western part of the groundwater divide would shift about 100 m to the south (this scenario is not shown in Fig. 12 and water budgets are not listed in Table 1).

In case contaminated groundwater reached the drainage system of the construction site, immediate action would be necessary. If extracted groundwater exceeded concentration limits, discharge into the river or injection back into the aquifer would be prohibited. In this situation, injection could not be supplemented by the remaining extraction wells. Figure 12c shows a simulation with a failure of groundwater injection. It is obvious that, due to the proximity of the injection wells to the construction site, before the failure some of the injected water amounting to 50 ls^{-1} had to be extracted again by the construction site drainage, leading to a kind of short circuit. However, the simulation results indicate that, during a failure, extraction rates on the construction site drainage could be reduced by 19 ls^{-1}. This reduction is considerably low, compared to the previous injection of 50 ls^{-1}. This fact reconfirmed once more that the injection mainly influences the northern part of the model area. Due to such a failure, the entire groundwater flow regime north of the steep slope would be changed. In this case, the drawdown would be observed beyond the French border. The capture zone of the drainage would widen significantly and extend from the Rhine to the western model boundary. The groundwater divide would be displaced far to the north beyond the model boundary.

The future state illustrates the situation after completion of the tunnel road taking into account the final permeability in the vicinity of construction parts reaching below the water table and an additional groundwater user with extraction rates of 20 ls^{-1} north of the main track (Fig. 12d). The regional groundwater flow regime is comparable to that of March 2003. Furthermore, the effect of backwater along the main track is still observable. Additional groundwater use, even behind the tunnel construction, would be possible.

Local groundwater flow regimes

Changes in the local groundwater flow regimes are documented by means of calculated groundwater budgets and groundwater flow velocities for selected areas. The subregion, called zone 1, is characteristic for the total flow rate through the northern industrial area. In addition, the inflow budgets from different directions to the drained construction site were evaluated (Fig. 2 and Table 1).

Groundwater budgets calculated across zone 1 showed that the largest change was caused by the open sump drainage during the construction of an emergency exit, located to the north of the main track in section 2 (Fig. 1). This resulted in flow rates of 18 ls^{-1}.Maximum extraction rates up to 15 ls^{-1} for this drainage are relatively low (not listed in Table 1). However, given the small hydraulic gradient in the northern industrial area, the influence of this drainage was still considerably high. During the remaining construction phases, flow rates across zone 1 were below 10 ls^{-1}. Flow velocities were in the range of 5-10 $mday^{-1}$. Even during the construction phase of Tunnel Luzernerring, the groundwater flow regime of the northern model area and the northern industrial area in particular is still predominantly influenced by the drainages of construction section 2. Groundwater budgets calculated for March 2003 and for the future state after 2008 are comparable (Table 1).

Based on model simulations of high hydraulic heads and a flood event in the Rhine, groundwater budgets calculated for the construction site drainage indicate that most of the extracted groundwater, with rates up to 125 ls^{-1} during flood events, originates south of the main track. By contrast, only some 5-7 ls^{-1} derive from the northern model area. In case of a failure of groundwater injection, the distribution of the relative inflow amounts would not change significantly. Apart from the western model area, the inflow would be reduced by about 13 ls^{-1}.

Industrial groundwater use

For all scenarios calculated, the consequences for the industrial groundwater users were investigated. Furthermore, the modified capture zones were assessed in regards to the evaluation of remaining groundwater levels in the vicinity of the individual users.

During hydrological conditions with high groundwater levels as well as during flood events in the Rhine, an overall high abundance of groundwater resources exist and the supply of groundwater for the industrial users is assured. By contrast, during conditions of low hydraulic heads and low water levels in the Rhine, model simulations result in a decrease of groundwater extraction rates on the construction site. Also, the capture zones of extraction wells are enlarged and, in the worst case, contaminated areas would suddenly lie within some of these capture zones.

Likewise, in case of a failure of groundwater injection, the supply of groundwater for industrial users in the vicinity of the construction site would be endangered. In analogy with hydrological conditions with low hydraulic heads, the capture zones of extraction wells is enlarged and contaminated areas could suddenly lie within some of these capture zones. A coincidence of low hydraulic heads together with a failure of groundwater injection would further aggravate the situation.

The model calculations for the situation after the completion of the tunnel road indicate that backwater in the vicinity of the completed tunnel construction is negligible and additional groundwater use would be possible without considerably changing the groundwater flow regime.

Groundwater quality

Based on data obtained from routine groundwater-quality measurements, deviations of specific parameters could be recognized and investigated in the context of the groundwater flow regime. In combination with the model, flow path and transport calculations from contaminated areas could be simulated. This helped in optimizing locations for additional observation wells.

Because of the low hydraulic gradient in the northern industrial area, the groundwater divide shifts during the various drainage phases of the construction sections. Therefore, the main emphasis is placed on this northern area and contaminated areas close to the French border. In order to maintain the groundwater flow regime in the northern area, adequate hydraulic measures such as groundwater injection wells were introduced. This also resulted in additional observation wells at the northern model boundary.

In most cases, the inflow of contaminated groundwater could be prevented. An exception occurred during the drainage of section 4 of the construction. In this case, groundwater modeling allowed description of transport flow patterns and the origin of the contamination to be localized. Long-term monitoring will show how far the recovery of the groundwater will be able to reach pre-construction levels.

5 Summary and Conclusions

It was possible to demonstrate that an integrated conceptual approach incorporating methods of an adaptive groundwater management system can help to meet challenges posed by major constructions in sensitive urban environments. While some of this work may be specific to this case study, it is expected that the overall conceptual approach and the methodologies will be directly transferable to other urban areas.

A holistic perspective was necessary to consider all solitary impacts on the regional groundwater flow regime simultaneously, recognizing that impacts should not only be taken as locally limited but could have effects on the regional scale. Therefore, all stresses on the system, like groundwater extractions, injections, building activities and subsurface tunnel road constructions and their impacts on the groundwater flow regime were taken into account together with possible interactions with contaminated areas.

Until now, the results show that the predefined goals at both the local and the regional scale could be achieved satisfactorily. Due to the groundwater management, changes in the groundwater flow regime, especially towards the north, are comparatively low. With the aid of groundwater modeling, the dynamics of the groundwater flow regime under changing spatial and temporal constraints could be simulated and evaluated. In order to avoid a permanent negative impact to the groundwater flow regime, particularly concerning quantitative and qualitative groundwater protection and irreversible deterioration of aquifer systems, recommendations for the optimization of the groundwater management were proposed and constructional arrangements were provided. The optimum dimension, operation and selection of locations, as required for injection wells and culverts, could be evaluated. The modeling results were used to improve the groundwater monitoring system. The latter was adapted to project needs. Next to the management of the various groundwater extractions and injections, the requirements for groundwater protection (groundwater flow regime, groundwater quality) were achieved satisfactorily. The groundwater management system also helped to identify changes in groundwater chemistry. Negative consequences for the industrial groundwater users could be minimized. Until now, it was not necessary to install supplementary injection or interception wells to ensure the supply of groundwater for the industrial users, or to prevent the attraction of contaminated groundwater. Simulation results indicate that, after completion, groundwater budgets and groundwater flow velocities are in the same order as observed at the initial state.

In addition, the way in which the different elements of the approach were accepted by the stakeholders of the project was investigated. Their implementation during major urban development projects requires close cooperation with the general public, civil engineering planners, supervisors of the construction and industrial sites, consulting and geotechnical engineers, environmental bureaus and geoscientists. This cooperation resulted in a general acceptance and a better mutual understanding during the progressive construction phases. Therefore, groundwater protection as well as policy and management aspects should already be considered at the early stages of urban planning to reconcile the various individual and often conflicting interests.

Obviously, the knowledge of local geological and hydrological conditions as well as the understanding of the groundwater flow regime can considerably contribute to solutions for regional problems (Huggenberger 1999). However, many innovative technologies proposed for groundwater management, including groundwater modeling and scenario development, are confronted with enormous implementation barriers. Confidence in their success is often low, and conventional and more expensive technologies are preferred (Prokop 2003).

A systematic consideration of groundwater in urban development and the implementation of groundwater management systems can serve as a decision tool for project planners and official departments. This allows ongoing adaptation dealing not only with current issues but also with future demands. The results and methods can serve as guidelines for future projects. They can also assist in taking effective and optimum measures for groundwater protection and improve the sustainability of resource exploitation. Short-term and long-term strategies in groundwater management can result in improved sustainable management strategies during construction and also facilitate controlled sustainable development thereafter.

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References

Aldrick RJ, Rivett MO, Hepburn SL (1999) Urban groundwater and environment management: Hull, east Yorkshire. In: Chilton J (ed) Groundwater in the urban environment: selected city profiles. Balkema, Lisse, The Netherlands, pp 91–96

Altshuler A, Luberoff D (2003) Mega-projects: the Changing Politics of Urban Public Investment. Brookings, Washington, DC

Bedford B (1996) The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecol Appl 6:57–68

Chiang WH (2005) 3D-Groundwater Modeling with PMWIN: a simulation system for modeling groundwater flow and transport processes, 2nd edn. Springer, Berlin

Chilton J, Hiscock K, Younger P, Morris B, Puri S, Nash H, Aldous P, Tellam J, Kimblin R, Hennings S (eds) (1997) Groundwater in the urban environment: problems, processes and management. 27th Congr. Int. Assoc. Hydrogeologists (IAH), 21–27 Sept 1997, Nottingham, Balkema, Lisse, The Netherlands

EEA (1999) Environment in the European Union at the turn of the century. European Environment Agency, Copenhagen, Denmark

Eiswirth M (2001) Hydrogeological factors for sustainable urban water systems. In: Howard K, Israfilov R (eds) Current problems of hydrogeology in urban areas, urban agglomerates and industrial centers. Kluwer, Dordrecht, The Netherlands, pp 159–183

Eiswirth M, Hötzl H, Cronin A, Morris B, Veselič M, Bufler R, Burn S, Dillon P (2003) Assessing and improving sustainability of urban water resources and systems. RMZ Mater Geoenviron 50:117–120

Eiswirth M, Wolf L, Hötzl H (2004) Balancing the contaminant input into urban water resources. Environ Geol 46:246–256

Ellis B (ed) (1999) Impacts of urban growth on surface water and groundwater quality. IAHS 259, IAHS, Wallingford, UK

Eyles E (ed) (1997) Environmental geology of urban areas. Spec. Publ. 3, Geological Association of Canada, London, ON

Fatta D, Naoum D, Loizidou M (2002) Integrated environmental monitoring and simulation system for use as a management decision support tool in urban areas. J Environ Manage 64:333–343

Foster SSD (2001) The interdependence of groundwater and urbanization in rapidly developing cities. Urban Water 3:185–192

Gossell W, Herfert J, Chowanietz U, Hermel U (1999) Sustainable groundwater management for the Berlin region. In: Chilton J (ed) Groundwater in the urban environment: selected city profiles. Balkema, Lisse, The Netherlands, pp 139–143

GSchG (1991), Bundesgesetz über den Schutz der Gewässer, 814.20 (Federal Law for the Protection of Water Bodies, 814.20)

GSchV (1998) Gewässerschutzverordnung, 814.201 (Federal Law for the Protection of Water Bodies, 814.201)

Harbaugh AW, Banta ER, Hill MC, Mc Donald MG (2000) Modflow-2000: the US geological survey modular groundwater model-user guide to modularization concepts and the ground-water flow process. US Geol Surv Open-File Rep 00–92

Howard KF (2006) Urban groundwater: meeting the challenge. IAH selected paper series, Taylor & Francis, London

Howard KWF, Israfilov R (2002) Current problems of hydro-geology in urban areas, urban agglomerates and industrial centers. Kluwer, Dordecht, The Netherlands

Hufschmied P (2006) Hydrogeological and geotechnical problems during construction of traffic lines in Central Berlin. Presentation at the Swiss Hydrogeological Society, Geneva, 12–13 May 2006

Huggenberger P (1999) Urban geology: the example groundwater (in German). Uni Nova April 99, Basel, Switzerland

Huggenberger P, Epting J, Spottke I, Regli C, Zechner E (2006) Fluss-Grundwasser-Interaktion, Interreg III Projekt A MoNit: Modellierung der Grundwasserbelastung durch Nitrat im Oberrheingraben, Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe [River-groundwater-interaction, Interreg III Project A MoNit: modeling of nitrate impact to the groundwater in the upper Rhine graben]. Engelhart & Bauer, Karlsruhe, Germany

Lerner DN (1996) Guest editor’s preface: theme issue on urban groundwater. Hydrogeol J 4:4–5

Lerner DN (2003) Urban groundwater pollution. International contributions to hydrogeology, ICH 24. IAH, Taylor & Francis, London

Moench AF (1997) Flow to a well of finite diameter in a homogeneous, anisotropic water table aquifer. Water Resour Res 33:1397–1407

National Research Council (1990) Groundwater models: scientific and regulatory applications. National Academy

Press, Washington, DC

National Research Council (1992) Global environmental change.: understanding the human dimensions. Stern PC, Young OR, Druckman D (eds) Committee on the Human Dimensions of Global Change; Commission on Behavioral and Social Science and Education. National Academy Press, Washington, DC

Neuman SP (1974) Effect of partial penetration on flow inunconfined aquifers considering delayed gravity response. Water Resour Res 10:303–312

Pahl-Wostl C (2006) NeWater Newsletter No. 1: new Approaches to Adaptive Water Management under Uncertainty. NeWater at the World Water Forum in Mexico. Mexico City, March 2006, http://www.newater.info. Cited June 2006

Pahl-Wostl C, Möltgen J, Sendzimir J, Kabat P (2005) New methods for adaptive water management under uncertainty–the NeWater project. Paper accepted for the EWRA Conference 2005, Menton, France, September 2005

Prokop G (2003) Sustainable management of soil and groundwater resources in urban areas. Proceedings of the 2nd IMAGETRAIN Cluster Meeting, Krakow, Poland, 2–4 Oct 2002

SGH (Swiss Hydrogeological Society) (2006) Urban Hydrogeology(in German and French). Spring time conference on Urban Hydrogeology, Geneva, Switzerland, 12 May 2006

Vázquez-Suñé E, Sánchez-Vila X, Carrera J (2005) Introductory review of specific factors influencing urban groundwater, an emerging branch of hydrogeology, with reference to Barcelona, Spain. Hydrogeol J 13:522–533

Wagner U, Huggenberger P, Schaub D, Thater M (2001) Interreg III: Erkundung der Grundwasserleiter und Böden im Hochrheintal [Interreg III: investigation of the aquifers and soils in the Hochrheintal]. Landratsamt Waldshut, Waldshut, Germany, 101 pp

Wolf L, Morris B, Burn S (2006) AISUWRS Urban Water Resources Toolbox: integrating groundwater into urban water management. IWA, London

Part II

Integrated Methods for Urban Groundwater Management Considering Subsurface Heterogeneity

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Integrated Methods for Urban Groundwater Management Considering Subsurface Heterogeneity

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Open space in urban areas is very rare and new infrastructure is increasingly constructed in the subsurface. These constructions may temporarily affect urban groundwater systems during construction and permanently after completion. As regards these impacts together with ancient contaminated industrial sites, particular focus was placed on determining the data required to understand changes affecting groundwater flow and transport. The extended knowledge of groundwater flow regimes could lead to reducing and minimizing, as far as possible, the negative impacts throughout the construction phases, and to developing sustainable groundwater use and management tools.

The consideration of subsurface heterogeneity is often based on pumping tests, leading to a characteristically large-scale zoning of aquifer parameters. This study compares groundwater modeling results from integrating large-scale zoning of aquifer parameters on the one hand, and a sedimentary structure-based heterogeneous description of the aquifer properties on the other.

This approach was applied to an ongoing subsurface highway construction northwest of the city of Basel, Switzerland – an area formerly contaminated by industrial activities. Today, urban groundwater resources are extensively used by industry. An integrated multidisciplinary approach was chosen to predict, mitigate or prevent environmental problems, as well as to ensure groundwater supply throughout construction. It includes integration of geological and hydrological data and results into a groundwater management system comprising: (1) extensive groundwater monitoring; (2) development of a database application facilitating lithofacies-based interpretation of drill-core data; (3) geostatistical analyses of the aquifer's heterogeneity and simulations of hydraulic parameter distributions as well as; (4) regional and local high-resolution groundwater modeling. The combination of techniques presented exemplifies the fusion of quantitative and qualitative geological and hydrological information of different quality.

Keywords: urban groundwater, geostatistics, aquifer heterogeneity, hard and soft data fusion, groundwater modeling, subsurface infrastructure development, quantitative hydrogeology

1 Introduction

Urban areas are characterized by an increasing number of constructions below the surface or even below the groundwater table, resulting in significant changes in groundwater quality and dynamics of both local and regional groundwater flow regimes. This includes a reduction of cross-sectional groundwater flow and aquifer-storage capacities. To develop concepts and methods for sustainable groundwater use in urban areas, environmental impact assessments not only have to include above-ground impairments, such as ground motions with effects on existing buildings and infrastructures, as well as noise exposure and air pollution, but also the negative impacts on groundwater flow regimes. The term groundwater flow regime comprises groundwater flow paths, velocities and budgets for a defined region in a temporal context. Among the various other possible sources of groundwater pollution observed in urban environments, subsurface construction may be a source of interference of a previously balanced urban groundwater flow regime.

Numerous urban areas in Central Europe and North America are located in flood plains of rivers canalized last century. Coarse gravelly sediments of braided rivers form one particular, frequently occurring environment within these valley fills. In most practical engineering studies, the subsurface is still represented as homogeneous or at least one consisting of a set of homogeneous layers. Groundwater flow and solute transport processes within these coarse, permeable sediments are strongly influenced by subsurface heterogeneities and require detailed knowledge of aquifer properties, such as hydraulic conductivity, porosity and dispersivity, together with their spatial distribution. This heterogeneity originates from sediment sorting processes in a dynamic environment of aggradational and erosional processes typical of braided river deposits (Huggenberger and Regli 2006). Hydraulic conductivity variations over several magnitudes are of key importance for groundwater flow and solute migration (Rehfeldt et al. 1993; Adams and Gelhar 1992; Gelhar 1986). Since continuous 3D information on hydraulic properties cannot be obtained in fluvial sediments, different methods have been developed to map aquifer properties. Koltermann and Gorelick (1996) distinguish three main types of methods: (1) ***Structure-imitating methods*** using any combinations of Gaussian and non-Gaussian statistically and geometrically-based relationships to match observed sedimentary patterns. (2) ***Process-imitating methods*** consisting of aquifer calibration techniques, which solve governing equations of fluid flow and transport, as well as geological process models combining mass and momentum conservation principles with sediment transport equations. (3) ***Descriptive methods*** using different field methods to translate the resulting geological sedimentary structure models into hydrofacies models with characteristic aquifer properties. All these methods have already been applied in coarse glacio-fluvial gravel deposits typical of braided river environments (e.g. Bridge and Lunt 2006; Nowak and Cirpka 2006; Rubin et al. 2006; Teles et al. 2004; Regli et al. 2004; Huggenberger and Aigner 1999; Weissmann et al. 1999; Rauber et al. 1998; Carle et al. 1998; Fogg et al. 1998; Deutsch and Wang 1996; Webb and Anderson 1996; Koltermann and Gorelick 1996; McKenna and Poeter 1995; Jussel et al. 1994; Webb 1994; Bridge 1993; Ashmore 1993; Paola et al. 1992; Heller and Paola 1992; Brierley 1991; Anderson 1989; Miall 1985; Ashmore and Parker 1983; Allen 1978, Miall 1978). However, for reasons of complexity of the aquifer structures in these coarse-grained sediments and effects on hydraulic property distribution, stochastic modeling was rarely applied to practical problems (Dagan

2002). The literature only provides a few examples of investigations conducted on adequately instrumented field sites and related risk analysis (e.g. river-groundwater interaction, Rhine/Wiese sand and gravel aquifer, Switzerland, Regli et al. 2003; bacterial and virus transport and attenuation processes in Dornach, Munich gravel plain aquifer, Germany, Flynn 2003; hierarchical geostatistics and multifacies systems, Boise Hydrogeophysical Research Site, Idaho, USA, Barrash and Clemo 2002; physical scale modeling of the Ashburton River gravels, Canterbury Plains, New Zealand, Ashworth et al. 1999, 2004; flow and contaminant transport in quaternary gravel deposits, Steisslingen, Germany, Klingbeil et al. 1999; sand and gravel pit in Stoughton, Wisconsin, USA, Anderson et al. 1999; field study of dispersion in a heterogeneous aquifer, Columbus Site, Mississippi, USA, Boggs et al. 1992; methodologies for groundwater driven health risk assessment in heterogeneous aquifers, Maxwell and Kastenberg 1999, Maxwell et al. 1998; environmental research field site Horkheimer Insel, Germany, Teutsch and Kobus 1990; various studies on flow and transport in a sand aquifer, Borden site, Canada, Sudicky 1986, Mackay et al. 1986).

The generally scarce information on outcrop and the existing buildings and infrastructures preventing high resolution Ground Penetrating Radar (GPR) are important reasons for not considering heterogeneity in practical applications, particularly in urban areas. Therefore, drill-core descriptions with the known disadvantages concerning data quality and sedimentary structure recognition (Regli et al. 2002) are the only sedimentological data available. In urban areas, large amounts of geological and hydrological data are generally available but spread in different institutions. Since localizing this data is often difficult and its preparation for specific questions time-consuming, a Geological Database (GeoData) for northwestern Switzerland was set up (Kirchhofer 2006). It comprises a systematic data collection, analysis of drill-core data, and assessment of metadata from geological and hydrological reports. GeoData can be linked to a Geographic Information System (GIS) to provide together with groundwater head and further hydrological data, a unique data source suitable for empirical studies and hypothesis testing in the field of quantitative information on urban hydrological questions. A method of combined sedimentary structure and geostatistical analyses of drill-core data was presented by Regli et al. (2002). The results of the analyses are used to develop various simulations of stochastically generated aquifer properties, which can subsequently be integrated into multilayer high-resolution groundwater models. The investigations center on determining to which extend available drill-core descriptions may be used to describe heterogeneity in coarse river systems and how the different strategies influence the understanding as well as prediction of the impacts and changes on groundwater flow regimes.

This study describes subsurface heterogeneity investigations during groundwater management of a subsurface highway construction (Fig. 1). During single construction phases, considerable groundwater drawdown was necessary, leading to significant changes in the groundwater flow regime. The effect of open sump drainage during construction of an emergency exit is presented. Furthermore, a comparison was established of the changes observed before and after this construction phase. The three investigated situations reveal considerable differences in hydrological and operational boundary conditions and allow evaluating the influence of alternating boundary conditions against the various aquifer heterogeneity simulations. The results are also compared in the context of the varying boundary conditions assuming: (1)

uniform distribution of equivalent aquifer parameters and (2) heterogeneous distribution of aquifer parameters resulting from sequential indicator simulations based on drill-core data. The results obtained are discussed on the basis of groundwater budgets, flow paths and flow velocities.

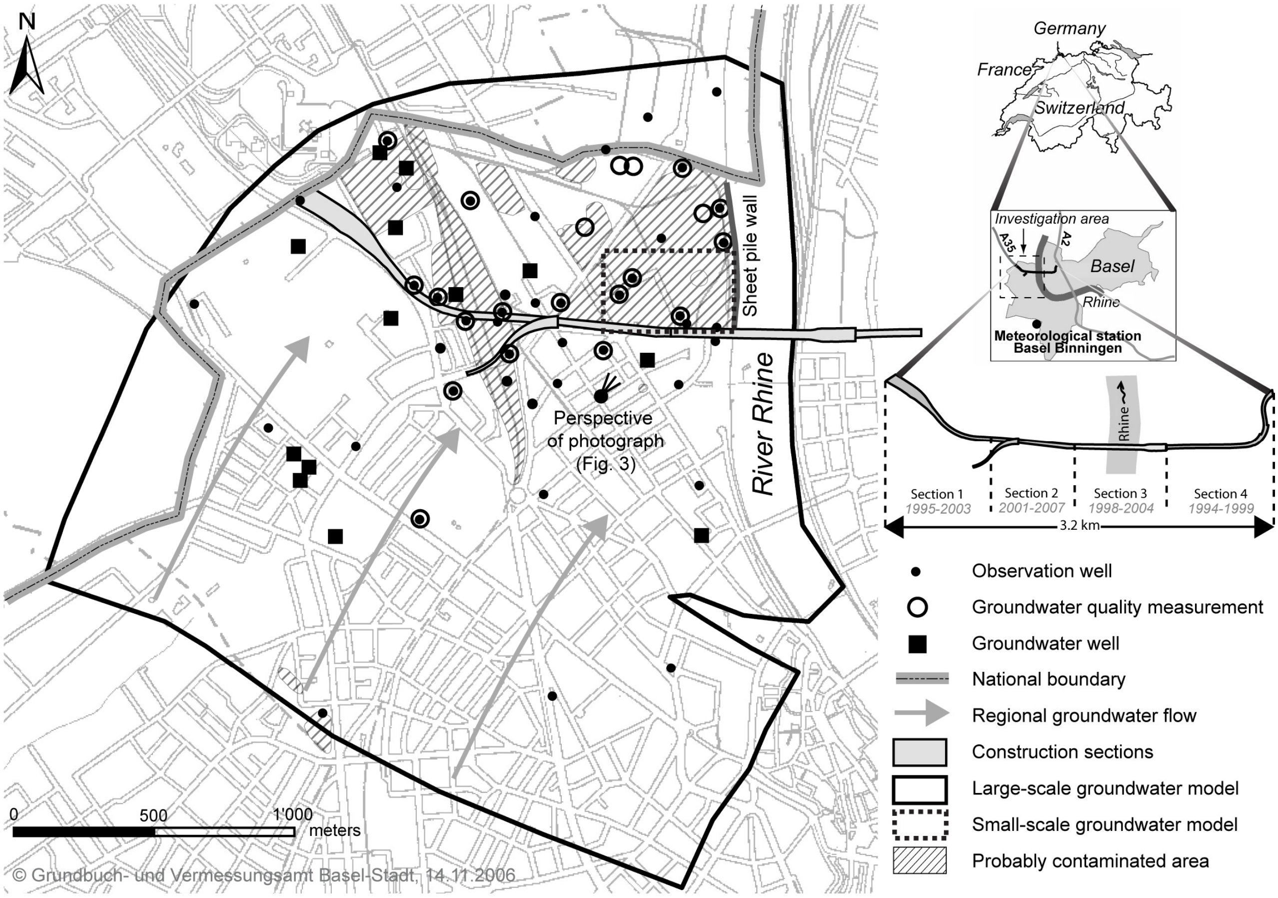

Fig. 1 Investigation area in the city of Basel, northwestern Switzerland. The regional groundwater flows mainly from southwest to northeast. Note that construction of the tunnel highway runs at an approximately 60° angle (CCW) to the regional groundwater flow. Construction years of each section are given in the center of the right column

Groundwater protection as well as policy and management aspects should already be considered at the early stages of urban planning to reconcile the various individual and often conflicting interests. The main objectives of engineers and constructors are to complete construction with minimal effort as regards guaranteed drawdown levels, inexpensive groundwater disposal and safeguarding nearby groundwater use. The environmental and civil engineering offices involved rather focus on possible mobilization of contaminants and changes in the groundwater flow regime during and after construction. However, to achieve a sustainable development of urban groundwater resources, the sum of all impacts on groundwater flow regimes should be taken into account. The investigations focus on the applied aspects of data fusion within the context of subsurface highway construction.

2 Settings

2.1 Hydrogeological setting

Basel, located in northwestern Switzerland, borders both Germany and France. The Rhine enters Basel from the east and changes its course at an angle in northern direction (Fig. 1). The highway construction sections outlined in this book chapter are located in the northern part of Basel to the left of the river Rhine.

The shallow unconfined aquifer mainly consists of late Pleistocene gravel deposited by the Rhine. The gravel deposits, interbedded with fine-grained, flood plain sediments result in variable conductivity within the aquifer. The thickness of the aquifer ranging between 15 and 35 m is underlain by an aquiclude composed of Oligocene mud to clay rich sediments. The general slope and the main direction of the regional groundwater flow are from southwest to northeast.

The river-groundwater interactions along the Rhine are an important element of the regional groundwater flow regime. Depending on the hydrological constraints, the river acts both as a receiving and an infiltrating stream.

The long-term average for yearly precipitation is 788 mma^{-1}, measured during the 30-year period 1961-1990 at the Binningen meteorological station (Fig. 1). Urbanization has led to an increase in impermeable surfaces, thereby causing a reduction in direct groundwater recharge and generation of additional surface runoff from precipitation. As a result, a large spatial and temporal variability in recharge rates over short distances can be observed (Huggenberger et al. 2006).

At the beginning of last century, to stabilize the river bank for harbor facilities an approximately 500-m long and 20-m deep sheet pile wall was driven down to the bottom of the aquifer on the left river bank north of the main course of the tunnel road (Fig. 1). It acts as a low-permeable barrier and reduces locally the interaction between river and groundwater. Regionally, it forces the groundwater to flow either south or north of this wall, thereby creating an area of low flow velocity near the sheet pile wall, and a groundwater divide running east to west behind the wall. Since the position of this groundwater divide was shifted during the different construction phases, it provides a key indicator for changes in the northern groundwater flow regime.

2.2 The subsurface highway construction project

The 3.2-km long subsurface highway connects the French highway A35 (Mulhouse - Basel) to the Swiss A2 (Basel - Gotthard - Milan). It is divided into four sections, of which about 87% are tunnel constructions situated in the gravel deposits; the remaining 13% are covered by the bridge across the Rhine and the various tunnel entrances (Fig. 1).

The progressive shift of the construction sites, requiring different drainage systems, affected the groundwater flow regime throughout construction. Depending on the excavation technique applied, complexity of the groundwater drainage degree varied and was realized either as an open sump drainage, the dewatering of residual groundwater in areas enclosed by sheet pile walls, or a combination of both methods. Open sump drainages are generally associated with major changes in groundwater flow regimes.

A significant change in the local groundwater flow regime in the northern industrial area was caused by the open sump drainage during construction of an emergency exit located north of the main track in the second section of the highway (Fig. 1 and 2). Maximum extraction rates ranging between 15 and 20 ls^{-1} are relatively low. Nevertheless, on account of the small hydraulic gradient in the adjacent industrial area to the north, the effect of this drainage on the regional groundwater flow regime was relatively large and resulted in a change in groundwater flow paths and a shift of the local groundwater divide.

In some areas, the tunnel is permanently below the groundwater table leading to a reduction of cross-sectional groundwater flow and aquifer-storage capacities. Once the construction is completed, connectivity of the groundwater will be enhanced by technical measures, such as the installation of highly permeable culverts as well as drawing sheet pile walls and slide pales.

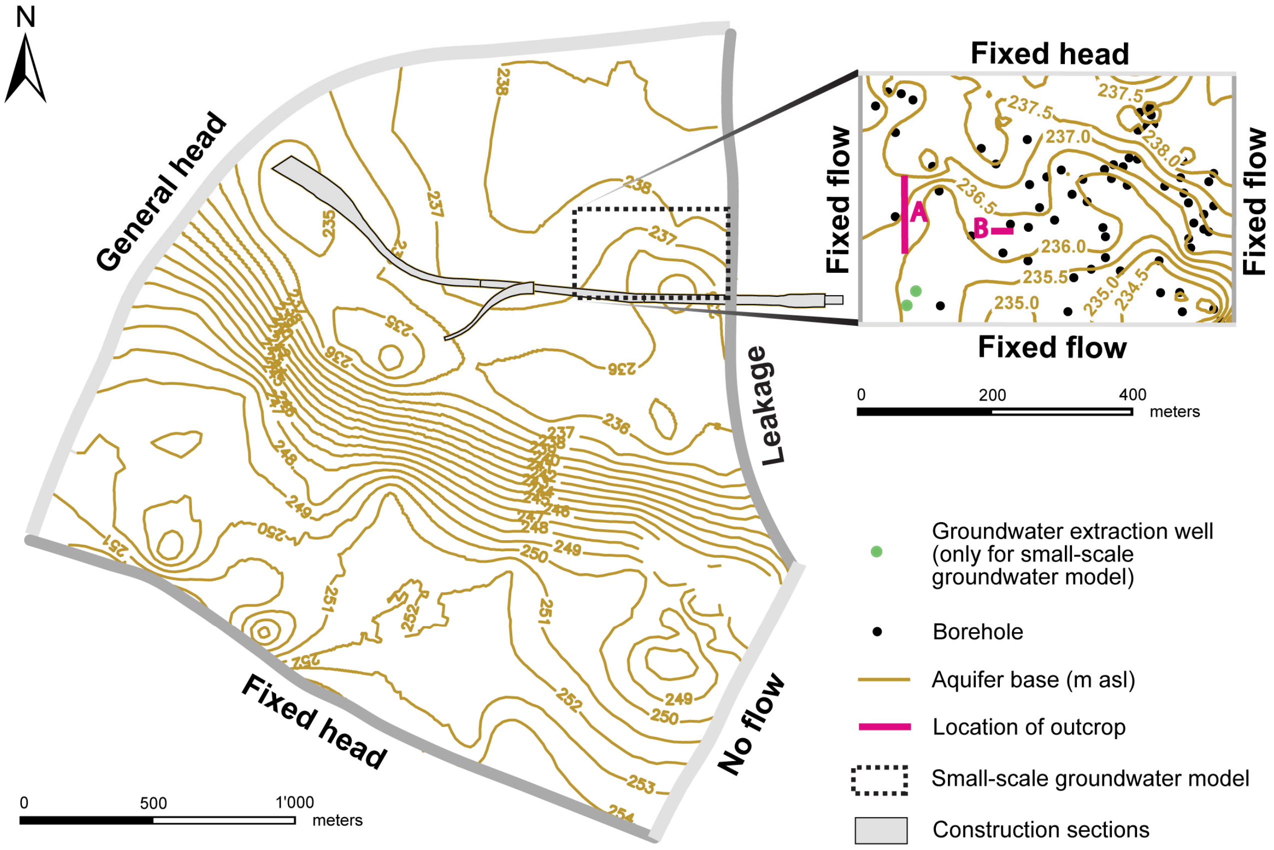

Fig. 2 Surface of the aquifer base and boundary conditions used for large and small-scale groundwater models. Note the steep slope in the center of the model area of the large-scale groundwater model

2.3 Former industrial sites

Since Basel turned into a major industrial center for the chemical and pharmaceutical industry in the 19th century, vast areas have been or are likely to be contaminated (Fig. 3). In addition, other abandoned sites of small enterprises and numerous contaminated areas (fillings of former gravel pits) on adjacent French territory lie close to the construction site (Fig. 1). A considerable risk with regard to mobilization of contaminants will thus be caused by groundwater extraction and drawdown of the groundwater table throughout the different construction phases. A reversal of flow lines may lead to contaminated areas suddenly lying in the capture zones of the industrial groundwater wells or within the groundwater drainage of the construction site. In the worst case, contaminants could reach the extraction wells of the construction site or those of the industrial groundwater users. The risk of such incidents would require the development of concepts and methods for groundwater protection and management, including installation of additional recharge wells.

Fig. 3 The industrial development in the 19th century. The photo illustrates the small-scale groundwater model area. A perspective is given in Figure 1

3 Conceptual approach and methodology

The conceptual approach and methodology used to answer a series of questions generally arising in the context of urban subsurface road constructions include the following points: (1) Is the available data sufficient to adequately investigate groundwater flow and transport, and what questions can be answered with the existing data? (2) What additional data could improve predictions? (3) How could data acquisition be optimized?

A regional-scale groundwater model was used, adapted and calibrated regularly during the various construction site drainages and throughout construction. Due to the numerous calibrations (at least two times per year) the prediction capabilities of the groundwater model were continuously enhanced. This facilitated optimizing extraction and recharge rates during construction site drainages and detecting changes in the groundwater flow regime. Aquifer parameters obtained from pumping tests are therefore of prime importance. However, to adequately model groundwater transport, further knowledge of subsurface heterogeneity and the distribution of aquifer parameters are essential. This knowledge may to a certain degree be derived from drill-core information, sedimentary structure analysis at outcrops and from geophysical as well as hydraulic measurements.

The conceptual approach is given in Figure 4. The investigated area was delineated and comprises an inventory of all relevant boundaries characterizing the regional and local groundwater flow regime, including all possible impacts. The following three-step approach for data fusion was chosen: (1) determination of data requirements; (2) data processing and finally

(3) data evaluation. The presented example of data fusion first identified and collected the required data and subsequently formulated the basic requirements for setting up groundwater models with accurate boundary conditions. The data required comprises hard and soft data. Hard, reliable data is derived for example from outcrops and groundwater head measurements. Soft data is obtained from drill-core descriptions and groundwater quality analyses. The first element of the groundwater management system at this level of data fusion consists in: (i) a dense groundwater-monitoring network where hydraulic heads are measured and groundwater chemistry is analyzed regularly. The data obtained is then processed in a second step. The second main element of the groundwater management system comprises: (ii) a database together with the development of an application facilitating lithofacies-based interpretation of drill-core data. Export of this information can directly be deployed in the third element of the groundwater management system consisting of: (iii) geostatistical analyses of the aquifer heterogeneity leading to conditioned stochastic aquifer simulations. The fourth element of the groundwater management system consists in: (iv) regional and local high-resolution groundwater modeling. The geostatistical simulations are integrated into the local groundwater models. The third and last step of data fusion finally comprises an evaluation of the processed data. Assisted by a GIS, the simulation results are visualized to improve the understanding among engineers and all other stakeholders. The four elements are described in detail in the following text.

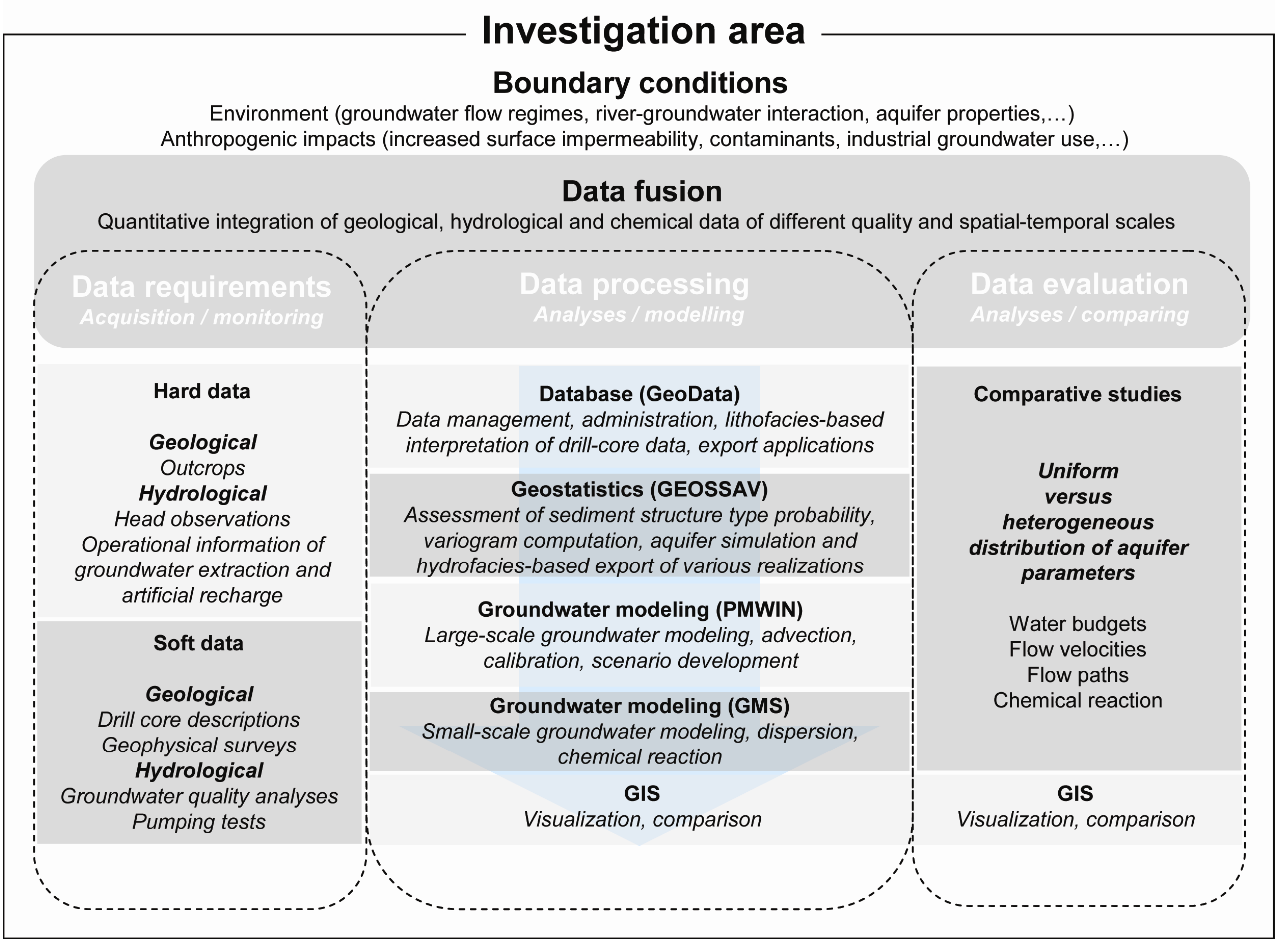

Fig. 4 Conceptual approach of data fusion for practical urban hydrogeological applications

3.1 Groundwater monitoring network

The network comprises a total of 44 observation wells instrumented by automated water-level loggers for continuous measurement of the hydraulic head (Fig. 1). The hydrographs of this observation network are analyzed monthly. A total of 21 observation wells are sampled regularly for groundwater quality measurements. Furthermore, the extracted water for industrial groundwater use and for settling tanks on the construction sites is sampled at regular intervals. The monitoring program was adapted to the progress of the various construction sections, to the current groundwater management requirements and to the results obtained from groundwater modeling. Interpretation of the changes observed in groundwater quality measurements together with the modeling results allowed optimizing the localization of new observation wells.

3.2 Geological database

GeoData (Kirchhofer 2006) of the city of Basel includes some 3,000 drill-core descriptions. It can be used for almost any question arising during setup and operation of other elements of the groundwater management system. Application of GeoData for calculation of the aquifer base, evaluation of aquifer parameters and for lithofacies-based interpretation of drill-core data is summarized hereafter.

Calculation of aquifer base and evaluation of aquifer properties

The aquifer base in the large-scale groundwater model includes information on more than 400 drill-cores, whereas the small-scale groundwater model includes information on 71 drill-cores (Fig. 2).

Distribution of horizontal conductivity zones in the large-scale groundwater model was based on different type and quality data sets available from GeoData including various pumping tests. Furthermore, additional information from reports outlining regional geological questions, including pumping test data, was used to determine hydraulic parameter distribution.

Combining outcrop with drill-core data for sedimentary structure analyses

Information on the architecture of the aquifer is required to adequately model subsurface heterogeneity. Outcrop and drill-core information contains data of different quality and resolution at different scales. Outcrops of natural deposits above the groundwater table reveal distinct and coherent structural elements such as lenses and layers of different gravel types (Jussel et al. 1994; Siegenthaler and Huggenberger 1993; Huggenberger et al. 1988). Outcrop investigations therefore provide extremely reliable hard data. However, outcrops are restricted to one large excavation pit north of the investigation area and, to some extent, to outcrops within the tunnel itself. Due to easy access and visibility, undisturbed sedimentary structures and textures at the outcrops could be examined in detail and the sedimentary structure patterns of the investigation site defined. Definition of sedimentary texture types is based on grain-size distribution and sediment sorting. Sediment structure types are made up of one or a combination of two possibly alternating sediment texture types.

Drill-core data provides limited information on the spatial distribution of sedimentary structures and subsurface properties such as hydraulic conductivity, porosity and dispersivity. Drilling may destroy sedimentary structures and smear the interface with adjacent layers. Typically, drill-core layer descriptions are not very detailed and do not clearly indicate explicit sedimentary structure types. Furthermore, the quality of individual drill-core descriptions varies considerably depending on the geotechnical or sedimentological approach used, thus permitting limited and speculative conclusions on sedimentary structures. Results on a drill-core scale have to be evaluated carefully, as fractures common in a drill-core may not clearly reveal the overall flow on a field scale for lack of interconnectivity or dominance of high permeable porous sedimentary structure types. Breaks in cores may also be attributed to core drilling and handling processes. Consequently, drill-core data is regarded as soft data. The concept of determining sedimentary texture and structure types is based on the concept developed for the Rhine gravel as described by Rauber et al. (1998), Jussel et al. (1994), Siegenthaler and Huggenberger (1993). The interpretation method of drill-core data is elucidated in Regli et al. (2002).

Sedimentary structure types of this area include: open-framework gravel (OW), open-framework/bimodal gravel couplets (OW/BM), gray gravel (GG), brown gravel (BG), alternating gray and brown gravel layers (GG/BG), horizontally-layered or inclined, silty gravel (SG), sand lenses (SA), and silt lenses (SI). Regli et al. (2002) and Huggenberger and Regli (2006) give a detailed description of the sedimentary structure types.

Sedimentological drill-core descriptions of coarse gravel deposits provide information on composition and texture of deposits. More specifically, details of grain-size categories, sorting, composition of major constituents and proportion of each grain-size fraction can be determined and information obtained on color, chemical precipitation, thickness of a deposit, and its transition through the underlying layer. The quality of the descriptions varies considerably. Important sedimentary structure types, such as the highly permeable OW, are generally overlooked due to smearing with overlying and underlying layers during the drilling process. Occurrence and size of OW determine, however, variance and correlation length of the hydraulic conductivity in coarse gravel deposits (e.g. Jussel et al. 1994). Consequently, an important gap exists between outcrop and drill-core descriptions. The strong association of OW to the related structure type OW/BM has led to the concept of a gradual sedimentary structure-based interpretation of outcrop, drill-core and GPR data. The method presented by Regli et al. (2002) allows a probability assessment of drill-core layer descriptions representing defined sedimentary structure types.

Based on drill-core information, defined sedimentary structure pattern for the investigation site and on the interpretation method for drill-core data, GeoData allows analysis of sedimentary structure and provides data sets of point information with arbitrary separation distances along drill-cores. The point information includes space data (x-, y-, z-coordinates), probabilities of sedimentary structure types (probability that a drill-core layer description represents a defined sedimentary structure type) and an indication of the most likely sedimentary structure type (Fig. 5).

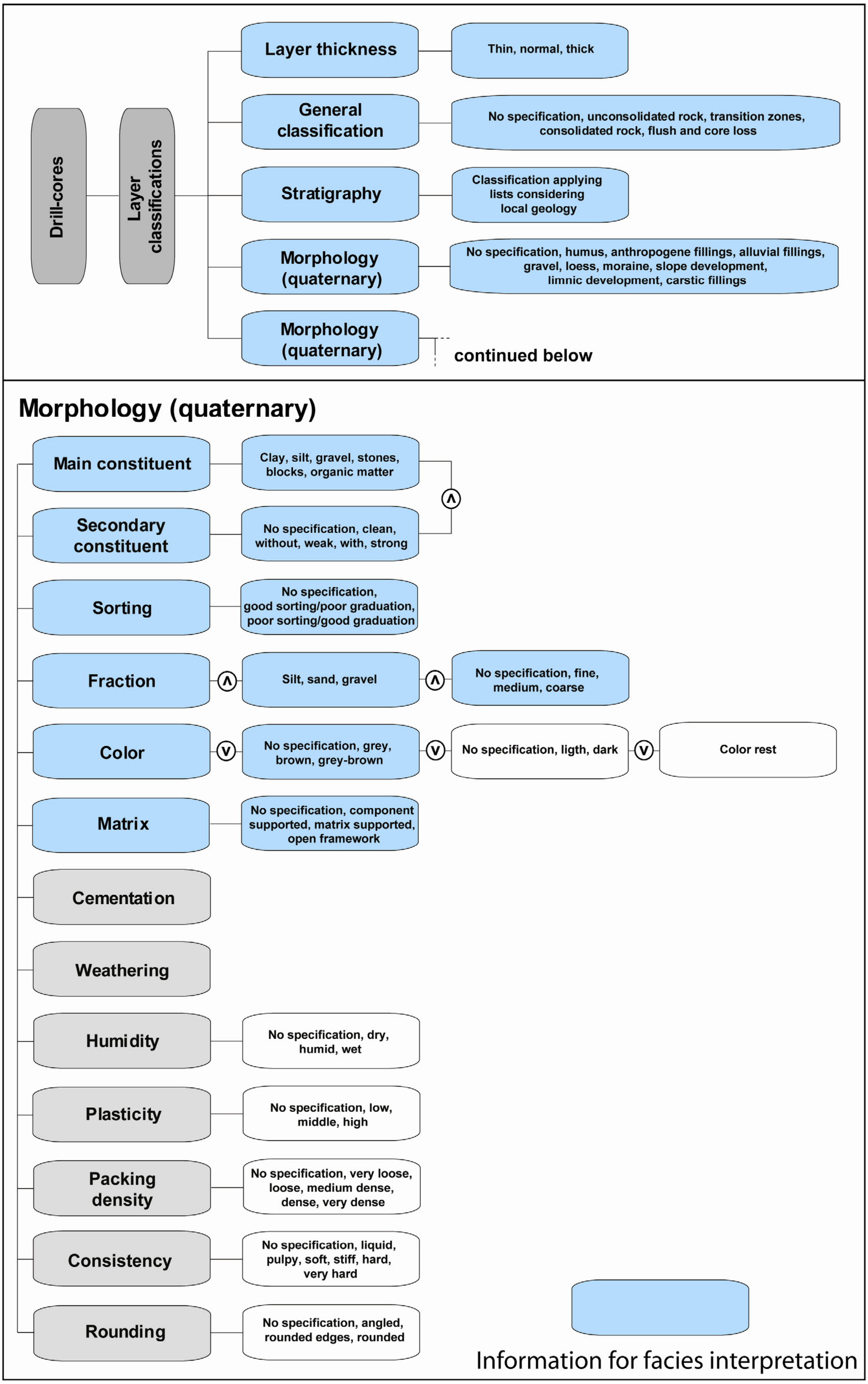

Fig. 5 Drill-core input mask for GeoData (V: or; Λ: and). The information used for sedimentary structure interpretation is highlighted

3.3 Geostatistics

Modeling spatial data variability is the key to any subsurface simulation. A variogram describes the spatial correlation of data as a function of the separation vector h between two data points. Computation of the indicator variogram was based on the drill-core data. Indicator transformation at grid node locations was set at unity for sedimentary structure types s_k, $k = 1,...,K$, with the highest probability values; otherwise it was set at zero (Deutsch and Journel 1998):

$$i(u_\alpha ; s_k) = \left[\begin{array}{l} \text{if } s(u_\alpha) = s_k \\ 0, \text{ otherwise,} \end{array} \right. \qquad (3.3.1)$$

where u_α refers to a particular data location and $s(u_\alpha)$ to a particular data value.

Experimental indicator variograms were calculated after Eq. 3.3.2 for various directions (azimuth, dip, plunge) using GEOSSAV (Regli et al. 2004), an interface to selected geostatistical programs available from the Geostatistical Software LIBrary, GSLIB (Deutsch and Journel 1998):

$$\gamma_I(h; s_k) = \frac{1}{2N(h)} \sum_{1}^{N(h)} \left[i(u; s_k) - i(u + h; s_k) \right]^2 , \qquad (3.3.2)$$

where $N(h)$ is the number of data pairs, $i(u; s_k)$ is the indicator at the start or tail of the pair, and $i(u + h; s_k)$ is the corresponding end or head indicator.

To derive maximum benefit from available textural and structural information, the aquifer structure was derived by sequential indicator simulation. For a specific category, the indicator kriging estimate, i.e. the probability that s_k prevails at location u, is written as a linear combination of the n nearby indicator-coded data (Deutsch and Journel 1998):

$$\begin{aligned} &[i(u; s_k)]^*_{SK} = [Prob\,\{S(u) = s_k \mid (n)\}]^*_{SK} = \\ &\sum_{\alpha=1}^{n} \lambda_\alpha(u; s_k) i(u_\alpha; s_k) + \left[1 - \sum_{\alpha=1}^{n} \lambda_\alpha(u; s_k) \right] F(s_k), \end{aligned} \qquad (3.3.3)$$

where $F(s_k)$ is the stationary prior probability of category s_k, and the $\lambda_\alpha(u; s_k)$'s are the indicator kriging weights corresponding to category s_k, which depend on the closeness of the data considered for the estimation.

The sequential indicator simulation principle is an extension of conditioning and comprises all data available within the neighborhood of a model cell, including the original data and all previously simulated values. Sequential indicator simulations are processed by a number of steps. An initial step establishes a grid network and coordinate system. This is followed by assigning data to the nearest grid node. Where more than one data point may be used at a node, the closest data point is assigned to the grid node. In a third step, a random path through all grid nodes is determined. For a node on a random path, adjacent data and previously simulated grid nodes are searched to allow assessment of the conditional distribution by indicator kriging.

Based on this distribution, a simulated sedimentary structure is randomly drawn and set as hard data before selecting the next node in the random path prior to repeating the process. By using this approach, the simulation grid is sequentially built up. During the final step of the sequential indicator simulation, results are checked to ensure that orientations and sizes of the simulated sedimentary structures concur with those observed.

For groundwater modeling, the simulated sedimentary structure needs to be transformed into hydraulic parameters. The generated sedimentary structures are characterized by average and randomly selected hydraulic conductivity and porosity values provided by average and standard deviations calculated by Jussel et al. (1994) (Table 1). Files containing distributions of hydraulic conductivity, effective porosity and dispersivity values were generated and exported to groundwater models. According to sedimentological and geostatistical analyses of the aquifer, each aquifer simulation corresponds to various equiprobable representations of the subsurface at variable degrees of uncertainty in hydraulic parameter values and geometry of the sedimentary structures.

Table 1 Hydraulic parameters of sedimentary structure types used in the characterization of aquifer simulations (after Jussel et al. 1994). Refer to chapter 3.2 for the abbreviations

	Sedimentary structure type								
	OW	OW/BM	GG	BG	GG/BG horizontal	GG/BG inclined	SG	SA	SI
Hydraulic conductivity K [mms^{-1}]	100	10	0.15	0.02	0.08	0.1	0.008	0.26	0.005
Standard deviation $\sigma_{\ln K,1}$ [-]	0.8	0.8	0.5	0.6	0.8	0.8	0.5	0.4	0.4
Porosity n [%]	34.9	30	20.1	14.1	17	17	25	42.6	40
Local longitudinal dispersivity [mm]	25	30	25	30	30	30	3	0.3	0.05

3.4 Groundwater modeling

Regarding selection and setup of an appropriate groundwater model, it is important to ensure that the chosen model and desired resolution are capable of answering relevant questions simultaneously. When applying groundwater models, one of the key requirements is high-quality, site-specific data (National Research Council 1990). Before setting up a groundwater model, groundwater budgets and boundary conditions – the main components of a groundwater system – must be identified and analyzed.

A large and a small-scale groundwater model combination were chosen for this case study (Fig. 1 and Fig. 2). While the large-scale groundwater model was used to simulate the regional groundwater flow regime throughout the entire construction period of the tunnel road, analyses of aquifer heterogeneity were integrated into the small-scale groundwater model. For selected construction phases, the large-scale groundwater model allowed to define boundary conditions for the telescoped small-scale groundwater model. Both large and small-scale groundwater models were simulated using the 3D finite difference code MODFLOW (McDonald et al. 2000):

$$div\left(K \cdot \vec{\nabla} h\right) + W = S_s \frac{\partial h}{\partial t}, \qquad (3.4.1)$$

where K, are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the hydraulic head (L); W is a volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow in (T-1); S_s is the specific storage of the porous material (L-1); and t is time (T). Eq. 3.4.1, when combined with boundary and initial conditions, describes three-dimensional groundwater flow in a heterogeneous and anisotropic medium, provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions. The groundwater flow process solves Eq. 3.4.1 using the finite-difference method in which the groundwater flow system is divided into a grid of cells. Further, the solver package PCG2 (preconditioned Conjugate Gradient) with modified incomplete Cholesky preconditioning was applied (Hill 1990).

The graphical user interface Processing Modflow (PMWIN) of Chiang (2005) was used for the large-scale groundwater model. The graphical interface Groundwater Modeling System (GMS) of Environmental Modeling Systems Inc. (2006) was applied to the small-scale groundwater model. Two different graphical user interfaces were applied, as the large-scale model has already been in operation with PMWIN since 2001, and the telescoped, small-scale model has recently been operated with GMS.

3.4.1 Large-scale groundwater modeling

The large-scale groundwater model covers an area of 2,720 m x 2,860 m (about 8 km^2; Fig. 1 and Fig. 2). The spatial discretisation resulted in cell sizes varying between 5 m x 5 m (near the construction site) and 30 m x 30 m in totally 132,500 cells. An approach with four horizontal layers was chosen to vertically integrate the construction. Construction itself was integrated either as inactive cells or as horizontal flow barriers with defined hydraulic conductivities. During construction, progressive adjustments were made. The surface of the aquifer base and distribution of horizontal hydraulic conductivity zones were derived from different type and quality data sets available from GeoData.

The hydraulic conductivity values range between 3.1E-3 ms^{-1} and 1.3E-4 ms^{-1}. A 10:1 ratio between horizontal and vertical hydraulic conductivity was chosen. Since the southern part of the model area has a broad steep slope in the aquifer base without any detailed geological information, hydraulic conductivity had to be estimated (Fig. 2). For all model runs, divergence of calculated and observed hydraulic heads is highest in this part and is in the order of 1 m. However, the divergence for the remaining hydraulic heads averages in 0.2 m.

Based on a one-day test measurement of groundwater levels (Wagner et al. 2001) model boundary conditions are of the first type (fixed head) along the southern side, and of the third type (leakage) along the Rhine. The western and northern boundaries are specified as no flow in a first phase and as general head in a second phase, thus resulting in a groundwater outflow south and a groundwater inflow north of the steep slope in the aquifer base. Hydraulic conductivity of the riverbed was set at 5.0E-5 m^{2}s^{-1}.

A total of 48 extraction wells were integrated, i.e. nine production wells and one recharge well for industrial groundwater use, 35 wells extracting groundwater along the various construction sections as well as three recharge wells. The hydraulic head was continuously monitored in totally 44 observations wells. As a routine procedure, the groundwater model was calibrated at least biannually.

3.4.2 Small-scale groundwater modeling

The small-scale groundwater model covers an area of 450 m x 300 m (0.135 km^2; Fig. 1 and Fig. 2). The spatial discretisation resulted in totally 1,350 cells of 10 m x 10 m cell size. For an appropriate vertical integration of aquifer heterogeneity, an approach with 13 horizontal layers was chosen. Each layer is 2-m thick and the total maximum vertical thickness amounts to 26 m. The interpolated surface of the aquifer base was then cut with the model grid, thus resulting in partly inactive cells in the two lower model layers. Finally, the interpolated aquifer properties (hydraulic conductivity, effective porosity and longitudinal dispersivity) were assigned to the prepared grid.

The large-scale groundwater model provided the boundary conditions. Model boundary conditions are of the first type (fixed head) along the northern side, and of the second type (fixed flow) along the eastern, southern and western side to account for the variable inflow and outflow rates across the boundaries. The eastern side covers residual leakage of the Rhine through the sheet pile wall, the southern side the groundwater flow beyond the tunnel construction and the western side focuses on the regional groundwater flow through this area.

Since hydraulic conductivity varies with scale of measurement, it can increase to over several orders of magnitude. As larger blocks of the subsurface are tested for subsurface flow, preferred pathways are encountered that increase the measured average hydraulic conductivity value (Carrera 1993). The preferred pathways are provided by sedimentary structure heterogeneities, fractures or flow conduits (Schulze-Makuch et al. 1999).

Distribution of hydraulic conductivity for the large-scale groundwater model is derived from a series of pumping tests describing the average hydraulic conductivity for this region. A 2.0E-3 ms^{-1} average value obtained from this distribution is also used for the small-scale groundwater model of uniform aquifer parameter distribution. Together with the median from the geostatistical analyses, the scaling factors obtained for hydraulic conductivity range between 13 and 20. Furthermore, the scaling behavior by an empirical power law of the hydraulic conductivity proposed by Schulze-Makuch et al. (1999) was employed:

$$K = 10^{c}\left(V\right)^{m}, \tag{3.4.2.1}$$

where K is the hydraulic conductivity, c is a parameter characteristic for a geological medium that relates to geological variables such as average pore size and pore interconnectivity in porous media, V is the volume of tested material (used as scale measure), and m is the scaling exponent (slope of the line on the log-log plot). For unconsolidated media and alluvium parameters, for c and m values of *-4.8* and *0.5,* respectively, are proposed. The volume taken account of in this case study for the small scale groundwater model amounts to approximately 3.5E6 m^3. This results in a calculated hydraulic conductivity value of 3.7E-3 ms^{-1}, which is in the same order of magnitude as the average hydraulic conductivity of 2.0E-3 ms^{-1} used in the large scale groundwater model. When applied to the present study, the scaling factors range between 25 and 37. Finally, a decimal power-scaling factor 10 was chosen and a 10:1 ratio between horizontal and vertical hydraulic conductivity.

The value for effective porosity is the determining parameter for the advective processes and the time scale of contaminant transport in the aquifer (Graf and Schäfer 2002). Porosity may also vary with scale, however, such variations are assumed to be minimal compared to those encountered for hydraulic conductivity and generally ranging over several orders of magnitude (Schulze-Makuch et al. 1999). Evaluations reveal that the 0.2 value assumed for the uniform distribution of porosity from the large-scale groundwater model is of the same order of magnitude as the value for the various aquifer heterogeneity simulations. In unconfined aquifers, the value for the specific yield is the same as the one for effective porosity. An empirical value of 1.0E-4 m^{-1} for sandy gravel was chosen for specific storage (Anderson and Woessner 1992).

Simulations were conducted for three sets of hydrological and operational boundary conditions (Table 2): Set 1 considers boundary conditions for an ordinary situation, preceding the major drawdown phases (March 23, 2003). Set 2 covers the period with the most significant changes in the local groundwater flow regime north of the industrial area and caused by the open sump drainage during construction of an emergency exit located north of the main track in Section 2 (October 28, 2004). Set 3 describes again boundary conditions for an ordinary situation and accounts for low groundwater levels and Rhine infiltration after the major drawdown phase (February 16, 2006).

Table 2 Water budgets across model boundaries, extraction rates of construction site drainage and altitude of the specified head in the north. Flows are considered “in” if they are positive and “out” if they are negative

	Flow budgets [m^3d^{-1}]				Specified head [m asl]
	East	South	West	Wells	North
March 23, 2003	-198.7	-691.2	+423.4	0.0	245.54 – 244.88
October 28, 2004	+60.5	+380.2	+691.2	-604.8	245.20 – 244.96
February 16, 2006	+34.6	+120.96	+155.2	0.0	244.71 – 244.56

Flow velocities

GMS allows determining groundwater flow velocity and seepage velocity. The velocity calculator uses three scalar data sets from which it creates a vector data set. Head, porosity and hydraulic conductivity are the three input data sets used. Furthermore, a vertical anisotropic factor has to be chosen. Darcy’s law is applied to the calculations:

$$v_s = \frac{v_d}{n} = \frac{ki}{n}, \qquad (3.4.2.2)$$

where v_s is the seepage velocity, v_d is the Darcy velocity, n is the effective porosity, k is the hydraulic conductivity, and i is the head gradient.

In 3D, the equation is:

$$div\left(v + K \cdot \vec{\nabla} h\right) = 0, \qquad (3.4.2.3)$$

where K, are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T); h is the hydraulic head (L). To calculate the hydraulic gradient vector the finite differences are computed by:

$$\frac{\partial h}{\partial x} = \frac{\dfrac{h_{i_{+1}jk} - h_{ijk}}{x_{i_{+1}jk} - x_{ijk}} + \dfrac{h_{ijk} - h_{i_{-1}jk}}{x_{ijk} - x_{i_{-1}jk}}}{2}. \qquad (3.4.2.4)$$

The units of the calculated flow velocities are length over time (L/T).

4 Results

4.1 Outcrop and drill-core analyses

The outcrop within the perimeter of the former industrial sites above the groundwater table (Fig. 6) clearly reveals a prevalence of poorly sorted, clean gravel without significant fine sediment fraction on top of the sequence. Below, sets of gravel couplets were observed comprising OW and OW/BM interspersed with thin layers of poorly sorted sometimes sandy clean gravel. The Pleistocene Rhine gravel along the upper Rhine valley generally exhibits a higher amount of high permeable structure types in the lowest part of the sequence. Based on the preservation potential of different sedimentary structure types (Huggenberger and Regli 2006) it is assumed that the gravel below the groundwater table most likely follow this trend.

Separation to generate point information for sedimentary structure analyses was set at 0.5-m distance. Therefore, a total of 1,999 data points were generated for all drill-cores. The fraction of sedimentary structure types, which is derived in percentage, represents the initial probability density functions for stochastic aquifer simulation (Table 3).

Table 3 Parameters used for the sequential indicator simulation to define the geometric anisotropy of the sedimentary structure types. Refer to chapter 3.2 for the abbreviations. Values in italics are estimates; the isotropic nugget constants of the sedimentary structure types are zero; the variogram models of the sedimentary structure types are exponential; the dip and plunge of the sedimentary structure types are established at zero degrees

	Sedimentary structure type								
	OW	OW/BM	GG	BG	GG/BG horizontal	GG/BG inclined	SG	SA	SI
Relative fraction amount [-]	0.004	0.05	0.49	0.26	0.01	0.03	0.12	0.04	0.002
Azimuth [°]	300	270	320	300	300	280	330	260	300
Maximum horizontal range [m]	2.5	16	9	16	20	20	14	4.3	4
Minimum horizontal range [m]	1.5	5	9	15	10	15	8	3.2	2
Vertical range [m]	0.1	2.5	1.5	1.5	1.5	1.5	2.5	0.6	0.1

In relation to overbank deposits composed of SA and SI (see Fig. 6A), the large GG and BG fractions are interpreted as products of significant sediment aggradation during lower channel mobility of the former braided river system. In fact, the last landscape-shaping flood events in this area date back 5,000 to 6,000 BC (Rentzel 1994). Scour and trough fill deposits, mainly consisting of sets of OW/BM couplet cross-beds (see Fig. 6B), are readily found in outcrops. However, the percentage fraction in drill-cores appears to be highly underestimated.

The results of relative sedimentary structure types of the present study are compared with those of Jussel et al. (1994) and Regli et al. (2004) within the context of the fluvial systems, methodological aspects and observed sedimentary structures at the outcrops of the individual investigation sites (Table 4). The investigation site of the present study is located distal of aggradational areas of the Rhine. The present study focuses mainly on drill-core descriptions and some outcrops analyses. Jussel et al. (1994) investigated average distributions of sedimentary structure types in fluvio-glacial deposits of ten gravel pits located in the Rhine, Reuss, Aare, Limmat, and Thur valleys in northeastern Switzerland. The sites are mainly located proximal to aggradational areas of the rivers, and the investigations centered on outcrop analysis. Regli et al. (2004) examined gravels in the confluence system of Rhine and Wiese in Basel, northwestern Switzerland. The investigations are focused on GPR data interpretation and some drill-cores.

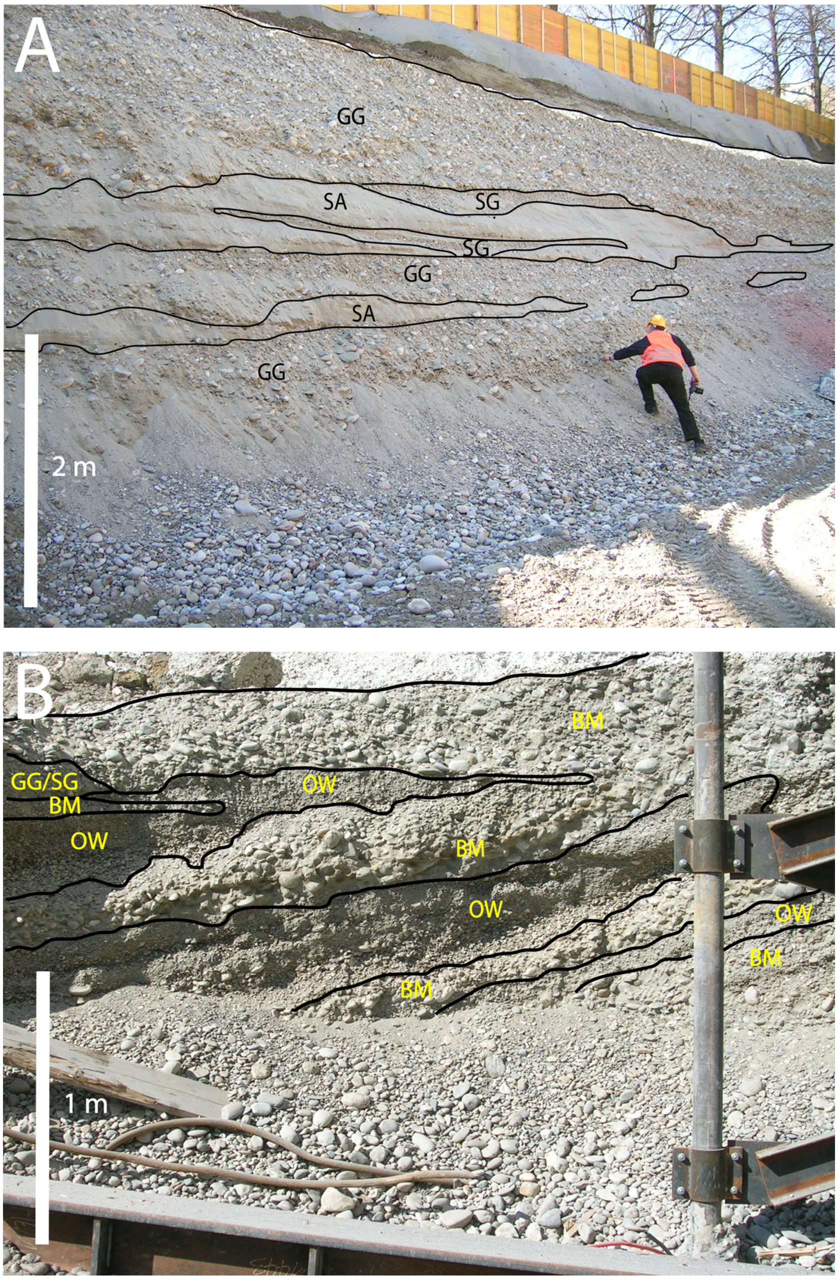

Fig. 6 Sedimentary structures of Pleistocene Rhine gravel in Basel. A: flooding dominated sequences in a section approximately parallel to the former flow direction. B: trough-fill dominated sequences approximately perpendicular to the former flow direction (see Fig. 2 for location of outcrops). Refer to chapter 3.2 for the abbreviations

Table 4 Comparison of relative fraction amounts of different sedimentary structure types in different case studies. Refer to chapter 3.2 for the abbreviations; [a] Jussel et al. (1994), average distribution of sedimentary structure types in fluvio-glacial deposits of ten gravel pits located in the Rhine, Reuss, Aare, Limmat, and Thur valleys (northeastern Switzerland); [b] Regli et al. (2004), GPR data interpretation in the area of the confluence of the rivers Rhine and Wiese (northwestern Switzerland)

	Sedimentary structure type								
	OW	OW/BM	GG	BG	GG/BG horizontal	GG/BG inclined	SG	SA	SI
Current case study	0.004	0.05	0.49	0.26	0.01	0.03	0.12	0.04	0.002
Jussel et al. [a]	0.028	0.053	0.095	0.158	0.577	0.044	-	0.05	0.004
Regli et al.[b]	0.02	0.06	0.13	0.05	0.50	0.05	0.03	0.04	0.01

According to Jussel et al. (1994) and Regli et al. (2004), the relative amount of OW is clearly higher than that observed in the present case study. We actually expected a larger amount of OW and OW/BM from the topographic position within the vertical record of the site and from the larger amounts of SA facilitating lateral migration (Church 2002). Owing to destruction of sedimentary structures and mixing of different units during drilling, we conclude that OW is underestimated for sedimentary structure analysis from drill-core descriptions. The relative amount of OW/BM is similar in all three case studies. This sedimentary structure type indicates trough structures. The larger GG amount may be explained by GG dominance near the top of the vertical section caused by the Rhine abandoning this area in 6,000 BC and subsequent lack of river dynamics. Compared to data from outcrops and GPR, differentiation is considerably more difficult between GG, BG, GG/BG-horizontal and GG/BG-inclined in the various drill-cores of the present study. The sums of the relative amounts of these different sedimentary structure types are, however, of similar range in all case studies. The fact that the GG fraction predominates in the present case study is attributed to predominating aggradational processes or at least to lower fluvial system dynamics. This is supported by the theory that proximal regions and confluence systems are highly energetic and dynamic fluvial systems. Compared to the other two investigations, the relatively higher amount of fine-grained structure types, such as SG, SA and SI in the present case study, indicates slightly large-scale inundations of the entire floodplain.

4.2 Geostatistical analyses

Variogram computation

Table 3 includes the resulting parameters of variogram computation for the nine sedimentary structure types identified at the investigation site. Azimuth (both dip and plunge are zero degrees) and the ranges corresponding to maximum and minimum horizontal and vertical spatial correlation distances (Journel and Huijbregts 1989) characterize the geometric anisotropy of the sedimentary structure types. The results of the variogram analyses, providing orientation of the sedimentary structures, represent the main flow direction of the Rhine during sediment aggradations. The relatively wide spatial correlation ranges from a few meters up to a few tens of meters for the different sedimentary structure types, may be greatly influenced by the density of the data sampled from the drill-core information.

Aquifer simulation

A sequential indicator simulation is presented in Figure 7. The regular model grid is defined by 45 × 30 × 13 cells of 10 m × 10 m × 2 m cell size. Each simulated sedimentary structure distribution is termed an aquifer realization. In each model run, the resulting probability density functions of the sedimentary structure types deviate less than ±10% from the initial probability density functions, which represent the expected volumetric fractions of the sedimentary structure types over the entire model domain. At least 100 or 1,000 runs are necessary to determine statistical moments and their confidence limits by Monte Carlo type modeling. In our case, the number of aquifer realizations was limited and the effects of subsurface heterogeneity along with changing boundary conditions illustrated qualitatively. A total of three different simulations were prepared, comprising different distributions of hydraulic conductivity, porosity and longitudinal dispersivity. These three simulations were again calculated for mean and distributed aquifer parameters, thus resulting in six realizations. These six realizations were then integrated into the small-scale groundwater model using three sets of hydrological and operational boundary conditions. For the three sets of boundary conditions, an equivalent uniform distribution of aquifer parameters over the entire model grid was also considered. Finally, a total of 18 simulations could be evaluated and compared.

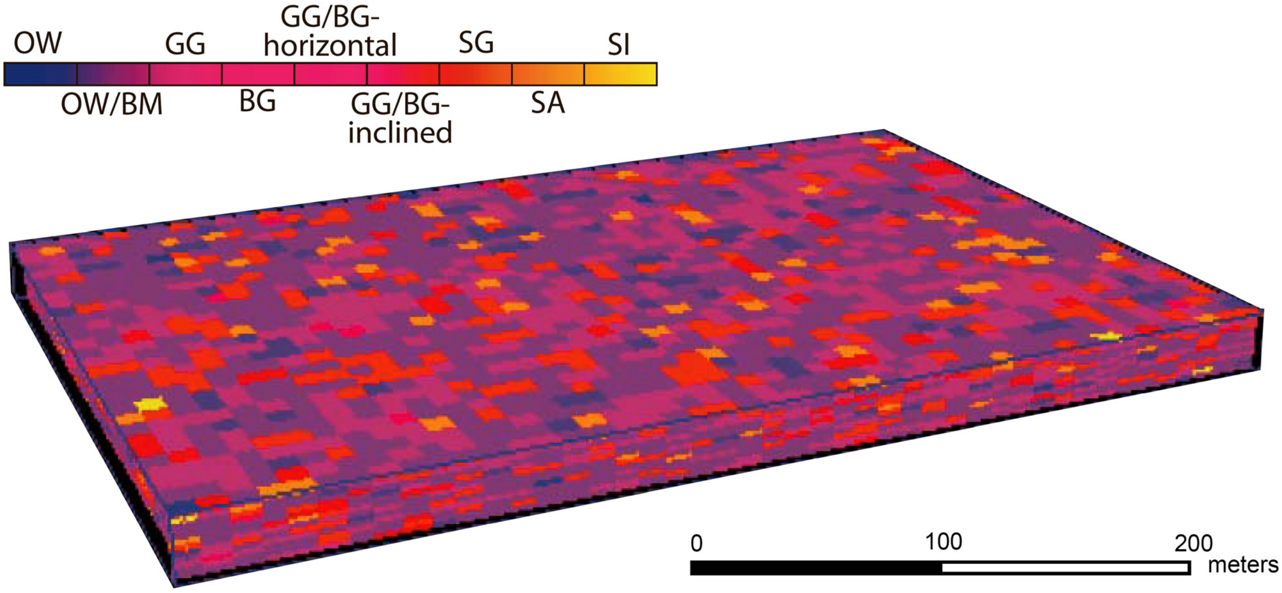

Fig. 7 Realization of sequential indicator simulation representing the distribution of sedimentary structure types identified at the investigation site. Refer to chapter 3.2 for the abbreviations

4.3 Groundwater modeling

Groundwater flow regime

Figure 8A-F illustrates the head distribution and flow paths for the three modeled boundary conditions, assuming uniform distribution of aquifer parameters (to the left) and for one of the simulations of the heterogeneously distributed aquifer parameters (on the right). The situation on March 23, 2003 (Fig. 8A&B) reflects the groundwater flow regime before the major construction phases and describes an ordinary situation. Note the backwater effect behind the sheet pile wall and the diversion of flow paths. The situation on October 28, 2004 (Fig. 8C&D) reflects the groundwater flow regime during construction of the emergency exit. Note the inflow running towards the construction site drainage. The situation on February 16, 2006 (Fig. 8E&F) reflects the groundwater flow regime after completion of the emergency exit with the overall low groundwater levels. Note the low gradient of the hydraulic heads, the Rhine infiltration and, beyond the southern model boundary, the effect of the construction site drainages and industrial groundwater use.

A distinct influence of the current boundary conditions can be observed. The situation in March 2003 is balanced. However, the effect of both construction site drainage in October 2004 and Rhine infiltration and construction site drainages outside the model domain with their influence along the southern model boundary in February 2006 is clearly visible. Integration of aquifer heterogeneities leads to an undulating progression of hydraulic heads.

Flow paths, visualized by particle tracks, reveal that high conductivity zones have a similar effect as optical lenses. The high hydraulic conductivity units (i.e. OW) are identifiable as they “focus” on the flow lines. Due to the complex interspacing of sedimentary structures, correlations between zones of high particle concentration and their associated sedimentary structure are visible only in a few places as illustrated in Figure 8D, i.e. in the center of the model domain where particle tracks are bundled when entering a high conductivity zone. Overall flow velocities are low especially during the low groundwater levels in February 2006.

Note that although the hydraulic conductivity field is complex and heterogeneous, the resulting hydraulic head field is relatively smooth. In contrast, the local velocity field, as reflected by the movement of particles through the system, is quite complex and reflects more clearly the heterogeneity of the system.

Water budgets

The total flow budget was calculated for each sedimentary structure type. However, only those model layers were taken into account which do not dry out during the modeling process. The evaluation was limited to layers seven to eleven in model calculations of the boundary condition of March 23, 2003 and October 28, 2004. Due to low groundwater levels of the boundary condition on February 16, 2006, the evaluation was restricted to layers eight to eleven only.

Figure 9 illustrates the relative amounts of flow budgets through the individual sedimentary structure types for one simulation of heterogeneously and uniformly distributed aquifer parameters. Note that the groundwater mainly flows through the GG and BG sedimentary structure types. As regards the heterogeneous distribution of aquifer parameters, the flow budgets of the more conductive sedimentary structure types OW and OW/BM are higher than those of the corresponding flow budgets of same cells, revealing uniform distribution of aquifer parameters. Also note that the three modeled boundary conditions show little influence on the overall distribution of the flow budgets.

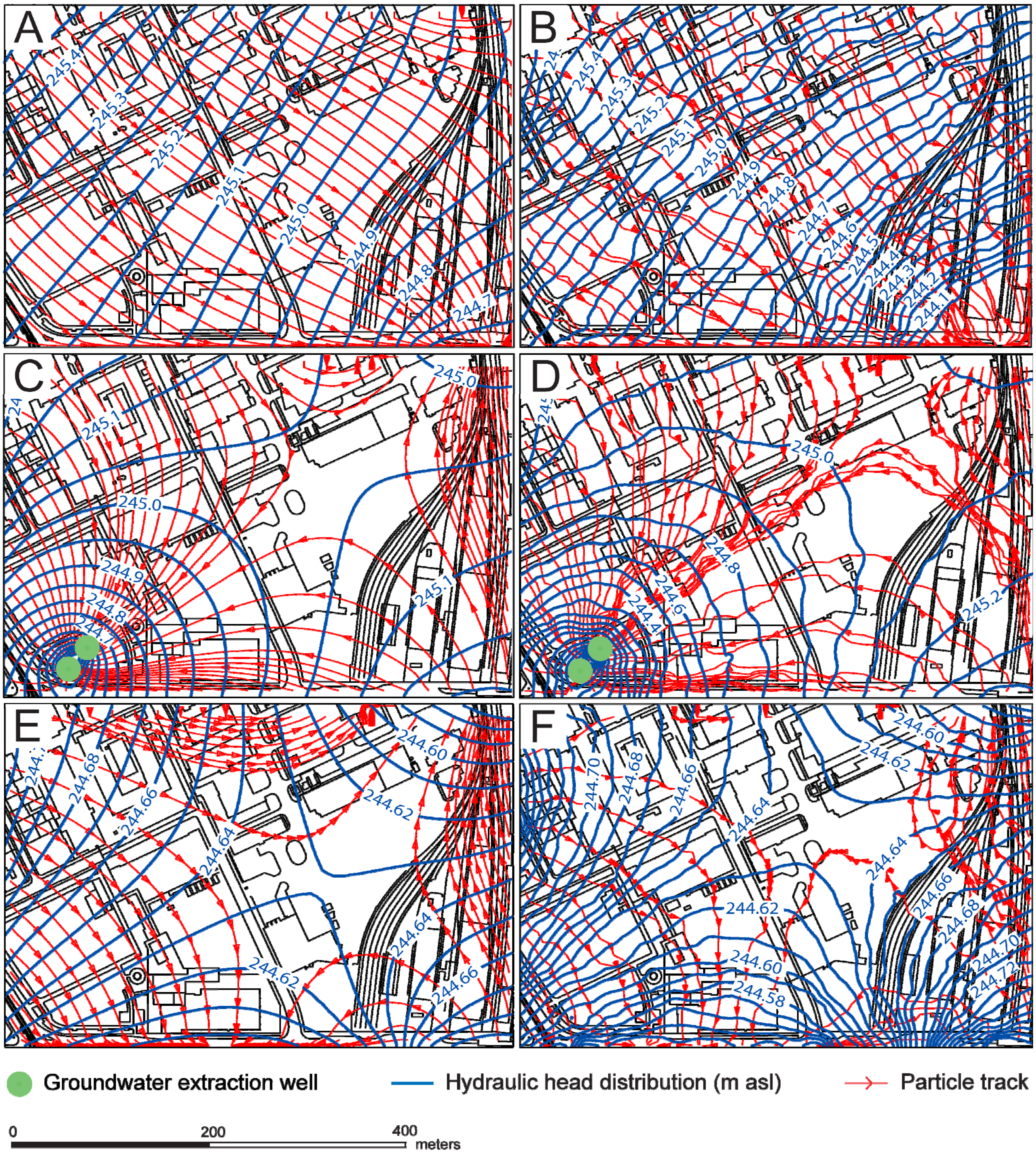

Fig. 8 Visualization of hydraulic head distributions (A, B, C: 0.05 m resolution; D: 0.1 m resolution; E, F: 0.01 m resolution) and flow paths illustrated by particle tracks (distance between two arrow heads indicates 100-day travel time) for three modeled situations for Layer 11. While the results for A, C and E are derived from a uniform distribution of aquifer properties, those for B, D and F are derived from a heterogeneous distribution of aquifer properties

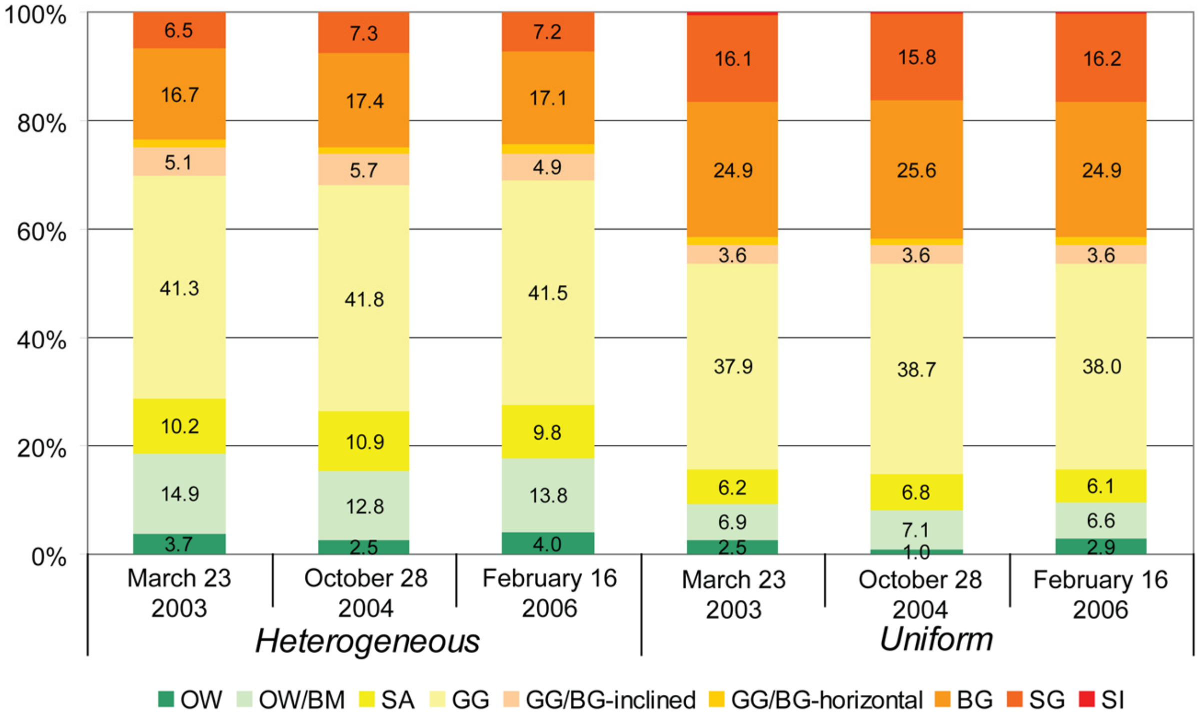

Fig. 9 Relative amounts of flow budgets through the individual sedimentary structure types diagramed for one aquifer heterogeneity simulation and for the uniform distribution of aquifer parameters. To facilitate comparison, relative flow budgets for the uniform distribution were calculated for the same cells as characterized by the sedimentary structure types for the heterogeneity simulation. Water budget values for the following sedimentary structure types were excluded in the graph: SI ranging between 0.1 and 0.5% and GG/BG-horizontal ranging between 1.1 and 1.6%. Refer to chapter 3.2 for the abbreviations

Drill-core layer descriptions generally include mixed information of varying sedimentary structure types (Regli et al. 2002). Moreover, only a small number of indications of OW strata may often be identified in drill-core layer descriptions. Nevertheless, many outcrop observations reveal that OW and OW/BM occur frequently. Consequently, hydrogeological models based on drill-core data may reproduce effective hydraulic conductivities, but they underestimate their standard deviations (Huggenberger and Regli 2006). To assess the influence of larger amounts of sedimentary structure types OW and OW/BM, their relative amount was increased steadily. While the original simulations considered OW and OW/BM amounts of about 5.4%, the linear increase of these sedimentary structure types eventually totaled 54.0%. To allow a comparison of the different simulations and resulting flow budgets, the northern, fixed head model boundary was converted to fixed flow. Figure 10 illustrates the results of these simulations. By increasing OW and OW/BM amounts, a linear influence on the overall distributions of relative flow budgets was observed:

$$y = 6.05x + 13.61 \; (R^2 = 0.99) . \qquad (4.3.1)$$

However, considering merely OW, results in an increase in relative flow budgets capable of being described by a power law:

$$y = 2.74e^{0.24x} \; (R^2 = 0.97) . \qquad (4.3.2)$$

It should be noted, that these equations are adequate for this case study only and will differ from those of other case studies.

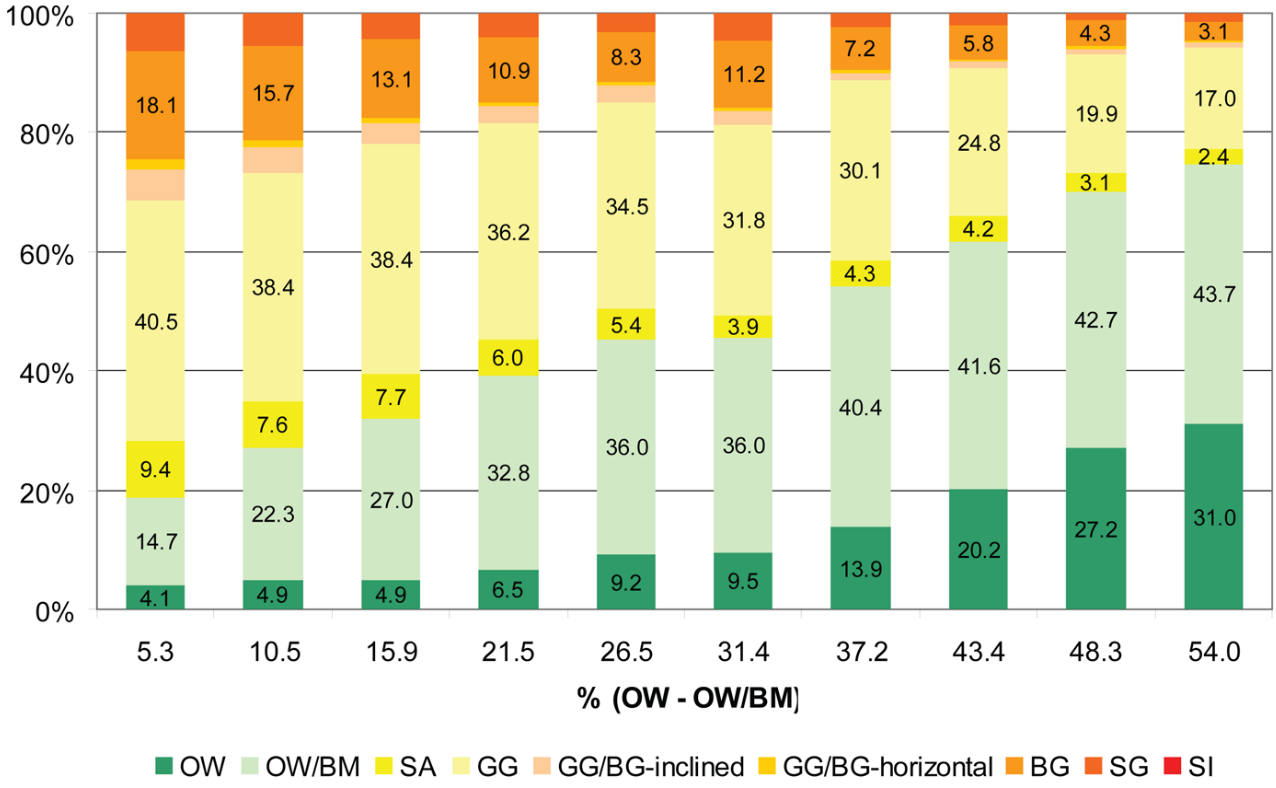

Fig. 10 Relative amounts of flow budgets through the individual sedimentary structure types diagrammed for the modeled boundary condition on March 23, 2003. The graph illustrates the distribution of flow budgets assuming a successive increase in relative abundance of the sedimentary structure types OW and OW/BM. Note that by increasing the relative amounts of water budgets for both OW and OW/BM, a linear influence is observed. However, an increase in the relative amounts of water budgets for OW alone results in an exponential influence. Water budget values for the following sedimentary structure types were excluded in the graph: SI ranging between 0 and 0.1%; SG ranging between 1.3 and 6.3%; GG/BG-horizontal ranging between 0.2 and 1.8% and GG/BG-inclined ranging between 1.0 and 5.0%. Refer to chapter 3.2 for the abbreviations

Flow velocities

As a result of the high spatial variability of aquifer parameters, heterogeneities in the aquifer structure strongly affect transport behavior and also lead to a corresponding variability in the distribution of flow velocities through the individual sedimentary structure types. In fact, heterogeneity leads to small head variations, whereas those of velocities and travel time to large ones, as instinctively prognosticated when considering a layered aquifer with flow parallel to the bedding: although vertical heterogeneity does not produce any variations in the head distribution over the vertical, velocities may vary significantly from one layer to the next (de Marsily et al. 2005). The wide range of flow velocities is caused by uncertainty in hydraulic conductivity and flow paths. De Marsily et al. (1998) produced similar results but used particle arrival times to explain this effect.

The calculated average velocities v_x, v_y and v_z (see section 3.4.2) were evaluated for each sedimentary structure type. However, only those model layers were taken into account that do not dry out during the modeling process or do not comprise most of the inactive cells. The evaluation was thus restricted to layers eight to eleven. Figure 11 illustrates the distributions of flow velocities for boundary conditions on October 28, 2004.

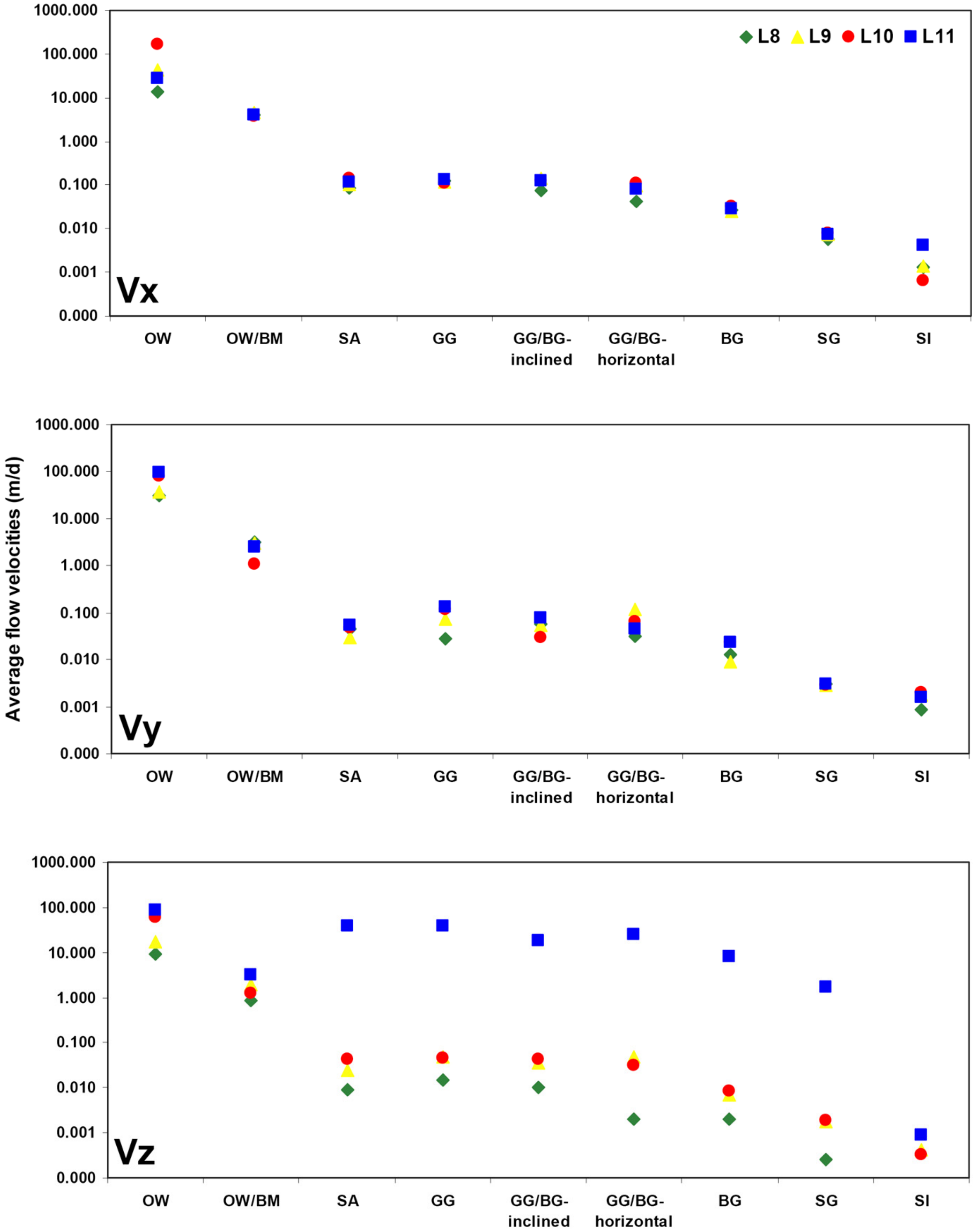

Fig. 11 Distributions of flow velocities for the boundary conditions on October 28, 2004. Note that the velocity values for the specific sedimentary structure types and the various layers lie within the same range, thereby revealing characteristic flow velocities for sedimentary structure types. Note also that the relative high vertical flow velocities in Layer 11 can be attributed to groundwater extractions. Refer to chapter 3.2 for the abbreviations

A comparison was established between the horizontal (vx and vy) and vertical (vy) flow velocities for boundary conditions on March 23, 2003 and October 28, 2004. Highest average flow velocities on March 23, 2003 were observed in the sedimentary structure types OW and OW/BM with horizontal velocities ranging from 32.0 to 57.3 md^{-1} and 4.3 to 6.1 md^{-1}, and averaging 42.9 and 5.2 md^{-1}. Lowest horizontal flow velocities were observed in the sedimentary structure types SG and SI with velocities ranging from 7.0E-3 to 8.9E-3 md^{-1} and 2.0E-4 to 5.4E-3 md^{-1}, and averaging 7.9E-3 and 3.3E-3 md^{-1}. An evaluation of vertical flow velocities reveals highest flow velocities in the sedimentary structure types OW and OW/BM with velocities ranging from 22.8 to 79.6 md^{-1} and 2.6 to 5.8 md^{-1}, and averaging 50.8 and 4.4 md^{-1}. Lowest vertical flow velocities are observed in the sedimentary structure types SG and SI with velocities ranging from 1.8E-3 to 4.8E-3 md^{-1} and 1.1E-4 to 3.1E-3 md^{-1}, and averaging 3.6E-3 and 1.7E-3 md^{-1}. Highest flow velocities on October 28, 2004 were again observed in the sedimentary structure types OW and OW/BM with velocities ranging from 13.5 to 163.5 md^{-1} and 1.1 to 4.6 md^{-1}, and averaging 61.7 and 3.3 md^{-1}. Lowest horizontal flow velocities were observed in the sedimentary structure types SG and SI with velocities ranging from 2.9E-3 to 7.8E-3 md^{-1} and 6.4E-4 to 4.1E-3 md^{-1}, and averaging 5.0E-3 and 1.7E-3 md^{-1}. The results of October 28, 2004 further reveal considerable differences in flow velocities of the individual layers. An evaluation of vertical flow velocities is difficult due to the varying influence of groundwater abstraction, especially in layer eleven.

A sedimentary structure type-dependent flow velocity can be observed for both boundary sets. A comparison of the results of both boundary sets reveals that the velocity values for the specific sedimentary structure type and the various layers lie within the same range. As foreseen, this reveals characteristic flow velocities for sedimentary structure types and boundary conditions. However, compared to the results of October 28, 2004, the results of March 23, 2003 further indicate that this range is narrower and the differences more distinct between flow velocities of the individual layers. This can be attributed to the more balanced boundary conditions on March 23, 2003. However, although flow velocities are noticeably affected by the various boundary conditions, their distribution is dominated by the individual sedimentary structure type.

5 Conclusions

This case study was conducted in an urban area recently subjected to major changes in groundwater flow regime caused by subsurface tunnel road construction. Groundwater investigations generally focus on the required drawdown and dimensioning of construction site drainages. However, this approach is unsatisfactory as contamination is an additional factor to be considered in urban areas. To adequately evaluate potential mobilizations of contaminants, focus should be placed on aquifer heterogeneity. The presented methods, particularly their combination, exemplify quantitative data fusion as a practical tool for urban hydrogeology. The applied techniques allow integrating data of different quality into groundwater models. Furthermore, the potentials and limitations of this approach have also been identified. Since sedimentological information on the subsurface is often restricted to drill-cores, data on outcrops and geophysical surveys in urban areas is generally scarce. This may lead to one of the main constraints in geostatistical approaches, as it fails to derive connectivity properties of the sedimentary structures and generates disconnected ellipsoids of either high or low conductivity. Future work should focus on the distribution and connectivity of high-permeability sedimentary structure types (e.g. Proce et al. 2004).

The dynamics of the groundwater flow regime under changing spatial and temporal constraints were simulated and evaluated on the basis of a regional groundwater model. To prevent permanent negative impacts on the groundwater flow regime, particularly on groundwater quantity and quality, as well as irreversible deterioration of aquifer systems, recommendations for optimizing groundwater management are proposed and structural alternatives provided. Optimal dimension, operation and selection of sites appropriate for recharge wells and culverts are evaluated and their applicability verified. The modeling results are used to improve the groundwater monitoring system subsequently adapted to project requirements. Aside from managing various groundwater extraction and recharge operations, adequate groundwater protection (groundwater flow regime and quality) was also ensured. The groundwater management system also helped to identify changes in groundwater chemistry. Negative effects for industrial groundwater use could be minimized. So far, installation of supplementary recharge or interception wells was not necessary to ensure groundwater supply, or to prevent attracting contaminated groundwater. Simulation results reveal that the subsurface construction after completion does not significantly alter groundwater budgets or groundwater flow velocities.

Furthermore, as regards contaminant transport on a local scale, the applied techniques present an approach to quantify the effect of groundwater flow budgets and velocities in the individual hydrofacies. Obviously, groundwater flow in heterogeneous media occurs largely through interconnected highly permeable geological aquifer structures. Together with hydrological and operational boundary conditions they govern the groundwater flow and transport regime. However, the relative amounts of groundwater budgets through the individual hydrofacies do not appear to alter significantly for the various boundary conditions investigated. Moreover, single hydrofacies and their relative occurrence determine the distribution of groundwater budgets. Furthermore, an underestimation of the occurrence of highly permeable OW and OW/BM sedimentary structures and shift of relative amounts of groundwater budgets through the various sedimentary structure types was investigated.

When investigating contaminant transport, focus should be placed on relevant boundary conditions and origin, particularly on the depth of relevant substances. Modeling results reveal that the different sedimentary structures and simulated layers vary considerably in water budgets, flow paths and velocities. Investigations by Tompson and Gelhar (1990), Frind et al. (1988) and others reveal that heterogeneity dominates the movement of a contaminant plume at an early stage, and that the initial configuration of the plume influences its long-term evolution.

The outcrop in the investigation area clearly demonstrated the size of the relevant sedimentary structure types which are in the order of several tens to 100 m. A lithological description (nature and shapes of sedimentary structure) is required to describe as accurately as possible heterogeneity in sedimentary structure models and their resulting properties. Optimized acquisition of geological recording of drill-core data and less destructive drilling methods (drill cores in plastic liners) could significantly improve the characterization of sedimentary structure types. This includes more comprehensive hydrogeological investigations, i.e. a systematic collection and interpretation of drill-cores as a function of lithofacies as well as hydraulic and hydrogeochemical parameters. Such innovations could involve tailored exports from geological databases such as separation of sedimentary lithocomponents into light and dark-colored components. Since color variations are assumed to be an indicator of organic carbon content, they influence sorption capacities and sorption kinetics of the material. These informations are of prior importance considering groundwater transport processes.

However, numerous innovative technologies proposed for groundwater investigations face enormous implementation problems. As successful application is often questioned, conventional and more expensive approaches, such as extensive analytical programs, are favored. Applied and problem-oriented investigations should focus on a more sustainable management of groundwater resources in a sensitive urban environment. The described integrated approach, incorporating sedimentological and geostatistical analyses as well as groundwater modeling, may assist in meeting the challenges presented by such a sensitive urban environment and lead to more target-oriented remediation strategies. These include an evaluation of contaminated sites, risk assessment of waste disposal and parameterization of numerical groundwater models, thereby leading to the development of new approaches for complex practical problems. Although the results of this study are case-specific, the overall conceptual approach and methodologies used may be directly transferred to other urban areas.

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References

Adams EE, Gelhar LW (1992) Field study of dispersion in a heterogeneous aquifer, 2, Spatial moment analysis. Water Resour Res 28:3293-3308

Allen JRL (1978) Studies in fluviatile sedimentation: An exploratory quantitative model for the architecture of avulsion-controlled alluvial suits. Sed Geol 21:129-147

Anderson MP, Aiken JS, Webb EK, Mickelson DM (1999) Sedimentology and hydrogeology of two braided stream deposits. Sed Geol 129:187-199

Anderson MP, Woessner WW (1992) Applied groundwater modeling. Academic Press, San Diego

Anderson MP (1989) Hydrogeologic sedimentary structure models to delineate large-scale spatial trends in glacial and glaciofluvial sediments. Geological Society of America Bulletin 101:501-511

Ashmore P (1993) Anabranch confluence kinetics and sedimentation processes in gravel braided streams. In: Best JL, Bristow CS (eds) Braided Rivers, Geological Society Spec Publ 75:129-146

Ashmore P, Parker G (1983) Confluence scour in coarse braided streams. Water Resour Res 19:392-402

Ashworth PJ, Best JL, Jones M (2004) The relationship between sediment supply and avulsion frequency in braided rivers. Geol 32:21-24

Ashworth PJ, Best JL, Peakall J, Lorsong JA (1999) The influence of aggradation rate on braided alluvial architecture: field study and physical scale modelling of the Ashburton River gravels, Canterbury Plains, New Zealand. In: Smith ND, Rogers J (eds). Fluvial Sedimentology VI. Spec Publ Int Ass Sediment 28:333-346

Barrash W, Clemo T (2002) Hierarchical geostatistics and multifacies systems. Boise Hydrogeophysical Research Site, Boise, Idaho, Water Resour Res 38(10):1196

Boggs MJ, Young SC, Beard LM, Gelhar LW, Rehfeld, KR, Adams, EE (1992) Field study of dispersion in a heterogeneous aquifer. 1. Overview and site description. Water Resour Res 28(12):3281-3291

Bridge JS, Lunt IA (2006) Depositional models of braided rivers. In: Sambrook-Smith GH, Best JL, Bristow CS, Petts GE (eds). Braided Rivers: Process, Deposits, Ecology and Management. IAS Special Publication 36:11-50

Bridge JS (1993) The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: Best JL, Bristow CS (eds) Braided Rivers. Geological Society Spec Publ 75:13-71

Brierley GJ (1991) Bar sedimentology of the Squamish river, British Columbia: definition and application of morphostratigraphic units. J of Sed Petr 61:211-225

Carle SF, LaBolle EM, Weissmann GS, Van Brocklin D, Fogg GE (1998) Conditional simulation of hydrofacies architecture: A transition probability / Markov approach. In: Fraser GS, Davis JM (eds). Hydrogeologic Models of Sedimentary Aquifers. SEPM, Concepts in Hydrogeology and Environmental Geology, 1:147-170

Carrera J (1993) An overview of uncertainties in modeling groundwater solute transport. J of Con Hyd 13(1-4):23-48

Chiang W-H (2005) 3D-Groundwater Modeling with PMWIN – A simulation system for modeling groundwater flow and transport processes. 2nd edn Springer, Berlin, 397pp

Church M (2002) Geomorphic thresholds in riverine landscapes. First international symposium on landscape dynamics of riverine corridors, Ascona, Switzerland, March 2001. Freshwat Biol 47:541-557

Dagan G (2002) An overview of stochastic modelling of groundwater flow and transport. From theory to applications. EOS (Trans Am Geophys Soc), 83/53:621-625

de Marsily G, Delay F, Gonçalvès J, Renard P, Teles V, Violette S (2005) Dealing with spatial heterogeneity. Hydrogeol J 13:161-183

de Marsily G, Schafmeister MT, Delay F, Teles V (1998) On some current methods to represent the heterogeneity of natural media in hydrogeology. Hydrogeol J 6:115-130

Deutsch CV, Journel AG (1998) GSLIB: Geostatistical software library and user's guide, 2nd edn Oxford University Press, Oxford, 369pp

Deutsch CV, Wang L (1996) Hierarchical object-based stochastic modelling of fluvial reservoirs. Math Geol 28:857-880

Environmental Modeling Systems Inc. (2006) GMS, groundwater modeling system v6.0. http://www.ems-i.com

Flynn R (2003) Virus transport and attenuation in perialpine gravel aquifers. PhD. Thesis, University of Neuchâtel, Switzerland, 178pp

Fogg GE, Noyes CD, Carle SF (1998) Geologically based model of heterogeneous hydraulic conductivity in an alluvial setting. Hydrogeol J 6:131-143

Frind EO, Sudicky EA, Schellenberg SL (1988) Micro-scale modelling in the study of plume evolution in heterogeneous media, In: Custodio E et al. (eds), Groundwater Flow and Quality Modelling. Reidel, Dordrecht:439-461

Gelhar LW (1986) Stochastic subsurface hydrology from theory to applications. Water Resour Res 22:135S-145S

Graf H, Schäfer W (2002) Simulation des Nitrattransports im Einzugsgebiet eines Wasserwerks. Grundwasser 4/2002:233-242

Heller P, Paola C (1992) The large-scale dynamics of grain-size variation in alluvial basins, 2: Application to syntectonic conglomerate. Basin Res 4:73-90

Hill MC, Banta ER, Harbaugh AW, Anderman ER (2000) MODFLOW-2000, the U.S. Geological Survey. Modular Ground-Water Model—User guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs: U.S. Geological Survey Open-File Report 00-184, 210 pp

Huggenberger P, Regli C (2006) A sedimentological model to characterise braided river deposits for hydrogeological applications. In: Sambrook-Smith GH, Best JL, Bristow CS, Petts GE (eds). Braided Rivers: Process, Deposits, Ecology and Management. IAS Special Publication 36:51-74

Huggenberger P, Epting J, Spottke I, Regli C, Zechner E (2006) Fluss-Grundwasser-Interaktion, Interreg III Projekt A MoNit: Modellierung der Grundwasserbelastung durch Nitrat im Oberrheingraben, Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe

Huggenberger P, Aigner T (1999) Introduction to the special issue on aquifer-sedimentology: problems, perspectives and modern approaches. Sedimentary Geology 129:179-186

Huggenberger P, Siegentaler C, Stauffer F (1988) Grundwasserströmung in Schottern: Einfluss von Ablagerungsformen auf die Verteilung der Grundwasserfliessgeschwindigkeit. Wasserwirtschaft 78:202-212

Journel AG, Huijbregts CJ (1989) Mining Geostatistics. Academic Press, New York

Jussel P, Stauffer F, Dracos T (1994) Transport modeling in heterogeneous aquifers: 1. statistical description and numerical generation of gravel deposits. Water Resour Res 30(6):1803-1817

Kirchhofer RT (2006) GeoData. Geological Data-base of the city of Basel and northwestern Switzerland

Klingbeil R, Kleineidam S, Asprion U, Aigner T, Teutsch G (1999) Relating lithofacies to hydrofacies structure: outcrop-based hydrogeological characterisation of Quaternary gravel deposits. Sed Geol 129:299-310

Koltermann CE, Gorelick SM (1996) Heterogeneity in sedimentary deposits: A review of structure-imitating, process-imitating, and descriptive approaches. Water Resour Res 32:2617-2658

Mackay DM, Freyberg DL, Roberts PV, Cherry JA (1986) A natural gradient experiment on solute transport in a sand aquifer. 1. Approach and overview of plume movement. Water Resour Res 22(13):2017-2029

Maxwell RM, Pelmulder SD, Tompson AFB, Kastenberg WE (1998) On the development of a new methodology for groundwater-driven health risk assessment. Water Resour Res 34(4): 833-847

Maxwell RM, Kastenberg WE (1999) Stochastic environmental risk analysis: an integrated methodology for predicting cancer risk from contaminated groundwater. Stochastic Environmental Research and Risk Assessment 13:27-47

McDonald MG, Harbaugh AW, Banta ER, Hill MC (2000) Modflow-2000. The U.S. geological survey modular ground-water model-user guide to modularization concepts and the ground-water flow process. US Geological Survey Open File Report 00-92

McKenna SA, Poeter EP (1995) Field example of data fusion in site characterization. Water Resour Res 31:3229-3240

Miall AD (1985) Architectural-element analysis: A new method of sedimentary structure analysis applied to fluvial deposits. Earth-Science Rev 22:261-308

Miall AD (1978) Lithofacies types and vertical profile models in braided rivers: a summary. In: Miall AD (ed), Fluvial Sedimentology. Can Soc Pet Geol Mem 5:605-625

National Research Council (1990) Groundwater models: Scientific and regulatory applications. National Academy Press, Washington, DC

Nowak W, Cirpka OA (2006) Geostatistical inference of hydraulic conductivity and dispersivities from hydraulic heads and tracer data, Water Resour Res 42(8)

Paola C, Heller P, Angevine C (1992) The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory. Basin Res 4:73-90

Proce CJ, Ritzi RW, Dominic DF, Dai Z (2004) Modeling multiscale heterogeneity and aquifer interconnectivity. Ground Water 42(5):658-670

Rauber M, Stauffer F, Huggenberger P, Dracos T (1998) A numerical three-dimensional conditioned/unconditioned stochastic sedimentary structure type model applied to a remediation well system. Water Resour Res 34(9):2225-2233

Regli C, Rosenthaler L, Huggenberger P (2004) GEOSSAV: a simulation tool for subsurface applications. Computers & Geosciences 30:221-238

Regli C, Rauber M, Huggenberger P (2003) Analyses of aquifer heterogeneity within a well capture zone, comparison of model data with field experiments: A case study from the river Wiese, Switzerland. Aquatic Sciences 65:111-128

Regli C, Huggenberger P, Rauber M (2002) Interpretation of drill-core and georadar data of coarse gravel deposits. J of Hydrol 255:234-252

Rehfeldt KR, Boggs JM, Gelhar LW (1993) Field study of dispersion in a heterogeneous aquifer, 3, Geostatistical analysis of hydraulic conductivity. Water Resour Res 28:3309-3324

Rentzel P (1994) Geologisch-bodenkundliche Untersuchungen an den Niederterrassenfeldern bei Basel unter besonderer Berücksichtigung der späteiszeitlichen Fundstelle Basel-Gasfabrik, Jahresbericht der Archäologischen Bodenforschung des Kantons Basel-Stadt:31-52

Rubin Y, Lunt IA, Bridge JS (2006) Spatial variability in river sediments and its link with river channel geometry. Water Resour Res 42(6)

Schulze-Makuch D, Carlson DA, Cherkauer DS, Malik P (1999) Scale dependency of hydraulic conductivity in heterogeneous media. Ground Water 37(6):904-919

Siegenthaler C, Huggenberger P (1993) Pleistocene Rhine gravel: deposits of a braided river system with dominant pool preservation. In: Best JL, Bristow CS (eds) Braided Rivers. Geological Society Spec Publ 75:147-162

Sudicky EA (1986) A natural gradient experiment on solute transport in a sand aquifer: Spatial variability of hydraulic conductivity and its role in the dispersion process. Water Resour Res 22(13):2069-2082

Teles V, Delay F, de Marsily G (2004) Comparison of genesis and geostatistical methods for characterizing the heterogeneity of alluvial media: groundwater flow and transport simulations. J Hydrol; 294(1–3):103-121

Teutsch G, Kobus H (1990) The environmental research field site „Horkheimer Insel“: Research Program, instrumentation and first results. J Hydraulic Res 28(4):491-501

Tompson AFB, Gelhar LW (1990) Numerical simulation of solute transport in three-dimensional randomly heterogeneous porous media. Water Resour Res 26(10): 2541-2562

Wagner U, Huggenberger P, Schaub D, Thater M (2001) Interreg III, Erkundung der Grundwasserleiter und Böden im Hochrheintal. Herausgeber: Landratsamt Waldshut, pp101

Webb EK, Anderson MP (1996) Simulation of preferential flow in three-dimensional, heterogeneous conductivity fields with realistic internal architecture. Water Resour Res 32:533-545

Webb EK (1994) Simulating the three-dimensional distribution of sediment units in braided-stream deposits. J Sediment Res B64:219-231

Weissmann GS, Carle SF, Fogg GE (1999) Three-dimensional hydrofacies modeling based on soil surveys and transition probability geostatistics. Water Resour Res 35(6):1761-1770

Part III

Groundwater Protection in Urban Areas Incorporating Adaptive Groundwater Monitoring and Management

Reconciliation of Water Engineering Measures along Rivers

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Groundwater protection in urban areas incorporating adaptive groundwater monitoring and management

Reconciliation of water engineering measures along rivers

Jannis Epting[a], Christian Regli[b], Peter Huggenberger[a]

This study investigates groundwater systems and their usage related to interference during flood events and water engineering activities along rivers in urban areas. In the context of river training for flood protection a multitude of river engineering measures are currently planned in Europe. Due to the experience gained from hazardous flood events in the last twenty years, most countries have acquired a more comprehensive view of rivers. This includes the consideration of processes at the catchment scale as well as ecological aspects. Multiple interests concerning groundwater use and protection challenge the intentions of water engineering and groundwater protection schemes that can only be solved by simultaneously considering all of the various interests.

Extending current protection concepts with process-based approaches that consider the interaction between surface and subsurface waters could enhance sustainable development of groundwater resources. Knowledge of the composition of groundwater quality, including an adequate consideration of variable hydrologic boundary conditions and fluctuations of loads in rivers, is therefore of great importance.

Previously, decisions concerning impacts on urban groundwater flow regimes were typically taken at the level of the individual project. However, it is the sum of all impacts, and their interaction in time and space, that has to be considered. To accomplish this, it is necessary to develop instruments that facilitate to adequately quantify the consequences of the cumulative effects of numerous decisions concerning the groundwater flow regime and groundwater quality. At the same time, system profiles must be identified together with the delineation of boundaries and specific targets that lead to defined overall goals for specific groundwater areas.

These instruments form part of groundwater management systems, comprising among others, the setup of groundwater observation systems, high resolution numerical groundwater modeling, and the development and evaluation of scenarios. Applying methods of scenario development facilitates the assessment of effects of water engineering measures on riverine groundwater and its usage for drinking water. The implementation of these process-based approaches is illustrated by selected examples in the agglomeration of the city of Basel, Switzerland.

Keywords: Urban groundwater, Groundwater management, Groundwater protection, Water engineering, River restoration, Protection concepts, Scenario development

1 Introduction

Groundwater in urban areas is under increasing pressure: According to the European Environmental Agency about 70% of the European population lives in urban areas, which cover in total about 25% of the total territory (EEA 1999). With over 40% of the water supply of Western and Eastern Europe and the Mediterranean region coming from urban aquifers, efficient and cost-effective management tools for this resource are essential to maintain the quality of life and ensure that water is available for use by future generations (Eiswirth et al. 2003; Eiswirth et al. 2004). Sustainable use of soil and groundwater resources and protection and conservation of their quality are hence a key issue of European environmental policy and an enormous challenge for European research (Prokop 2003).

The challenge to develop and implement integrated and adaptive water management in urban areas requires innovative approaches that take into account the full complexity of the systems to be managed (Pahl-Wostl 2006). The basic principles of these approaches, including groundwater monitoring and modeling, are already established (Eiswirth et al. 2003; Fatta et al. 2002; Pahl-Wostl et al. 2005). However, their application in urban planning processes has rarely been accomplished.

Although legal frameworks for groundwater protection as well as groundwater policy strategies have continuously been adjusted in the last decades, considerable damage to groundwater flow regimes still occurs. There are several reasons for this: (1) more attention is paid to purely technological problems concerning groundwater management rather than to issues dealing with sustainable groundwater use; (2) site selection for extraction wells has been undertaken under outdated legal frameworks and would not be approved today because more restrictive laws pertaining to groundwater, as well as changed perceptions and policy concerning groundwater, now apply; (3) realization of groundwater protection is still oriented mainly towards documentation of changes in the groundwater flow regime and groundwater quality, whilst less attention is paid to the prediction of future demands and to the management of groundwater resources; and (4) until now, the impacts of engineering measures on groundwater systems were only regarded as solitary limited impacts and examination of the interactions between them and other activities as well as changing boundary conditions were not attempted. The term ***groundwater flow regime*** includes all groundwater flow patterns, velocities and budgets for a defined region in a temporal context.

The purpose of this paper is to understand and predict the cumulative effects of the numerous single impacts on groundwater resources during flood protection and river restoration as well as to discuss strategies at the regional scale of the agglomeration of Basel. In a first step of the proposed conceptual approach, current profiles of groundwater systems are identified. Hereby, hydrogeological boundary conditions and already existing or possible impacts concerning the groundwater flow regime are considered. Following the identification of system profiles, specific targets are defined that lead to overall goals for particular groundwater areas and a desired long-term development of urban groundwater resources. As individual targets may interfere with qualitative aspects of groundwater production, techniques that facilitate the comparison of interference must be applied. This can be accomplished by the development of scenarios and the implementation of equivalence and acceptance criteria (Bedford 1996). The conceptual approach could be accomplished by the combination of instruments that facilitate to adequately identify the influences of the various single impacts on the complete system. Core elements of such adaptive groundwater management systems include groundwater monitoring networks and numerical groundwater models. Based on these elements, comparative studies as well as scenario development are focused on predefined development goals. Furthermore, both impacts that only affect the system in its immediate vicinity and impacts with influence on the system on a regional scale have to be investigated (Epting et al. 2006).

Selected examples show how the proposed conceptual approaches can be applied. These focus on river-groundwater-interaction, quality-oriented groundwater monitoring as well as adaptive groundwater management, and consist of the following case studies: (1) groundwater modeling and scenario development along the river Wiese, suggesting differentiated solutions when considering river restoration in urban areas; (2) groundwater modeling and scenario development along the river Birs suggesting extensive groundwater monitoring before, during and after water engineering measures; and (3) data analysis from these monitoring programs during flood events along the river Birs, including the results from transient groundwater modeling. Whereas the results from examples 1 and 3 are derived from already completed investigations, example 2 is an investigation that is currently underway (Fig. 1).

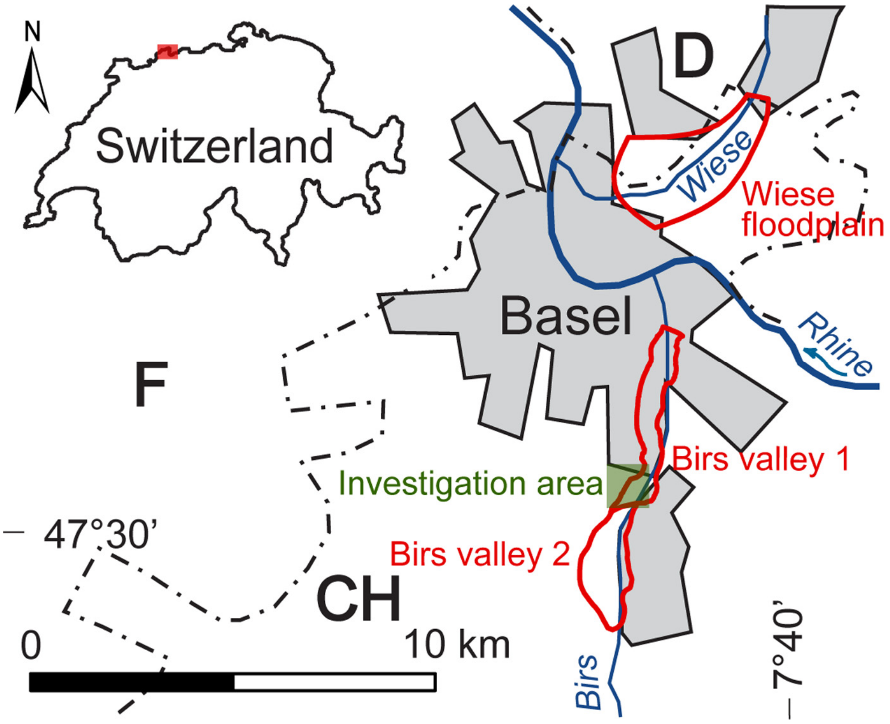


Fig. 1 Investigation areas in the agglomeration of Basel

2 Settings

In Switzerland, about 40% of the drinking water is derived from gravelly aquifers in river valleys. Contemporary flood protection involves objectives on the catchment scale such as the mitigation of effects from hazardous flood events and to provide rivers the required space. At the same time it was recognized that groundwater and the aquifer are habitats of a natural biocenosis that interacts with surface waters. That is the reason why there are currently some efforts to reestablish some of the natural functions of riverine landscapes. A sustainable, integrated water management thus will play an important role on local as well as on regional and national levels.

The interaction of surface and subsurface waters are subject to continuous dynamics involving water budgets, water quality and flow patterns. Riverine groundwater consequently does not have a uniform and constant physical, chemical and biological signature. The composition can temporally vary significantly depending on the dynamics of particular systems and the location within the riverine groundwater. In addition, groundwater quality may be degraded due to sporadic impact loads from surface waters, i.e. caused by urban storm water drainage or by effluents from sewage treatment plants. Furthermore, in Swiss river floodplains an important part of groundwater recharge is formed by artificial recharge (infiltration) of river water.

When rivers are able to exert their natural dynamics, sediment erosion, transport and deposition processes are influenced. As a consequence, the variance of the riverbed permeability is increased temporarily, influencing infiltration rates and groundwater mixing ratios as well as residence times of groundwater of different provenance. A detailed, site-specific understanding, including the consideration of various hydrological boundary conditions as well as careful and comprehensive evaluations of riverine groundwater and its usage, is the basic requirement for water engineering measures along rivers.

Our concept for adaptive groundwater management during water engineering measures is illustrated by selected examples from two rivers that are located in important groundwater production sites in the context of park-like environments in the urban agglomeration of Basel (Fig. 1). The first example is from the floodplain of the river Wiese near the confluence of the river Rhine and covers an area of about 6 km^2. The second and third examples are from the river Birs in the lower Birs valley, and cover an area of about 12 km^2, bounded by tectonically influenced higher ground to the east and to the west. In both areas the drinking water supply competes with other interests and demands such as river training, flood control, recreation and change of land-use.

3 Concepts and methodologies

3.1 Concepts

3.1.1 Resource Protection

The principle of resource protection is based on prevention and reduction, respectively, of contaminant release into the environment and on the conservation of groundwater resources. Protection goals involve the preservation of the physical properties of the aquifer, the aquiclude, the overlying stratum and of the natural hydrodynamics as well as the conservation of the natural chemical composition and biocenosis of groundwater. Criteria for the dimensioning of groundwater protection are among others the formal separation of surface and subsurface water systems, the protection properties of the overlying stratum as well as the groundwater residence times and the minimum distance in the direction of inflow. In accordance with Regli and Huggenberger (2007), important factors or processes of river-groundwater-interaction influencing exploitable aquifers in urban environments are:

(1) Formal separation of surface and subsurface water systems

In the 19th and far into the 20th century the canalization of rivers progressively limited the transversal and vertical interconnectedness of rivers with their floodplains and groundwater together with a reduction of the thickness of the hyporheic zone. Furthermore, the longitudinal connectivity (river continuum) between the various river reaches and the main river was restricted. In many places this lead to an entire loss of the natural dynamics of river systems. Canalization measures lead to uniform flow patterns and increased peak floods. Bank and bed protection prevented the erosion of sediments and, therefore, relocation within the active channel-belt. Mostly this has lead to a lack of bed load and a clogging of the riverbed and the interstitial. As a result, river-groundwater-interactions are reduced along with a decreased filtration of surface water in the pore space of gravel beds (Kozel 2005; Regli and Huggenberger 2006).

(2) Protection properties of the overlying stratum (protective soil cover)

In the context of river-groundwater-interaction the basic concept of protection capacity of the soil cover is not valid. In riverbeds the soil cover is missing and the infiltration rates can show strong spatial and temporal changes according to the leakage, thickness and permeability of the riverbed, the structure and permeability of the river bank and the relationship between flow depth and groundwater table. In addition, in the presented examples river-groundwater-interaction can be reduced or enhanced by riverine groundwater extraction or artificial recharge.

(3) Groundwater residence times

In the past, groundwater extraction wells were often constructed very close to rivers. The reason for the site selection near river banks were high conductivities and storage properties that were favorable for drinking water production. Nowadays, the proximity to the rivers is disadvantageous, because groundwater residence times and filtration capacities are often below or close to threshold values. During flood events a part of the infiltrated river water stays only a few days in the subsurface before it enters the extraction well (Hoehn 2005).

(4) Groundwater mixing ratios

Due to the different infiltration rates, the mixing ratios of riverine groundwater are controlled by dynamic changes. The consideration of transient infiltration and the resulting changes in groundwater mixing ratios during different hydrological conditions enhance the understanding of the interaction processes between surface and subsurface water systems. Furthermore, they are a necessary basis for estimating the risk of pollution for riverine groundwater and its usage, resulting in site-specific, adequate protection measures and adapted groundwater management strategies for extraction wells.

(5) Filter capacity between river and extraction well

The elimination of particles in the subsurface passage due to filtration, sorption and biochemical processes is the determining factor for the microbial quality of groundwater. These processes mainly occur in the soil and subordinate in the non-saturated and saturated zone (BUWAL 2004).

3.1.2 Determination of groundwater system profiles

In the first step of the proposed conceptual approach (Fig. 2), the investigation area has to be delineated, encompassing an inventory of all relevant hydrogeological boundaries characterizing current regional groundwater flow regimes as well as all possible impacts to it. In the next step, the hydrogeological boundaries and impacts have to be identified that may be subject to changes during water engineering measures at specified times. These groundwater system states can be described by profiles, comprising the identification and description of initial profiles, as well as the definition of desirable future profiles. Together with the identification of groundwater system profiles, specific targets can be defined that lead to overall goals for specific groundwater areas and a desired long-term development of urban groundwater resources. Whereas goals focus on a sustainable system development after water engineering measures, targets also comprise groundwater protection issues during the development of projects (Epting et al. 2006).

In order to achieve qualitative and quantitative goals for groundwater systems the present profiles of systems have to be recognized and future profiles have to be defined. Targets to reach these goals could comprise: (1) minimization of changes to the groundwater flow regime during water engineering measures, including the maintenance of (a) position of groundwater divides, (b) longitudinal and lateral extent of capture zones, (c) groundwater budgets for selected cross-sections and (d) groundwater flow fields and velocities; (2) finding technical solutions guaranteeing groundwater quality standards; (3) safeguarding groundwater quality issues during water engineering measures; and (4) ensuring groundwater supply (quantity and quality).

As the individual targets may interfere with each other they may not necessarily lead to a desired overall goal. Therefore, techniques that facilitate the comparison of interferences can be applied. This can be accomplished by the development of scenarios and the implementation of equivalence and acceptance criteria (Bedford 1996). They allow assessment of the technical benefits of the different monitoring or optimization concepts, the development of the groundwater flow regime and the improvement of overall groundwater quality.

Formulated goals for a sustainable development of groundwater systems guide mitigation strategies and refer to defined standards, i.e. natural composition of groundwater or quality standards defined by existing regulations. They also establish a standard against which individual decisions are made. Goals with respect to the groundwater flow regime should be based on knowledge of the physical properties governing the system. General goals could be, e.g.: (1) minimization of river water infiltration during high flows; (2) enhancement of the interaction between surface and subsurface waters; (3) maintenance of groundwater flow regimes; (4) quality-oriented groundwater management; (5) consideration of future groundwater use; and (6) long-term improvement of groundwater quality.

3.2 Methodologies

To identify groundwater system profiles in urban hydrogeological cycles, methodologies to quantify and control these profiles must be developed and applied. This can be achieved by the setup of groundwater management systems that involve following elements among others: (1) groundwater observation systems and (2) setup of numerical groundwater models combined with scenario development. Besides a simple documentation of changes in groundwater quantity and quality, the goal of the management system is to predict undesired developments.

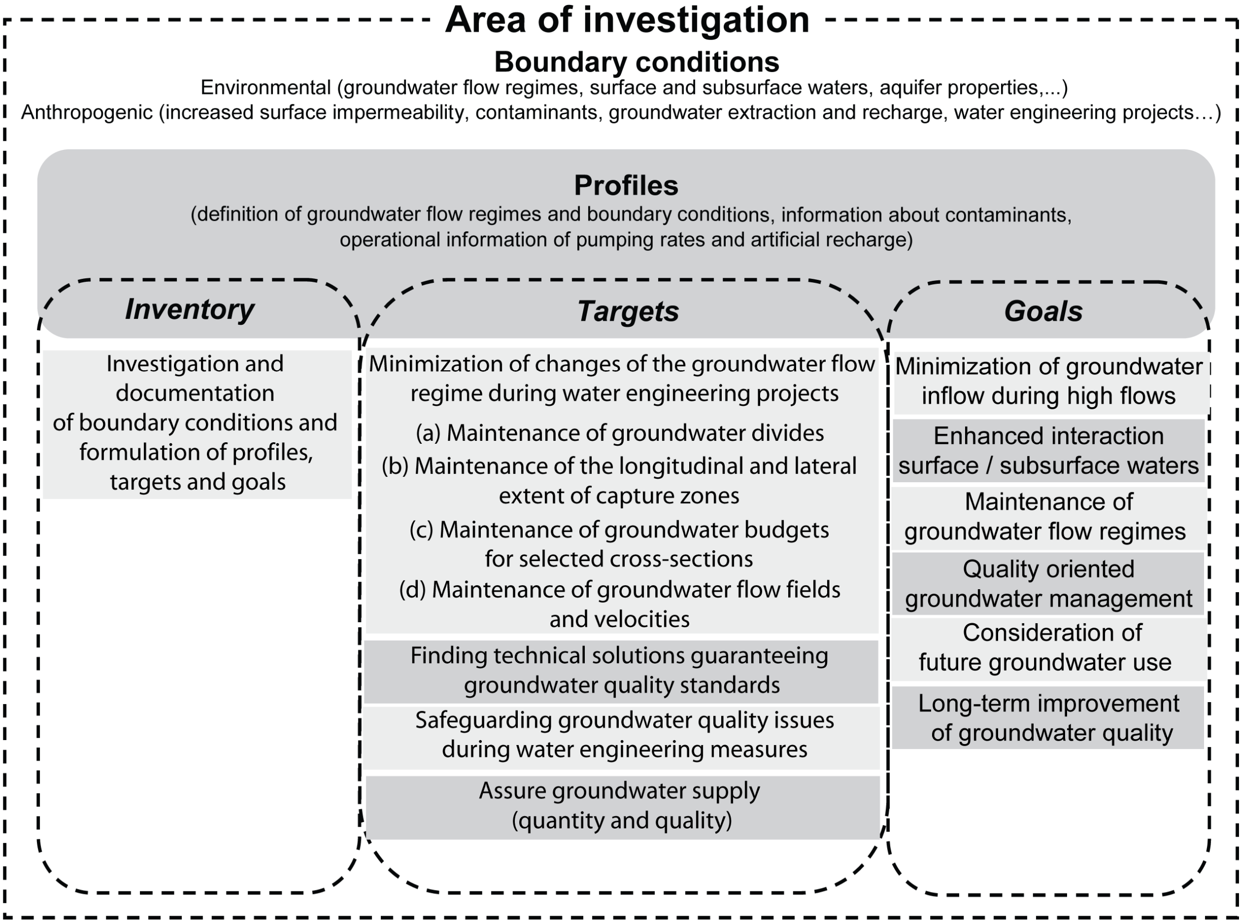


Fig. 2 Conceptual approach

3.2.1 Groundwater modeling

For the illustration of effects of water engineering measures on groundwater flow regimes as well as for the quality-assessments of drinking water supplies, the use of numerical simulation models is suited to several project phases. Groundwater models are valuable tools, to simultaneously include hydrological and hydrogeological as well as operational data and to assess the related groundwater flow regimes with respect to groundwater extraction for drinking water. They facilitate the evaluation of system sensitivities, allowing the investigation of certain parameters and boundary conditions. The combination of groundwater models with hydrodynamic river models, when considering transient problem solving in particular, can be very useful and facilitates the development and application of different scenario techniques.

3.2.2 Scenario development

By means of scenario development, possible impacts of water engineering measures along rivers and from flood events on riverine groundwater and its usage can be acquired and corresponding endangerment and risk assessments can be conducted. Furthermore, these scenarios have to include the relevant operation-states of the extraction wells. Scenarios represent possible real events and event sequences and serve to acquire and illustrate a representative selection of possible dispositions and process sequences. Scenario development also involves the simplification and restriction of essential boundary conditions that affect the system (Regli and Huggenberger 2007).

Scenarios can be assigned to four groups: (1) simulation and optimization of groundwater management strategies; (2) comparison of water engineering measures, with respect to feasibility and impact on water systems during construction and after completion; (3) investigation of changing hydrogeological constraints; and (4) worst case scenarios.

4 Examples

A combination of groundwater modeling and scenario development is exemplified by case studies in the agglomeration of Basel (Fig. 1). To define the specific profiles of groundwater systems high-resolution groundwater models are applied that have been calibrated with time-series of groundwater head data and river stages as well as extraction and recharge rates. In the presented examples, the strongly transient character of river-groundwater-interactions in urban areas is illustrated. Scenario techniques have been developed to assess consequences of decisions and to optimize particular measures such as channel widening and their influence on groundwater quality.

4.1 Wiese floodplain

The first example illustrates the application of scenario techniques for evaluating solutions for river restoration, with emphasis on conflicts with groundwater protection issues.

Before entering the river Rhine, the river Wiese flows through its former floodplain that widens towards the river Rhine. Whereas the position of the active channel migrated considerably at earlier times, the river bank has been fixed for the last 150 years. Due to the vicinity to major urban areas (Basel, Lörrach and Weil) the floodplain area of ca. 700 ha is primarily used as groundwater production area. Plans to reconnect the headwaters with the river Rhine and to provide a habitat for salmon were the main reason for an ongoing controversy on river restoration versus groundwater protection. This was the starting point for the setup of a groundwater monitoring system together with a high resolution groundwater model for the whole area (details are given in Huggenberger et al. 2006). Based on this model the current profile of the groundwater system was determined, including the present risk of river-groundwater-interaction. Based on the modeling tool different scenarios that also allowed increasing the degree of freedom for river restoration measures could be calculated. Scenarios could be grouped into conceptual-, technical- and hydraulical-oriented scenarios (Regli et al. 2004).

Examples of conceptual-oriented scenarios are: (1) investigation, planning and dimensioning of groundwater extraction areas; (2) enhancement of surface water quality; (3) optimization of urban drainage, e.g. sewage drainage into larger receiving streams; (4) reduction of water consumption, which would allow some of the extraction wells to be abandoned; and (5) planning and investigating alternative well locations.

Examples of hydraulic measures and their influence on the river-groundwater-interaction are illustrated in Figure 3 (above). By adequate arrangement and operation of groundwater recharge areas, hydraulic barriers can be generated. Thereby, groundwater recharge areas would function as temporarily wetted floodplain surfaces. However, minimum groundwater residence times must be ensured according to defined threshold values.

Examples of technical measures and their influence on the river-groundwater-interaction are illustrated in Figure 3 (below). The insertion of sealing walls in the vicinity of riverine groundwater wells result in vertical barriers that prevent the infiltration of river water into the aquifer. A more reasonable ecological alternative could be technical solutions such as geo-textiles that decrease infiltration rates as well as amounts of fines and reduce seepage velocities.

Calculated scenarios include the consideration of several minor creeks with adapted infiltration capacities, the relocation of extraction wells and groundwater recharge areas (Fig. 4). For the evaluation of the various scenarios the capture zones of groundwater extraction wells were evaluated and compared. For the consideration of conceptual-oriented scenarios several riverine wells were abandoned and new wells at locations more distant to the river were introduced. This allowed the influence of inflow from infiltrated river water to be reduced.

Figure 4a shows the profile of the groundwater system in its initial state. Figure 4b illustrates the hydraulical-oriented scenario including an alternating operation of possible groundwater recharge areas along the river Wiese. Optimization of capture zones can be achieved by alternative arrangement and operation of groundwater recharge areas and the location of extraction wells, taking into consideration the river hydrograph. Figures 4c&d show the capture zones of the extraction wells, when considering technical-oriented scenarios with vertical and horizontal barriers. The conceptual-oriented scenarios shown in Figure 4e illustrate the influence of reducing and relocating groundwater extraction wells.

4.2 Birs valley 1

The second example illustrates current profiles of a groundwater system in an urban environment that is influenced by artificial groundwater recharge and river-groundwater-interactions as well as agricultural and industrial activities. Extensive analytical groundwater monitoring programs during and after a water engineering project allowed the definition of particular profiles of the groundwater system. This was accomplished by the setup of a transient groundwater model and the evaluation of various scenarios in the Birs valley (Münchenstein, Switzerland; Fig. 5, see Fig. 1 for location). The technical measures focus on flood protection and the protection of the river bank (erosion) as well as on an ecological reassessment of the river Birs. Therefore, a 250 m section of the river board will be restored. Additionally, a groundwater extraction well is located within 50 m of the river. However, the proposed changes should not degrade the quality of extracted groundwater. The groundwater models allowed to define critical river reaches and capture zones of wells during different hydraulic conditions. Based on this information construction measures are proposed that reduce, or at least do not increase, the infiltration of river water into groundwater. A monitoring concept is proposed, that allows detection of changes to the composition of raw water quality in the extraction well during the construction phase. The concept comprises continuous groundwater monitoring in the extraction well by incorporating measuring sensors (electric conductivity, turbidity/particles, UV-extinction, temperature) that should allow detection of the signature of infiltrated river water that only remains a few days in the subsurface. Furthermore, the monitoring program includes extensive analysis of the raw water for selected microbiological contaminations before, during and after the water engineering measures.

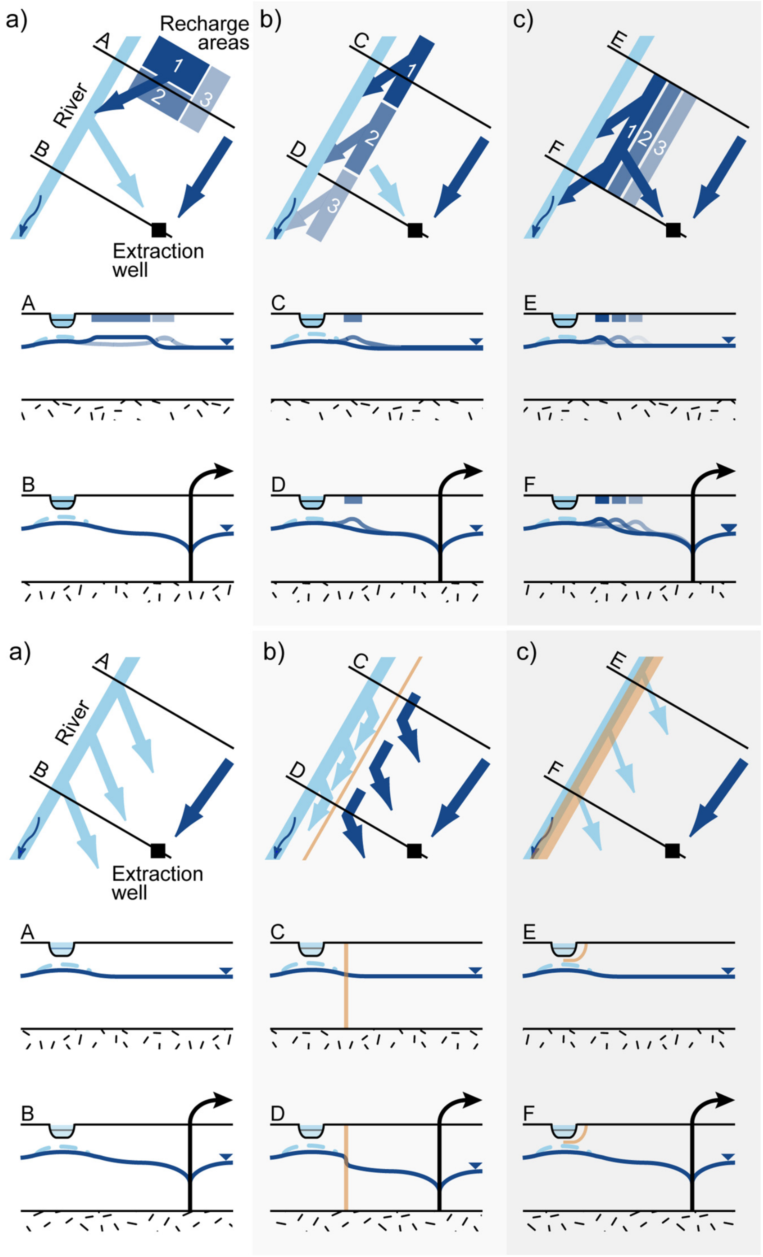


Fig. 3 Above: Hydraulic measures and their influence on river-groundwater-interaction: a) Current status in the Wiese floodplain; b) groundwater recharge areas parallel to the river; c) several groundwater recharge areas parallel to the river. Numbers on the recharge fields indicate alternating time periods of recharge operation. Below: Technical measures and their influence on river-groundwater-interaction: a) Current status in the Wiese floodplain; b) vertical barriers parallel to the river; c) horizontal barriers of single river segments

For groundwater modelling and the developed scenarios, different hydrological and operational boundary conditions are considered. Based on average hydrological boundary conditions, average extraction rates (10 l/s) and average river infiltration rates, several boundary conditions were changed to evaluate the influences on the capture zone of the groundwater extraction well (Fig. 5): (1) For overall average boundary conditions, the inflow to the extraction well is mainly from the agricultural area to the southwest. This is supported by groundwater quality data (high nitrate and microbiological content). (2) When elevating the groundwater extraction rates, the capture zone is widened and includes parts of the river Birs. This might reduce the nitrate concentration but elevates the risk of microbiological impacts. (3) When considering low hydrological boundary conditions, less groundwater is derived from the agricultural area to the southwest whilst more comes from southern areas. This should not change groundwater quality significantly. (4) When elevating the riverbed conductance the capture zone of the groundwater extraction well moves away from the river. Considering average hydrological and operational boundary conditions as well as an elevated riverbed conductance, more groundwater exfiltrates into the river (and no river water infiltrates into the groundwater). Thus no effect on the groundwater quality is expected. (5) During flood events the extracted groundwater is derived from short passages to the river. Thereby significant microbiological vitiations can be expected.

Model Scenarios **Groundwater model**

a) **Initial state**

- River Wiese regulated (blue)
- Existing extraction wells (red) and artificial recharge areas (ligth blue)
- Model boundary (dark green)

b) Scenario 1, hydraulic-oriented

- Wiese widened, several creeks inside the channel belt (brown)
- Artificial recharge areas along the Wiese (ligth blue)
- Abandonement of several extraction wells

c) Scenario 2, technical-oriented

- Wiese widened, several creeks inside the channel belt (brown)
- Barriers along the Wiese (red)
- Abandonement of several extraction wells

d) Scenario 3, technical-oriented

- Wiese widened, several creeks inside the channel belt (brown)
- Sealing of the river bed left hand side of the Wiese (red)
- Abandonement of several extraction wells

e) Scenario 4, conceptual-oriented

- Wiese widened, several creeks inside the channel belt (brown)
- Abandonement of several extraction wells
- Three new wells (marked)

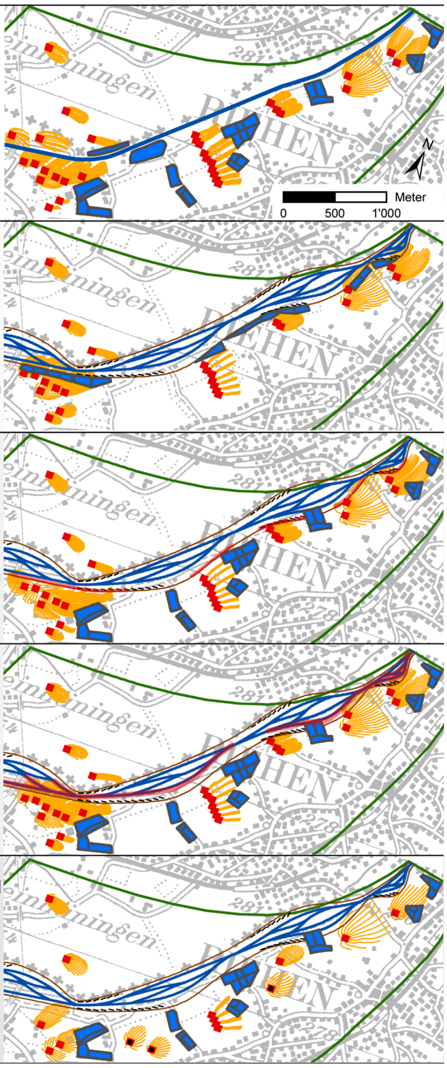
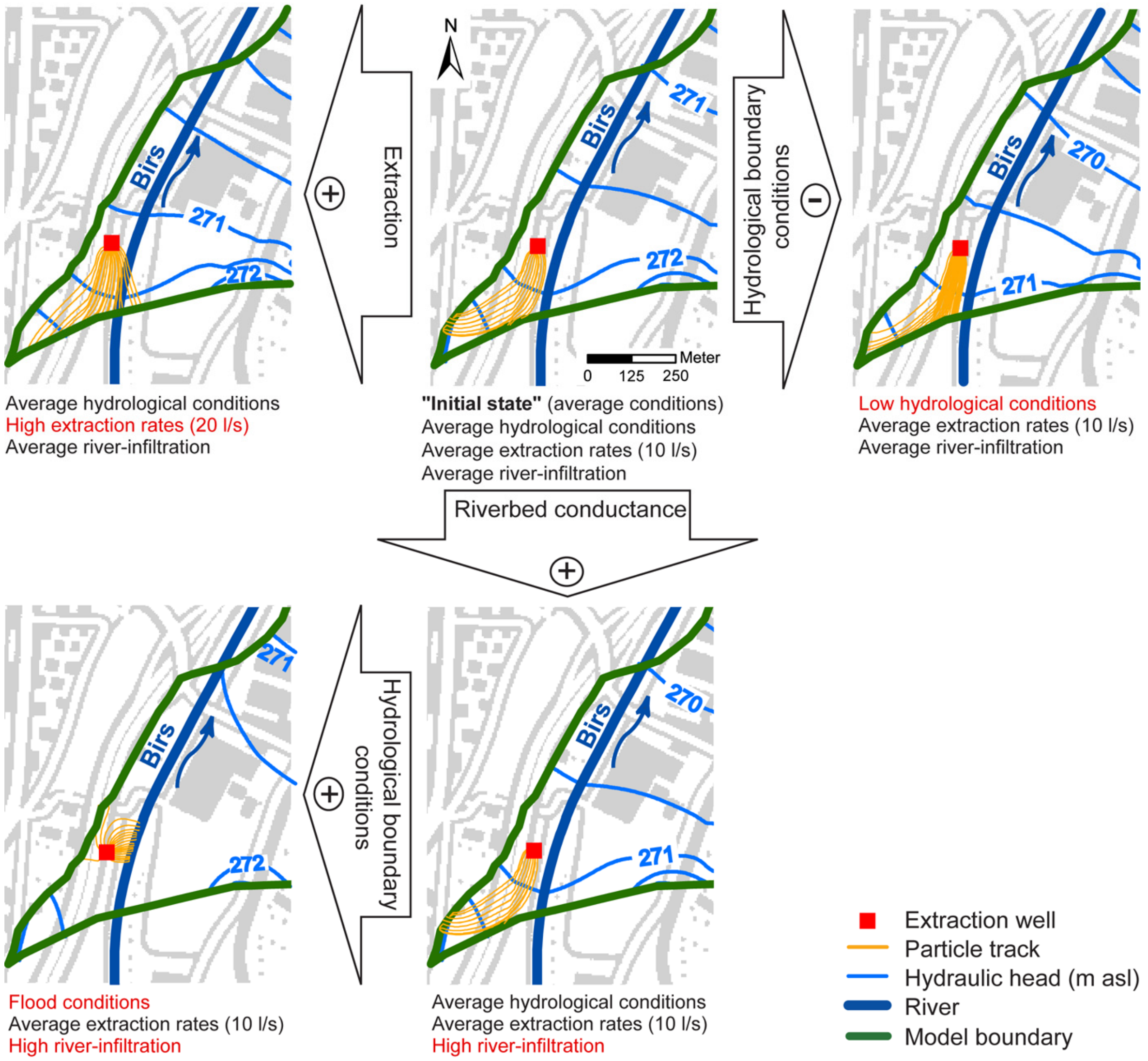


Fig. 4 Model scenarios and capture zones (yellow) of groundwater extraction wells in the Wiese floodplain (10-day-period including a flood event)

4.3 Birs valley 2

The third example illustrates the transient character of river water infiltration (Reinach, Switzerland; details are given in Huggenberger et al. 2006). Figure 6 shows the flow stages at average discharge conditions of the river Birs (Situation A) and during a flood event (Situation B). The effect of the artificial groundwater recharge in the southern part of the model area is distinct. During flood events this groundwater recharge is stopped. Although the hydraulic head distribution is comparable for both discharge situations, the development of the groundwater levels in observation wells 24J20 and 24J22 is more complex (Fig. 7). Preceding the flood event, groundwater levels are beneath the river stage (- 0.4 m) and afterwards above the river stage (+ 0.6 m). During the flood event the potential difference between the river stage and the groundwater level is rapidly increased. In addition, the permeability of the riverbed has changed. Thereby, the infiltration rate increases and the groundwater levels rise.



Average hydrological conditions
High extraction rates (20 l/s)
Average river-infiltration

"Initial state" (average conditions)
Average hydrological conditions
Average extraction rates (10 l/s)
Average river-infiltration

Low hydrological conditions
Average extraction rates (10 l/s)
Average river-infiltration

Flood conditions
Average extraction rates (10 l/s)
High river-infiltration

Average hydrological conditions
Average extraction rates (10 l/s)
High river-infiltration

Fig. 5 Groundwater modeling and scenario development in the Birs valley (see Fig. 1 for location; + increase, - decrease)

Figure 8 shows the comparison of measured and calculated groundwater levels in observation wells 24J20 and 24J22. Until the beginning of the flood event the progression is in good accordance. However, during and after the flood event the calculated groundwater levels are considerably beneath the measured ones. In order to consider an increase in river infiltration during and after flood events, the leakage-coefficient of the riverbed must be treated as a transient parameter in groundwater models.

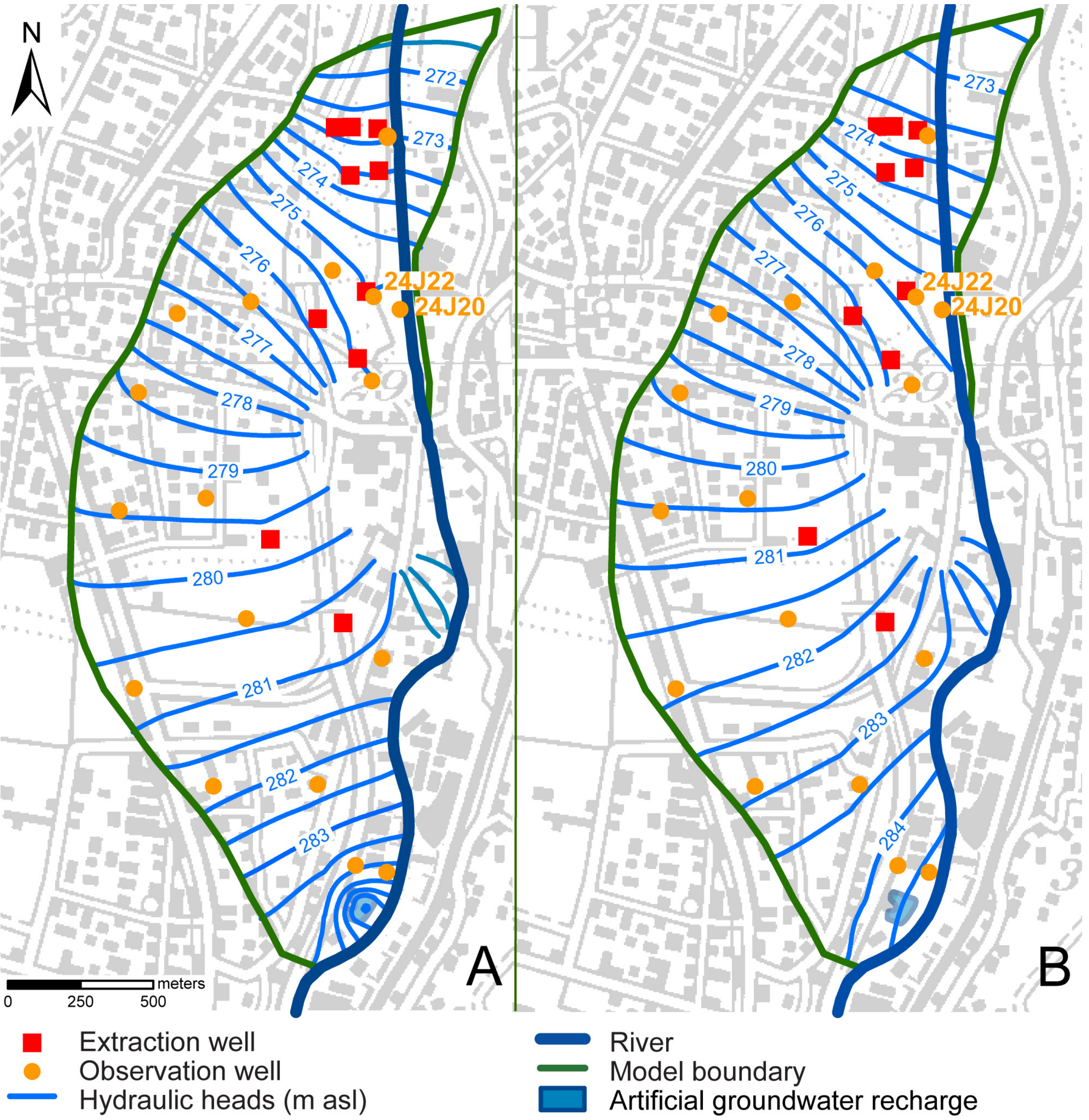


Fig. 6 Flow stages in the lower Birs valley (see Fig. 1 for location). Situation A: average river discharge, 24 October 2004, 10 m^3/s; Situation B: flood event, 27 October 2004, 148 m^3/s

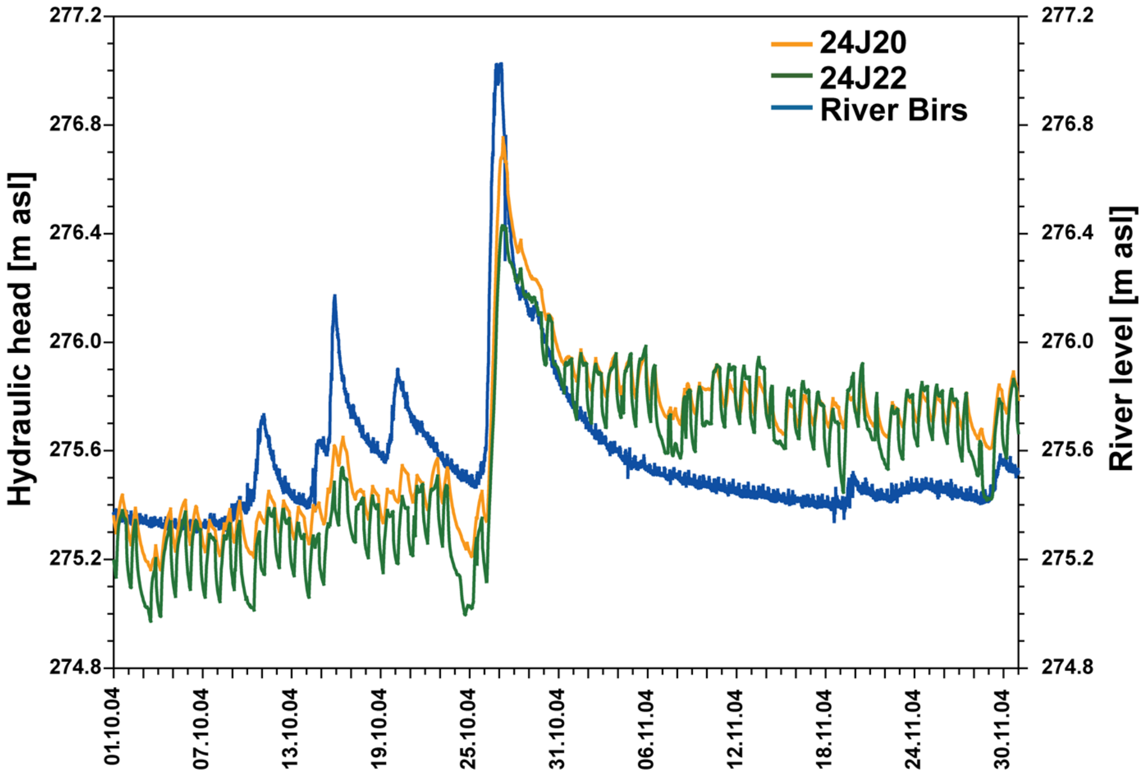


Fig. 7 Groundwater levels in riverine observation wells 24J20 and 24J22 (location of observation wells see Fig. 6) compared with the river stage in the Birs (BAFU river gauge 2106)

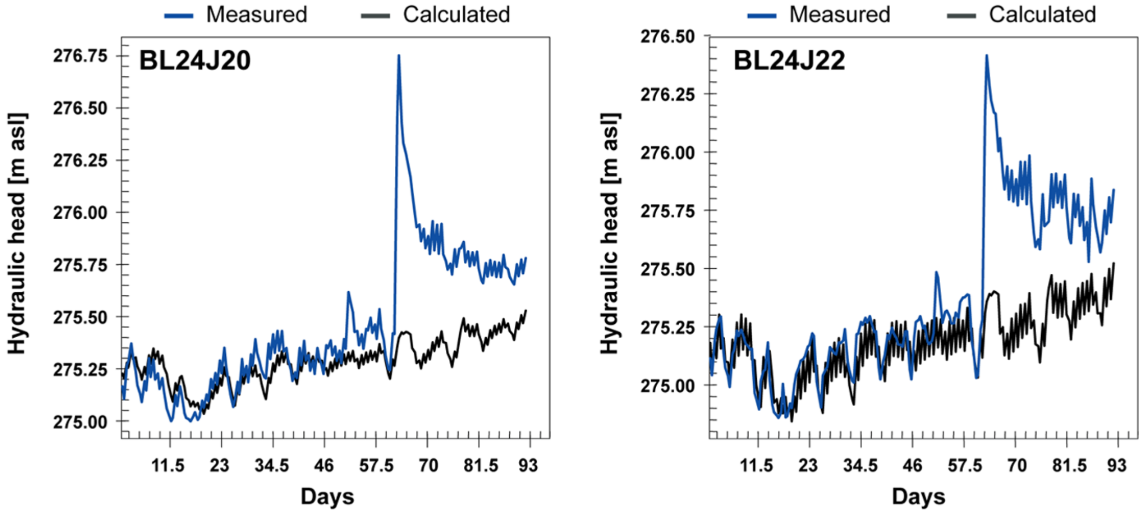


Fig. 8 Comparison of measured and calculated groundwater levels in observation wells 24J20 and 24J22 (location of observation wells see Fig. 6)

5 Discussion

Many engineering projects along rivers that could affect riverine groundwater production lack efficient groundwater protection concepts. Also it has to be accepted that, in particular cases, changes in river structures can not be completed without endangering groundwater quality.

The multitude of strongly transient processes makes risk assessment for particular well locations difficult. A clear definition of the present groundwater system profile, including its transient character, would help to define realistic goals and targets for site specific conditions. Considering the bandwidth of possible solutions, from the abandonment of riverine groundwater wells to the foregoing of corresponding interferences to water systems, there should be options of adequate measures (Hoehn 2005). In some cases the goal is to work out options that provide adequate space for groundwater usage as well as for river systems. These challenges increase the requirements for investigation and assessment methods.

A prerequisite for sustainable groundwater protection is the knowledge of the development of the groundwater quality at a specific location. Results from site-specific hydrogeological investigations of extraction wells and their operation are the basis for the evaluation of possible interferences. This includes impacts of water engineering measures on groundwater flow regimes and its usage, and also facilitates flood protection and land use authorities to take the various interests into account and make coordinated decisions.

Effective and efficient groundwater protection during flood events and water engineering measures along rivers demands detailed hydrological and geological knowledge as well as the willingness to suggest dynamic changes of hydrological conditions and load variations in rivers. By means of planning, organizational and technical measures the options for water engineering measures along rivers increase. If, in a specific case, both goals (efficient groundwater protection and water engineering measures) are not achievable, one goal has to be favored.

5.1 Holistic perspective

In general, decisions to compensate for negative impacts are often made at the level of the individual project. Mitigation in an urban river-groundwater-interaction context should primarily shift the scale used to establish regulatory criteria from the individual project to a broader aquifer scale. The effect of mitigation policy on the groundwater flow regime in urban areas depends in part on how the regulatory community defines “equivalence.” The basic premise of compensatory mitigation is that measures taken compensate for, or at least reduce, the effects of local damage. However, cumulative effects of water engineering measures could have an influence at considerable distances from the specific impact location. This required the development of instruments that facilitate to adequately quantify the consequences of cumulative effects arising from the numerous decisions concerning the groundwater flow regime and groundwater quality (Epting et al. 2006).

An enhanced reconciliation of the various usage demands with groundwater protection issues includes, along with aspects concerning water quality and quantity, the restoration of rivers in their function as species-rich ecosystems that form landscapes and interlink different habitats. Water engineering measures along rivers have to be accomplished to mitigate the impact of hazardous flood events and the conservation and recovery of natural functions of water systems. Therefore, such projects have to incorporate the interests of qualitative, quantitative and ecological groundwater protection issues. The development goals for natural or near-natural rivers (sufficient space for rivers, sufficient discharge and reasonable water quality; BUWAL 2004) thus have to be coordinated with those of groundwater protection. Furthermore, it must be considered that water engineering measures along rivers not only locally affect the groundwater system, but can also influence the groundwater flow regime, groundwater quality and the ecology downstream. The spatial context is hence not only restricted to the vicinity of planned impacts on water systems, but can often concern system dynamics covering large areas of the floodplain (Huggenberger et al. 2006).

5.2 Endangerment and risk assessment

A schematic illustration of the quality of infiltrated river water (e.g. a substance concentration in the river) against the filter performance in the region between the riverbed/foreland and the extraction well allows the designation of different areas (Fig. 9; Regli and Huggenberger 2007). The illustration facilitates the formulation of requirements for water engineering measures along rivers. The separation of these areas is defined by a line, marking the threshold value of a substance (dotted line, exceeding a threshold value or substance concentration). The choice of one or several parameters (e.g. E.coli), that are considered for safety evaluations of drinking water supplies, should be accomplished in accordance to problematic substances in the river or in the catchment areas. The filter performance, defined as the ratio of the substance concentration in the extracted groundwater to that in the infiltrated river water or river water, is particularly dependent on the load of the river water, the structural properties of the riverbed and the aquifer (infiltration rates, groundwater mixing ratios, residence times) and groundwater flow patterns, as well as the properties of substances and of the groundwater.

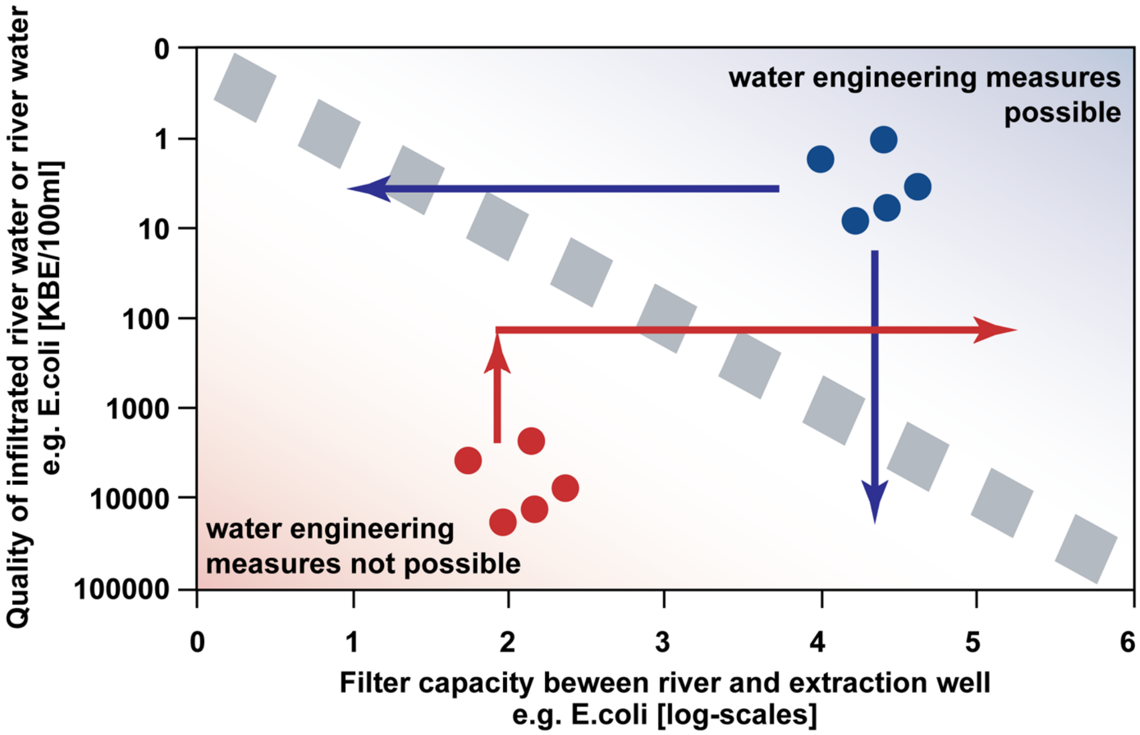


Fig. 9 Conceptual diagram for the evaluation of water engineering measures along rivers. Dotted line: definition of target size, e.g. adherence of threshold values in the extraction well

Due to strong heterogeneities of aquifers and the transient character of hydraulic conditions during flood events the attenuation of specific compounds or particles can vary considerably. Figure 9 illustrates which measures of water quality might, at least temporarily, be increased (blue horizontal arrow). To achieve quality objectives for drinking water supplies, falling below the line that marks the threshold value for a specific substance in the drinking water should be avoided. When the quality of infiltrated river water or river water, is degraded (impact loads during flood events) the threshold line could also be undercut (blue vertical arrow). If for a riverine extraction well, a scatter plot can be characterized that lies beneath the threshold line (quality objectives for drinking water can not be achieved), the quality of the infiltrated river water or river water, and/or the filter performance have to be improved (red arrows). This would result in a better chance and higher degree of freedom to facilitate water engineering measures. Furthermore, it must be considered that when improving the ecological state of rivers, the filter performance of the riverbed and the interstitial is also enhanced. The quantification of the achieved quality improvements, however, is difficult. In river segments with permanent exfiltration, water engineering measures are unproblematic.

The challenge is to define protection goals with a basic reflection on possible risks. Accordingly, impacts from water engineering measures and flood events for riverine groundwater usage can effectively and efficiently be reduced to an acceptable degree. For risk assessment of water engineering measures and forthcoming flood events the magnitude of floods must be defined that restrict the operation of extraction wells (e.g. frequency of events or discharge quantities; maximum substance concentrations in rivers; duration of accepted usage restrictions).

The consideration of the elimination or attenuation capacity between river and extraction well and groundwater mixing ratios facilitates an estimation of the endangerment for riverine extraction wells caused by planned water engineering measures and flood events. The risk results from the frequencies of corresponding flood events and the involved extent of damage to drinking water supplies.

5.3 Possible measures

To increase the degree of freedom for water engineering measures along rivers, planning, organizational and technical measures are possible and should be considered during the early phase of planning and when evaluating different options. Thereby, the discussion of drinking water consumption should be focused on the regional level (separation of groundwater production concerning drinking and processing water for industrial use). Measures on the catchment scale include, e.g. the optimization of settlement drainage, target an improved river water quality. Considering organizational and technical arrangements on extraction wells, such as updated concessions, linked systems, adaptation of groundwater extractions in relation to discharge combined with load variations (impact loads) or the shutdown of extraction wells (adaptive groundwater management), UV-installations, etc., the smallest irreversible constructional measures are necessary. Possible technical measures are, e.g., the adaptation of the planned interferences in the river, the relocation of riverine extraction wells (enlargement of the filter passage and consequently the filter performance), the injection of groundwater or the installation of geo-textiles (hydraulic and technical barriers, changing the groundwater flow regime). All these measures require elaborate reconcilement among the various authorities (Regli and Huggenberger 2007).

6 Conclusions

The changes in interactions between surface and subsurface water systems, when applying engineering measures along rivers often cannot be adequately evaluated based on existing groundwater protection concepts. Thus the protection concepts could be extended by process-based approaches.

These approaches should involve a comprehensive management on the catchment scale, i.e. surface and subsurface waters, wetlands and terrestrial ecosystems as well as the consideration of issues concerning water quality, water budgets and the structure of aquatic systems. Together with the setup of extensive groundwater monitoring systems, field experiments and groundwater models that allow the definition of specific groundwater system profiles and scenario techniques, the dynamics of capture zones to groundwater extraction wells should be optimized, thereby considering changing hydrological and operational boundary conditions.

Furthermore, a holistic perspective is necessary to consider all solitary impacts on the regional groundwater flow regime simultaneously, recognizing that impacts should not only be taken as locally limited but could have effects on the regional scale. Therefore, all stresses on the system, such as groundwater extractions, injections and recharge as well as water engineering measures and their impacts on the groundwater flow regime have to be taken into account. The definition of goals could help to evaluate the impact of individual measures on a larger scale of the groundwater system.

A systematic consideration of groundwater in urban development and the implementation of groundwater management systems can serve as a decision tool for project planners and official departments. This allows ongoing adaptation dealing not only with current issues but also with future demands. One step towards a better mutual understanding among the various involved authorities is the foundation of the river-groundwater-interaction working group within the Swiss Hydrogeological Society in the year 2004.

The knowledge of local geological and hydrological conditions as well as the understanding of the groundwater flow regime can considerably contribute to solutions for regional problems (Huggenberger 1999). However, many innovative technologies proposed for groundwater management are confronted with enormous implementation barriers. Confidence in their success is often low, and conventional but more expensive technologies are preferred (Prokop 2003).

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References

Bedford B (1996) The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecological Applications 6: 57-68

BUWAL (2004) Wegleitung Grundwasserschutz. Vollzug Umwelt. Bundesamt für Umwelt, Wald und Landschaft, Bern, 1-141

EEA (1999) Environment in the European Union at the turn of the century. European Environment Agency, Copenhagen, Denmark pp 446

Eiswirth M, Hötzl H, Cronin A, Morris B, Veselič M, Bufler R, Burn S, Dillon P (2003) Assessing and improving sustainability of urban water resources and systems. RMZ, Materials and Geoenvironment 50: 117-120

Eiswirth M, Wolf L, Hötzl H (2004) Balancing the contaminant input into urban water resources. Environmental Geology 46: 246-256

Epting J, Huggenberger P, Rauber M (2006) Integrated methods and scenario development in urban groundwater management, and protection during tunnel road construction - A case study of urban hydrogeology in the city of Basel, Switzerland. Peer reviewed for Hydrogeology Journal

Fatta D, Naoum D, Loizidou M (2002) Integrated environmental monitoring and simulation system for use as a management decision support tool in urban areas. Journal of Environmental Management 64: 333-343

Hoehn E (2005) Flussnahes Grundwasser strömt in Etagen. gwa 11: p 905

Huggenberger P (1999) Stadtgeologie – Das Beispiel Grundwasser. Uni nova April 99, Basel, Schweiz

Huggenberger P, Epting J, Regli C, Spottke I und Zechner E (2006) Fluss-Grundwasser Interaktion. MoNit: Modellierung der Grundwasserbelastung durch Nitrat im Oberrheingraben. INTERREG III A-Projekt. Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe, 110 Seiten

Kozel R (2005) Viele Pumpbrunnen stehen zu nahe am Fluss. Aquaterra 2: 11-12

Pahl-Wostl C, Möltgen J, Sendzimir J, Kabat P (2005) New methods for adaptive water management under uncertainty - The NeWater project. Paper in EWRA conference proceedings 2005, Menton, France

Pahl-Wostl C (2006) Newsletter No. 1. http://www.newater.info. Cited June 2006

Prokop G (2003) Sustainable management of soil and groundwater resources in urban areas. Proceedings of the 2nd IMAGE-TRAIN Cluster Meeting, Krakow, Poland, Oct 2–4, 2002

Regli C, Guldenfels L, Huggenberger P (2004) Revitalisierung von Fliessgewässern im Konflikt mit der Grundwassernutzung, gwa 4, 261-272

Regli C, Huggenberger P (2006) Entwicklung nachhaltiger Strategien für den Grundwasserschutz. In: Revitalisierung urbaner Flusslandschaften, Schlussbericht zum MGU-Forschungsprojekt F1.03: 47-61

Regli C, Huggenberger P (2007) Grundwasserschutz bei wasserbaulichen Eingriffen in Fliessgewässer - Hydrogeologische Aspekte, gwa 7, 261-272

Part IV

A Concept for Integrated Investigations of Karst Phenomena in Urban Environments

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A Concept for Integrated Investigations of Karst Phenomena in Urban Environments

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Whereas theories that describe karst systems are often limited to conceptual models, the development of tools that allow the description and calibration of karst evolution are rare.

Subsidence of a river dam and an adjacent highway, both constructed on gypsum-containing rock, Southeast of Basel, Switzerland, required remedial construction measures. To safeguard surface and subsurface water resources during the construction measures, an extensive monitoring network was set up.

The primary project goal was to develop tools that enable a continuous characterization of the groundwater flow regime and that facilitate the evaluation of the long-term performance of the infrastructures. Investigation methods included high-resolution 3D hydrogeological modeling, and the integration of geological, hydrometrical and hydrogeophysical field data of varying quality. Particular focus was placed on the hydraulic behavior of the complex conduit system.

Results help to understand the evolution of distinct karst features and zones of preferential flow. The location of fracture zones and parts of the old meandering river course, playing a major role in the karst evolution process, could be identified. Together with the hydrometrical investigations and hydrogeological modeling, the evolution of the karst system and its dynamics can be interpreted in relation to the groundwater flow regime.

Key words: Dam site; Subsidence; Karst evolution; Gypsum dissolution; Conduit development; Hydrogeophysics

1 Introduction

The need for upgrading and developing transportation infrastructures in urban areas often requires construction measures under difficult geotechnical and hydrogeological conditions, while maintaining the entire operation of city life. It is often the case that infrastructure development and the associated changes in land-use consider only the benefits of an improved infrastructure, and planning largely takes the pragmatic form of engineering for short-term economic objectives. To maintain the rapid pace of city life while ensuring that safety standards are met on the construction site, geotechnical measures such as cement injections for subsurface stabilization are commonly used. Such measures may lead to adverse effects on groundwater flow regimes with regard to quantity and quality of water resources. Furthermore, the change in water fluxes can also have negative impacts on existent adjacent infrastructures. As a consequence water resources, especially in urban areas, are under increasing pressure. They are subject to ongoing adaptations under changing boundary conditions.

In the past, decisions related to water engineering projects and their impacts on urban hydrogeology were typically taken at the level of the individual project. However, it is the sum of all impacts, and their interaction in time and space, including the determination of relevant parameters and an adequate evaluation of variable hydrologic and geotechnical boundary conditions, that influence the groundwater flow regime and which have to be considered. Existing legal frameworks for groundwater protection usually focus on the local monitoring of a set of parameters instead of on understanding the fundamental processes and long-term changes. Therefore, the implementation of sustainability concepts during engineering projects is a key objective of urban hydrogeology. Such concepts should include innovative approaches that take into account the complexity of the system and facilitate the adequate quantification of the site-specific aspects, as well as of the consequences of cumulative effects at a larger scale. Such approaches can be summarized as adaptive groundwater management concepts as outlined by Eiswirth et al. (2003), Fatta et al. (2002), Pahl-Wostl et al. (2005), Pahl-Wostl (2006), Epting et al. (2007), Epting et al. (2008a). However, these concepts have rarely been applied successfully in urban planning. The basic principles of adaptive groundwater management include the identification of the current profiles of groundwater systems at relevant scales, together with the formulation of specific targets that lead to the achievement of the overall goals (Epting et al., 2007).

In the view of the fact that infrastructures in karst regions, particularly in gypsum, are prone to subsidence, severe problems can arise in urban areas (Gutiérrez, 1996; Lamont-Black et al., 2002). While the characterization and modeling of flow in heterogeneous and fractured media has been investigated intensively, there are no well-developed long-term hydrogeological research sites for gypsum karst. This case study documents the integration of investigative methods in the context of the planning and construction phases of the upgrade of a subsided highway. The main goal of the engineering part of the project was to prevent further subsidence of the highway. At the beginning of the project, system knowledge was limited to purely conceptual models and sparse accurate groundwater observation data. Subsequently, to safeguard surface and subsurface water resources during the construction measures, an extensive observation network was set up. A principal focus of this project was the recognition of the current stage of the groundwater flow regime within the rapidly developing gypsum karst. This included a more fundamental understanding of the rock-groundwater interactions.

The present concept considers local investigations in the context of regional urban landscape development. Within the investigation area, multiple interests with regard to surface and subsurface water use and protection challenge the aims of water engineering and protection schemes. Interests include (1) the use of hydropower from a small hydro-electric power plant, especially with a view to future energy demands; (2) the protection of the existent infrastructure from potential further subsidence, including the river dam and an adjacent highway; (3) flood protection issues, as well as (4) safeguarding surface and subsurface water protection measures. Generally speaking, protection concepts basically have a monitoring character, while collected data correspond to historiography. Therefore, the expansion of current protection concepts by means of process-based approaches is of great importance (Epting et al., 2008b). The establishment of an extensive groundwater observation system together with a series of non-invasive ERT profiles made it possible to integrate not only point-, but also spatial and temporal information into the hydrogeological models. The present conceptual approach includes the integration and continuous adaptation of field measurements and modeling techniques. On the basis of the information content and accuracy of the multiple data sets collected, which themselves are of different type and quality, the data are classified as soft or hard (Regli et al., 2002). Investigation methods focused on the identification and evaluation of the relevant processes governing the system together with their temporal and spatial dynamics.

Pre-investigation studies since the 1990's focused on drilling campaigns providing 1D lithostratigraphic profiles from borehole logs. However, such intrusive exploration methods deliver limited information on the geometry of karst features and their connectivity; in addition they are costly, time-consuming and can leave the hydraulic connection between and beyond the boreholes. In the current case study, the drilling of several boreholes resulted in a connection of groundwater-bearing horizons in the gravel deposits and of the easily soluble evaporitic bedrock. This caused the accelerated vertical groundwater movements to locally stimulate karstification. Therefore, especially for subsurface investigations in the vicinity of engineering structures, non-invasive and non-destructive imaging and monitoring techniques take on a particular relevance.

A number of geophysical techniques may potentially be applicable to investigations of geological structures near the surface. They are based on physical contrasts between the target and the surrounding media. Each method has limitations in depth of exploration and resolution, depending on the settings. Among others, Dahlin (1996), Donner (1997), Pellerin (2002), Khalil (2006), and Loke and Barker (1996) describe various Electrical Resistivity Tomography (ERT) applications for environmental sciences and hydrological questions. Geophysical mapping with ERT has been successful for investigating and mapping features in karst terrains (e.g. McGrath et al., 2002; Šumanovac and Weisser, 2001; van Schoor, 2002), exploring shallow subsurface cavities and voids (El-Qady et al., 2005; Leucci and De Giorgi, 2005; Soupios et al., 2007) within complex geological areas (Griffiths and Barker, 1993; El-Hussain et al., 2000), and in urban areas (e.g. Wise'n et al., 2000). Furthermore, numerous ERT investigations focus on dam leakage (e.g. Al-Saigh et al., 1994) and buried paleochannels (Baines et al., 2002; Maillet et al., 2005). ERT measurements were performed on several days, taking into account different hydraulic and geotechnical boundary conditions at low, average and high river discharge before and after extensive construction measures. The non-uniqueness is well known in the inversion of ERT data. The use of different geophysical methods results in more accurate definition and interpretation of anomalies. However, Ground Penetrating Radar (GPR) surveys failed due to major background noises. To consolidate the interpretation, ERT results are interpreted together with: (1) lithostratigraphic profiles from borehole logs; (2) geological information on piling measures and locations with supplementary cement injection, and (3) the national geological map (Bitterly-Brunner et al., 1984, 1989). Subsequently, observed features are interpreted together with the hydraulics and water budgets derived from high resolution 3D hydrogeological models as well as a morphological analysis of the interface of weathered and non-weathered rock.

As karst aquifers are extremely heterogeneous and hydraulic conductivities can span many orders of magnitude, modeling groundwater flow in karst environments poses an enormous challenge. Results often are highly uncertain because of the complexity of flow paths and lack of site-specific information. Quinn et al. (2006) summarized the various modeling approaches for simulating flow in karst environments. In the appendix these include: (1) models using equivalent porous medium in which flow is governed by Darcy’s law (Anderson and Woessner, 1992); (2) models in which the preferred flow paths are simulated with a very high hydraulic conductivity relative to the surrounding matrix material (double porosity); (e.g. Teutsch, 1989; Mace, 1995; Eisenlohr et al., 1997; Josnin et al., 2000); (3) “black-box” approaches in which functions are developed to reproduce input and output system responses (recharge and flow at discharge springs; e.g. Dreiss, 1989a,b), as well as “global” approaches which include the hydrological dynamics of the conduit and the diffuse flow system (Butscher and Huggenberger, 2008); (4) fracture network simulations in which individual factures are mapped and then studied (Long et al., 1982; Long and Brillaux, 1987), and (5) open channel equivalents (Thrailkill et al., 1991). However, for realistic simulation of groundwater flow in karst systems (drain network and matrix), numerical models that represent double continuum media typical of karst aquifers have to be developed (Kovacs, 2003). The 3D hydrogeological model presented in this paper includes a deterministic finite difference approach which takes into account an equivalent porous medium for weathered and non-weathered rock, and a coupling of the system with drains that represent the conduit component of flow (mixed-flow in karst settings; Quinn and Tomasko, 2000; Quinn et al., 2006). To enhance model certainty the following procedure was applied: (1) calibration of the groundwater model and comparison of observed and calculated heads in numerous groundwater observation wells; (2) inverse modeling, including parameter estimation and sensitivity analysis, and (3) scenario development, including drains and different extensions of the weathered rock. Scenarios were developed using the hydrogeological model and different hydraulic and geotechnical boundary conditions were evaluated.

2 Settings

2.1 Investigation area and construction measures

The area of investigation is located along the Birs River southeast of Basel, Switzerland (Fig. 1). The hydrology is strongly affected by a man-made river dam and the use of hydropower from a small hydro-electric power plant. The dam in its current dimension was constructed in the 1890's (Golder, 1984). However, documentation of man-made impacts in this region, including the deviation of water for early manufacturing purpose in Basel, goes back as far as the 11th century (Fechter, 1856).

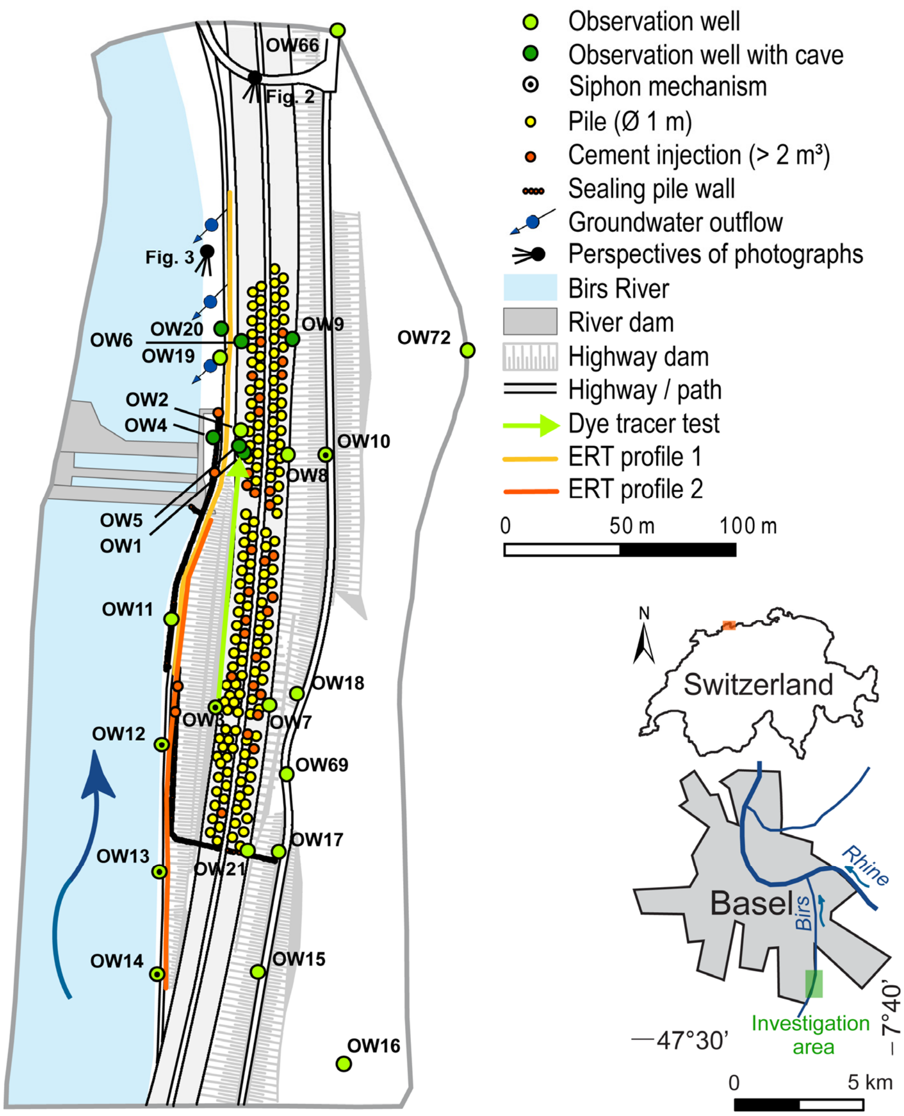


Fig. 1: Investigation area in the urban agglomeration of Basel

The height difference to the base level downstream of the dam is 7.3 m. As there is sufficient water supplied by the Birs River, the height of the impounded water upstream of the dam is practically constant at 266.2 m a.s.l. The river-groundwater interaction is dominated by the hydraulic river head and variations of riverbed conductance upstream of the dam during flood events. Upstream of the dam, river water infiltrates into the highly permeable fluvial gravels and into the weathered bedrock, follows the hydraulic gradient around and beneath the dam and exfiltrates downstream into the river. These processes enhance karstification in the soluble units of the "Gipskeuper" and result in an extended weathering zone within the bedrock as well as in the development of preferential flow within voids and conduits. As a consequence, subsidence of the dam and the highway has been observed over the last 30 years (Figs. 2 and 3).

Fig. 2: Investigation area (a perspective is given in Fig. 1)

Fig. 3: River dam at low river discharge (9 m^3/s; 16.06.2006). Note, as evidence for the subsidence of the dam structure, that the crest is only overflowed on its left side (a perspective is given in Fig. 1)

To prevent further subsidence, construction measures were carried out in two major project phases in 2006 and 2007. The highway was supported by 166 piles and by a sealing pile wall, consisting of approximately 300 piles (Fig. 1), to prevent infiltrating river water from circulating around the dam and beneath the foundation of the highway. Piles extended down to the non-weathered rock at a depth of 20 to 25 m. Caves encountered when the piles were being installed were filled with a total of 168.2 m^3 of supplementary cement, in order to plug all existing underground water channels and stabilize the ground beneath. To safeguard surface and subsurface water resources during the construction measures an extensive observation network was set up.

2.2 Geology and hydrogeology

The stratigraphic column includes the lithological sequences for the geological and hydrogeological modeling and extends from the Quaternary river gravels to the Gipskeuper sequence (Fig. 4). Quaternary gravels, silty flood deposits, as well as artificial fillings beneath the highway overlie the Triassic and Jurassic strata on the right side of the river. On the map in Figure 4, the Quaternary sequence has been removed, and the complex pattern of lithological changes in some parts of the investigation area is illustrated. These sequences consist of marls and clays (Obere Bunte Mergel), dolomites (Gansinger Dolomit) and sandstones, marls (Untere Bunte Mergel/Schilfsandstein) and, for most of the investigation area, of Gipskeuper. Gipskeuper is made up of a series of evaporates and intercalations of marls. The lithological term ‘‘Gipskeuper’’ as used in this paper generally includes the mineral ‘‘gypsum’’ and also refers to ‘‘anhydrite,’’ which, in the deeper subsurface, is the more common, anhydrous form of calcium sulfate. In its non-weathered appearance the Gipskeuper is characterized as being rather low permeable. Hydraulic conductivities for these sediments, as tested in borehole and modeling studies in northern Switzerland, were between 1E-14 ms^{-1} and 1E-07 ms^{-1} (Nagra, 2002). However, with its weathered appearance, Gipskeuper can be considered as a heterogeneous (karstified) aquifer. Areas below the bedrock surface are strongly weathered due to gypsum dissolution in Gipskeuper rock and are loosened over several meters of thickness.

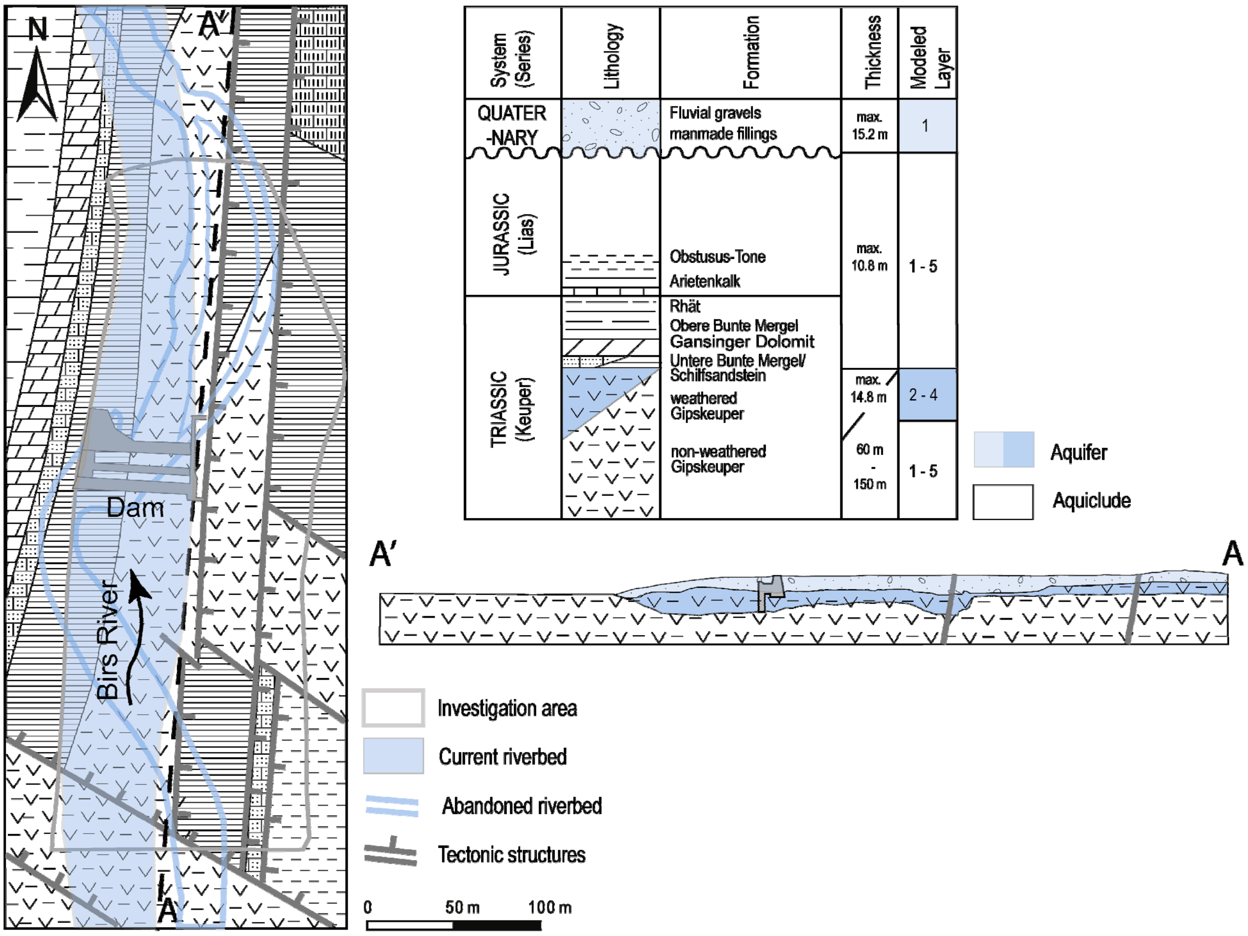


Fig. 4: Geological, tectonic map with removed Quaternary sequence (modified after unpublished data, Pfirter 1973), as well as lithostratigraphy, hydrostratigraphy, modeled geological units (modified after Bitterli-Brunner et al. 1989, Gürler et al. 1987, Pearson et al. 1991, Spottke et al. 2005) and longitudinal cross section

The investigation area is characterized by the Eastern Rhinegraben Master fault accompanied by an intense tectonic segmentation into compartments (Schmassmann, 1972). The Triassic strata dip at an angle of approximately 45° to the West and are subdivided by a series of NNE-SSW normal faults. Fracture zones are associated with rock weakness and can locally increase permeability within sequences, resulting in an enhanced groundwater leakage and the development of paths for preferential flow (Tectono-karstic voids).

Borehole data suggest that the occurrence of caves, and consequently the development of conduits, is concentrated at the base of the weathered Gipskeuper (lixiviation front), where most of the voids and solution cavities were encountered. The majority of the encountered caves contain clay; gravel and calcite fillings. During episodic floods, these fillings can be flushed partially and subsequently more aggressive water can enter the system, giving evidence that the development of conduits occurs in response to the flooding of passages. The map also shows the course of the Birs River in the year 1798 compared to the situation in the year 1983. The river was straightened in the 19th century and cut into the Triassic bedrock, resulting in a narrow couloir.

3 Methods

3.1 Conceptual approach

Figure 5 illustrates the conceptual approach proposed for practical urban hydrogeological applications. The principal approach includes local investigations in the context of regional urban landscape development and consists of the following iterative procedures: (1) delineation of the investigation area, including an inventory of all relevant environmental and anthropogenic/geotechnical ***boundary conditions*** for the specific area of the engineering project, as well as adjacent zones of possible interferences or negative impacts; (2) definition of system ***profiles*** that describe the system before, during and after the completion of engineering projects, whereas the concluding profile comprises the general goals for the desired future development of the system; profiles allow decision-makers to see the impact of past and present modification patterns of the system; (3) ***system analysis***, including the documentation of the current system profile as well as stationary or non-stationary processes; (4) definition of ***milestones***, which represent moments in a project when available knowledge is evaluated with respect to decisions and based on previously defined criteria, i.e., the minimization of qualitative or quantitative changes of surface and subsurface waters, safeguarding water quality measures during water engineering projects, as well as the development of technical solutions that guarantee sustainable development of surface and subsurface waters, and finally, (5) the formulation of ***goals*** for a sustainable development, including sustainable use of surface and subsurface water resources, long-term improvement of water quality, and taking into account long-term impact of geotechnical measures and future changes in usage. Whereas goals focus on a long-term sustainable development after the completion of engineering projects, milestones center on surface and subsurface water protection and geotechnical issues during engineering measures. An overall goal of the present case study is a better understanding of the long-term behavior of the surface subsurface flow system (surface water, shallow groundwater and karst system). The conceptual approach (***conceptualization***) incorporates the different geological, hydrogeological and engineering information as well as the determination of the relevant parameters and is accomplished by combining instruments that facilitate the adequate identification of the influences of the various single impacts on the complete system. The core elements of this adaptive procedure include the ***integration and combination of different investigative methods*** such as the setting up of extensive monitoring systems (e.g. hydrometrical and geophysical) and numerical groundwater modeling. The developed tools allow the relevant processes to be monitored and can have a predictive character. Together with the ***development of scenarios,*** possible future impacts and remedial strategies can be defined and evaluated.

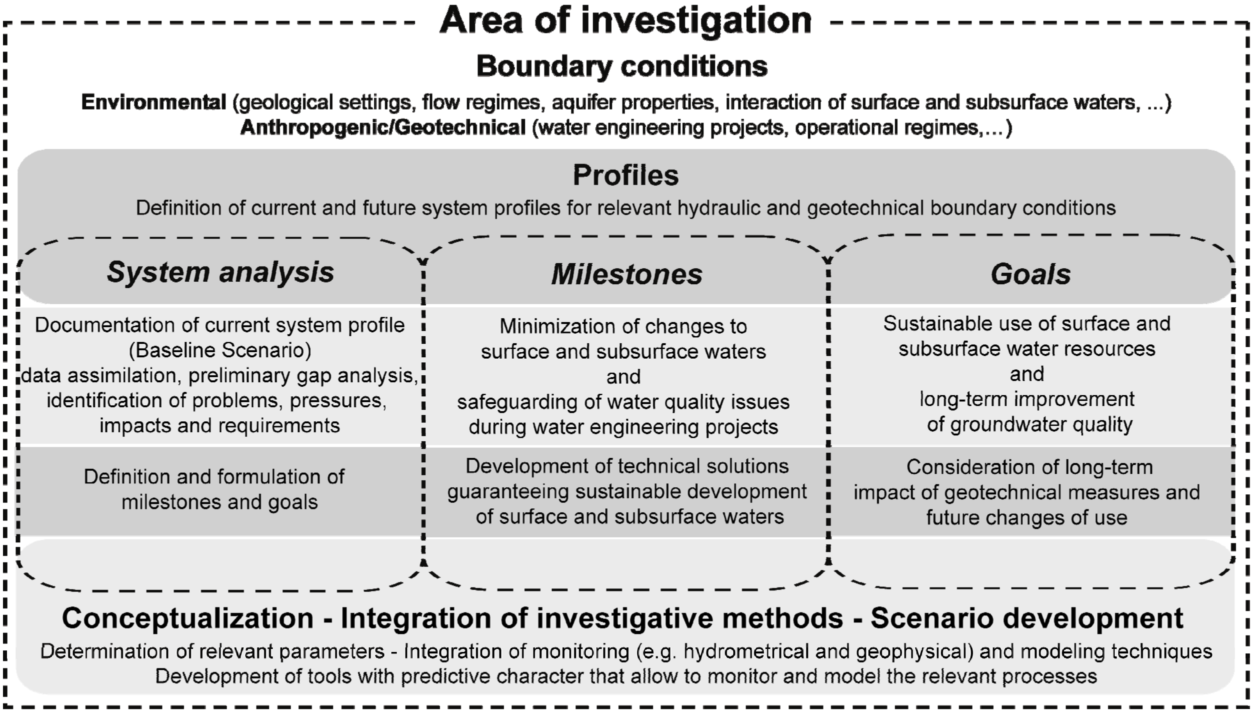


Fig. 5: Conceptual approach for practical urban hydrogeological applications

The various information on subsurface heterogeneity can be of quite different type and quality (cf. Regli et al., 2002): (1) partially available outcrop information; (2) borehole information (e.g. drill-core description, pumping tests) providing only a limited view of the structural setting, and (3) geophysical information (e.g. GPR, ERT) allowing the delineation of zones with different properties and behavior over time. The most reliable ***hard data*** derive from outcrop and laboratory investigations. The information on several outcrops was incorporated to the geological map (Fig. 4), which formed the basis for the delineation of the 3D hydrogeological models. Drill-core data provide limited information on the spatial distribution of subsurface properties, especially in karst environments where the probability of encountering voids is considerably low and relies on a hit-or-miss approach. The quality of individual drill-core descriptions varies considerably, depending on the geotechnical approach used, thus permitting limited and speculative conclusions. The same is true of geophysical data. Consequently, drill-core and geophysical data are regarded as ***soft data***. The designation of “hard” and “soft” data can also be applied to hydrometric data deriving from hydraulic measurements as well as from tracer tests. Whereas hydraulic measurements of the river head can be considered as hard data, data from groundwater observation wells are hard data only if they independently sample one aquifer. In the case where observation wells connect aquifers, data interpretation is not distinct and consequently such measurements should be considered as soft data. Tracer tests can undoubtedly confirm hydraulic links between injection and observation locations; this information corresponds to hard data. The path of preferential flow between these locations, however, is ambiguous and relies on further interpretation, resulting in soft data. Additional data that are documented during construction measures, as for example, lithological information derived during the installation of piles, or information on locations and quantities of supplementary cement injections, generally lack accuracy and should also be considered as soft data. Nevertheless, this kind of information can be indispensable in the process of setting up the hydrogeological model.

3.2 Data sources and hydrometrical investigations

Multiple data sources were available: (1) lithostratigraphic profiles from borehole logs; (2) continuous groundwater measurements; (3) coarse geological information on piling measures and locations with supplementary cement injection; (4) dye tracer tests, and (5) the national geological map. A total of 24 vertical boreholes were drilled in several investigation phases from 1993 to 2007 (Fig. 1, Table 1). Most boreholes were developed as observation wells for groundwater or subsidence measurements. In total, 12 observation wells were fitted with automatic data loggers for monitoring the physical parameters, hydraulic head, temperature and electric conductivity. Additional lithostratigraphic information could be derived from reports made during the installation of the piles. Hydraulic links and flow velocities within the investigation area were investigated by a dye tracer test in 1996.

Table 1: Compilation of borehole information

OW	monitoring	filter section in	status	from (m a.s.l.)	to (m a.s.l.)	difference
1	inclinometer	Gipskeuper	void (filled)	259.48	257.18	2.30
2	-	fluvial gravels and Gipskeuper	connection sealed	-	-	-
3	head, T, EC	fluvial gravels and Gipskeuper (separate)	connection unclear, siphon mechanism	-	-	-
4	head, T, EC	fluvial gravels and Gipskeuper	void, connection	250.92	248.62	2.30
5	-	Gipskeuper	void (filled), connection sealed	254.20	251.50	2.70
6	-	-	void (filled), connection sealed	253.60	252.80	0.80
7	head, T, EC	Gipskeuper	-	-	-	-
8	-	-	sealed	-	-	-
9	head, T, EC	fluvial gravels and Gipskeuper	void (filled), connection	257.05	256.25	0.80
10	head, T, EC	fluvial gravels and Gipskeuper	connection, siphon mechanism	-	-	-
11	-	-	sealed	-	-	-
12	head, T, EC	fluvial gravels	siphon mechanism	-	-	-
13	head, T, EC	fluvial gravels and Gipskeuper	connection unclear, siphon mechanism	-	-	-
14	head	artificial fillings and Gipskeuper	connection unclear, siphon mechanism	-	-	-
15	-	-	sealed	-	-	-
16	head	unweathered rock	dry	-	-	-
17	-	-	sealed	-	-	-
18	head	slope clay to Obere Bunte Mergel	-	-	-	-
19	inclinometer	-	-	-	-	-
20	head, T, EC	weathered Gipskeuper	void	252.17	250.77	1.40
			void	249.87	249.57	0.30
21	head	artificial fillings, Schilfsandstein, Gipskeuper	connection	-	-	-
66	-	-	-	-	-	-
69	-	-	-	-	-	-
72	-	-	-	-	-	-

3.3 Electric Resistivity Tomography (ERT)

ERT surveys were performed using a resistivity meter and 42 electrodes (Advanced Geosciences, Inc. (AGI), Sting/Swift R1 resistivity meter). Reynolds (1997) summarizes the strengths and weaknesses of the commonly used electrode arrangements (arrays) for ERT (Wenner, Schlumberger and dipole-dipole). The Wenner setup was chosen because of the high signal strength within areas where major background noise is expected. Within the investigated area various lines and subsurface installations (electric, gas and water) are documented that might influence the measurements. However, a disadvantage of the Wenner setup is the poor resolution of vertical changes in the subsurface. An electrode spacing of 5 m for all measurements resulted in profile lines of 205 m and a maximum prospecting depth of around 30 m. Reaching this depth allowed the entire thickness of the weathering zone to be investigated, as documented by the boreholes and the depth of the subsurface structures of the dam. For post-processing and data interpretation, the inversion program RES2DINV (Geotomo Software, 2007) was applied. It automatically determines the 2D resistivity models, topographically corrected, of the subsurface by inverting the data obtained from electrical imaging (Griffiths and Barker, 1993). A robust inversion was used because it is more suitable for detecting and sharpening linear features such as faults and contacts within complex geological settings of karst regions. Inversion parameters were kept constant in order to render the various measurements comparable. The topography, information of subsurface structures, and the lithostratigraphic information from boreholes in the vicinity of the profile line were integrated into the ERT profiles. Additionally, information on locations where supplementary cement was injected during the installation of piles could be considered for the validation of the interpreted karst features.

On the one hand, measurements were taken under different hydrologic boundary conditions, assuming that areas of preferential flow are water saturated to a varying degree at low, average or high river discharge. At high river discharge the hydraulic gradient from up- to downstream of the dam rises and the colmatage of the riverbed opens, making it possible for more surface water to infiltrate into the groundwater system upstream of the dam. On the other hand, in order to describe the change in system behavior, measurements were carried out both before and after extensive construction measures. The interpretation of the ERT surveys focuses on the description of distinct geological and hydrogeological features in correlation with river discharge, and (1) flow around the dam as well as (2) flow beneath the dam; (3) locations of voids and conduits; (4) delineation of the weathering horizon within the Gipskeuper; (5) the locating of solution-enlarged near surface faults and fracture zones, and (6) the location of buried paleochannels. The first and second measurements were performed before the construction measures of April 3rd and May 18th, 2007 at river discharges of 27 and 51 m^3s^{-1}, respectively. The third and fourth measurements took place after completion of the construction measures on March 26th and April 2nd, 2008 at river discharges of 15 and 26 m^3s^{-1}, respectively. The first three measurements are on the same profile line using the exact same electrode locations. The final measurement comprises the river bank upstream of the dam within the investigation area (Fig. 1).

3.4 3D geological and hydrogeological modeling

3D geological and hydrogeological simulations were performed using the Groundwater Modeling System GMS v6.0 (Environmental Modeling Systems Inc., 2006), together with the 3D finite difference code MODFLOW (Harbaugh et al., 2000). To construct 3D geological structures the “solid modeling” approach was employed (Lemon and Jones, 2003). Solids (volumetric layers representing hydrostratigraphic sequences) were built using the horizons method, based directly on the lithostratigraphic data from 25 boreholes, 166 piles beneath the highway and 273 piles of the pile wall and the introduction of 42 support points. The support points were interpolated from stratigraphic information from adjacent boreholes and, in the case of the riverbed up- and downstream of the dam, by topographic information obtained from river cross sections. Each lithological sequence can be represented by a separate solid. To gain more control over the resulting solids, the horizons method was modified with 14 lateral and 19 longitudinal cross sections in addition to the borehole data. Furthermore, the interpolation algorithm (inverse distance weighting) was constrained by geological boundary conditions obtained from boreholes and the national geological map. Like this pinchouts, embedded seams and locations of faults could be represented directly in the solid model geometry. In order to simplify the geological model, the formations of non-weathered Gipskeuper were grouped with the formations of Schilfsandstein and Mergel-Dolomit, resulting in three different materials, including the Quaternary cover, weathered Gipskeuper and non-weathered lithological sequences. In a final step aquifer properties could be assigned to the cells of the various solids. The 3D geological model is delimited: (1) to the West by the Birs River, since to the left of the river, the Schilfsandstein is encountered, which is less vulnerable to weathering processes; (2) to the North by the course of the local groundwater flow regime within the Quaternary; (3) to the East by the adjacent slope, and (4) to the South by an encountered tear fault. Vertically, the model extends from the topographic surface to the non-weathered Gipskeuper (Fig. 4 & 6).

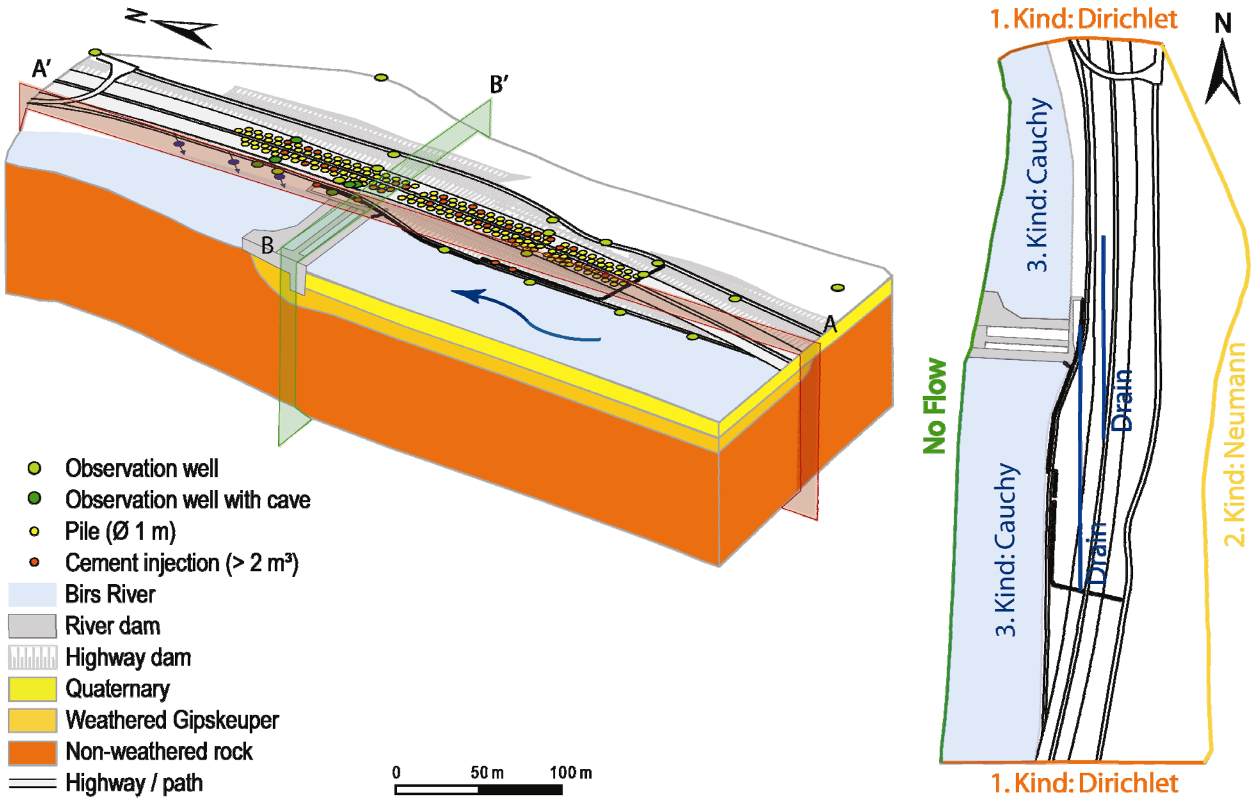


Fig. 6: Left: 3D geological model with locations of cross sections (see Figure 4 for longitudinal cross section A-A' and Figure 14 for transversal cross section B-B'). Right: conceptual 3D groundwater model setup with hydraulic boundary conditions

The grid for the 3D groundwater model was automatically generated from the solid model geometry (Jones et al., 2002). Hydraulic properties and their sensitivity were determined by a combination of manual and automated parameter estimation procedures, which are based on numerical optimization algorithms within the nonlinear regression code PEST (Doherty, 1994). The groundwater model comprises 5 model layers. The location of voids and conduits could more accurately be represented by a 3-layer approach for the weathered Gipskeuper (Fig. 4). The horizontal discretisation of the grid is regular (5 by 5 m). Hydraulic boundary conditions of the simulations were defined as follows (Fig. 6): (1) the northern and southern boundaries were defined as specified head (Dirichlet), corresponding to available groundwater head measurements in the local Quaternary Aquifer; (2) the eastern boundary was defined as specified flow (Neumann) with an assumed inflow from the adjacent catchment of 10 ls^{-1}; (3) the western boundary was chosen as no-flow boundary, according to the abundance of comparatively impermeable geological sequences (see above); (3) the Birs River was simulated as general head boundary (GHB) condition (Cauchy), where infiltration and exfiltration are calculated in proportion to the difference between river level and hydraulic groundwater head, and a conductance of the riverbed, and (4) areal recharge was assumed to average 3E-0.8 ms^{-1} (areal precipitation 946 mma^{-1}). Hydraulic conductivities, riverbed and drain conductance were determined from model calibration results. The basic model was modified and a series of model scenarios were set up to simulate (1) weathered Gipskeuper extending beneath the dam, and (2) the effect of drain networks within the weathered Gipskeuper. The thickness of the weathered Gipskeuper beneath the dam was interpolated from the stratigraphic information of boreholes adjacent to the dam. Modeling the complex flow using a finite-difference approach, with drain networks, representing the conduit component of flow, was approached by introducing the conduits using the drain feature within MODFLOW (Quinn et al., 2006). In order to investigate the effect of drain features, two drains were introduced that correspond to information obtained from the 1996 dye tracer test and the location of fracture joints (Fig. 1 & 4). Drains were introduced in model layer 4 corresponding to information obtained from the boreholes, indicating that voids were generally encountered at the bottom of the weathering zone. To ensure active flow in the drains, the drain elevation was chosen using values of nearby groundwater head measurements. The conductance values of the drains were optimized by model calibration.

4 Results

4.1 Data sources and hydrometrical investigations

The primary purpose for drilling boreholes was to find significant permeable zones within the underlying bedrock and already developed voids. Although the probability of encountering voids is fairly low and relies on a hit-or-miss approach, in total 7 voids, with diameters ranging from 0.3 to 2.7 m, were detected at a depth of 15 to 18 m. The data suggest that the vertical extension of the weathered Gipskeuper ranges from 2.2 to 14.8 m. Additionally, in the 1990's several boreholes left a stratigraphic connection and hydraulically connected aquifers. The connection is documented by drill-core protocols and was recently confirmed by geochemical and hydraulic data (Table 1).

Figure 7 shows examples of hydrographs that characterize the hydrological settings. In most observation wells considerable reactions of the groundwater heads and the electric conductivities during the construction works can be observed (e.g. OW3, 4 and 20). It is worth mentioning that the investigation period is characterized by the 300-year flood of August 9th 2007. After the flood event some groundwater heads remain for approximately 4 months on a higher level until they fall back to their original level (e.g. OW20), others continue on the higher level (e.g. OW12 and 13).

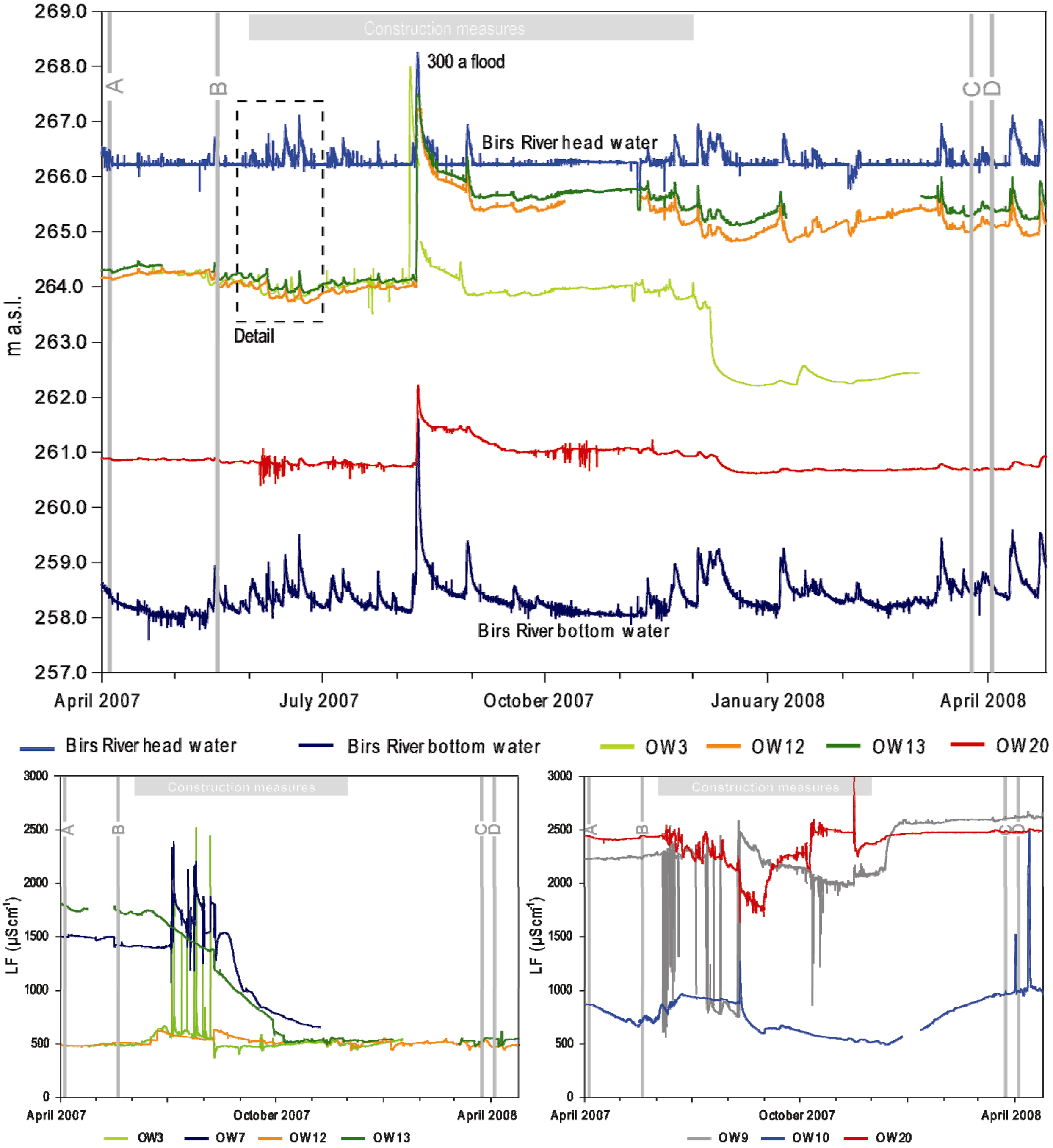


Fig. 7: Top: Examples of measured groundwater heads; Bottom: Examples of measured electric conductivities; A-D: Dates of geophysical surveys (See Fig. 1 for location of observation wells)

In December 2007 the groundwater head in OW3 drops by about 1.8 m and remains on this lower level, clearly illustrating the effect of the pile wall that was completed approximately 10 days before. Measured electric conductivities range between approx. 500-2 500 µScm^{-1}. On the one hand, low electric conductivities are in the range of measured values for river water (450-500 µScm^{-1}) indicating short residence times ("younger water") within the system after water infiltrated from the river. On the other hand, high electric conductivities indicate longer residence times of water ("older water") within the system and higher solution contents. During the construction measures a mixing of water components can be observed, thereby "older water" mixes with “younger water” (e.g. OW9) or vice versa (e.g. OW3). In the course of the construction measures, formerly high electric conductivities measured in OW7 and 13 fall to a lower level, indicating that injections of supplementary cement during the installation of piles and the filling of encountered caves resulted in a disconnection of these observation wells from the conduit system.

Surprisingly, analysis revealed that the progression of some of the hydrographs could be explained by a siphon mechanism according to the hydrological characteristics of the river stage. This mechanism generally is observed in underground rhythmic springs (ebb and flow springs, intermittent springs) that belong to the group of springs which appear exclusively in karstified terrains (e.g. Bögli, 1980). Bonacci and Bojanić (1991) give an overview of the presence of such springs and the corresponding authors who describe it. In Figure 8 the operation of the siphon mechanism is illustrated schematically. When the water level in the cave rises above level A, all the water in the cave from level A to level B suddenly flows out. This emptying is effected according to the siphon mechanism. When the water level falls below level B, outflow ceases until water level A is reached again. When the water level is above level A, and when the inflows are greater than the maximum capacity of the siphon, then the siphon mechanism is interrupted and the hydrograph rises according to the hydraulic pressure head in the river. Three magnitudes of floods can be distinguished: (a) moderate flood events causing no initiation of siphon mechanism and slightly raised river infiltration upstream of the dam; (b) medium flood events causing an initiation of the siphon mechanism and raised river infiltration upstream of the dam, and (c) elevated flood events causing a flooding of the entire siphon system resulting in an interruption of the mechanism and overall high river infiltration upstream of the dam. Furthermore, the emptying of the siphon karst structures is associated with an outflow of mineralized waters and sediment load. Subsequently, less mineralized, more aggressive water can enter the system.

The strong reactions of measured groundwater heads and electric conductivities and the observed siphon mechanism indicate that the karst system is already well developed, whereas various cave or conduit systems are either connected in series or are configured in a somewhat independent, parallel way.

Additional lithostratigraphic information could be derived from reports made during the installation of the piles. Based on the lithostratigraphic information of the boreholes, relatively precise cross sections of the investigation area could be constructed (Fig. 4 & 14).

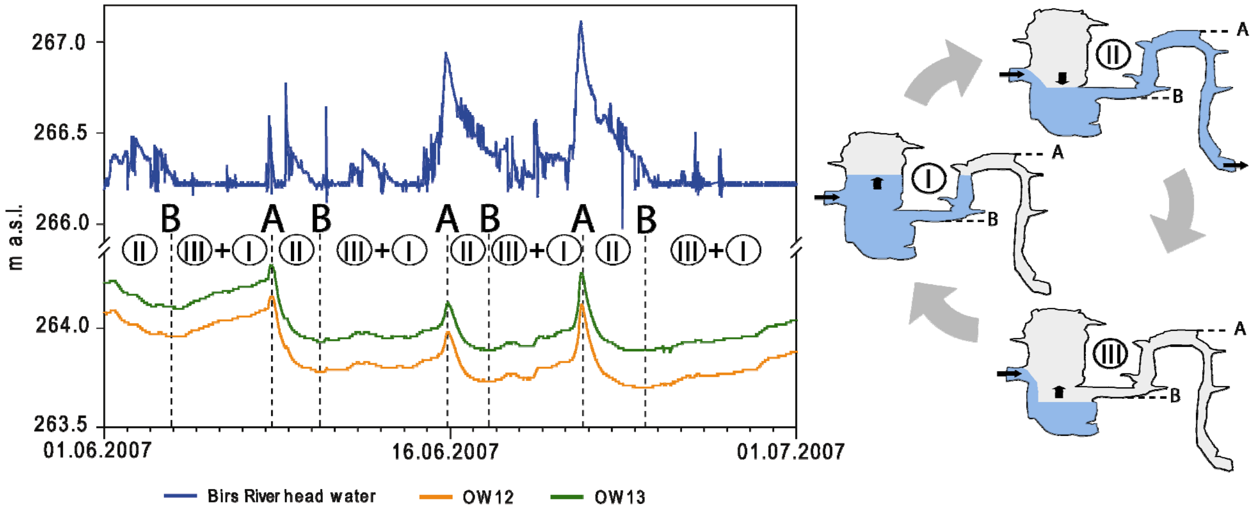


Fig. 8: Detailed view of measured groundwater heads (see Fig. 7) and schematic illustration of the siphon mechanism

Hydraulic links within the investigation area were confirmed by the 1996 dye tracer test (Cantonal Archive Basel, unpublished reports). The direction of the hydraulic links corresponds with one of the main directions of fracture joints within the investigation area (Fig. 4). The dye was injected in OW3 and sampled in OW2, 4 and 5 (Fig. 1). Highest concentrations were measured in OW5, which is nearest to the injection well. A second maximum was observed, representing a further preferential pathway. Measurements in the other observation wells resulted in lower concentration values indicating that they are influenced by infiltrating river water to a certain degree. Maximal groundwater flow velocities range from 85 to 111 md^{-1}, values typical for conduits within well-developed mature karst systems. Measured groundwater flow velocities allow the approximate hydraulic conductivities to be calculated for the conduit flow system using the equation $v = (-K/n)(\partial h/\partial l)$, where v is the groundwater velocity, n is the porosity of the conduit, K is the conductivity of the conduit, and $\partial h/\partial l$ is the hydraulic gradient between the observation well where the tracer was injected and the observation wells used for sampling. The porosity of the conduit will be influenced by the sediments in the conduits (fillings of voids, see above) and the variations in the size and shape of the conduit. Since these details are not known for the study area, (1) a maximum porosity value of 1 was assumed for air-filled voids, and (2) the effect of fillings in the conduits was considered by attributing a porosity value of 0.5 (Table 2). This results in approximate hydraulic conductivities for the conduit system ranging between 3.5E-02 and 4.7E-02 ms^{-1} for an assumed porosity of 1, and between 1.7E-02 and 2.4E-02 ms^{-1} for a porosity value of 0.5.

Table 2: Results of dye tracer test and interpretation

	Distance l	**Time** t	**Velocity** v		**Head** h	**Hydraulic gradient** $\partial h/\partial l$	**Conductivity** K	
							n = 1	n = 0.5
	(m)	(h)	(mh-1)	(md-1)	(m)	(-)	(ms-1)	
OW 3	Injection							
OW 2	124	26.8	4.6	111	3.3	2.7E-02	4.7E-02	2.4E-02
OW 4	116	32.8	3.5	85	3.3	2.8E-02	3.5E-02	1.7E-02
OW 5	112	26.8	4.2	100	3.3	2.9E-02	4.0E-02	2.0E-02
Birs R.	137	32.8	4.2	100	-	-	-	-

4.2 Electric Resistivity Tomography (ERT)

For all measurement values for the calculated RMS error values are less than 5 %, indicating that the measurements were undisturbed and that the resistivity models are plausible (Donner, 1997). The interpretation of the ERT surveys focuses on the description of distinct geological and hydrogeological features in correlation with river discharge, and (1) shallow subsurface flow; (2) groundwater flow around the dam, as well as (3) groundwater flow beneath the dam; (4) locations of voids and conduits; (5) delineation of the weathering horizon within the Gipskeuper; (6) areas where solution appeared in the vicinity of faults and fracture zones, and (7) locations of buried paleochannels. The occurrence of the following ERT anomalies is anticipated and used in these interpretations: (a) different hydrologic boundary conditions result in variable water-saturated areas of preferential flow at low, average or high river discharge; at high river discharge the hydraulic gradient from up- to downstream of the dam rises and the colmatage of the riverbed opens, enabling more surface water to infiltrate into the groundwater system upstream of the dam; (b) drainage phenomena of karst features such as voids, conduits, fractures and fault zones generally result in a resistivity increase if these are filled with air (near-infinite electrical resistance), and a decrease if they are filled with clay and water, providing there is a resistivity contrast with the surrounding host rock. Although clay content will decrease resistivities more than water, in real exploration their influence cannot be determined due to the shape of the features and the fact that the degree of the filling is, most of the time, unknown; and (c) resistivity contrasts between various sedimentological sequences and their degree of weathering.

Shallow subsurface flow

The top layer of all inversion models shows a very heterogeneous resistivity distribution (Fig. 9). This heterogeneity is the result of shallow subsurface installations, the numerous anthropogenic interferences in the past, and root penetration of the riverine vegetation. The second measurement at high river discharge before the construction measures resulted in lower resistivity values downstream of the dam indicating the infiltration of rainwater following preferential flow paths in the shallow subsurface (Fig. 9B). However, these regions are mainly above the zone of the weathered Gipskeuper and consequently are not considered in the interpretation of karst features.

Groundwater flow around the dam

The inversion model of the first measurement at average river discharge before the construction measures shows two distinct zones with rather low resistivity values between 10 and 30 Ωm (Fig. 9A). The first zone lies between 60 and 108 m and is most pronounced at a depth of 15 m. The second zone lies between 10 and 20 m at a depth of approx. 10 to 20 m. These zones are interpreted as contributing to preferential groundwater flow around the dam. Low resistivity values result from water with high solution contents within water-saturated clays. Particularly within these zones, the weathering process resulted in the removal of gypsum and the remains of the clay component. These zones become expanded during the second measurement at high river discharge before the construction measures are carried out, suggesting larger areas participating in the flow processes or higher contents of electrolytes in the groundwater (Fig. 9B). The inversion model of the third measurement at low river discharge after completion of the construction measures generally shows lower resistivities in vicinity of the dam indicating that after the 300-year flood of August 9th 2007 (Fig. 7) existing flow paths in the vicinity of the dam were flushed or new ones generated (Fig. 9C). Whereas the resistivity distribution downstream of the dam of the third measurement is comparable to the first measurement, resistivities upstream of the dam are generally higher. After the construction of the pile wall upstream of the dam, less river water can infiltrate into the groundwater system, resulting in areas with lower water saturation behind the pile wall.

This finding is supported by groundwater level measurements in observation well OW3 behind the pile wall (Fig. 7). Profile 1 in Figure 10 presents a conceptual model for the first two measurements. Regions with resistivities under 30 Ωm are highlighted. This limiting value was adopted from Schön (1983), who assigned resistivity values higher than 30 Ωm to the rocks of the Keuper sequence with medium water saturation. At high river discharge the low resistivity zone upstream of the dam extends vertically by about 2.5 m to the surface. An evaluation using geological information derived from boreholes and reports made during the installation of the piles indicate that the zone is in the transition zone between the weathered and non-weathered Gipskeuper. At high river discharge, the low resistivity zone downstream of the dam extends vertically by about 10 m to the surface. Noticeably high resistivity values in the vicinity of the dam are explained by the high hydraulic gradient in this region. At the beginning of flood events, “old water” with long residence times within the groundwater system and high solution content (electrolytes) is flushed, resulting in a zone with relatively high resistivity values caused by “younger water” infiltrated from the river. Depending on the distance to the profile line, locations with supplementary cement injections were included in the conceptual geological models. Green- and red-colored bars indicate supplementary cement injections of 2.4 to 15.5 m^3. They are related to the conduit system downstream of the dam and correlate with the interpretations of the resistivity models. The red-colored bar with supplementary cement injections of 5 m^3 lies directly on the profile line at 80 m and correlates with the local minima of the second resistivity model, indicating pronounced water flow in this area. The blue-colored bars upstream of the dam are located at a 10-30 m distance to the profile line. They represent the more distant flow around the dam which cannot be correlated with the resistivity models (cf. Fig. 14). In Profile 2 (Fig. 10) three distinct zones with resistivities under 30 Ωm are highlighted. The two larger zones are interpreted to contribute to the more distant flow around the dam. Low resistivity values again result from water with high solution contents within water-saturated clays. Particularly within these zones the weathering process resulted in a removal of gypsum and remains of the clay component. Results are confirmed by the progression of the bedrock surface that was constructed based on geological information derived from boreholes and reports made during the installation of the piles.

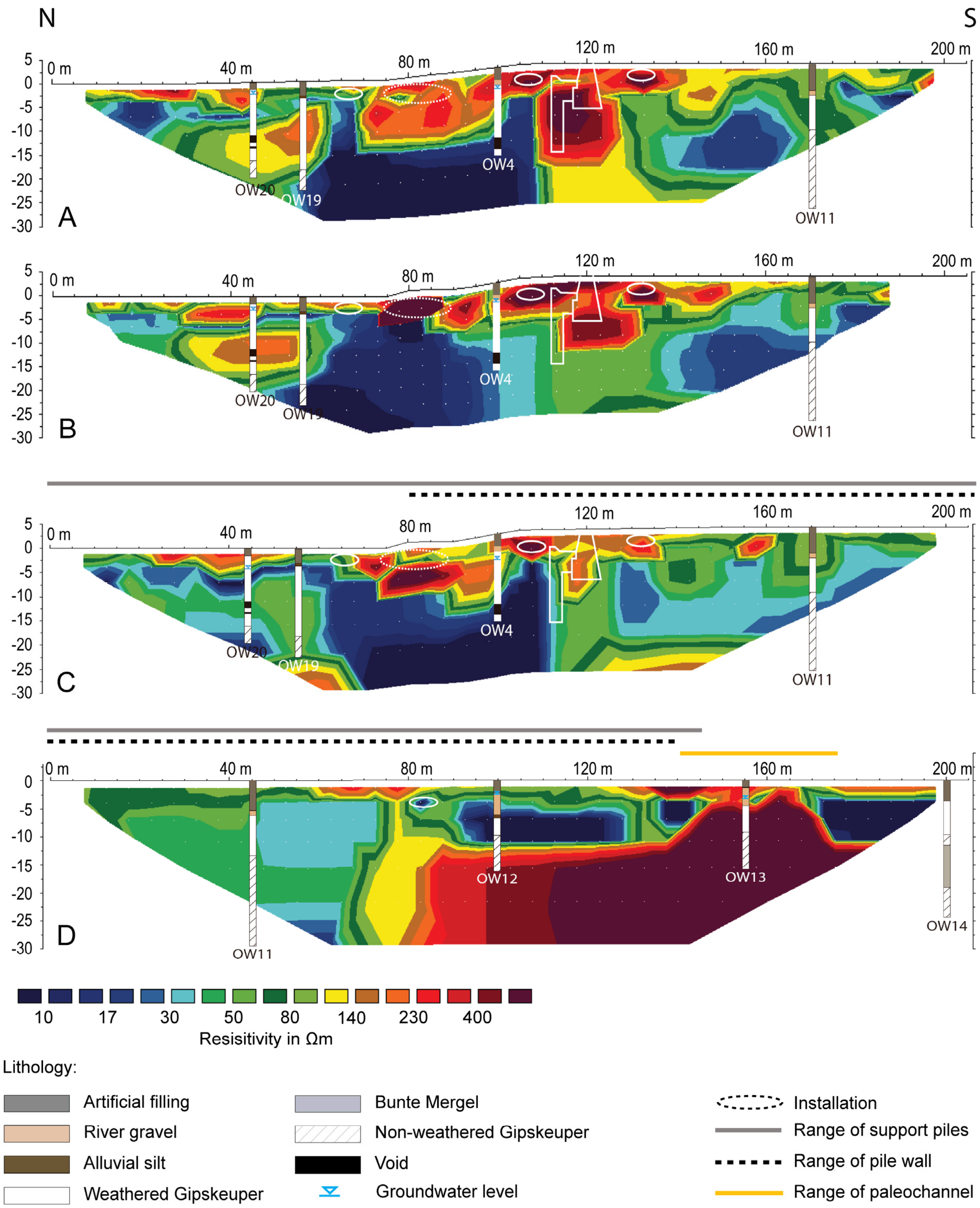


Fig. 9: ERT results illustrated together with lithostratigraphic information on boreholes. White framing indicates the dam structure and documented subsurface installations

A: Profile 1 at average river discharge before construction measures (03.04.07)

B: Profile 1 at high river discharge before construction measures (18.05.07)

C: Profile 1 at low river discharge after construction measures (26.03.08)

D: Profile 2 at average river discharge after construction measures (02.04.08)

Groundwater flow beneath the dam

The inversion models of the first two measurements before the construction measures show very high resistivities above 200 Ωm in the central part where subsurface structures of the dam are located, as well as in areas of documented subsurface installations (Fig. 9AB). In these areas strong resistivity contrasts can be observed. However, the zone with high resistivity values in the central part of the second inversion model does not reach as deep as in the first part. This decrease in resistivity indicates elevated undercurrent below the dam during flood events. An evaluation with geological information derived from boreholes and reports made during the installation of the piles indicates that the zone is in the non-weathered Gipskeuper. This confirms the assumptions that also beneath the dam, zones within the Gipskeuper exist that already are weathered and contribute to flow processes. Results are illustrated in the conceptual model of Profile 1 (Fig. 10). Regions with resistivities under 140 Ωm are highlighted. This limiting value was adopted from Schön (1983) assuming that resistivity values above 140 Ωm are not typical for rocks of the Keuper sequence. Additionally, in the inversion model of the third measurement conducted after the construction measures, a region with elevated resistivities can be observed in the central part where subsurface structures of the dam are located. However, this region generally shows a lower resistivities in the vicinity of the dam indicating that after the 300-year flood of August 9th, 2007 (Fig. 7), existing flow paths in the vicinity of the dam were flushed or new ones generated (Fig. 9C).

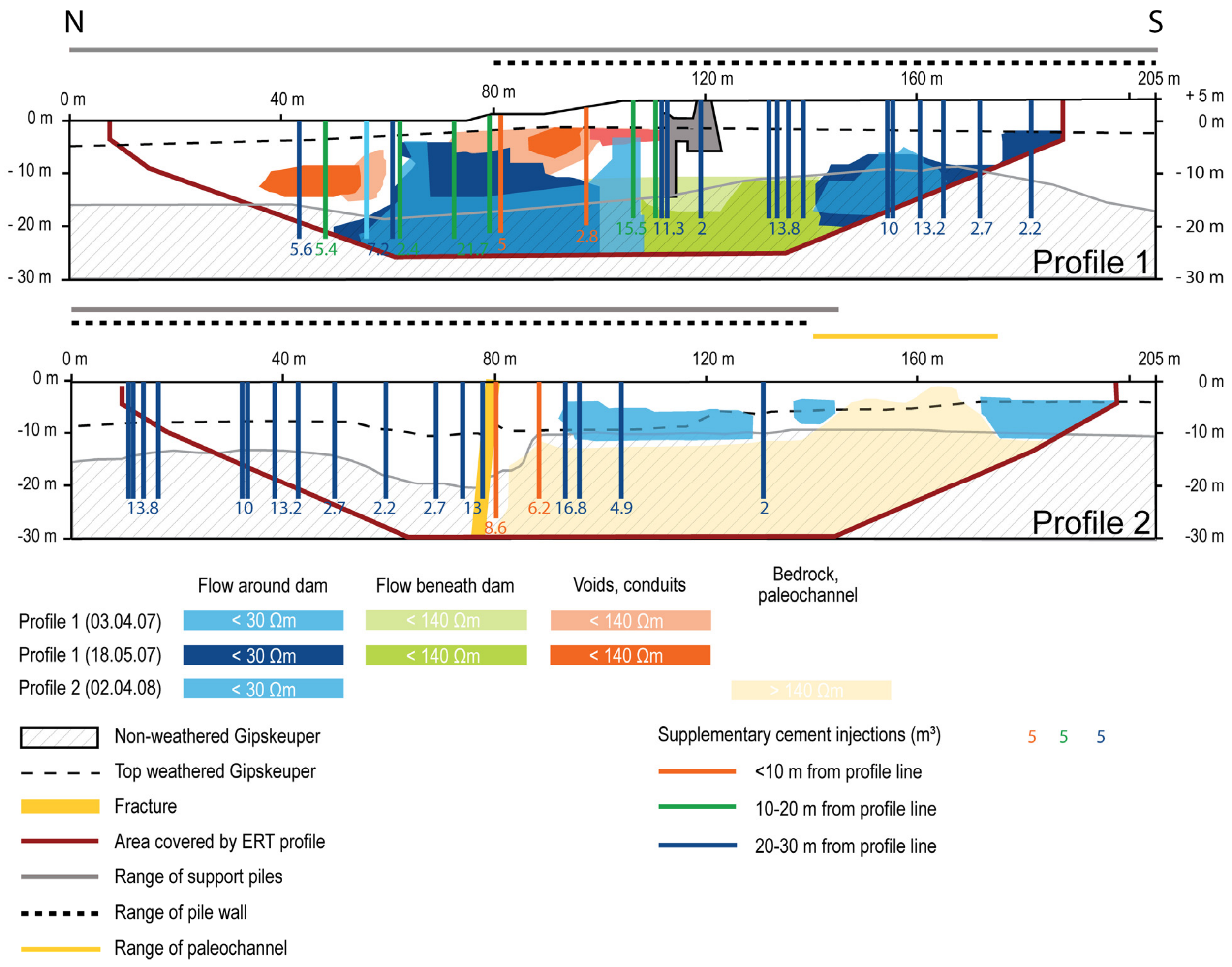


Fig. 10: Conceptual models with interpretation of ERT measurements

Voids and conduits

In the inversion models of the first two measurements between 35 and 70 m and within depth of 5 to 15 m, relatively high resistivity values between 140 and 200 Ωm can be observed (Fig. 9AB). It is assumed that this zone is part of the conduit system as at a depth of 11 to 13.6 m a void was encountered during the installation of borehole OW20, which lies directly on the profile line. At average river discharge the conduit system is only partially water saturated. At higher river discharge the zone with high resistivity values shrinks, indicating elevated water saturation. The zone is not distinct in the inversion model of the third measurement (Fig. 9C); this can be explained by the injection of supplementary cement during the installation of the piles, the filling of encountered caves and consequently an interruption in the conduit system. The extension of a second zone with relatively high resistivity values between 140 and 200 Ωm in the vicinity of borehole OW4 differs considerably for the first three measurements. A void was encountered in borehole OW4, which lies directly on the profile line at a depth of 14.6 to 16.9 m. Although the zone with relatively high resistivity values is not at the same depth as the encountered void, a conduit system could have developed since the installation of the borehole in 1995, due to the heterogeneity within the weathered Gipskeuper. During flood events the zone with relatively high resistivity values during the first measurement becomes more saturated, resulting in a reduction of resistivity values during the second measurement. Consequently, these conduit systems are related to the flow processes around the dam. Some of the green- and red-colored bars indicating supplementary cement injections of 2.4 to 15.5 m^3 can be directly related to the zones with high resistivity values (Fig. 10, Profile 1). Between 80 and 85 m on Profile 2 at a depth of 2.5 to 5 m, a zone with low resistivity values under 10 Ωm can be observed (Fig. 9D). At this location a water pipe is documented that crosses the ERT profile perpendicularly. The detection of the water pipe provides an indication of sensitivities that can be expected from such anthropogenic features.

Delineation of the weathering horizon within the Gipskeuper

Results of the ERT measurements could not be used for detecting the thickness of the weathered zone, as was derived from the information on boreholes and the reports made during the installation of the piles for Profile 1. This is evidence that the extension of weathered and non-weathered Gipskeuper is strongly heterogeneous and not sharply separated. However, between 85 and 185 m on Profile 2 at depths of 10 to 12.5 m, resistivity values >140 Ωm indicate the surface of non-weathered rocks. This is confirmed by the lithostratigraphic information from OW12, 13 and 14 and the piling installations.

Faults and fracture zones

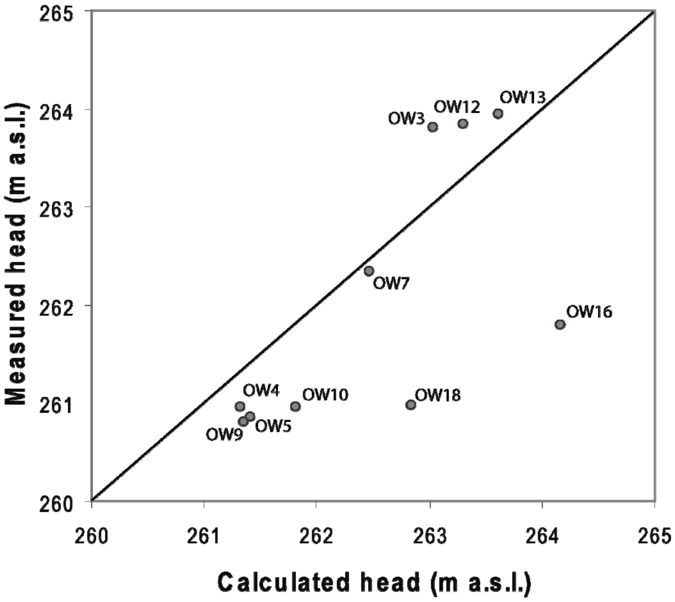
The investigation area is characterized by an intense tectonic segmentation into compartments. Both ERT profiles precede parallel to the Eastern Rhinegraben Master fault (Fig. 4). Between 70 and 85 m on Profile 2, ERT measurements resulted in a distinct vertical structure with resistivity values above 120 Ωm. The location of this structure correlates with the location of displaced tear faults on the geological map. The dipping of the fault is indicated at 20 to 30° North.

Buried paleochannels

Profile 2 between 140 and 175 m, ERT measurements resulted in resistivity values above 140 Ωm. In this region an abandoned river course from 1798 is documented (Fig. 4). The explanation for the rather high resistivity values could be the existence of coarse fluvial gravel with high porosities that were deposited in the abandoned main channel bed and that are not water saturated.

4.3 3D geological and hydrogeological modeling

A maximum of seven parameters were calibrated with inverse simulations. The initial values were chosen as follows: (1) hydraulic conductivity of the non-weathered rock deriving from modeling studies in northern Switzerland (Nagra, 2002); (2) hydraulic conductivity of the weathered Gipskeuper deriving from regional modeling studies; (3) hydraulic conductivity for the Quaternary cover representing an empirical value for Quaternary deposits; (4) initial conductance values for the GHB, and drains deriving from manual calibration with the basic model. These initial parameters were varied by one order of magnitude for the hydraulic conductivity of the Quaternary and the weathered Gipskeuper and by two orders of magnitude for the hydraulic conductivity of the non-weathered rock and the conductance of the GHB and the drains. Figure 11 illustrates the divergence of measured and calibrated groundwater heads at the observation wells ranging between 0.14 and 2.38 m; one observation well falls dry. Table 3 summarizes the initial set of employed and calibrated parameter values for the extended model with drains at average discharge before and after the construction measures. Upper boundary values within the weathered Gipskeuper and non-weathered rock are reached, indicating that the extended weathered zone beneath the dam and drains has been adequately considered. The reason for the calibrated high values of hydraulic conductance downstream of the dam structure compared to those upstream could be the occurrence of groundwater outlets in the more heterogeneous riverbed downstream (high flow velocities and turbulent flow in the vicinity of the dam overflow) and the more colmated riverbed upstream of the dam structure (area with low flow velocities and sedimentation of fine material). Results of sensitivity analyses indicate that the highest parameter sensitivity was calculated for the hydraulic conductivity of the non-weathered rock and the conductance of the GHB upstream of the dam. Calibrated hydraulic conductivities for the lithostratigraphic units correspond to a regional scale value; calibrated hydraulic river conductance values are in the range of the published data for various Swiss rivers (Höhn, 2002; Huggenberger et al., 2006); calibrated hydraulic conductance of the drain features is less than that calculated from the dye tracer test, indicating that the effect of drain features is not overestimated.



OW	Measured head (m a.s.l.)	Calculated head (m a.s.l.)	Difference
3	263.80	263.04	-0.76
4	260.95	261.32	0.37
5	260.86	261.42	0.56
7	262.33	262.47	0.14
9	260.81	261.35	0.54
10	260.96	261.81	0.85
12	263.84	263.30	-0.54
13	263.95	263.62	-0.33
14	264.01	Dry	Dry
16	261.79	264.17	2.38
18	260.98	262.84	1.86

Fig. 11: Calibration results

Figure 12 shows hydraulic heads and flow paths illustrated by particle tracks in layer 2 for the extended steady state groundwater model with drains at average discharge before and after the construction measures. Note the bulge of the weathered Gipskeuper to the South of the modeling domain which can be explained by the abandoned riverbed (Fig. 4). It is assumed that in earlier times, increased solution took place beneath the abandoned riverbed resulting in the bulge of weathered Gipskeuper. For the simulation after the construction measures, the sealing pile wall was integrated into the model layers 1 to 4 and its hydraulic conductivity calibrated by minimizing the divergence between observed and calculated heads in OW3, resulting in 1.0E-09 ms^{-1}. The groundwater flow regimes for both model scenarios clearly show the influence of the dam structure. Backwater can be observed in front of the sealing pile wall, towards the river. The effect of the drains is striking, as they focus on the flow paths. The gradient in the non-weathered rock is steeper than in the weathered Gipskeuper and the Quaternary cover. In Table 4, water budgets across model boundaries and through defined cross sections are summarized for the steady state groundwater model. Calculated water budgets indicate that model outflow through the GHB downstream of the dam is slightly higher than model inflow through the GHB upstream of the dam. Flow through the drains ranges between 5.0 and 6.1 ls^{-1}. Flow through Zone 1 is higher than flow through Zones 2 and 3. The effect of the sealing pile wall is clearly visible for the simulation after the construction measures. Residual flow through the sealing pile wall reaches 1.8 ls^{-1}.

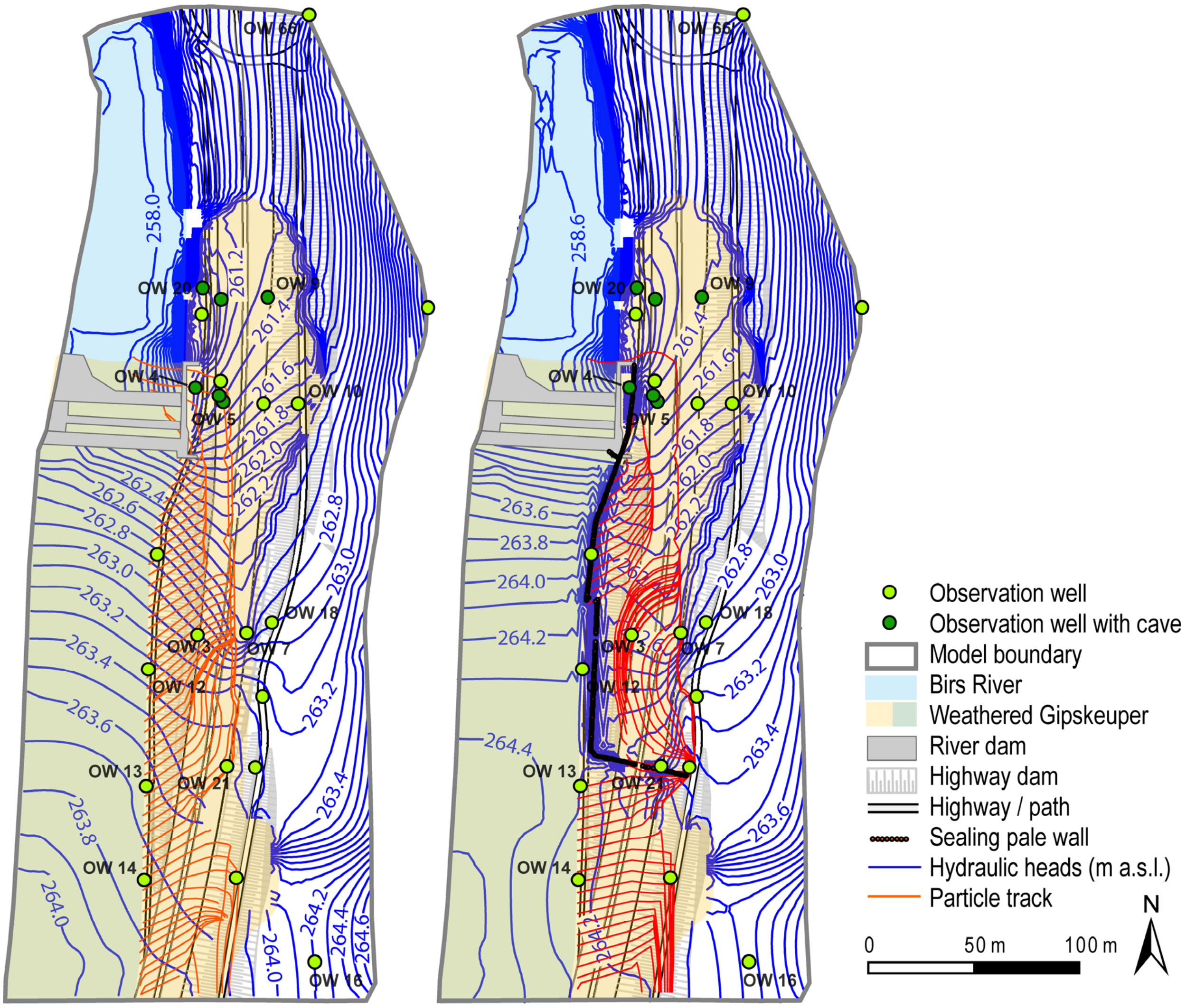


Fig. 12: Visualization of hydraulic heads and particle tracks in model layer 2 (0.1 m resolution)
Left: Groundwater flow regime at average river discharge before construction measures (07.02.06)
Right: Groundwater flow regime at average river discharge after construction measures (15.01.08)

Table 3: Initial and calibrated hydraulic parameters

	Initial parameters	Calibrated parameters
HK_Quaternary (ms^{-1})	5.0E-03	9.8E-04
HK_weathered Gipskeuper (ms^{-1})	1.0E-05	1.0E-04
HK_non-weathered rock (ms^{-1})	1.0E-07	1.0E-05
GHB_upstream (s^{-1})	2.0E-06	2.7E-07
GHB_downstream (s^{-1})	2.0E-06	9.4E-05
Drain 1 (ms^{-1})	2.0E-03	6.0E-04
Drain 2 (ms^{-1})	2.0E-03	8.1E-03

Table 4: Water budgets (in ls-1) across model boundaries and defined zones of the cross section (see Fig. 6 for location of boundaries and Fig. 14 for location of zones for water budgets)

	Before construction measures		After construction measures	
	IN	OUT	IN	OUT
1. Kind, Dirichlet	0.5	2.2	0.4	2.6
3. Kind, Cauchy	10.2	13.4	7.8	11.6
Drains	0.0	6.1	0.0	5.0
ZONE 1	5.6	5.4	5.7	5.7
ZONE 2	2.0	2.1	1.3	1.3
ZONE 3	1.6	1.7	1.3	1.4

4.4 Integration of the investigative methods

An iterative integration and combination of investigative methods together with the analysis of multiple data sets considerably improved the description of the gypsum karst system within the investigation area. Associated uncertainties in data interpretation and numeric modeling are approached by (1) classifying data quality, (2) parameter sensitivity analysis, and (3) scenario development and evaluation. On the basis of information content and the accuracy of the multiple collected data sets, which are of quite different type and quality, data were classified as soft or hard (Regli et al., 2002). As part of the sensitivity analysis, the most relevant parameters governing the system could be determined, which are the hydraulic conductivity of the non-weathered rock, and the conductance of the GHB upstream of the dam. On the basis of calculated scenarios, variable geological, hydrological and geotechnical boundary conditions that influence the groundwater flow regime could be evaluated.

Boreholes provided general lithostratigraphic information, including details about the vertical extension of the weathered Gipskeuper and significant permeable zones, as well as already developed voids. Ever since the 1990’s several boreholes have left a stratigraphic connection and locally stimulated karstification. Initial, coarse cross sections could be developed using the information on the national geological map. Additional lithostratigraphic information could be derived from the reports made during the installation of the piles, resulting in more precise cross sections of the investigation area. Extensive groundwater monitoring revealed that, in most observation wells, strong reactions at the groundwater heads and electric conductivity were observed during the construction work, and that some of the hydrographs exhibit a siphon mechanism in line with the hydrological characteristics of that river stage. Hydraulic links within the investigation area were confirmed by a dye tracer test with groundwater flow velocities typical for conduit systems. These results indicate that the karst system is already well developed, whereas solution conduits developed along a system of fractures and interconnected joints, suggesting a three-dimensional conduit network.

ERT methods can result in a more comprehensive and detailed site characterization than could be achieved by drilling alone, especially in complex environments such as karst areas and at unstable sites, where invasive techniques, such as drillings, cannot be performed (Gabbani et al., 2000; Lapenna et al., 2000; Sretenovic et al., 2000; Yaramanci and Kiewer, 2000, Fenning et al., 2000). As locations and geometries of dominant karst features, controlling the flow, are not known with the required accuracy, geophysical techniques provide innovative information to improve hydrogeological models of karst aquifers. Results from ERT measurements, taken at different hydrologic and geotechnical boundary conditions allowed the description of (1) preferential flow in the shallow subsurface; (2) zones that are related to groundwater flow around the dam, including flow dynamics; (2) zones that are related to groundwater flow beneath the dam; (3) drainage phenomena of karst features like voids and conduits; (4) the weathering horizon within the Gipskeuper; (5) near surface faults and fracture zones, and (6) buried paleochannels. Thanks to the multiple data sources and hydraulic data from high-resolution hydrogeological modeling, it was possible to partially eliminate ambiguity in data interpretation and to describe the interrelation of observed features in a spatial context. Furthermore, delineating the structural patterns of conduits, voids and faults may contribute to increasing the safety of the buildings within the study area.

The multiple data sets facilitated the development of comprehensive 3D hydrogeological models which were adapted and calibrated continuously. The magnitude of calibrated parameters corresponds to regional hydrogeological investigations and field experiments. This indicates that calculated flow paths and flow budgets through defined zones, and especially their proportions, are plausible. The development of model scenarios facilitated the evaluation of (1) the extension of the weathered Gipskeuper beneath the dam; (2) drain networks within the weathered Gipskeuper and (3) construction measures.

Figure 13 shows the integration of information from the ERT measurements along the two profiles and the results of the groundwater model at average discharge before the construction measures. The 2D cross sections illustrate the vertical hydraulic heads together with interpreted features resulting from the ERT measurements, as well as water budgets across the longitudinal cross section (Fig. 4 & 6). The influence of the various lithostratigraphic sequences on the hydraulic head distribution is clearly evident as they refract the groundwater head isolines. The hydraulic gradient is the highest in the vicinity of the dam structure. From about 200 to 30 m in the lower part, the gradient of illustrated vertical hydraulic heads gradually orients more towards the surface. Here regions with considerably low resistivities were measured and preferential groundwater flow is assumed. Water budgets are highest in the Quaternary, beneath the dam, in the vicinity of the drains, and at the interface of weathered and non-weathered rock. The two zones with relatively high resistivity values north of the dam, which were interpreted to be part of the conduit system (Fig. 9 & 10), correspond with high water budget zones. The region with relatively low water budgets in the shallow subsurface between 30 and 65 m can be explained by model cells that fall dry during the simulation.

Figure 14 illustrates schematically the complexity of subsurface flow around and beneath the dam. The highest hydraulic gradient is observed and permanent flow occurs in the vicinity of the dam (blue); in this region most voids were encountered and ERT measurements resulted in fairly low resistivity values. Regions further away from the dam contribute to flow processes mainly during flood events (light blue). The delineation of this region follows the from abandoned river channels, and is delimited by the occurrence of more resistant rocks to the east (cf. Fig. 4).

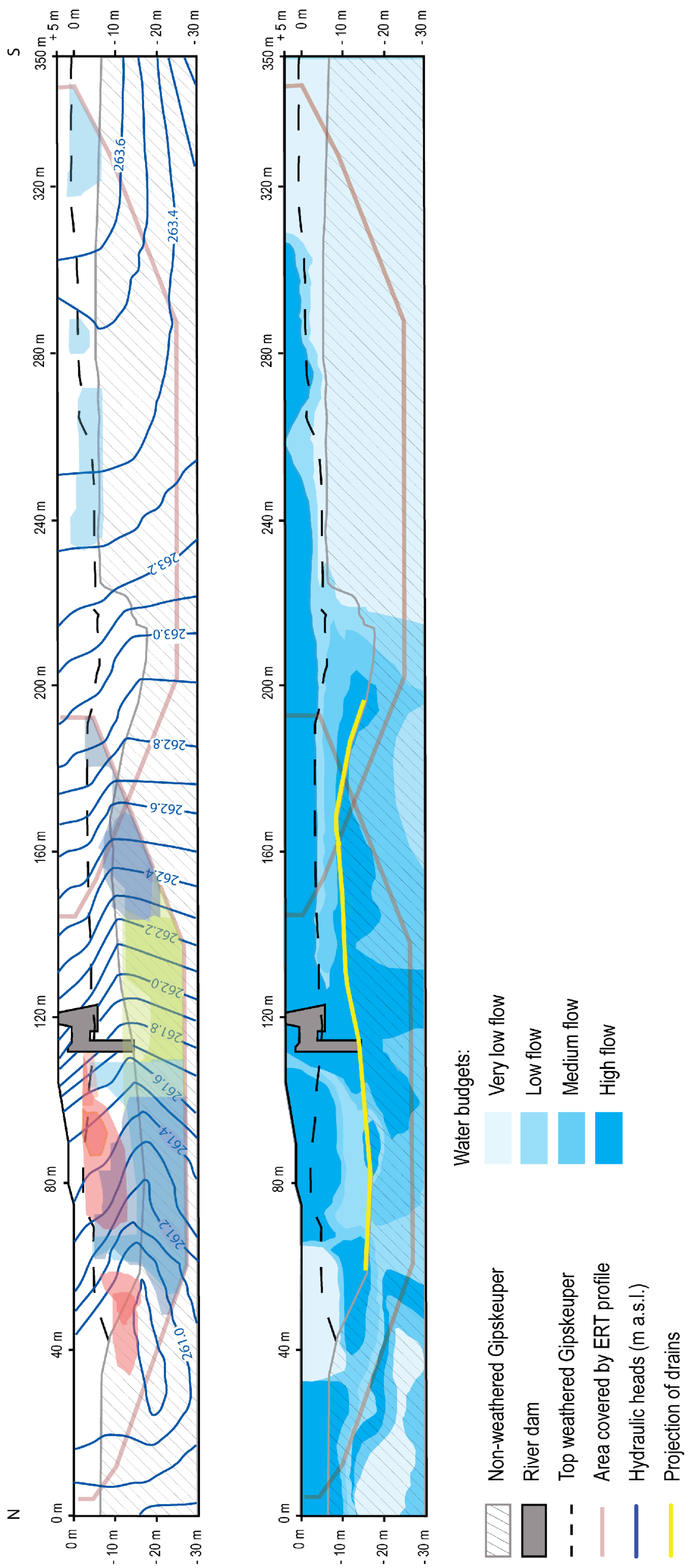


Fig. 13: Integration of information from ERT measurements and results of the groundwater model at average discharge before the construction measures (07.02.06)

Top: Vertical hydraulic heads (m a.s.l.; 0.1 m resolution) together with interpreted features of ERT measurements

Bottom: Water budgets across longitudinal cross section (very low flow cells 0 to 1E-02 ls^{-1}; low flow cells 1E-02 to E-02 ls^{-1}; medium flow cells 2E-02 to 3E-02 ls^{-1}; high flow cells > 3E-02 ls^{-1})

(See Fig. 1 for the location of ERT profiles, Fig. 4 for longitudinal cross section and Fig. 9 for the legend of interpreted features of ERT measurements)

Figures 4 and 14 show several longitudinal and transversal cross sections illustrating the depressions in the bedrock surface. The transverse cross section shows the channel of the abandoned bending river to the east. The longitudinal cross section in Figures 4 and 14 illustrate the progression of cascades parallel to the current river course, whereas the cross section C-C' derives from morphological analysis of the interface of weathered and non-weathered rock. Initially the surface morphology was shaped by the bending river course consisting of an asymmetric progression of cascades. This morphology was modified subsequently by artificial fillings to facilitate the construction of the river dam and the highway. Today the former cascading system is limited to one single step of 7.3 m formed by the river dam. It is assumed that these depressions form cascading subsurface conduit systems. This is confirmed by groundwater head measurements that indicate two dominant groundwater levels up- and downstream of the dam (Fig. 7). Such settings would explain the functioning of the described siphon mechanism, whereas the various system elements communicate via phreatic loops. The hydrogeological regime is still very much influenced by the subsurface morphology, especially in regions beneath the highway, whereas most enlargements occur along connected conduits that lie along a direct path between recharge and discharge locations and cascade along a hydraulic gradient.

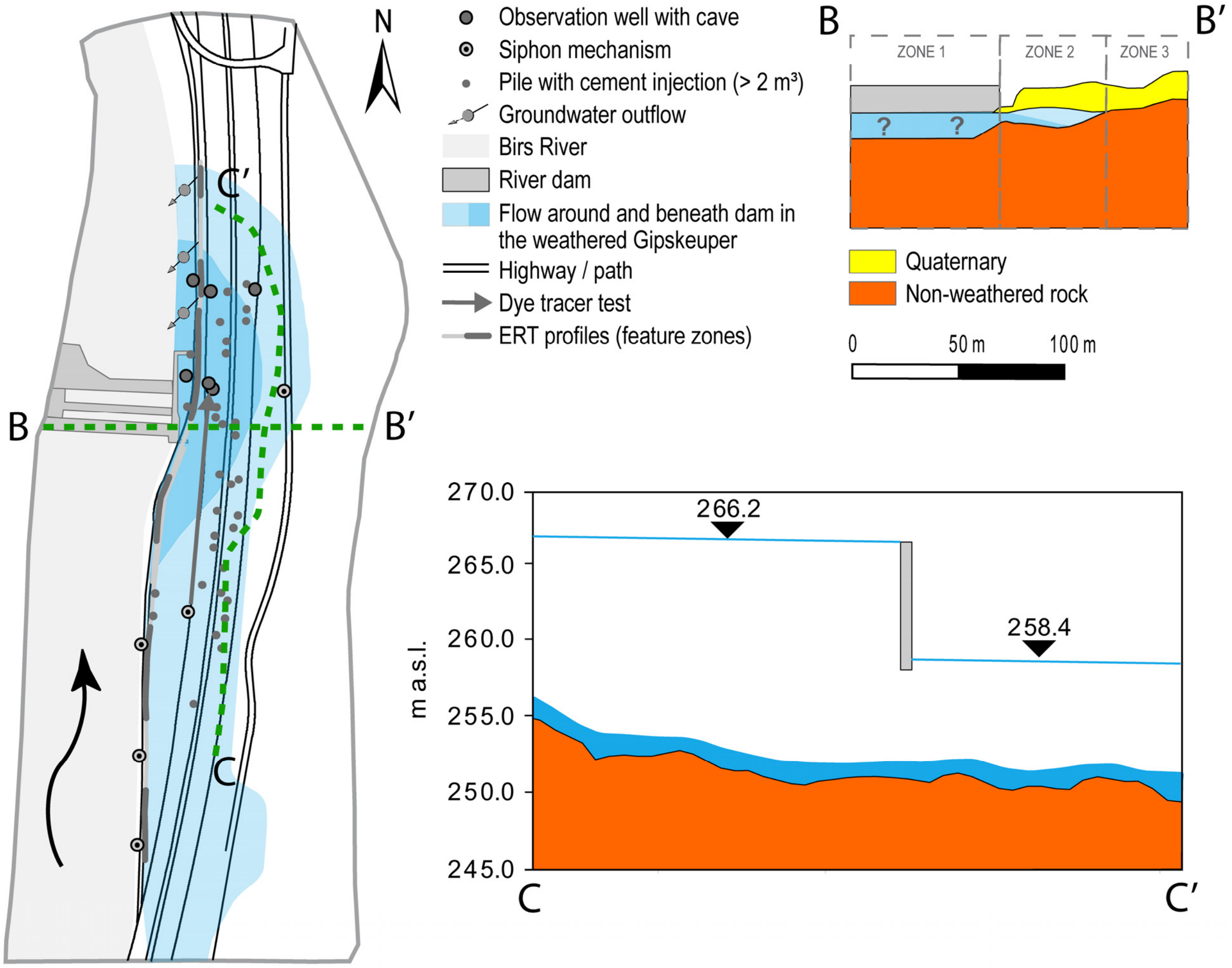


Fig. 14: Schematic illustration of flow around and beneath the river dam in the weathered Gipskeuper, transverse cross section (B-B') with defined regions for water budgets and longitudinal cross section (C-C', vertical magnification: 20) illustrating the succession of cascades and an assumed ancient river level parallel to the current river course in relation to the present hydraulics up- and downstream of the river dam

5 Discussion and Conclusions

Integrated and adaptive surface and groundwater monitoring and management in urban areas require innovative process-oriented approaches. To accomplish this, it is necessary to develop and combine interdisciplinary instruments that facilitate the adequate quantification of cumulative effects on hydrogeological regimes. While the impacts of major construction projects on water resources and groundwater flow regimes must be viewed from a holistic perspective, it is also necessary to consider the various impacts simultaneously and to recognize that they are often not limited in a local way and can have effects on the regional scale. The implementation of sustainability concepts during engineering projects is a key objective of urban hydrogeology. It is clear that the processes must first be understood at the local or project scale. Next, the changes induced in adjacent systems or at the regional scale have to be evaluated. And finally, the development of scenarios should facilitate the optimization of technical measures, including the minimization of negative impacts with respect to the interests of various groups.

The clear definition of system profiles and goals fosters an optimal evaluation of the impact of individual measures in the context of urban landscape development as it relates not only to current issues, but also to future demands. The knowledge of local geological and hydrological conditions as well as the understanding of the water flow regimes can contribute greatly to finding solutions to regional problems (Huggenberger, 1999) and can serve as a decision-making tool for project planners and administrators.

Generally speaking, decisions made during geotechnical projects are based on the limited information available from various lithological, hydrogeological and geotechnical drill-core descriptions, data derived from monitoring and borehole tests, as well as simple conceptual models. Furthermore, the funds allotted are intended only for data collection that is directly related to the individual project. This limited information often does not describe the spatial heterogeneity of subsurface structures, especially in karst areas. These structures determine rock-water interaction as well as hydraulics and the dynamics of groundwater flow regimes and thus the evolution of the karst system.

Protection schemes and geotechnical investigations that are necessary for engineering projects often provide “windows of opportunity”, that is the opportunity possibility to change perceptions concerning the sustainable development of water resources, and to coordinate future measures. Extended monitoring systems combined with field experiments as well as modeling and scenario techniques provide tools that increase the understanding of system behavior and the dynamics of groundwater flow regimes. Furthermore, they make it possible to predict the long-term behavior of the system and the performance of the affected infrastructures. The iterative integration and combination of the applied process-oriented investigation methods will significantly support the optimization of (1) future karst investigation methods; (2) observation networks with a predictive character for adaptive surface and subsurface water as well as subsidence monitoring, and (3) future remedial measures, including the determination of locations where excessive grout material is required. The cost of setting up the described monitoring system, including a series of ERT profiles and integrated hydrogeological modeling, is relatively low compared to the total cost of the engineering project.

In the course of this engineering project, the present concept allowed the system behavior and impacts of construction measures to be evaluated in the context of sustainable development of urban landscape. The developed tools facilitated the determination of the relevant parameters governing the system, a better understanding of the fundamental processes involved, and the approximation of long-term changes. Several distinct geological and hydrogeological features of different hydraulic and geotechnical boundary conditions could be interpreted, suggesting that the karst system is already in a well-developed, mature state. The interaction of these features resulted in the observed subsidence of the dam and the highway. Flow processes around and beneath the dam are accelerated at high river discharge, whereas extended regions are water saturated and contribute to flow processes and preferential flow in the conduit system. The analysis of groundwater measurements, the setup of a 3D hydrogeological model, and the development of scenarios for different hydraulic and geotechnical boundary conditions contributed greatly to a better understanding of the interrelationship of the various observed features.

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References

Al-Saigh, N.H., Mohammed, Z.S., Dahham, M.S., 1994. Detection of water leakage from dams by selfpotential method. Engineering Geology 37, 115-121.

Anderson, M.P., Woessner, W.W., 1992. Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press, Inc., New York.

Baines, D., Smith, D.G., Froese, D.G., Bauman, P., Nimeck, G., 2002. Electrical Resistivity Ground Imaging (ERGI): a new tool for mapping the lithology and geometry of channel-belts and valley-fills. Sedimentology 49, 441-449.

Bitterli-Brunner, P., Fischer, H., Herzog, P., 1984. Geologic map Blatt Arlesheim 1067 (in German). Geological Atlas of Switzerland.

Bitterli-Brunner, P., Fischer, H., 1989. Explanations map Blat Arlesheim 1067 (in German). Geological Atlas of Switzerland.

Bögli, A., 1980. Karst Hydrology and Physical Speleology. Springer Verlag, Berlin.

Bonacci, O., Bojanić, D., 1991. Rhythmic karst springs. Hydrological Science Journal, 36(1), 35-47.

Butscher, C., Huggenberger, P., 2008. Intrinsic vulnerability assessment in karst areas: a numerical modeling approach. Water Resources Research 44 (3), W03408.

Dahlin, T., 1996. 2D resistivity surveying for environmental and engineering applications. First Break 14 (7), 275-283.

Doherty, J., 1994. PEST Model-Independent Parameter Estimation. Watermark Computing, Corinda, Australia.

Donner, F., 1997. Modern measurement and evaluation procedures for resistivity geoelectrics, with application examples (in German). Zeitschrift für angewandte Geologie 42/3.

Dreiss, S.J., 1989a. Regional scale transport in a karst aquifer: 1. Component separation of spring flow hydrographs. Water Resources Research 25 (1), 117-125.

Dreiss, S.J., 1989b. Regional scale transport in a karst aquifer: 2. Linear systems and time moment analysis. Water Resources Research 25 (1), 126-134.

El-Hussain, I., Holbrook, J., Sneed, C., 2000. Integrated geophysical and geological methods to delineate buried paleochannels in the New Madrid seismic zone of southeastern Missouri, in Proceedings for SAGEEP 2000, Washington D.C., 253-262.

El-Qady, G., Hafez, M., Abdalla, M.A., Ushijima, K., 2005. Imaging subsurface cavities using geoelectric tomography and ground-penetrating radar. Journal of Cave and Karst Studies, 67 (3), 174-181.

Eisenlohr, L., Bouzelboudjen, M., Kiraly, L., Rossier, Y., 1997. Numerical versus statistical modeling of natural response of a karst hydrogeological system. Journal of Hydrology 202, 244-262.

Eiswirth, M., Hötzl, H., Cronin, A., Morris, B., Veselič, M., Bufler, R., Burn, S., Dillon, P., 2003. Assessing and improving sustainability of urban water resources and systems. RMZ, Materials and Geoenvironment 50, 117-120.

Epting, J., Regli, C., Huggenberger, P., 2007. Groundwater protection in urban areas incorporating adaptive groundwater monitoring and management. In: Adaptive and Integrated Water Management, Coping with Complexity and Uncertainty. Pahl-Wostl, C., Kabat, P., Möltgen, J. (eds), 2007, Springer; XIV.

Epting, J., Huggenberger, P., Rauber, M., 2008a. Integrated methods and scenario development in urban groundwater management, and protection during tunnel road construction; A case study of urban hydrogeology in the city of Basel, Switzerland. Hydrogeology Journal 16, 575-591.

Epting, J., Huggenberger, P., Regli, C., Spoljaric, N., Kirchhofer, R., 2008b. Integrated methods for urban groundwater management considering subsurface heterogeneity. In: Quantitative Information Fusion for Hydrological Sciences. Cai X, Jim Yeh TC (Eds.) 2008, Springer Series: Studies in Computational Intelligence; X, 79.

Fatta, D., Naoum, D., Loizidou, M., 2002. Integrated environmental monitoring and simulation system for use as a management decision support tool in urban areas. Journal of Environmental Management 64, 333-343.

Fenning, P.J., Brown, A.J., Nind, D., 2000. Geophysical surveys across a ground subsidence feature, in Proceedings for SAGEEP 2000, Washington D.C., 857-866.

Fechter, D., 1856. Topography with the consideration of the cultural and conventional history (in German). In: Basel in the 14th century.

Gabbani, G., Lavorini, G., Pacini, L., 2000. Geophysical and geotechnical investigation of an areal landslide in the Tuscan Northern Apennines (Italy) with an extensive consolidation design. In: Proceedings for the EEGS-ES 2000 Annual Meeting, Bochum, Germany.

Golder, E., 1984. 100 years Birswuhr Neue Welt (in German). Published by: Baudepartement Basel-Stadt, Tiefbauamt.

Griffiths, D.H., Barker, R.D., 1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. Journal of Applied Geophysics 29, 211-226.

Gutiérrez, F., 1996. Gypsum karstification induced subsidence: effects on alluvial systems and derived geohazards (Calatayud Graben, Iberian Range, Spain). Geomorphology 16, 277-293.

Gürler, B., Hauber, L., Schwander, M., 1987. Geology of the surrounding area of Basel with suggestions usage options of geothermal energy (in German). In: Beitrag zur Geologischen Karte der Schweiz.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model - User Guide to Modularization Concepts and the Ground-Water Flow Process. Open-File Report 00-92U.S., Geological Survey, Reston, Virginia.

Höhn, E., 2002. Hydrogeological issues of riverbank filtration – a review. Pages 17–41 in C Ray und NATO, editors. Riverbank filtration understanding contaminant biogeochemistry and pathogen removal. Kluwer, Dordrecht.

Huggenberger, P., 1999. Urban geology: the example groundwater (in German). Uni Nova April 99, Basel, Switzerland.

Huggenberger, P., Epting, J., Regli, C., Spottke, I., Zechner, E., 2006. River-groundwater Interaktion. MoNit: Modelling of nitrate groundwater contamination in the Upper Rhine Graben. INTERREG III A-Projekt. Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe.

Jones, N.L., Budge, T.J., Lemon, A.M., Zundel, A.K., 2002. Generating MODFLOW grids from boundary representation solid models. Ground Water 40 (2), 194-200.

Josnin, J.-Y., Pistre, S., Drogue, C., 2000. Modélisation d'un système karstique complexe (basin de St. Chaptes, Gard, France): un outil de synthèse des données géologiques et hydrogéologiques. Canadian Journal of Earth Sciences 37, 1425-1445.

Khalil, M.H., 2006. Geoelectric resistivity sounding for delineating salt water intrusion in the Abu Zanima area, west Sinai, Egypt, Journal of Geophysics and Engineering 3, 243-251.

Kovacs, A., 2003. Geometry and hydraulic parameters of karst aquifers: A hydrodynamic modeling approach.; Thèse de Doctorat, CHYN, Univ de Neuchâtel.

Lamont-Black, J., Younger, P.L., Forth, R.A., Cooper, A.H., Bonniface, J.P., 2002. A decision-logic framework for investigating subsidence problems potentially attributable to gypsum karstification, Engineering Geology 65 (2-3), 205-215.

Lapenna, V., Perrone, A., Pietro, L., Piscitelli, S., Rizzo, E., Sdao, F., 2000. 2D resistivity and 3D self-potential tomographies in the study of the Giarrossa landslide (southern Italy), in Proceedings for the EEGS-ES 2000 Annual Meeting, Bochum, Germany.

Lemon, A.M., Jones, N.L., 2003. Building solid models from boreholes and user-defined cross-sections. Computers & Geosciences 29 (5), 547-555.

Leucci, G., De Giorgi, L., 2005. Integrated geophysical surveys to assess the structural conditions of a karstic cave of archaeological importance. Natural Hazards and Earth System Sciences 5, 17-22.

Loke, M.H., Barker, R.D., 1996. Rapid least-squares inversion of apparent resistivity pseudosections using a quasi-Newton method, Geophys. Prosp., 44, 131-152.

Long, J.C.S., Remer, J.S., Wilson, C.R., Witherspoon, P.A., 1982. Porous media equivalents for networks of discontinuous fractures. Water Resources Research 18 (3), 645-658.

Long, J.C.S., Billaux, D.M., 1987. From field data to fracture network modeling: an example incorporating spatial structure. Water Resources Research 23 (7), 1201-1216.

Mace, R.E., 1995. Geostatistical description of hydraulic properties in karst aquifers: a case study in the Edwards Aquifer. Proceedings, International Symposium on Groundwater Management. American Society of Civil Engineers, New York, 193-198.

Maillet, G., Rizzo, E., Revil, A., Vella, C., 2005. High resolution electrical resistivity tomography (ERT) in a transition zone environment: Application for detailed internal architecture and infilling processes study of a Rhône River paleo-channel. Marine Geophysical Researches 26, 317-328.

McGrath, R.J., Styles, P., Thomas, E., Neale, S., 2002. Integrated high-resolution geophysical investigations as potential tools for water resource investigations in karst terrain. Environmental Geology 42, 552-557.

Nagra, 2002. Project Opalinuston: Syntheses of geoscientific investigation results (in German). NTB: 02-03.

Pahl-Wostl, C., Möltgen, J., Sendzimir, J., Kabat, P., 2005. New methods for adaptive water management under uncertainty - The NeWater project. Paper in EWRA conference proceedings 2005, Menton, France.

Pahl-Wostl, C., 2006. Newsletter No. 1. http://www.newater.info. Cited June 2006.

Pearson, F.J., Balderer, W., Loosli, H.H., Lehmann, B.E., Matter, A., Peters, T., Schmassmann, H., Gautschi, A., 1991. Applied Isotope Hydrogeology-a case study in northern Switzerland. Elsevier

Quinn, J., Tomasko, D., 2000. A numerical approach to simulating mixed flow in karst aquifers. In: Sasowsky, I., Wicks, C. (Eds.), Groundwater Flow and Contaminant Transport in Carbonate Aquifers. A.A. Balkema, Rotterdam, Holland, 147-156.

Quinn, J.J., Tomasko, D., Kuiper, J.A., 2006. Modeling complex flow in a karst aquifer. Sedimentary Geology 184 (3-4), 343-351.

Pellerin, L., 2002. Applications of electrical and electromagnetic methods for environmental and geotechnical investigations. Surveys in Geophysics 23, 101-132.

Regli, C., Huggenberger, P., Rauber, M., 2002. Interpretation of drill-core and georadar data of coarse gravel deposits. Journal of Hydrology 255, 234-252.

Reynolds, J.M., 1997. An Introduction to Applied and Environmental Geophysics. Wiley, New York.

Schmassmann, H., 1972. Baselbieter and western Aargauer Tafeljura (in German). In: Jäckli H, Kempf T, 1972, Erläuterungen zum Blatt Bözberg-Beromünster 1. Hydrogeologische Karte der Schweiz, 93-100.

Schön, J., 1983. Petrophysicsk (in German). Physikalische Eigenschaften von Gesteinen und Mineralen, Enke, Stuttgart.

Soupios, P., Papadopoulos, I., Kouli, M., Georgaki, I., Vallianatos, F., Kokkinou, E., 2007. Investigation of waste disposal areas using electrical methods: a case study from Chania, Crete, Greece. Environmental Geology 51.

Spottke, I., Zechner, E., Huggenberger, P., 2005. The southeastern border of the Upper Rhine Graben: A 3D geological model and its importance for tectonics and groundwater flow. International Journal of Earth Sciences 94, 580-593.

Sretenovic, B., Lokin, P., Sretenovic, N., Djordjevic, M., Kisin, S., 2000. Some possibilities of electrical scanning method in landslides exploration, in Proceedings for the EEGS-ES 2000 Annual Meeting, Bochum, Germany.

Šumanovac, F., Weisser, M., 2001. Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains. Journal of Applied Geophysics 47, 13-28.

Teutsch, G., 1989. Groundwater models in karstified terrains: two practical examples from the Swabian Alb (S. Germany). Proceedings, Solving Ground Water Problems with Models. International Ground Water Modeling Center, Indianapolis, Indiana, 929–953.

Thrailkill, J., Sullivan, S.B., Gouzie, D.R., 1991. Flow parameters in a shallow conduit-flow carbonate aquifer, Inner 350 J.J. Quinn et al. / Sedimentary Geology 184 (2006) 343–351 Bluegrass Karst Region, Kentucky, USA. Journal of Hydrology 129, 87-108.

van Schoor, M., 2002. Detection of sinkholes using 2D electrical resistivity imaging, Journal of Applied Geophysics 50 (4), 393-399.

Wise´n, R., Bjelm, L., Dahlin, T., 2000. Resistivity imaging as a preinvestigation method in urban environments. Proceedings EEGS-ES 6th Meeting, CH05.

Yaramanci, U., Kiewer, M., 2000. Geoelectrical Characterisation of the Opalinus ClayFormation in the Underground Rock Laboratory 'Mont Terri'. Mont Terri Project, Technical Note 99-27, ED-C Experiment. Technische Universität Berlin.

Part V

Integrating Field and Numerical Modeling Methods for Applied Urban Karst Hydrogeology

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Integrating Field and Numerical Modeling Methods for Applied Urban Karst Hydrogeology

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Infrastructures that are constructed on unstable geologic formations are prone to subsidence. Data have been collected in the context of an upgrading project for a highway located beside a river dam that was constructed on gypsum-containing formations. Surface water infiltrates upstream of the dam, circulates through the gravel deposits and into the weathered bedrock around and beneath the dam, and exfiltrates downstream into the river. As a result, an extended weathering zone within the bedrock and preferential flow paths within voids and conduits developed as part of a rapidly evolving karst system. These processes enhance karstification in the soluble units of the gypsum-containing formations and resulted in the subsidence of the dam and the highway.

Since 2006 changes in the hydrogeologic flow regime have been investigated continuously by different methods that also allow the evaluation of the long-term performance of the infrastructures. Geological (outcrops, lithostratigraphic information of boreholes), hydrometrical (extensive groundwater monitoring, dye tracer tests) and hydrogeophysical (Electrical Resistivity Tomography, ERT) field data of varying quality were integrated into high-resolution 3D hydrogeological and 2D karst evolution models. The applied investigative methods are validated and the sensitivity of relevant parameters governing the processes determined.

It could be demonstrated that the applied methods for karst aquifer characterization complement each other and allow the interpretation of short-term impacts and long-term development on system-dynamics in the context of hydrogeologic flow regimes of karst areas. This includes the description of the transient character of the hydrogeologic flow regime during and after episodic flood events (surface-groundwater interaction, conduit and diffuse model outflow) as well as the evaluation of time scales for karst evolution. Results allow the optimization of investigative methods for similar subsidence problems, leading from general measurements and monitoring technologies to tools with predictive character.

Key words: hydrogeological modeling, karst evolution, gypsum dissolution, subsidence, dam site, conduits

1 Introduction

While the characterization and modeling of flow in heterogeneous and fractured media has been investigated intensively, there are no well-developed long-term hydrogeological research sites for gypsum karst. Additionally, systems for monitoring the evolution of karst phenomena are rare. This case study documents the integration of different investigative methods in the context of an engineering project for the upgrade of a subsided highway located beside a river dam.

Surface and groundwater monitoring during engineering projects usually is restricted in order to comply with existing laws and regulations governing water quality issues during construction activities. In the current case study, sporadic measurements revealed that subsidence of the highway and the river dam has increased rapidly over the last ten years. At the beginning of the project, system knowledge was limited to purely conceptual models and sparse accurate monitoring data. As regards the locally specific engineering problem, and in order to plan appropriate remedial measures, it was recommended to set up instruments that allow this complex system to be examined under various hydraulic conditions. This included an assessment of the current hydrogeologic flow regime as well as the subsidence mechanism and its development over time. Such approaches require, along with the installation of surface and groundwater monitoring systems, specific field campaigns and modeling strategies to investigate the relevant processes. Furthermore, the developed tools should have not only a monitoring character; they should also enable long-term solidly based predictions to be made concerning the future evolution of the system and potential subsidence.

Infrastructures that are constructed on unstable geologic formations are prone to subsidence (Gutiérrez, 1996; Lamont-Black et al., 2002). When located close to artificial hydraulic structures such as river dams, natural processes of karstification can ensue due to: (1) the presence of evaporates; (2) elevated hydraulic gradients and (3) the presence of undersaturated water. Such boundary conditions can lead to increased leakage, to subsidence and to the failure and collapse of the hydraulic structures themselves and of nearby infrastructures, thereby endangering their survival existence. Especially when found within gypsum-containing formations, karst features develop much more rapidly than in carbonate formations. Engineering aspects related to gypsum karst and dam construction are discussed by James and Lupton (1978), James (1992), Klimchouk and Andrechuk (1996), Breznik (1998), Milanović (2000, 2004), Pearson (2002), Jarvis (2003), Johnson (2003a, b, c, 2005) and Payton and Hansen (2003). An example is the catastrophic failure of the Quail Creek Dike in southwest Utah in 1989 due to the flow of water through an undetected karstified gypsum unit beneath the earth-fill embankment (Johnson, 2008). A list of leakages at 42 dams worldwide is given by Milanović (2000).

The site-specific aspects of investigation projects and available data sets determine the complexity of modeling strategies used, e.g., issues related to water resource management of karst aquifers can be resolved by black box or global approaches. For process understanding and the integration of more complex groundwater flow in karst systems (drain network and matrix), numerical models that represent double continuum media typical of karst aquifers are to be applied (e.g. Kovacs, 2003).

Klimchouk et al. (2000) discussed the dynamics of the evolution of karst aquifers and Quinn et al. (2006) summarized the existing modeling approaches for simulating flow in karst environments. In the appendix these include: (1) models using equivalent porous medium in which flow is governed by Darcy's law (Anderson and Woessner, 1992); (2) models in which the preferred flow paths are simulated with a very high hydraulic conductivity relative to the surrounding matrix material (double porosity); (e.g. Teutsch, 1989; Mace, 1995; Kiraly, 1998; Eisenlohr et al., 1997; Josnin et al., 2000); (3) "black-box" approaches in which functions are developed to reproduce input and output system responses (recharge and flow at discharge springs; e.g. Dreiss, 1989a,b), as well as "global" approaches which include the hydrological dynamics of the conduit and the diffuse flow system (Butscher and Huggenberger, 2008); (4) fracture network simulations in which individual factures are mapped and then studied (Long et al., 1982; Long and Brillaux, 1987), and (5) open channel equivalents (Thrailkill et al., 1991).

For a more fundamental understanding of rock-groundwater interactions and the evolution of flow within karst aquifers, modeling techniques are applied that are based on fundamental and well-established physical and chemical principles. These models allow important processes, ranging from initial small-scale fracture networks to the mature karst, to be studied. The strength of such models lies in the assessment of evolution time scales and the quantification of rates at which processes operate. In the present case study, the simulation of the evolution of flow within the gypsum karst aquifer was approached by a simplified 2D finite difference method where hydrodynamic flow is coupled with equations of dissolutional widening. The evolution of two-dimensional karst aquifers has been intensively studied during the past decades (Groves and Howard, 1994; Clemens et al., 1996; Hanna and Rajaram, 1998; Siemers and Dreybrodt, 1998; Dreybrodt and Siemers, 2000; Gabrovšek et al., 2000; Gabrovšek and Dreybrodt, 2000, 2001; Kaufmann and Braun, 2000; Bauer et al., 2003, 2005; Romanov et al., 2002, Liedl et al., 2003), also close to dam structures (Dreybrodt, 1992, 1996; Dreybrodt et al., 2001, 2005; Romanov et al., 2003, 2007). These previous approaches to modeling karst evolution focused on hypothetical karst catchments with synthetic data. Few studies have attempted to integrate field data, which are sensitive to groundwater hydraulics, into real world applications which are related to locally specific issues.

An approach is presented which merges high resolution 3D hydrogeologic modeling (3D HGM) with 2D karst evolution modeling (2D KEM; Fig. 1). The different modeling techniques capture different aspects of the hydrologic processes and were employed by independent modeling teams. This allowed the estimated parameters to be cross-check and the results from both approaches to be evaluated continuously and interpreted separately. The 3D hydrogeological model (3D HGM) presented in this paper includes a deterministic finite difference approach which takes into account an equivalent porous medium for weathered and non-weathered rock, and a coupling of the system with drains that represent a generalization of the conduit component of model outflow (mixed flow in karst settings; Quinn and Tomasko, 2000; Quinn et al., 2006). The calibrated 3D HGM provided the geometric and hydraulic boundary conditions (modeling domain, groundwater and river head, hydraulic conductivity and conductance of the river bed) for the 2D KEM. The calibrated 2D KEM allowed the karst aquifer evolution to be simulated to its current state and the sensitivity of changing natural and anthropogenic boundary conditions to be investigated. Subsequently, resulting aquifer heterogeneities simulated using the 2D KEM were transferred to the 3D HGM. Applied modeling strategies complemented each other, in this process; results from the 3D HGM could be used for the validation of the 2D KEM, and vice versa.

Modeling results are validated, compared and discussed, together with multiple data sources (lithostratigraphic information of boreholes, extensive groundwater monitoring, dye tracer tests, hydrogeophysics) as well as water budgets through defined cross sections over time in the context of the hydrogeologic flow regime. The integration of different types and a varying quality of data sets into the different models, presented a particular challenge.

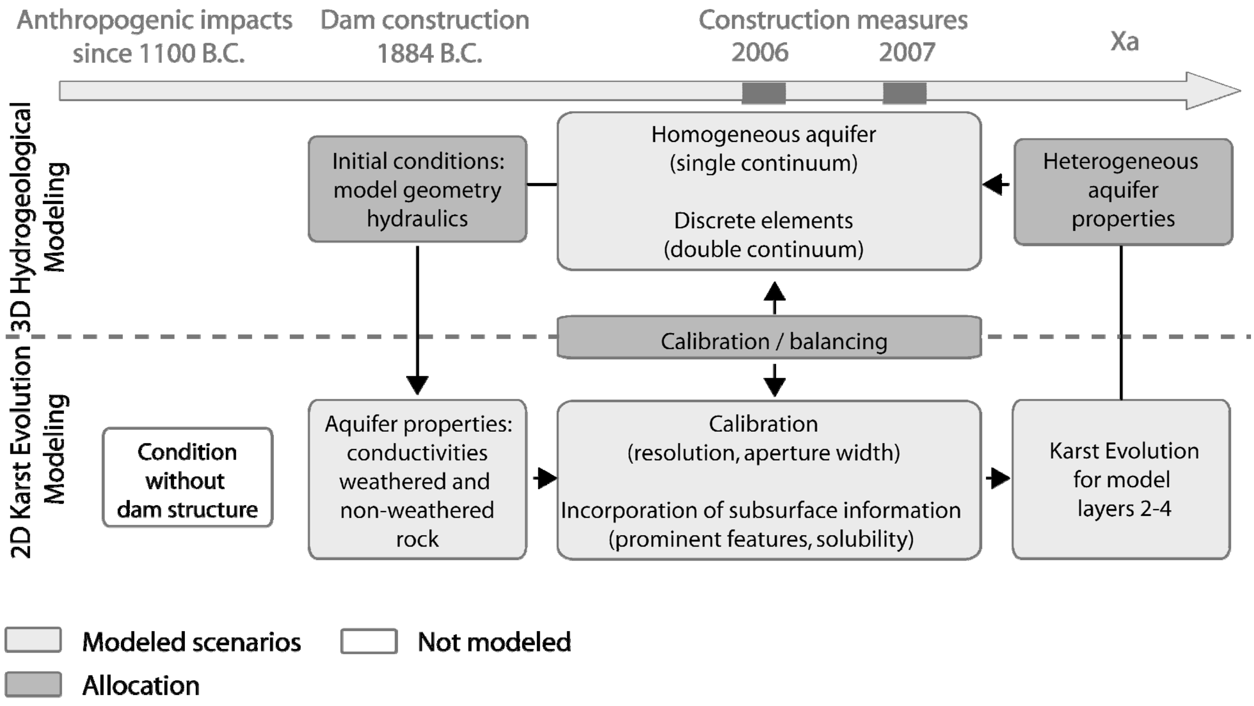

Fig. 1 Conceptual approach

2 Settings

The project area is located in the Lower Birs Valley southeast of Basel, Switzerland. Over the last 30 years subsidence of a manmade river dam and an adjacent highway has been observed (Fig. 2, 3 and 4). The dam in its current dimension was constructed in the 1890's (Golder, 1984). However, documentation of manmade impacts in this region, including the diversion of water for early manufacturing purposes in Basel, goes back as far as the 11th century (Fechter, 1856). The height difference to the base level downstream of the dam is 7.3 m. This hydraulic gradient is used for the generation of hydropower from a small hydro-electric power plant. As there is sufficient water supplied by the Birs River, the height of the impounded water upstream of the dam is practically constant at 266.2 m a.s.l. Surface-groundwater interaction is dominated by the hydraulic river head and variations in river bed conductance upstream of the dam during flood events. Upstream of the dam, river water infiltrates into the highly permeable fluvial gravels and the weathered bedrock, follows the hydraulic gradient around and beneath the dam and exfiltrates downstream into the river. These processes and the drilling of several boreholes in the 1990's that likely left a stratigraphic connection and hydraulically connected aquifers have led to the karstification in the soluble units of the “Gipskeuper” and resulted in an extended weathering zone within the bedrock as well as in the development of preferential flow within voids and conduits.

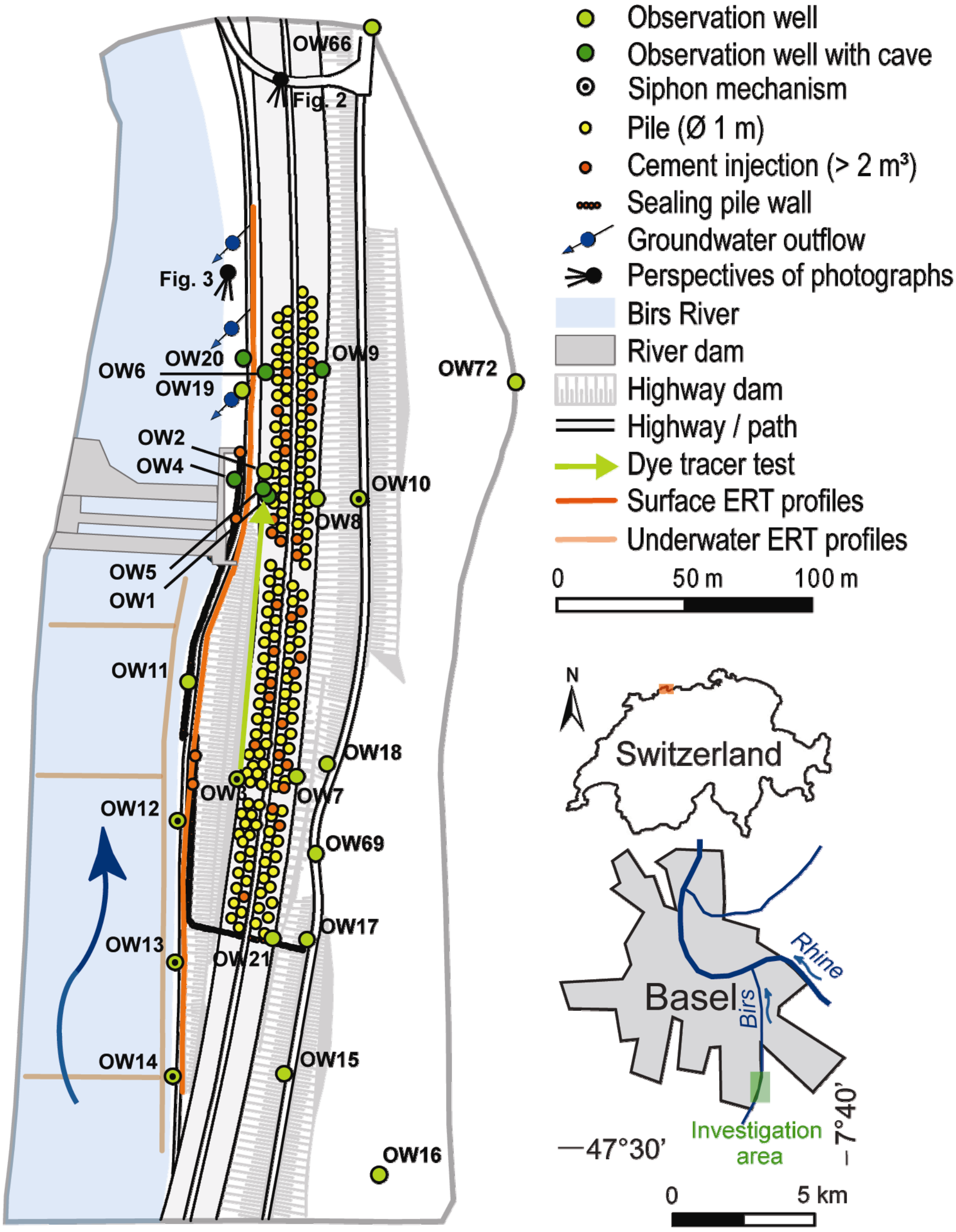

Fig. 2 Investigation area in the urban agglomeration of Basel

To prevent further subsidence, construction measures were carried out in two major project phases in 2006 and 2007. The highway was supported by 166 piles and by a sealing pile wall, consisting of approximately 300 piles (Fig. 2), to prevent infiltrating river water from circulating around the dam and beneath the foundation of the highway. Piles extend down to the non-weathered rock at a depth of 20 to 25 m. Caves encountered when the piles were being constructed were filled with a total of 168.2 m^3 of supplementary cement, in order to plug underground water channels and stabilize the ground beneath. In compliance with existing regulations, an observation network was installed in order to monitor surface and groundwater quality in the vicinity of the construction site and regional drinking-water supplies further downstream. Additionally, the observations allowed the identification and evaluation of the relevant processes. Online monitoring allowed the early detection and documentation of changes in hydraulic constraints in the vicinity of the construction site and the dam. In the event of breakthrough events and the mobilization of void fillings and cement injections, interventions could have been initiated to prevent surface and groundwater pollution.

Fig. 3 Investigation area (an overview diagram is given in Fig. 2)

Fig. 4 River dam at low river discharge (9 m³/s; 16.06.2006). Note, as evidence for the subsidence of the dam structure, that the crest is only overflowed on its left side (a diagram is given in Fig. 2)

2.1 Geology and Hydrogeology

The stratigraphic column in Figure 5 includes the Triassic, Jurassic and Quaternary units. Karst development mainly occurs in the gypsum-bearing parts of the Triassic. Quaternary gravels, silty flood deposits, as well as artificial fillings beneath the highway overlie the westward-dipping Triassic and Jurassic units on the right side of the river. For better visualization of the karst-relevant units and their orientation in space the Quaternary sequence has been removed. The tectonic settings (see below) result in a complex spatial distribution of the main geological formations which consist of marls and clays, dolomites and sandstones, marls and, for most of the investigation area, of Gipskeuper. The map also shows the course of the Birs River in the year 1798 compared to the situation in the year 1983. The river, which was straightened in the 19th century, cuts into the Triassic bedrock, resulting in a narrow couloir.

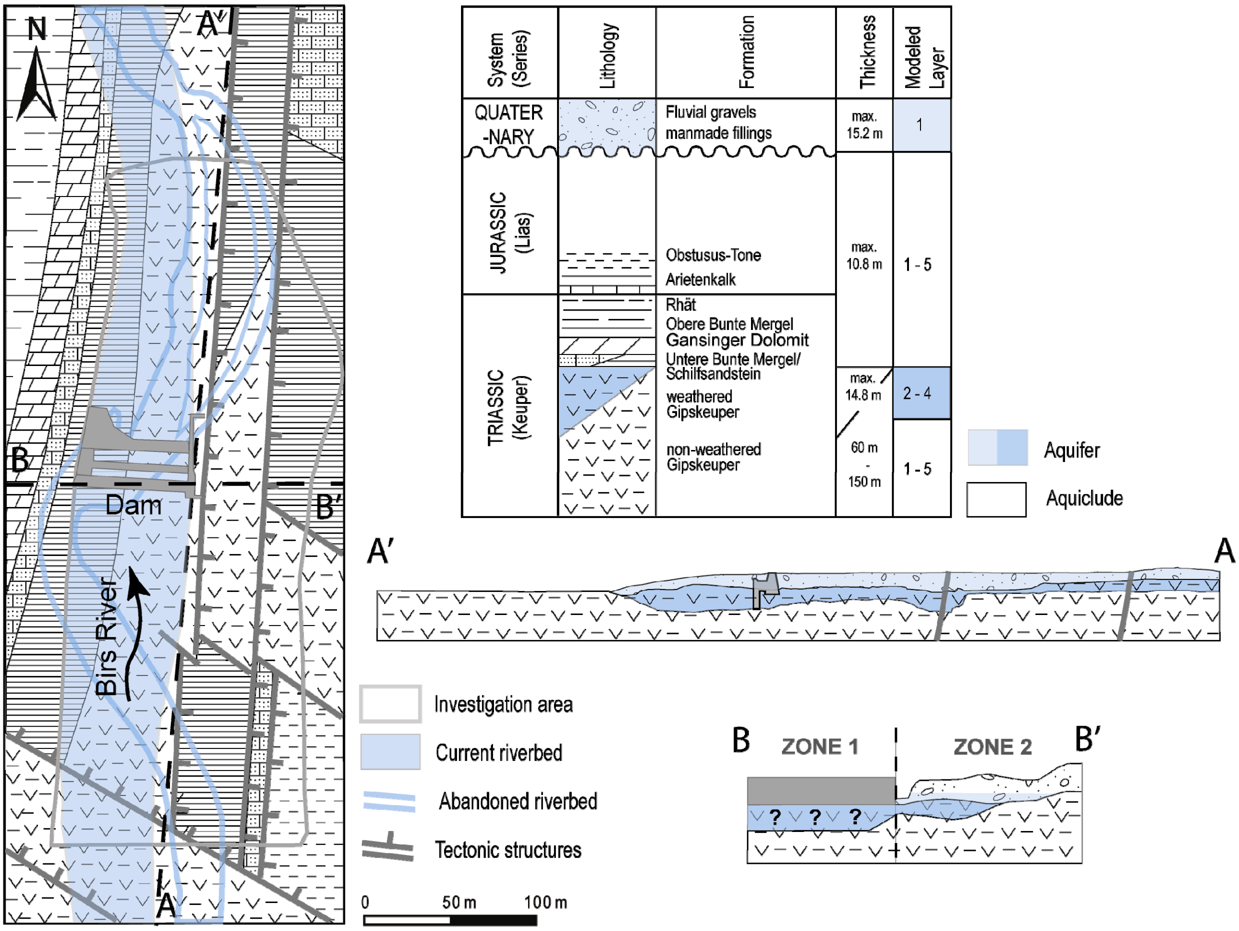

Fig. 5 Geological, tectonic map with removed Quaternary sequence (modified after unpublished data, Pfirter 1973), lithostratigraphy, hydrostratigraphy, modeled geological units (modified after Bitterli-Brunner and Fischer 1989, Gürler et al. 1987, Pearson et al. 1991, Spottke et al. 2005) as well as longitudinal and transversal cross section, including zones for water budgets

The Gipskeuper is made up of a series of anhydrites and intercalations of marls. The lithological term ‘‘Gipskeuper’’ as used in this paper generally includes the mineral ‘‘gypsum’’ and also refers to ‘‘anhydrite,’’ which, in the deeper subsurface, is the more common, anhydrous form of calcium sulfate. In the non-weathered state anhydrites dominate and the Gipskeuper is characterized as being rather low permeable. Hydraulic conductivities of Gipskeuper, as tested in borehole and modeling studies in northern Switzerland, vary between 1E-14 ms^{-1} and 1E-07 ms^{-1} (Nagra, 2002). However, in the weathered state, Gipskeuper shows features of a heterogeneous (karstified) aquifer (Klimchouk and Andrechuk, 1996).

The investigation area is characterized by the Eastern Rhinegraben Master fault accompanied by an intense tectonic segmentation into compartments (Schmassmann, 1972). Tectonically the lithological units dip at an angle of approximately 45° to the West. Several NNE-SSW normal faults subdivide the units into a series of fractured blocks with variable hydraulic properties. Fault and fracture zones are associated with rock weakness and can locally increase permeability within sequences, resulting in an enhanced groundwater leakage and the development of paths for preferential flow (tectono-karstic voids).

In general, reduced water velocities behind reservoir dams enable the sedimentation of fine material, resulting in a clogging layer that delays the infiltration of surface water into groundwater systems. During episodic floods, river bed permeability increases and processes of surface-groundwater interaction are enhanced. These processes are highly transient and consequently, changing hydraulic river bed conductance plays a key role in understanding surface-groundwater interaction. It is worth mentioning that the investigation period includes the 300-year flood of 9 August 2007 (discharge 370 m^3s^{-1}).

Borehole data show that most voids and solution cavities, which generally contain debris, clay, gravel and calcite fillings, are concentrated at the base of the weathered Gipskeuper (lixiviation front). During episodic flooding, these sediments can be partially flushed and subsequently, more aggressive water can enter the system, giving evidence that the development of conduits accelerates during the flooding of passages.

2.2 Hydrochemistry

Chemical analyses of samples taken at specific hydraulic boundary conditions allowed hydrochemical boundary conditions to be defined. SO_4-Ca content increases in the circulating groundwater within the gypsum formation. Solution rates depend on water chemistry and dynamics of the hydrogeological flow regime. Water entering the system is assumed to be dominated by the chemical composition of infiltrating river water. Calcium and Sulfate concentrations in the river indicate the lowest observed concentration values, ranging from 88.8 to 94.7 mgl^{-1} and from 7.8 to 15.8 mgl^{-1}, respectively. Highest concentrations were observed in groundwater samples taken at two different depths from observation well OW4 (Fig. 2), ranging from 256.4 to 277.3 mgl^{-1} for Calcium and from 118.7 to 116.8 mgl^{-1} for Sulfate. Water samples taken from the groundwater outlets downstream of the dam show intermediate concentrations, ranging from 135.9 to 204.4 mgl^{-1} for Calcium and from 53.3 to 92.4 mgl^{-1} for Sulfate.

The geochemical composition of the Gipskeuper formation is strongly heterogeneous, as indicated by mineralogical analysis. Therefore, the transition zone between weathered and non-weathered Gipskeuper should not be considered as a sharp boundary.

Dissolution kinetics and dissolution rates R of pure gypsum during water-rock interaction in laminar or turbulent flow were determined by Dreybrodt (1987, 1988, 1990) and Jeschke et al. (2001), respectively. R can be described by a rate law:

$$R_1 = k(1 - c / c_{eq}) \quad \text{for} \quad c \le c_s \qquad (1)$$

$$R_n = k_n(1 - c / c_{eq})^n \quad \text{for} \quad c \ge c_s\,, \qquad (2)$$

where c is the concentration of Calcium in the water and c_{eq} is equilibrium concentration with regard to gypsum. c_s is a switch concentration, where the dissolution rates ($molcm^{-2}s^{-1}$) switch from a linear rate law to a non-linear one with the order n. The values of c_s, k_n and n are characteristic for the mineral because they are entirely dependent on surface reactions. These characteristics of gypsum dissolution imply that although concentrations close to equilibrium concentrations are reached rapidly, infiltrating water has a remaining potential for solution over long time periods and after long percolation pathways within the system.

Based on hydrochemical boundary concentrations with regard to Calcium, the following can be derived from the results of the groundwater analysis above: Infiltrating river water into the aquifer system ranges from 2.2E-06 to 2.4E-06 molcm^{-3} (0.14 to 0.15 c_{eq}), water within the system (OW4) ranges from 6.4E-06 to 6.9E-06 molcm^{-3} (0.41 to 0.44 c_{eq}), and water at the groundwater outlets downstream of the dam ranges from 2.5E06 to 5.1E-06 molcm^{-3} (0.16 to 0.33 c_{eq}).

3 Methods

3.1 Conceptual Approach

The conceptual approach and the applied methodologies are based on a series of questions that generally arise in the context of urban hydrogeology (e.g. Epting et al., 2008): (1) Are the existing data sufficient to answer the relevant questions, and which hydrogeological concepts can be set up using this data? (2) Which additional data and experiments could improve predictions and allow hypotheses testing with respect to specific questions and process understanding? (3) How could data acquisition and experiment design be optimized? Consequently, the solution process is an iterative procedure of consecutive data acquisition deriving from specific experiments.

Hydraulic conductivities in karst aquifers are extremely heterogeneous, ranging from 10E-08 to 10E-05 ms^{-1} in the fracture systems, and up to 1 ms^{-1} in conduits (White, 1988; Ford and Williams, 1989). Structural features such as folds and faults can have further significant influence within karstified areas. As a result, modeling groundwater flow in site-specific karst environments is extremely challenging. Modeling results often are highly uncertain because of the lack of site-specific information on heterogeneous subsurface structures and the resulting complexity of flow paths.

A stepwise approach is presented where results from different investigative methods are merged. In a first step the investigated area was delineated, comprising an inventory of all relevant boundaries defining the hydrogeologic flow regime, including an evaluation and parameterization of the fundamental processes governing the system. A core element of the present approach is the merging of high resolution 3D HGM with 2D KEM (Fig. 1). The calibrated 3D HGM provides the geometric and hydraulic boundary conditions for the 2D KEM. The calibrated 2D KEM allowed karst aquifer evolution to its current state to be simulated. Resulting aquifer heterogeneities simulated using the 2D KEM were transferred to the 3D HGM. The applied modeling strategies complement each other. The results of the 3D HGM could be used for the validation of the 2D KEM and vice versa.

The data required for setting up the 3D HGM and 2D KEM with accurate boundary conditions can be of quite different type and varying quality which can be termed ***"hard"*** or ***"soft" data*** (cf. Regli et al., 2002). The most reliable hard data derive from outcrop and laboratory investigations. The information on several outcrops was incorporated into the geological map (Fig. 5), which formed the basis for delineating the models. Drill core data provide limited information on the spatial distribution of subsurface properties, especially in karst environments where the probability of encountering voids is quite low and relies on a hit-or-miss approach. The quality of individual drill core descriptions varies considerably, depending on the geotechnical approach used, thus permitting limited and speculative conclusions. The same is true of hydrogeophysical data which allow zones with different properties and behaviors to be delineated over time. Consequently, drill core and hydrogeophysical data are regarded as soft data. The terms of "hard" and "soft" data can also be applied to hydrometric data deriving from hydraulic measurements and from tracer tests. Whereas hydraulic measurements from the river head can be considered as hard data, data from groundwater observation wells are hard data only if they independently sample one aquifer. In the case where observation wells connect aquifers, data interpretation is not distinct and consequently such measurements should be considered as soft data. Tracer tests can undoubtedly confirm hydraulic links between injection and observation locations; this information corresponds to hard data. The path of preferential flow between these locations, however, is ambiguous and relies on further interpretation, resulting in soft data. Additional data that are documented during construction measures, as for example, lithological information derived during the installation of piles, or information on locations and quantities of supplementary cement injections, generally lack accuracy and should also be considered as soft data. Nevertheless, this kind of information can be indispensable in the process of setting up hydrogeological models.

3.2 Data Sources

Multiple data sources were available: (1) soft data from lithostratigraphic information from borehole logs and the national geological map (1:25'000; Bitterli-Brunner et al., 1984); (2) soft and hard data from continuous groundwater measurements within the Quaternary and Gipskeuper aquifers; (3) soft data from general geological descriptions of piling works and locations of supplementary cement injection; (4) soft and hard data from dye tracer tests, and (5) soft data from hydrogeophysical investigations. A total of 24 vertical boreholes were drilled in several investigation phases from 1993 to 2007 (Fig. 2). Most boreholes were developed as observation wells for groundwater or subsidence measurements. In total, 12 observation wells were fitted with automatic data loggers for monitoring physical parameters (hydraulic head, temperature and electric conductivity). Additional lithostratigraphic information could be derived from reports made during the construction of the piles. Hydraulic links and flow velocities within the investigation area were investigated by means of a dye tracer test in 1996. During the construction phases, groundwater and surface water were monitored by an extensive observation network. Hydrograph-analyses indicate that hydraulic boundary conditions in the vicinity of the dam have changed considerably after the flood event of 9 August 2007 (see Section 5.4). In particular, the interaction of the river with the groundwater system at different flow stages plays a major role in the initiation of movements within the void and conduit system. Surface and underwater hydrogeophysical measurements were carried out under different hydrologic boundary conditions, both before and after the construction activities. This interpretation focuses on the description of distinct geological and hydrogeological features in correlation with river discharge (Fig. 2, Epting et al., submitted).

4. Modeling Approach

4.1 3D Geological and Hydrogeological Model (3D HGM)

The main goals in setting up the high resolution 3D HGM were: (1) the description of the spatial distribution of the geological formations and the delineation of weathered units; (2) the simulation of the current hydrogeologic regime and changes to it in the context of the construction measures and future system developments and (3) the provision of model geometries and hydraulic boundary conditions for the 2D karst evolution modeling.

3D HGM simulations were performed using the Groundwater Modeling System GMS v6.0 (Environmental Modeling Systems Inc., 2006) together with the 3D finite difference code MODFLOW (Harbaugh et al., 2000). The "solid modeling" approach was employed for constructing the 3D geological structures (Lemon and Jones, 2003). Solids (volumetric layers representing hydrostratigraphic sequences) were built using the horizons method, based directly on the lithostratigraphic data from 25 boreholes, 166 piles beneath the highway and 273 piles at the pile wall, as well as the introduction of 42 support points. Each lithological formation can be represented by a separate solid. In order to simplify the geological model, the formations of non-weathered Gipskeuper were grouped with the formations of Schilfsandstein and Mergel-Dolomit, resulting in three different materials, including the Quaternary cover, weathered Gipskeuper and non-weathered lithological sequences. Vertically, the model extends from the topographic surface to the non-weathered Gipskeuper (Fig. 5 and 6).

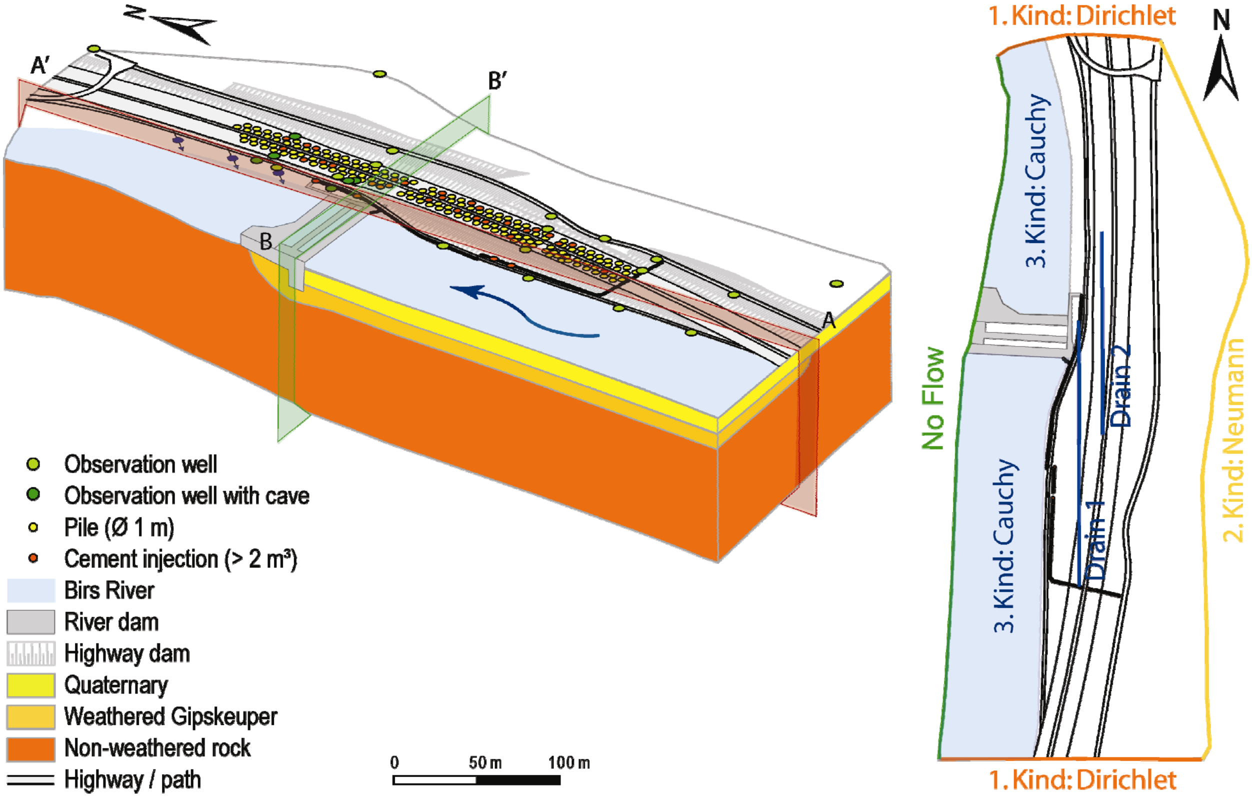

Fig. 6 Left: 3D HGM with locations of cross sections (transversal cross section B-B' and longitudinal cross section A-A', Fig. 5); Right: conceptual 3D HGM setup with hydraulic boundary conditions

The grid for the 3D HGM was automatically generated from the solid model geometry (Jones et al., 2002). The horizontal discretisation of the grid is regular (5 by 5 m). To represent the locations of drain features more accurately, a 5-layer approach was chosen. Hydraulic boundary conditions were defined as follows (Fig. 6): (1) the northern and southern boundaries were defined as specified head, corresponding to available groundwater head measurements of the regional hydrogeologic flow regime; (2) the eastern boundary was defined as specified flow from the adjacent catchment; (3) the western boundary was chosen as a no-flow boundary, according to the abundance of comparatively impermeable geological sequences (see above); and (4) the Birs River was simulated as General Head Boundary (GHB), where river infiltration and groundwater exfiltration are calculated in relation to the difference between river level and hydraulic groundwater head, as well as a conductance of the river bed. When modeling the complex flow using a finite-difference approach, with drain networks, representing the conduit component of model outflow was achieved by using generalized drain features (Quinn et al., 2006). Two drains were introduced in model layer 4 corresponding to information obtained from (a) boreholes, indicating that voids were generally encountered at the bottom of the weathering zone; (b) the 1996 dye tracer test and (c) the location of fracture joints (Fig. 2 and 5). The drain elevation was chosen using values of nearby groundwater head measurements to ensure active flow.

To enhance model certainty, the following procedure was applied: (1) calibration of the 3D HGM and comparison of observed and calculated heads in numerous groundwater observation wells; (2) inverse modeling, including parameter estimation and sensitivity analysis; (3) groundwater temperature data analysis of riverine observation wells in order to estimate hydraulic conductance values of the GHB upstream of the dam (Appendix A), and (4) scenario development, including the consideration of drains and different extensions of the weathered rock. Hydraulic conductivities of the lithological sequences as well as river bed and drain conductance were determined and their sensitivities evaluated by a combination of manual and automated parameter estimation procedures, which are based on numerical optimization algorithms within the nonlinear regression code PEST (Doherty, 1994).

4.2 2D Karst Evolution Model (2D KEM)

Distinct time intervals for karstification and the development of the aquifer can be defined for the present case study (Romanov et al., 2009). A first time interval covers the natural karstification process for a time period between several hundred and a few thousand years. The results from this evolution period are used as initial conditions for the second interval, which covers the time period from 1890 to 2007. This period is characterized by anthropogenic alterations to the system, including the construction of the river dam in the 1890’s and technical measures to prevent further subsidence of the highway in 2006 and 2007, which considerably changed the evolution of the aquifer. The third time period, covering the evolution of the aquifer after 2007, with regard to the effects of technical measures on boundary conditions, will be the subject of future investigations. This includes the application of the developed modeling tools for forecasts of aquifer development for the 100 years that follow.

The main goals in setting up the 2D KEM were: (1) to simulate the spatiotemporal development of karst features within the investigation area over the last 100 years; (2) to determine and evaluate the relationship of the investigated parameters; (3) to determine time scales for future system development, and (4) to provide heterogeneously distributed aquifer properties including distinct high conductive features for the 3D HGM. The reason for not modeling karst evolution with existing 3D codes is the complexity of model geometries and chosen boundary conditions that for the moment cannot be used without unreasonable effort and CPU. However, as 3D codes are gaining in efficiency, the available data sets will be transferred to 3D KEM in the near future.

The 2D KEM includes representative geological horizontal cross sections of the area around the dam structure. With respect to the high information density in the vicinity of the infrastructures, horizontal cross sections were preferred over the generally used vertical model setups. The geometric dimensions as well as the hydraulic and technical boundary conditions (modeling domain, groundwater and river head, hydraulic conductivities) of the 2D KEM correspond to those of the layers 2, 3 and 4 of the 3D HGM (see above). The modeling domain is 130 m wide (W-E), and 465 m long (S-N). Figure 7 shows the conceptual model setup, the impervious and insoluble dam structure and zones used to assign different hydraulic conductivities and solubilities. Flow within the karst aquifer is driven by infiltrating river water upstream of the dam that is directed towards the river downstream of the dam as a base level. In advanced scenarios, regional groundwater flows from South to North and from the adjacent slope to the East were considered.

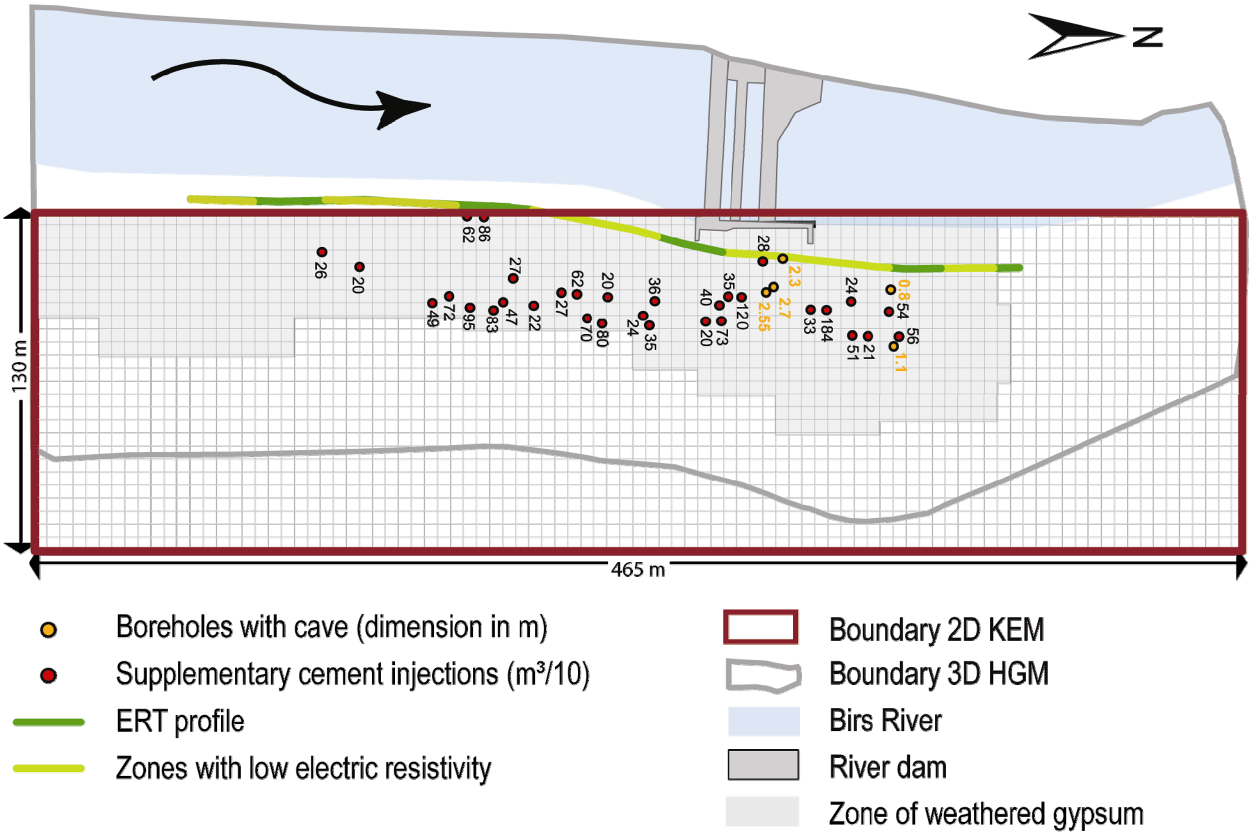

Fig. 7 Geometry and hydraulic boundary conditions of the horizontal 2D KEM superimposed on the model geometries of the 3D HGM. Illustrated also are zones for weathered and non-weathered aquifer properties as well as locations with information from ERT, caves and injections of supplementary cement

The network of the 2D KEM is characterized by the average spacing s of the fractures, their aperture widths a_0 and their widths b_0. This fracture system exhibits a hydraulic conductivity (Lee and Farmer, 1993) of:

$$K = \frac{\rho g}{6\eta} \cdot \frac{a_0^{\ 3}}{s} \ , \qquad (3)$$

where ρ is the density of water, η is the viscosity and g is earth's acceleration. Equation 3 was used consecutively for the transfer of hydraulic parameters of the 3D HGM to the 2D KEM and vice versa.

The application of gypsum dissolution kinetics (Dreybrodt, 1987, 1988, 1990; Jeschke et al., 2001) enables the simulation of void and conduit enlargement with time by chemical dissolution and solutional widening within the system. This selective enlargement increases conductivity by several orders of magnitude during the early phase of karstification. Thus flow characteristics change from more homogeneous to heterogeneous flow. An important moment for the stage of karst aquifer evolution is the so-called "breakthrough time", when flow changes from laminar to turbulent and increases by several orders of magnitude in a relatively short interval.

The influence of basic hydraulic and geochemical parameters on breakthrough time within reasonable evolution times is investigated by calculating scenarios and conducting the following sensitivity analyses: (1) required minimal size of model domain and resolution; (2) aperture width, average hydraulic conductivity for different zones; (3) introduction of prominent fractures and percolation networks; (4) additional diversification of weathered zones within the Gipskeuper, and (5) variation of the solubility within the Gipskeuper. In the present case study, evolution of distinct karst features should be in the range of 10 to 100 years, because: (1) the dam structure in its current dimension was built in the 1890's; (2) subsidence of the highway has been reported since the 1990's, and (3) previous dam site modeling indicates that under normal conditions, evolution periods of several thousands of years can be shortened to periods of several decades for karst aquifers in the vicinity of hydraulic structures such as dams.

A first set of scenarios allowed the determination of the required minimal model resolution and initial hydraulic conductivities for the different zones within the modeling domain. As the hydraulic conductivity depends on the fracture aperture widths and the distances between them, the same hydraulic conductivities are obtained from a network with large but sparsely distributed fractures, as well as for fine fractures with small distances between them. To analyze the sensitivity of this interrelationship adequately, numerous scenarios had to be calculated in order to obtain reasonable values for the fracture aperture widths, while time keeping the distance between fractures as large as possible (reduction of CPU). Therefore, calculations have been performed with relatively large time steps of 1 year, and only until turbulent flow after breakthrough occurred in the domain.

As structural initial conditions can influence karst evolution in a significant way (Birk et al., 2005), subsequent scenarios focused on the incorporation of specific subsurface information for the description of aquifer heterogeneity, including: (1) statistical distributions of hydraulic conductivity and solubility zones, and (2) discrete prominent fractures.

5 Results

5.1 Results from Borehole Data and the Dye Tracer Test

Analysis of drill cores enabled the determination of several permeable zones within the underlying bedrock and the already developed voids. Although the probability of encountering voids is fairly low and relies on a hit-or-miss approach, it was nevertheless possible to detect a total of 7 voids, with diameters ranging from 0.3 to 2.7 m, at a depth of 15 to 18 m. This information, considered as soft data, suggests that the vertical extension of the weathered Gipskeuper ranges from 2.2 to 14.8 m. It could be recognized that the drilling of several boreholes in the 1990's left a stratigraphic connection and hydraulically connected aquifers. These connections are documented in the drill core records and were confirmed independently by geochemical and hydraulic data (flowmeter measurements). It was possible to derive additional soft data from lithostratigraphic information in the reports made during the installation of the piles, and relatively precise cross sections of the investigation area were constructed based on the lithostratigraphic information from the boreholes (Fig. 5).

Hydraulic links within the investigation area were confirmed by the 1996 dye tracer test, representing hard data (Cantonal Archive Basel, unpublished reports). The direction of the hydraulic links corresponds to the main directions of fracture joints within the investigation area (Fig. 5). The dye was injected in OW3 and sampled in OW2, 4 and 5 (Fig. 2). Highest concentrations were measured in OW5, which is nearest to the injection well. A secondary maximum was observed, representing a further preferential pathway. Measurements in the other observation wells resulted in lower concentration values indicating that they are influenced to a certain degree by infiltrating river water. Maximal groundwater flow velocities range from 85 to 111 md^{-1}, values typical for conduits within well-developed mature karst systems (Birk et al., 2004). Determined dispersivities range between 1 and 3 m.

5.2 3D Geological and Hydrogeological Model (3D HGM)

Model Calibration and Sensitivity Analysis

Table 1 summarizes the initial set of selected parameters, the calibration range and calibrated hydraulic parameters for the extended model with drains. Additionally, normalized composite scaled sensitivities are summarized for the calibrated parameters of all investigated scenarios. The upper value of 1.0E-07 ms^{-1} resulting from modeling studies in northern Switzerland (Nagra, 2002) was chosen as initial value for the hydraulic conductivity of non-weathered rock. For the hydraulic conductivity of the weathered Gipskeuper, an initial value of 1.0E-05 ms^{-1} was chosen, assuming that the hydraulic conductivity of this lithological formation is much higher than the one of the non-weathered rock. The initial hydraulic conductivity value of 5.0E-03 ms^{-1} for the Quaternary cover represents an empirical value for fluvial deposits. In order to assess initial values for the conductance of the GHB and drains, these parameters were first calibrated manually with the basic model, resulting in 2.0E-06 s^{-1} and 2.0E-03 ms^{-1}, respectively. These initial parameters vary by one order of magnitude for the hydraulic conductivity of the Quaternary and the weathered Gipskeuper and by two orders of magnitude for the hydraulic conductivity of the non-weathered rock and the conductance of the GHB and the drains.

Table 1. Initial parameters, calibration range and calibrated hydraulic parameters for the extended model with drains as well as normalized composite scaled sensitivities for the calibrated parameters of all investigated scenarios

	Initial parameters	Calibration range of parameters		Calibrated values	Normalized Sensitivities (%)
HK_Quaternary (ms^{-1})	5.0E-03	5.0E-04	5.0E-02	9.8E-04	8
HK_weathered Gipskeuper (ms^{-1})	1.0E-05	1.0E-06	1.0E-04	1.0E-04	29
HK_non-weathered rock (ms^{-1})	1.0E-07	1.0E-09	1.0E-05	1.0E-05	28
GHB_upstream (s^{-1})	2.0E-06	2.0E-08	2.0E-04	2.7E-07	24
GHB_downstream (s^{-1})	2.0E-06	2.0E-08	2.0E-04	9.4E-05	10
Drain 1 (ms^{-1})	2.0E-03	2.0E-05	2.0E-01	6.0E-04	1
Drain 2 (ms^{-1})	2.0E-03	2.0E-05	2.0E-01	8.1E-03	1

Features included in the extended model setups are examples of potentially important processes that can improve the modeling results. Upper boundary values for the hydraulic conductivity within the weathered Gipskeuper and non-weathered rock are attained, indicating that the inclusion of an extended weathered zone beneath the dam and drains is adequate. The reason for the calibrated high values of hydraulic conductance downstream of the dam structure compared to those upstream could be the occurrence of groundwater outlets in the more heterogeneous river bed downstream (high flow velocities and possible turbulent flow in the vicinity of the dam overflow) and the more colmated river bed upstream of the dam structure (area with low flow velocities and sedimentation of fine material). The sensitivity analysis indicates the highest parameter sensitivity for the hydraulic conductivity of the non-weathered and weathered rock and for those of the GHB upstream of the dam. Drain conductance values resulted in rather low sensitivities. However, the arrangement, connectivity and numbers of drains were not covered by the preceding sensitivity analysis. Therefore, scenarios were set up with the 3D HGM considering (1) only the drain near to the river; (2) only the drain more distant from the river; (3) multiple drains, and (4) the connection of drains. Results show that, with the chosen boundary conditions, total drain-outflow for all simulation is generally identical. Whereas the consideration of multiple drains merely resulted in a further partitioning of outflow among the individual drains, the connection of drains resulted in an altered distribution of outflow within the drains (cf. Fig. 10). The setup of a transport model with the data from the 1996 dye tracer test indicates that the resulting breakthrough with primary and secondary maximum in some of the observation wells can be simulated adequately only with connected drains. As connectivity is determined by the stage of karst evolution, the scenarios with two drains which are unconnected or connected are discussed together with the results from the transient 3D HGM and 2D KEM (see below). Results from the temperature data analysis reveal the transient character of river water infiltration and allowed time-dependent conductance values to be provided which could be incorporated into the transient hydrogeologic model (Appendix A).

3D Hydrogeologic Modeling (3D HGM)

Figure 8 illustrates the simulated hydrogeologic flow regime at average discharge before and after the construction measures. The hydrogeologic flow regimes for both model scenarios clearly show the influence of the dam structure. The effect of the drains is striking, as they focus on the flow paths. The gradient in the non-weathered rock is steeper than in the weathered Gipskeuper and the Quaternary cover. For the simulation after the construction measures, the sealing pile wall was integrated and its hydraulic conductivity calibrated by minimizing the divergence between observed and calculated heads in OW3. As an effect of the sealing pile wall, backwater can be observed towards the river. Water budgets across model boundaries and through defined cross sections are summarized in Table 2. As an effect of the sealing pile wall, flow through Zone 2 (see Fig. 5) after the construction measures is 1/10 of the original flow around the dam. Calibrated residual flow through the sealing pile wall reaches 1.8 ls^{-1}.

In Figure 9 observed and calculated groundwater heads of 4 selected observation wells are compared for a 465-day period (23 August 2006 to 30 November 2007). OW12 and 13, both located at the upstream river bank (Fig. 2), illustrate the very good agreement of observed and calculated groundwater heads as a result of the simulated river water infiltration upstream of the dam. This result confirms applying transient conductance values derived from the temperature data analysis (Appendix A). Whereas OW20 is located at the downstream river bank and indicates groundwater exfiltration into the river, OW10 is located centrally within the model domain and is a sign of the more distant flow around the dam.

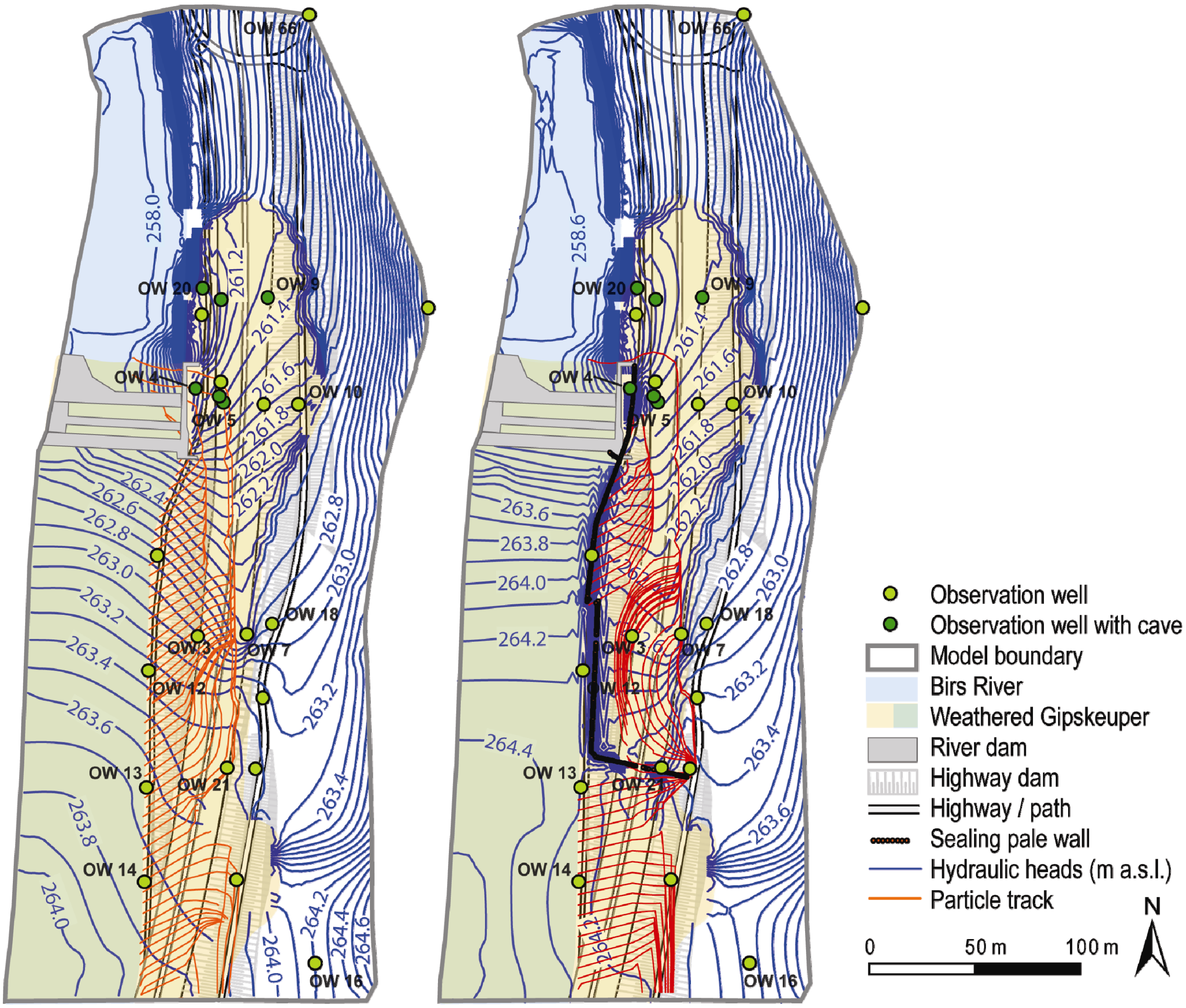

Fig. 8 Visualization of hydraulic heads and particle tracks in model layer 2 (0.1 m resolution); Left: Groundwater flow regime at average river discharge before construction measures (07.02.06); Right: Groundwater flow regime at average river discharge after construction measures (15.01.08)

In Figure 10 water budgets for the GHB up- and downstream of the dam are illustrated together with model outflow through the drains. Model inflow is dominated by the GHB upstream, indicating river water infiltration; model outflow is dominated by the GHB downstream, an indication of groundwater exfiltration (an approximate measure for the ***diffuse component of flow***) and through the drains (approximate measures for the conduit component of model outflow). Model inflow (GHB upstream) generally equals model outflow (GHB downstream and drains). The figure also shows the relative contributions to the flow systems (diffuse and conduit model outflow; Drains 1 and 2) before and after the major flood event. Flow through the drains amounts to approximately 64 % of total model outflow before the major flood event, ranging from 12 ls^{-1} at low to 66 ls^{-1} at high river discharge. After the major flood event, flow through the drains amounts to approximately 80 % of total model outflow, ranging from 30 ls^{-1} at low to 70 ls^{-1} at high river discharge. Model outflow by the GHB downstream is comparatively balanced and ranges from 6 ls^{-1} at low to 12 ls^{-1} at high river discharge. Whereas the diffuse component amounts to approximately 36 % before the major flood event, after the event it only amounts to approximately 20 % of total model outflow. The data illustrate that in general during flood events, the relative contributions of the conduit component of model outflow increases. After moderate to medium-scale flood events, the relative contributions of flow components return to ratios observed before the events. However, major episodic flood events, as the 300-year flood of 9 August 2007, can considerably change the relative amounts of flow components also after the event. The results of long-term data monitoring will show if and when the relative amounts of the two model outflow components will return to ratios observed before the major flood.

Table 2. Water budgets (in ls^{-1}) across model boundaries and defined zones of the cross section (see Figs. 5 and 6 for location of boundaries and zones for water budgets)

	Homogeneous aquifer properties				**Heterogeneous aquifer properties**	
	Before construction		**After construction**		**Before construction**	
	IN	**OUT**	**IN**	**OUT**	**IN**	**OUT**
1. Kind, Dirichlet	0.9	4.1	0.4	2.6	-	-
3. Kind, Cauchy	12.8	12.6	7.8	11.6	12.9	12.6
Drains	0.0	5.9	0.0	5.0	-	-
ZONE 1	6.3	6.2	5.7	5.7	6.4	6.6
ZONE 2	24.8	24.7	2.6	2.7	12.2	11.1

Figure 10 also shows model outflow through the two drains individually for scenarios with unconnected or connected drains. Model outflow through the drains for the scenario with unconnected drains before the major flood event is dominated by Drain 2 amounting to 77 % of total outflow through the drains. The dominance of Drain 2 can be explained by its location. It lies within the bedrock depression formed by the ancient river course resulting in a steep hydraulic gradient from the surrounding aquifer to the drain feature (Fig. 5). Simulated outflow through Drain 1 before the major flood event is comparatively low and amounts to only 23 % of total outflow through the drains. However, during flood events outflow through Drain 1 can have the same order of magnitude as outflow through Drain 2. This change in relative contributions of the two drains can be explained by the vicinity of Drain 1 to the infiltrating river. After the major flood event simulated outflow for both drains rises significantly. The elevated outflow through

Drain 1 after the major flood event results in a redistribution of the relative amounts of simulated outflow through the drains (see explanation above). The distribution of model outflow through the drains for the scenarios with connected and unconnected drains shows similar results. However, due to the connection more water is diverted to Drain 2. Before the major flood event outflow through Drains 1 and 2 amounts to 15 % and 85 %, respectively. After the major flood event drain outflow through Drains 1 and 2 amounts to 27 % and 63 %, respectively (see explanation above).

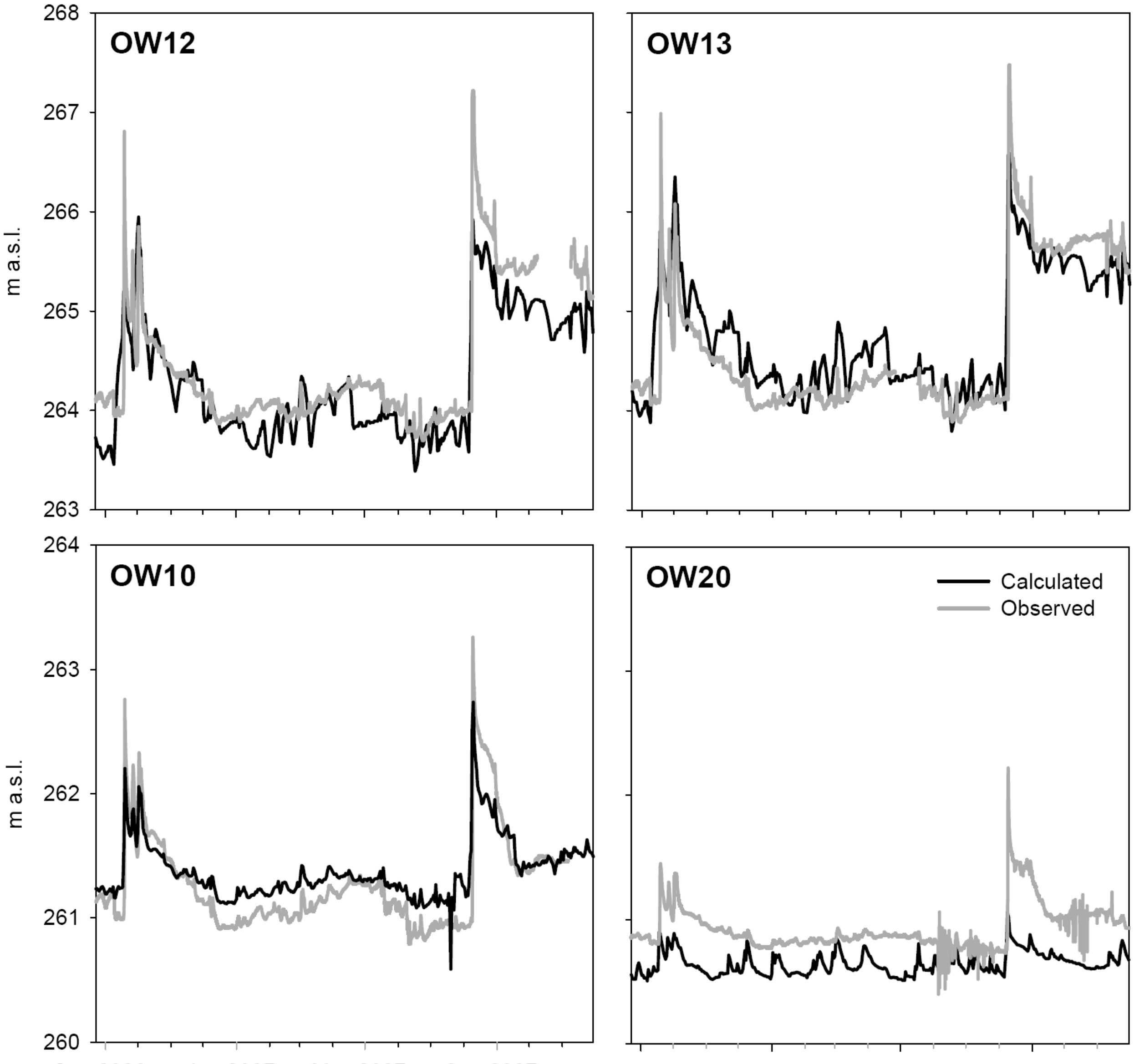

Fig. 9 Comparison of observed and calculated groundwater heads for 4 selected observation wells (see Fig. 2 for location of observation wells)

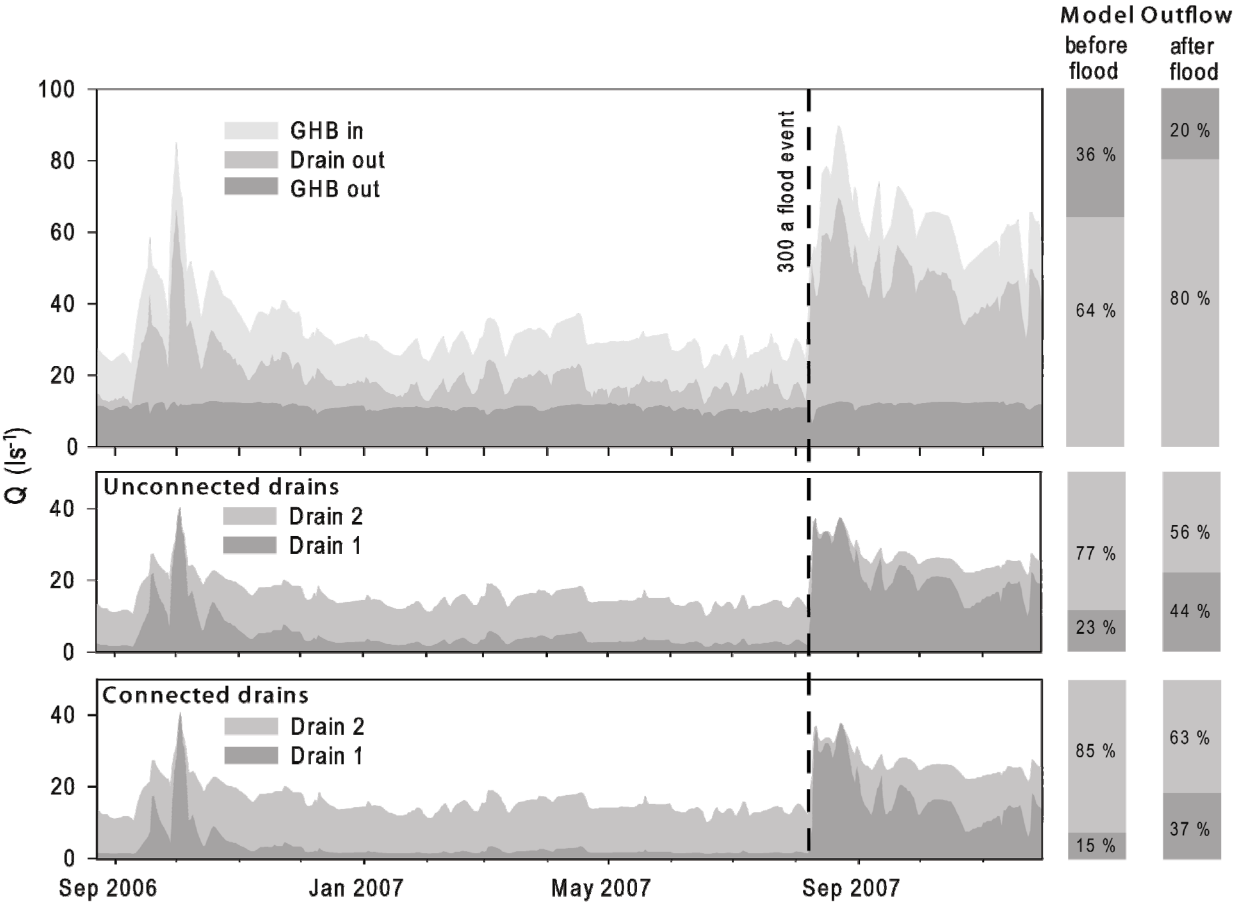

Fig. 10 Water budgets calculated with the transient 3D HGM

5.3 2D Karst Evolution Model (2D KEM)

The time interval investigated with the 2D KEM extends from 1890 to 2007. This time period is characterized by anthropogenic alterations to the system, including the construction of the river dam in the 1890's and technical measures to prevent further subsidence of the highway in 2006 and 2007, which considerably changed the evolution of the aquifer. The evolution of the weathered rock zones used as initial conditions for the 2D KEM can be attributed to the natural karstification beneath the ancient river bed for time periods between several 100 up to a few 1000 years.

Preliminary scenarios and sensitivity analyses with the 2D KEM allowed the definition of the sufficient model resolution. These scenarios demonstrated that, for a network having 100 cm spacing, the chosen size of the modeled domain is sufficient and that several to 100 years are reasonable time scales for karst evolution within the investigation area and with regard to the vicinity to the hydraulic structure. Whereas calculations with uniform aquifer properties and simple boundary conditions were carried out mainly for the illustration of system behavior and processes, statistical approaches used in more complex scenarios allowed the heterogeneity of the system to be described in more detail. In terms of the heterogeneity of fracture development within the system, statistical distribution of aperture width is more realistic, resulting in a more dendritic and diffuse distribution of fracture development.

In the following, the results of one scenario are discussed, including (1) statistical distributions of hydraulic conductivity and solubility zones, based on information on locations where caves were encountered and supplementary cement was injected, as well as where ERT resulted in low resistivity, and (2) of regional hydraulic gradients (Fig. 7).

Figure 11 shows the statistical distributions of hydraulic conductivities for the non-weathered and weathered rock used for the setup. The development of aquifer properties from the non-weathered to the weathered state for the period of natural karstification can be derived from the shift of the statistical distributions for hydraulic conductivities and solubilities. For the generation of statistical distributed properties of the aquifer (aperture width and solubility), spatial correlation lengths were incorporated which characterize the geometric anisotropy of the sedimentary structure types. Spatial correlation lengths of 1/10 of the longitudinal (i.e., 46.5 m S-N) and lateral (i.e., 13 m W-E) model domain were chosen. Values for the solubility of the non-weathered and weathered zones were averaged from borehole descriptions, resulting in 15 % of soluble fractures for the weathered and 40 % of soluble fractures for the non-weathered zone (Fig. 7). Figure 11 also illustrates the development of hydraulic conductivities from the initial state at 0 years (i.e. the 1890’s) to 100 years (i.e. the 1990’s). Please note the logarithmic scale of conductivities on the y-axis. While the gross distribution of conductivities does not change significantly, the resulting curve after 100 years evolution time illustrates: (1) a slight shift from lower to higher conductivity values, and (2) the development of a few fractures with very high conductivities. Comparing this to the results from simulated model outflows, it is obvious that the occurrence of a limited number of highly permeable structures and their interconnection can dominate the flow processes.

Figure 11 further illustrates the development of leakage around the dam for the 100-year time period from the 1890’s to the 1990’s. The graph shows a stepwise progression, while modeled outflow increases more rapidly at the beginning of the modeled time period, as remaining soluble zones within the weathered rock are dissolved. Subsequently, time spans between single steps increase. The single steps can be interpreted as ***local breakthrough events*** that lead to an abrupt increase of outflow. A steady increase in outflow can be observed between the single steps. As for the 2D KEM average boundary conditions are chosen, modeled outflow after 100 years evolution time, resulting in approximately 24 ls^{-1}, can be compared to the lower values of modeled outflow resulting from the 3D HGM. Outflow simulated with the transient 3D HGM resulted in values between 6 and 13 ls^{-1} for the GHB downstream and between 12 and 77 ls^{-1} for the Drains (cf. Fig. 10). Hence, modeled outflow with both modeling approaches during low to medium hydrologic boundary conditions are in the same order of magnitude.

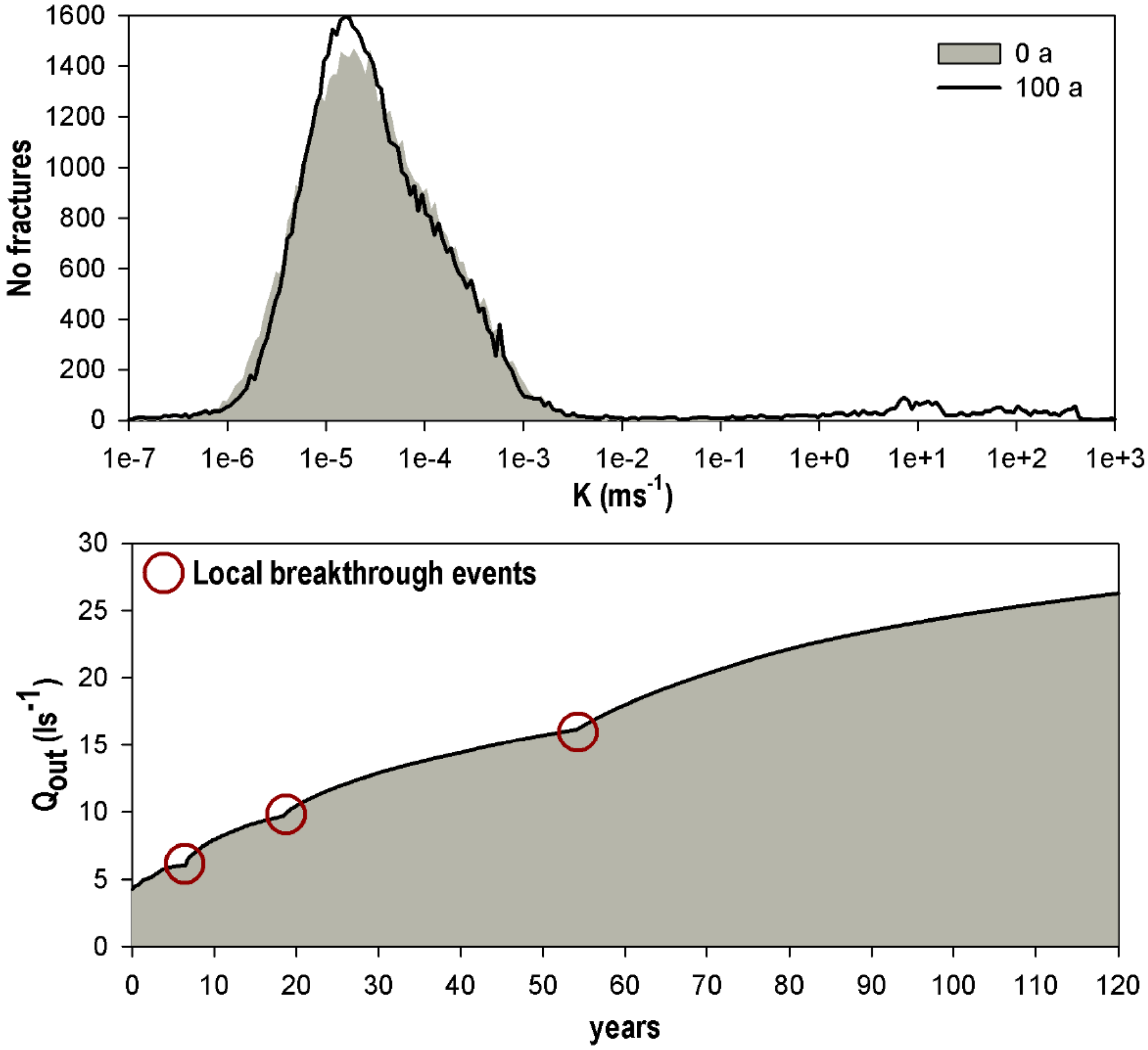

Fig. 11 Upper graph: Simulation results of karst evolution illustrated by the change of hydraulic conductivity distribution from the initial state to 100 a; Lower graph: Simulated model outflow

The results from the 2D KEM clearly illustrate that the amount of gypsum within the non-weathered and weathered rock can inhibit karstification and the development of connected percolation pathways necessary for breakthrough from infiltration locations to base levels. Moreover, local breakthrough events lead to delimited subsidence events as has been observed within the real world. The outflow progression, resulting from the 2D KEM and heterogeneously distributed solubility, can illustrate patterns of karstification within gypsum rocks.

5.4 Integration of Modeling Approaches

An iterative integration and combination of investigative methods together with the analysis of multiple data sets of varying quality considerably improved the description of the gypsum karst system within the investigation area. Associated uncertainties in data interpretation and numeric modeling were approached by (1) classifying data quality (soft and hard data); (2) parameter sensitivity analysis, and (3) scenario development and evaluation. As part of the sensitivity analysis, the most relevant parameters governing the system were determined using the two modeling approaches, which are the hydraulic conductivities of the rock and the conductance of the GHB upstream of the dam. On the basis of calculated scenarios, variable geological, hydrological and geotechnical boundary conditions that influence the hydrogeologic flow regime were evaluated.

Boreholes provided soft data and general lithostratigraphic information, including details about the vertical extension of the weathered Gipskeuper and significant permeable zones, as well as already developed voids. Ever since the 1990's, the drilling of several boreholes has left a stratigraphic connection and locally stimulated karstification. Initial, coarse cross sections could be developed using the information from the national geological map. Additional soft data from lithostratigraphic information was obtained from the reports made during the installation of the piles, resulting in more precise cross sections of the investigation area. Hydraulic links within the investigation area were confirmed by a dye tracer test with groundwater flow velocities typical for conduit systems. These results indicate that the karst system is already well developed, whereas solution conduits developed along a system of fractures and interconnected joints, suggesting a three-dimensional conduit network.

Results from surface and underwater ERT measurements, taken at different hydrologic and geotechnical boundary conditions, both before and after the construction measures, provided soft data and allowed the description of (1) preferential flow in the shallow subsurface; (2) zones that are related to groundwater flow around the dam, including flow dynamics; (3) zones that are related to groundwater flow beneath the dam; (4) drainage phenomena of karst features such as voids and conduits; (5) the weathering horizon within the Gipskeuper; (6) near-surface faults and fracture zones, (7) buried paleochannels, and (8) sediment thickness followed by weathered zones beneath the river upstream of the dam. Due to the multiple data sources of varying quality and hydraulic data from high-resolution 3D HGM, it was possible to partially eliminate ambiguity in data interpretation and to describe the relationship between the different observed features in a spatial context (Epting et al., submitted).

Mass balances allowed the estimation of the amount of gypsum removed from the system over the last 100 years, and the confirmation of the solid volume representing the weathered gypsum formation of the 3D HGM. Equivalent drain diameters along the entire length of the modeled drain could be calculated for Drains 1 and 2, illustrating the increase in the cross section for flow during flood events. During flood events, the hydraulic gradient forces water through the cavities and clay fillings are eroded (Appendix B).

Figure 12 illustrates how simulated aquifer heterogeneities from the 2D KEM are integrated into the 3D HGM. For the model layers 2 to 4 of the 3D HGM, separate karst evolution models were set up and calculated. In order not to lose connectivity of the simulated developed karst features, the original model resolution of 5 by 5 m had to be refined to 1 by 1 m. Hydraulic boundary conditions of the different layers for both modeling approaches correspond to each other. For model layer 1, a statistical distribution for the non-weathered rock of the GHB downstream and a uniform value for the Quaternary cover was chosen. For model layer 5, a statistical distribution of non-weathered rock was generated. As the modeling domain of the 3D HGM also comprises weathered zones beneath the river upstream of the dam (see Figs. 6, 7, 8) that were verified by ERT and that are not covered by the 2D KEM, data had to be interpolated to these zones. This was achieved by: (1) using the existing evolution patterns generated with the 2D KEM; (2) delimiting weathered zones beneath the river by the more resistant Schilfsandstein, and (3) assuming that weathering was intensified beneath the abandoned old meandering river bed and within zones of rock weakness (faults, fractures, etc.), which also resulted in the bulge in the southern modeling domain (see Figs. 7, 8).

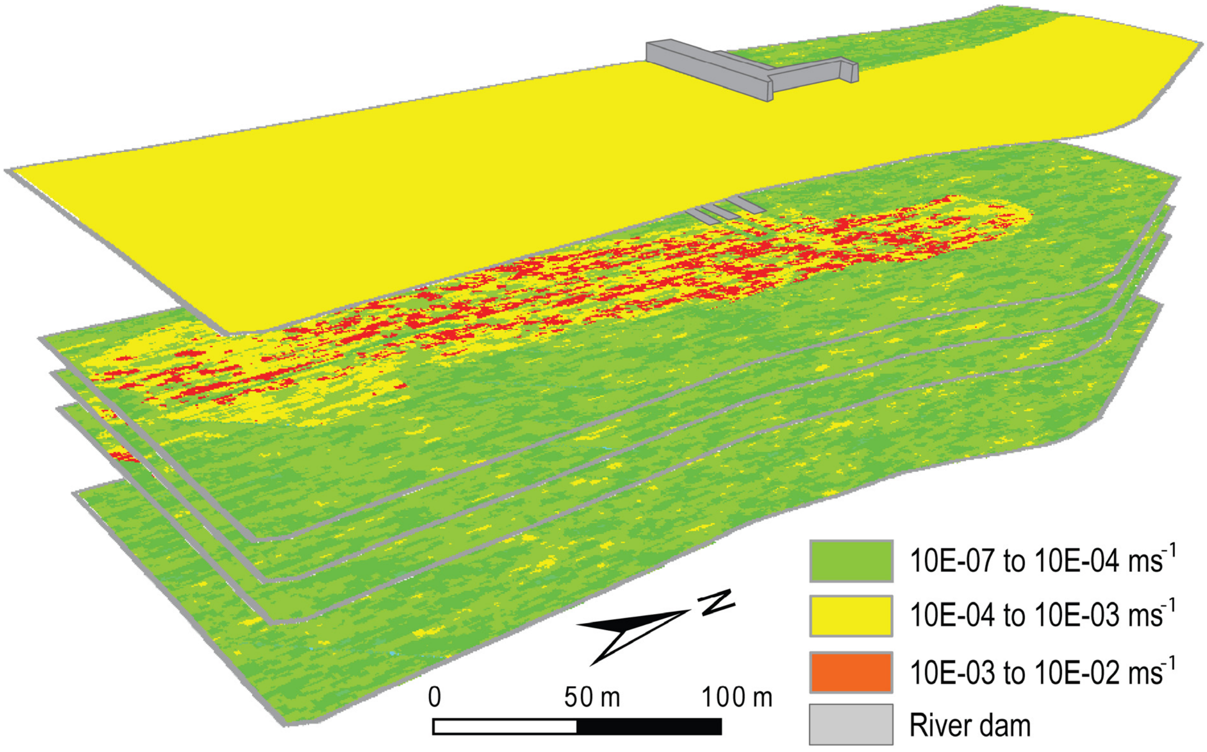

Fig. 12 Visualization of heterogeneous hydraulic conductivity distributions transferred from three realizations of the 2D KEM to 3D HGM (Layers 2 to 4). Aquifer properties distributions for Layers 1 and 5 are described in the text

Figure 13 illustrates the simulated hydrogeologic flow regime at average discharge for the model with heterogeneous hydraulic conductivities. As for the model with uniform hydraulic conductivities, the hydrogeologic flow regimes clearly show the influence of the dam structure. The gradient in the non-weathered rock is steeper than in the weathered Gipskeuper and the Quaternary cover. Generally the progression of hydraulic heads is comparable to the uniform model (cf. Fig. 8). However, hydraulic heads are more undulating and particles are focused to high conductivity zones. Due to the abundance of very low conductivity values and the predetermination of previously calibrated boundary conditions, calculated heads are generally too high compared to the measured ones. However, water budgets through defined cross sections of the 3D HGM with uniform and heterogeneous hydraulic conductivities show a good agreement (Table 2). While calculated flow budgets through the GHBs and beneath the dam are practically identical, flow budgets around the dam for the heterogeneous model are about half the size compared to those of the uniform model. This discrepancy can be explained again by the abundance of very low conductivity values and the predetermination of previously calibrated boundary conditions within the heterogeneous model.

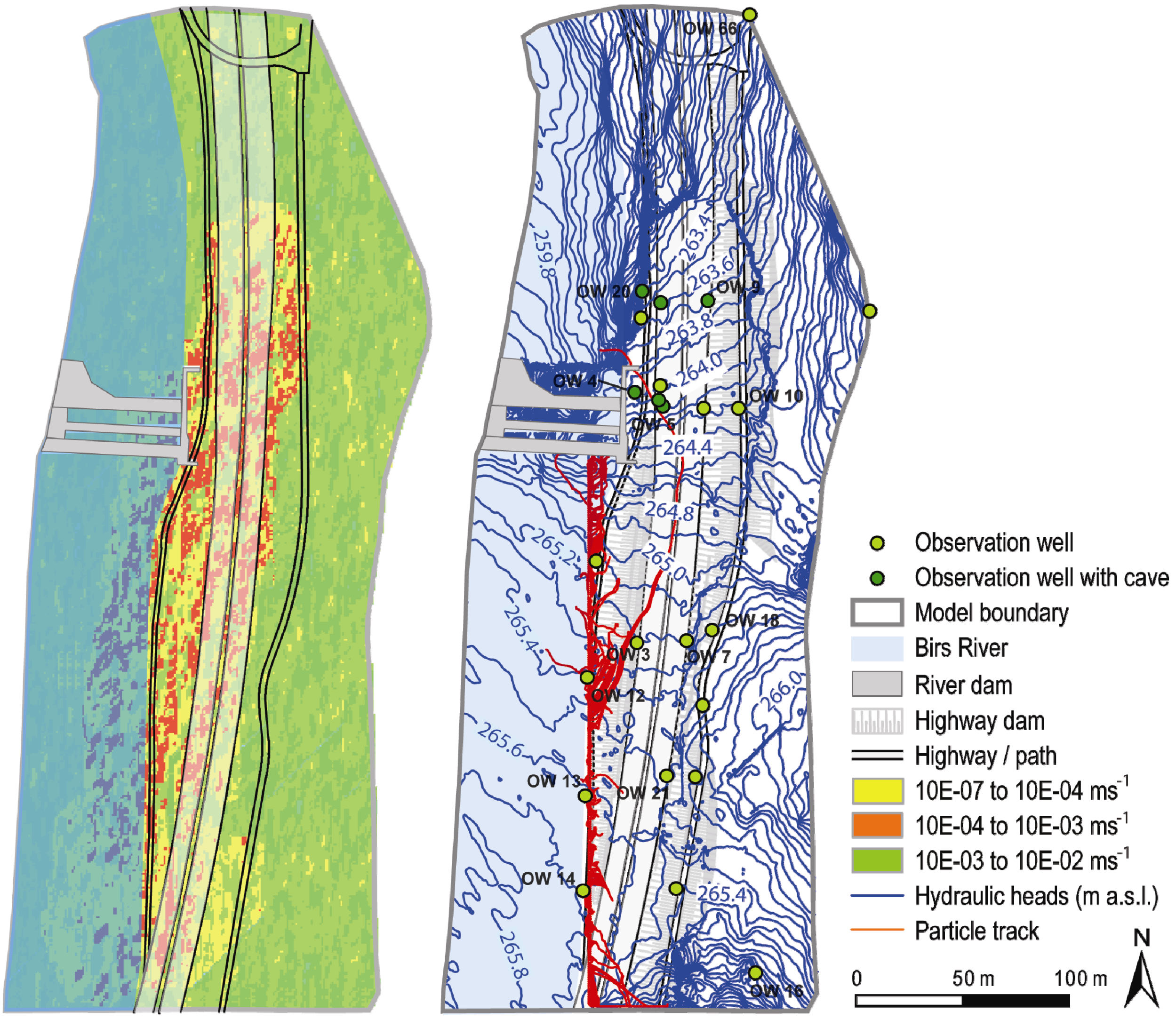

Fig. 13 Visualization of heterogeneous distribution of aquifer parameters derived from the 2D KEM (left) as well as hydraulic heads (0.1 m resolution) and particle tracks in model layer 2 before the construction measures (right)

6 Conclusions

The applied concept and methods have significantly contributed to a better understanding of the hydraulics of the karst system. The approach was illustrated by means of the following procedures: (1) determination of the extension of weathered and non-weathered rock and definition of pre-existing discontinuities; (2) identification of the relevant processes (transient character of system inflow, description of slow and fast flow components); (3) evaluation of the influence of episodic major flood events, accompanied by the flushing of conduit fillings and the inflow of more aggressive water, and (4) investigations of the long-term development of the system.

Comprehensive studies of transient 3D HGM facilitated the evaluation of the relevant groundwater hydraulics and revealed the dynamic character of the hydrogeologic flow regime during low frequency flood events, including river infiltration and diffuse and conduit components of model outflow. The magnitude of the calibrated parameters corresponds to regional hydrogeological investigations and field experiments. This indicates that calculated flow paths and flow budgets through defined zones, and especially their proportions, are plausible.

Temperature measurements and the applied heat pulse method (Appendix A) offer an attractive approach for monitoring time-variant infiltration rates through losing stream-reaches, and results can be incorporated in hydrogeological models to describe transient hydraulic conductance. 3D HGM facilitates current state descriptions of karst systems and provides sufficient information for: (1) estimating the transient composition of water budgets; (2) describing the transient character of the hydrogeologic flow regime, and (3) simulating and evaluating ***short-term impacts*** on processes such as those which occur during episodic flood events.

However, ***long-term evolution*** of karst systems and prognosis could only be achieved by setting up models that account for the change in hydraulic properties with time. The results presented in this paper show how 2D KEM can be calibrated to describe the current state of karst systems, and can be used for prognosis of system development and subsidence risk assessment in the near future. 2D KEM results illustrate that the fraction of gypsum within the soluble Gipskeuper can inhibit karstification and the development of connected percolation pathways necessary for system breakthrough. Moreover, local breakthrough events can lead to delimited subsidence events as can be observed in the real world. Time scales for the evolution for the present karst system could be estimated.

The application of different modeling techniques allowed specific aspects of the hydrologic processes to be captured and the required level of model complexity to be defined. Results from the independent approaches enabled the identification of sets of parameters for which the system behavior is described well. Generally, the transferability of the two approaches could be confirmed. The strengths of each individual model could be exploited. The results of both modeling approaches were evaluated and interpreted continuously. This allowed the identification of sources of associated uncertainties and the determination of relevant parameters governing the processes within the complex geological settings, including varying properties of the formations with regard to hydraulic conductivity and solubility. It is suggested that a significant reduction in the uncertainty of modeling karstic environments can be achieved by an appropriate, complementary combination of modeling approaches viewed as a multi-model ensemble (c.f. Makropoulos et al., 2008).

In addition, the development infrastructures (e.g., railways; Gutiérrez, 1996) in areas prone to subsidence requires special sets of rules and regulations (e.g. prohibiting the connection of aquifers) to minimize potential problems from present and future development. The described models require a step-wise approach; can have a predictive character and can be the basis for the development of effective long-term strategies within ***transient hydrogeological environments***.

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Appendix A: Determination of GHB Conductance

The bed and stage of the Birs River up- and downstream of the dam was represented as specified head boundary using the GHB package in MODFLOW (Anderson and Woessner, 1992). The GHB package requires the input of a hydraulic conductance C_d. For the polygon input method C_d can be obtained by:

$$C_d = K_v \cdot b^{-1}, \qquad (4)$$

where Kv is the vertical hydraulic conductivity of the interface (e.g., river bed sediments) and b is the thickness of the interface. The determination of C_d usually involves great uncertainty and therefore values generally are calibrated or adopted from the literature.

For the current case study C_d initially was calibrated by inverse modeling. Nevertheless, calibration results and sensitivity analysis revealed considerable uncertainties in the conductance values used, especially for the GHB upstream of the dam (Table 1), which varied in order of magnitudes. To gain additional confidence in the use of this crucial parameter, river and riverine groundwater temperature series data were analyzed. The results of the analysis allowed to apply the one-dimensional heat pulse technique that was already successfully used for ephemeral streams in arid regions (Constantz et al., 1994; Constantz and Thomas, 1996), in perennial streams (Silliman and Booth, 1993; Silliman et al., 1995) as well as for loosing river-reaches in karst areas (Dogwiler et al., 2007). The method provides a means of monitoring infiltration rates through losing stream-reaches using thermal variations which occur in the surface water and riverine groundwater as a proxy for infiltration rates. The rate of thermal flux is assumed to be controlled by downward advection of surface water into the underlying aquifer (Silliman et al., 1995). The heat pulse method involves measuring the lag time between a maximum (or minimum) of river water temperature and a corresponding maximum (or minimum) of the riverine groundwater temperature, as well as the distance between the infiltrating river water and groundwater monitoring locations (cf. Taniguchi and Sharam, 1990). For the application of the method a series of assumptions have to be made: (1) the process is 1D; (2) only advective heat transport is taken into account, conductive heat transport and hydrodynamic dispersion is neglected; (3) river-groundwater interaction occurs via diffuse seepage into the streambed, rather than at a discrete point, and (4) in addition to the phase shift, the amplitude of temperature differences decreases with infiltration distance.

The velocity at which a heat pulse migrates downward through the sediment is proportional to the rate at which water infiltrates through the sediment (specific infiltration rate), which can be calculated by:

$$q_i = n \cdot \beta \cdot v_a, \qquad (5)$$

where n is the effective porosity and the coefficient β can be determined by the ratios of the volumetric heat capacities of water (4184 $\mathrm{Jm^{-3}°K^{-1}}$) and wet sediment (e.g., 2368 $\mathrm{Jm^{-3}°K^{-1}}$; Lapham, 1989):

$$\beta = \frac{c_s \rho_s}{c_w \rho_w} = 0.57. \qquad (6)$$

The dimensionless coefficient β describes the distribution of thermal energy between water and soil (sediment) and ranges between 0.3 und 0.7 for natural conditions (De Marsily, 1986).

Together with the hydraulic gradient J the hydraulic conductivity K_v can be determined by Darcy's law:

$$K_v = q_i \cdot J^{-1}. \qquad (7)$$

Transient C_d values for the GHB upstream were calculated, incorporating hydraulic conductivities of the river bed sediments deriving from a temperature data analysis approach, and assuming that river sediments are about 3 m thick (see Section 5.4).

Analyzed data include temperature time series from the river water and the riverine observation wells OW12 and 13 from August 2006 to May 2008. Data loggers were programmed to record pressure and temperature at 1 hour intervals. The distance from observation wells OW12 and 13 to the river are 2.6 and 2.2 m, respectively. Previous studies focused on analyzing diurnal temperature variations. In the current case study these variations are marginal for the groundwater temperature measurements in the observation wells. Therefore, the heat pulse method was applied on distinct long-term variations of temperature patterns.

As mentioned above, an important assumption in the heat pulse method is that the rate of thermal flux is controlled by the downward advection of the surface water and is therefore a proxy for the infiltration rate q_i. Although temperature patterns strongly suggest advective-dominated heat transfer, the relative importance of conduction and convection in the substrate of the losing reach was assessed based on the calculated Peclet number. Following the approach of Silliman et al. (1995), the dimensionless Peclet number can be determined by:

$$Pe = \beta \cdot v_a \cdot n \cdot l / D, \qquad (8)$$

where the thermal diffusivity D is given by:

$$D = K_e / c_s \rho_s = 4.6E - 07 m^2 s^{-1}, \qquad (9)$$

K_e is thermal conductivity ($1 Jm^{-1}s^{-1}°K^{-1}$) and l is the characteristic length and set as 1 m. Determined flow velocities range between 8.7E-06 and 7.2E-05 ms^{-1}, resulting in Peclet numbers for the losing reach of 1.02 to 8.48. Hence, the Peclet number is greater than 1.0 and advection dominates.

Table 3 summarizes input parameters used and the results of the temperature data analysis. q_i ranges from 4.7E-07 to 3.9E-06 ms^{-1}, which is in good agreement with other determined q_i of Swiss rivers (Höhn, 2002; Huggenberger et al., 2006).

Since August 2007, generally higher conductivity values have been observed indicating enhanced river water infiltration after the 300-year flood of 9 August 2007. C_d obtained from the temperature analysis resulted in 5.8E-07 s^{-1} before the major flood event, which is in very good agreement with the calibrated C_d an average value of 2.7E-07 s^{-1} for the GHB upstream of the dam of the steady state 3D HGM (situation on 7 February 2006). After the flood event, C_d resulted in an average value of 1.1E-06 s^{-1}.

Table 3. Results from one-dimensional heat flux method

	OW12	**OW13**
Number of analyzed data pairs	19	104
Average time lag (h)	26	36
Average hydraulic gradient J (-)	0.42	0.72
Average velocity v_a (ms^{-1})	3.2E-05	2.0E-05
Average hydraulic conductivity k_f (ms^{-1})	4.1E-06	2.5E-06
Average specific infiltration rate q_i ($m^3m^{-2}s^{-1}$)	0.15	0.1
Average hydraulic conductance C_d (s^{-1})	1.7E-06	1.1E-06

The primary result of the heat pulse method is the qualitative identification of the gaining and losing reaches of small rivers. Transformations in the hydraulic properties of the streambed, as caused by flooding events, can be captured by applying this method. Furthermore it could be observed that gradients in the maximum temperatures are generally higher than those in the minimum temperatures (cf. Constantz and Thomas, 1996). A correlation between the magnitude of maximum or minimum temperature gradients and low and high flow could not be found.

The ranges in values for hydraulic aquifer properties determined using the heat pulse method is much smaller than the range obtained using Darcy-based methods.

Appendix B: Modeled Lithological Volumes and Drain Diameters

Measured values for Calcium and Sulfate at the groundwater outlets represent an average outflow concentration of 256.4 and 148.2 mgl^{-1}, respectively. Infiltrating river water has Calcium and Sulfate concentrations of 92.2 and 9.6 mgl^{-1}, respectively. This equals approximately 300 mgl^{-1} gypsum removed from the system. Modeled outflow at the GHB downstream and in the drains resulted in approximately 20 ls^{-1}. Consequently, 6 gs^{-1} gypsum are removed from the system, which means a total of approximately 500 kgd^{-1}, 200 ta^{-1} and 20’000 t in 100 years. Assuming a density of the gypsum of 2.3 to 2.4 gcm^{-3} would result in approximately 8’500 m^3 gypsum removed from the system over the last 100 years. This represents a cube with approximately 20 m edge length. However, system outflow increased over the last 100 years, and assuming an outflow of approximately 20 ls^{-1} over the whole time period is not justified. Incorporating modeled outflow from the 2D KEM (Fig. 11) would result in approximately 15’000 t or 6’400 m^3 gypsum removed from the system over the last 100 years.

The solid representing the weathered gypsum formation of the diffuse flow system within the 3D HGM has a volume of approximately 200’000 m^3. If 6’400 to 8’500 m^3 gypsum was removed from the above volume, the fraction of Calcium-sulfate minerals of the weathered gypsum formation was reduced by 3 to 4 % over the last 100 years. The concentration of gypsum removed from the system is assumed to be constant and effects during flood events are not considered. For 5 borehole profiles, the fraction of Calcium-sulfate minerals within the non-weathered and weathered Gipskeuper formation was determined ranging between 30 - 50 % and 5 - 15 %, respectively. Hence, the reduction of Calcium-sulfate minerals lies within the determined values.

Drain diameters can be calculated by applying the transformed Darcy-Weisbach equation (Bobok, 1993):

$$d = -\lambda \frac{l}{\Delta h} \frac{u^2}{2g}, \qquad (10)$$

where d is the drain diameter, λ is the friction factor, l is the length of the pipe, Δh is the head difference within the drain, $u = 4Q/(\pi d^2)$ is the average velocity with Q presenting discharge, and g is the earth’s gravitational acceleration. The friction factor depends on the velocity in the drain via the Reynolds number $Re = ud/v$, with v the kinematic viscosity of water (1E-06 m^2s^{-1}). For $Re > 2300$ turbulent flow is assumed. With regard to the measured flow velocities of around 100 md^{-1}, turbulent flow would start with drain diameters greater than 1.8 to 2.3 m. Although voids with a maximum height of up to 2.7 m were detected during drilling, it is assumed that there is no connected conduit system exceeding the drain diameters previously cited, that would be necessary for turbulent flow. Additionally, most detected voids were filled. Consequently, laminar flow is assumed and the Hagen-Poiseuille equation can be applied. The friction for laminar flow is calculated as:

$$\lambda = \frac{64}{d} \frac{v}{u} \qquad (11)$$

This expression can be substituted in the equation used for calculating drain diameters, and together with the simulated discharge Q passing through the drain cross section the drain diameter can be calculated as:

$$d = \sqrt[4]{\frac{128l\nu}{\pi}\frac{Q}{\Delta hg}} \qquad (12)$$

Equivalent drain diameter along the entire length of the modeled drain was calculated for Drains 1 and 2. For the scenarios with unconnected drains, calculations before the major flood event resulted in diameters for Drains 1 and 2 of 0.11 m and 0.15 m, respectively, and of 0.16 m and 0.18 m, respectively, after the major flood event. This means that the cross section for flow within Drains 1 and 2 increases by 31 % and 17 %, respectively, after the major flood event. For the scenarios with connected drains, calculations before the major flood event resulted in diameters for Drains 1 and 2 of 0.09 m and 0.16 m, respectively, and of 0.15 m and 0.18 m, respectively, after the major flood event. This means that the cross section for flow within Drains 1 and 2 increases by 40 % and 11 %, respectively, after the major flood event. Diameters calculated for both scenarios illustrate the increase in the cross section for flow during flood events, especially for Drain 1. As the determination of Δh is uncertain (as observed in Oswald and Kinzelbach 2004; Konz et al. 2009), the influence of lower Δh was investigated. While it is obvious that lower Δh result in a decrease in calculated drain diameters, relative changes in diameters before and after the major flood event remain unaffected. The increase of the cross section for flow after the major flood event is interpreted as follows: During the flood event the hydraulic head forced water through the cavities and the clay fillings eroded.

References

Anderson, M. P. and Woessner, W. W.: Applied groundwater modeling. Academic Press, San Diego, 1992.

Bauer, S., Liedl, R. and Sauter, M.: Modelling of karst aquifer genesis - influence of exchange flow. Water Resour. Res. 39 (10). doi:10.1029/2003WR002218, 2003.

Bauer, S., Liedl, R. and Sauter, M.: Modelling the influence of epikarst evolution on karst aquifer genesis: a time-variant recharge boundary condition for joint karst-epikarst development. Water Resour. Res., 1-12. doi:10.1029/2004WR003321, 2005.

Birk, S., Liedl, R. and Sauter, M.: Identification of localized recharge and conduit flow by combined analysis of hydraulic and physico-chemical spring responses (Urenbrunnen, SW-Germany), J. Hydrol., 286, 179-193, doi:10.1016/j.jhydrol.2003.09.007, 2004.

Birk, S., Liedl, R., Sauter, M. and Teutsch, G.: Simulation of the development of gypsum maze caves. Env. Geol., 48:296-306, 2005.

Bitterli-Brunner, P., Fischer, H. and Herzog, P.: Geologic map Blatt Arlesheim 1067 (in German). Geological Atlas of Switzerland, 1984.

Bitterli-Brunner, P. and Fischer, H.: Explanations map Blatt Arlesheim 1067 (in German). Geological Atlas of Switzerland, 1989.

Bobok, E.: Fluid Mechanics for Petroleum Engineers, 400 pp., Elsevier Sci., New York, 1993.

Breznik, M.: Storage Reservoirs and Deep Wells in Karst Regions. A. A. Balkema, Rotterdam, 1998.

Butscher, C. and Huggenberger, P.: Intrinsic vulnerability assessment in karst areas: a numerical modeling approach. Water Resour. Res. 44 (3), W03408, 2008.

Clemens, T., Hückinghaus, D., Sauter, M., Liedl, R. and Teutsch, G.: A combined continuum and discrete network reactive transport model for the simulation of karst development. In: Calibration and Reliability in Groundwater Modelling. IAHS Publications, vol. 237. Proceedings of the ModelCARE 96 Conference. pp. 309-318, 1996.

Constantz, J. and Thomas, C. L.: The use of streambed temperature profiles to estimate the depth, duration, and rate of percolation beneath arroyos: Water Resour. Res., v. 32, no. 12, p. 3597-3602. 1996.

Constantz, J., Thomas, C. L. and Zellweger, G.: Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge: Water Resour. Res., v. 30, no. 12, p. 3253-3264, 1994.

De Marsily, G.: Quantitative hydrogeology – Groundwater hydrology for engineers. Academic Press, San Diego, 1986.

Dogwiler, T., Wicks, C. M. and Jenzen, E.: An assessment of the applicability of the heat pulse method toward the determination of infiltration rates in karst losing-stream reaches. Journal of Cave and Karst Studies, v. 69, no. 2, p. 237-242, 2007.

Doherty, J.: PEST Model-Independent Parameter Estimation. Watermark Computing, Corinda, Australia, 1994.

Dreiss, S. J.: Regional scale transport in a karst aquifer: 1. Component separation of spring flow hydrographs. Water Resour. Res. 25 (1), 117-125, 1989a.

Dreiss, S. J.: Regional scale transport in a karst aquifer: 2. Linear systems and time moment analysis. Water Resour. Res. 25 (1), 126-134, 1989b.

Dreybrodt, W.: The kinetics of calcite dissolution and its consequences to karst evolution from the initial to the mature state, NSS Bull., 49, 31-49, 1987.

Dreybrodt, W.: Processes in karst systems-Physics, chemistry and geology, Springer Series in Physical Environments, vol. 5, Springer Berlin, New York, 1988.

Dreybrodt, W.: The role of dissolution kinetics in the development of karstification in limestone: A model simulation of karst evolution, J. Geol., 98, 639-655, 1990.

Dreybrodt, W.: Dynamics of karstification: a model applied to hydraulic structures in karst terranes. Appl. Hydrogeol. 1, 20-32, 1992.

Dreybrodt, W.: Principles of early development of karst conduits under natural and man-made conditions revealed by mathematical analysis of numerical models. Water Resour. Res. 32, 2923-2935, 1996.

Dreybrodt, W. and Siemers, J.: Cave evolution on two-dimensional networks of primary fractures in limestone. In: Klimchouk, A., Ford, D. C., Palmer, A. N. and Dreybrodt, W. (Eds.), Speleogenesis: Evolution of Karst Aquifers. Nat. Speleol. Soc., USA, pp. 201-211, 2000.

Dreybrodt, W., Romanov, D. and Gabrovšek, F.: Karstification below dam sites: a model of increasing leakage. In: Beck, B. F., Herring, J. G. (Eds.), Geotechnical and Environmental Applications of Karst Geology and Hydrology: Proceedings of the 8th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karsts, Louisville, Kentucky. Balkema, pp. 131-137, 2001.

Dreybrodt, W., Gabrovšek, F. and Romanov, D.: Processes of Speleogenesis: a modelling approach. Carsologica, Verlag ZRC Publishing, Ljubljana, ISSN ISBN 961-6500-91-0, 2005.

Eisenlohr, L., Bouzelboudjen, M., Kiraly, L. and Rossier, Y.; Numerical versus statistical modeling of natural response of a karst hydrogeological system. J. Hydrol. 202, 244-262, 1997.

Environmental Modeling Systems Inc.: GMS, groundwater modeling system v6.0, 2006. http://www.ems-i.com

Epting, J., Huggenberger, P. and Glur, L.: A Concept for Integrated Investigations of Karst Phenomena in Urban Environments, submitted to Eng. Geol.

Epting, J., Huggenberger, P. and Rauber, M.: Integrated methods and scenario development in urban groundwater management, and protection during tunnel road construction; A case study of urban hydrogeology in the city of Basel, Switzerland. Hydrogeol. J. 16, 575-591, 2008.

Fechter, D.: Topography with the consideration of the cultural and conventional history (in German). In: Basel in the 14th century, 1856.

Ford, D. C. and Williams, P. W.: Karst Geomorphology and Hydrology. Unwin Hyman, London, 1989.

Gabrovšek, F., Menne, B. and Dreybrodt, W.: A model of early evolution of karst conduits affected by subterranean CO2 sources. Environ. Geol. 39 (6), 531-543, 2000.

Gabrovšek, F. and Dreybrodt, W.: The role of mixing corrosion in calcite aggressive H2O-CO2-CaCO3 solutions in the early evolution of karst aquifers in limestone. Water Resour. Res. 36, 1179-1188, 2000.

Gabrovšek, F. and Dreybrodt, W.: A comprehensive model of the early evolution of karst aquifers in limestone in the dimensions of length and depth. J. Hydrol. 240 (3-4), 206-224, 2001.

Golder, E.: 100 years Birswuhr Neue Welt (in German). Published by: Baudepartement Basel-Stadt, Tiefbauamt, 1984.

Groves, C. G. and Howard, A. D.: Early development of karst systems 1. Preferential flow path enlargement under laminar flow. Water Resour. Res. 30 (10), 2837-2846, 1994.

Gutiérrez, F.: Gypsum karstification induced subsidence: effects on alluvial systems and derived geohazards (Calatayud Graben, Iberian Range, Spain). Geomorphology 16, 277-293, 1996.

Gürler, B., Hauber, L. and Schwander, M.: Geology of the surrounding area of Basel with suggestions usage options of geothermal energy (in German). In: Beitrag zur Geologischen Karte der Schweiz, 1987.

Hanna, B. R. and Rajaram, H.: Influence of aperture variability on dissolutional growth of fissures in karst formations. Water Resour. Res. 34, 2843-2853, 1998.

Harbaugh, A. W., Banta, E. R, Hill, M. C. and McDonald, M. G.: MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model - User Guide to Modularization Concepts and the Ground-Water Flow Process. Open-File Report 00-92U.S., Geological Survey, Reston, Virginia, 2000.

Höhn, E.: Hydrogeological issues of riverbank filtration – a review. Pages 17-41 in C Ray und NATO, editors. Riverbank filtration understanding contaminant biogeochemistry and pathogen removal. Kluwer, Dordrecht, 2002.

Huggenberger, P., Epting, J., Regli, C., Spottke, I. and Zechner, E.: River-groundwater Interaction. MoNit: Modelling of nitrate groundwater contamination in the Upper Rhine Graben. INTERREG III A-Projekt. Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe, 2006.

James, A. N. and Lupton, A. R. R.: Gypsum and anhydrite in foundations of hydraulic structures. Geotechnique 28:249-272, 1978.

James, A. N.: Soluble materials in civil engineering. Ellis Horwood Series in Civil Engineering. Ellis Horwood, Chichester, England. 434 pp, 1992.

Jarvis, T.: The money pit: karst failure of Anchor Dam, Wyoming. In: Johnson, K. S. and Neal, J. T. (eds) Evaporite karst and engineering/environmental problems in the United States. Okla. Geol. Surv. Circ. 109:271-278, 2003.

Jeschke, A. A., Vosbeck, K. and Dreybrodt, W.: Surface controlled dissolution rates of gypsum in aqueous solutions exhibit nonlinear dissolution kinetics. Geochim. Cosmochim. Acta, 65, 1, 27-34, 2001.

Johnson, K. S.: Evaporite-karst problems in the United States. In: Johnson, K. S. and Neal, J.T. (eds) Evaporite karst and engineering/environmental problems in the United States. Okla. Geol. Surv. Circ. 109:1-20, 2003a.

Johnson, K. S.: Gypsum karst and abandonment of the Upper Mangum Damsite in southwestern Oklahoma. In: Johnson, K. S. and Neal, J. T. (eds) Evaporite karst and engineering/environmental problems in the United States. Okla. Geol. Surv. Circ. 109:85-94, 2003b.

Johnson, K. S.: Gypsum karst as a major factor in the design of the proposed Lower Mangum Dam in southwestern Oklahoma. In: Johnson, K. S. and Neal, J. T. (eds) Evaporite karst and engineering/ environmental problems in the United States. Okla. Geol. Surv. Circ. 109:95-111, 2003c.

Johnson, K. S: Subsidence hazards due to evaporite dissolution in the United States. Environ Geol 48:395-409, 2005.

Johnson, K. S.: Gypsum-karst problems in constructing dams in the USA. Environ Geol (2008) 53: 945-950, 2008.

Jones, N. L., Budge, T. J., Lemon, A. M. and Zundel, A. K.: Generating MODFLOW grids from boundary representation solid models. Ground Water 40 (2), 194-200, 2002.

Josnin, J.-Y., Pistre, S. and Drogue, C.: Modélisation d’un système karstique complexe (basin de St. Chaptes, Gard, France): un outil de synthèse des données géologiques et hydrogéologiques. Canadian J. of Earth Sciences 37, 1425-1445, 2000.

Kaufmann, G. and Braun, J.: Karst aquifer evolution in fractured, porous rocks. Water Resour. Res., 36 (6), 1381-1392, 2000.

Kiraly, L.: Modeling karst aquifers by the combined discrete channel and continuum approach, Bull. Hydrogeol., 16, 77-98, 1998.

Klimchouk, A. and Andrechuk, V.: Environmental problems in gypsum karst terrains. In: Klimchouk A. (ed) Gypsum karst of the World. Int. J. Speleol. 25(3–4):145-156, 1996.

Klimchouk, A., Ford, D. C., Palmer, A. N. and Dreybrodt, W. (Eds.): Speleogenesis: Evolution of Karst Aquifers. Nat. Speleol. Soc., USA. 444 pp., 2000.

Konz M., Ackerer P., Younes A., Huggenberger P. and Zechner E.: Two-dimensional stable-layered laboratory-scale experiments for testing density-coupled flow models, Water Resour. Res., 45, W02404, doi:10.1029/2008WR007118, 2009.

Kovacs, A.: Geometry and hydraulic parameters of karst aquifers: A hydrodynamic modeling approach. Thèse de Doctorat, CHYN, Univ. de Neuchâtel, 2003.

Lamont-Black, J., Younger, P. L., Forth, R. A., Cooper, A. H. and Bonniface, J. P.: A decision-logic framework for investigating subsidence problems potentially attributable to gypsum karstification, Eng. Geol. 65 (2-3), 205-215, 2002.

Lapham, W. W.: Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity, U.S. Geol. Surv. Water Supply Pap. 2337, 35 pp., 1989.

Lee, C. and Farmer, I.: Fluid Flow in Discontinuous Rocks. Chapman & Hall, London, 1993.

Lemon, A. M. and Jones, N. L.: Building solid models from boreholes and user-defined cross-sections. Computers & Geosciences, Vol. 29 (5), 547-555, 2003.

Liedl, R., Sauter, M., Hückinghaus, D., Clemens, T. and Teutsch, G.: Simulation of the development of karst aquifers using a coupled continuum pipe flow model, Water Resour. Res., 39(3), 1057, doi:10.1029/2001WR001206, 2003.

Long, J. C. S., Remer, J. S., Wilson, C. R. and Witherspoon, P. A.: Porous media equivalents for networks of discontinuous fractures. Water Resour. Res. 18 (3), 645-658, 1982.

Long, J. C. S. and Billaux, D. M.: From field data to fracture network modeling: an example incorporating spatial structure. Water Resour. Res. 23 (7), 1201-1216, 1987.

Mace, R. E.: Geostatistical description of hydraulic properties in karst aquifers: a case study in the Edwards Aquifer. Proceedings, International Symposium on Groundwater Management. American Society of Civil Engineers, New York, 193-198, 1995.

Makropoulos, C., Koutsoyiannis, D., Stanic, M., Djordevic, S., Prodanovic, D., Dasic, T., Prohaska, S., Maksimovic, C. and Wheater, H. S.: A multi-model approach to the simulation of large scale karst flows. J. Hydrol. 348, 412-424, 2008.

Milanović, P. T.: Geological Engineering in Karst. Zebra Publishing, Belgrade, Yugoslavia, 2000.

Milanovic, P.: Water resources engineering in karst. London: CRC press, Taylor & Francis, 2004.

Nagra: Project Opalinuston: Syntheses of geoscientific investigation results (in German). NTB: 02-03, 2002.

Oswald, S. and Kinzelbach, W.: Three-dimensional physical benchmark experiments to test variable-density flow models, J. Hydrol. 290, 22-42, 2004.

Payton, C. C. and Hansen, M. N.: Gypsum karst in southwestern Utah: failure and reconstruction of Quail Creek Dike. In: Johnson, K. S., Neal, J. T. (eds) Evaporite karst and engineering/environmental problems in the United States. Okla. Geol. Surv. Circ. 109:293–303, 2003.

Pearson, R. M.: Gypsum karst of the Lykins Formation and effects for Colorado Front Range water projects; Horsetooth and Carter Lake Reservoirs. Geol. Soc. Am. Abstr. Programs 34(6):216, 2002.

Pearson, F. J., Balderer, W., Loosli, H. H., Lehmann, B. E., Matter, A., Peters, T., Schmassmann, H. and Gautschi, A.: Applied Isotope Hydrogeology-a case study in northern Switzerland. Elsevier, 1991.

Quinn, J. and Tomasko, D.: A numerical approach to simulating mixed flow in karst aquifers. In: Sasowsky, I. and Wicks, C. (Eds.), Groundwater Flow and Contaminant Transport in Carbonate Aquifers. A. A. Balkema, Rotterdam, Holland, 147-156, 2000.

Quinn, J. J., Tomasko, D. and Kuiper, J. A.: Modeling complex flow in a karst aquifer. Sed. Geol., Vol. 184 (3-4), 343-351, 2006.

Regli, C., Huggenberger, P. and Rauber, M.: Interpretation of drill-core and georadar data of coarse gravel deposits. J. Hydrol. 255, 234-252, 2002.

Romanov, D., Dreybrodt W., and Gabrovšek, F.: Interaction of fracture and conduit flow in the evolution of karst aquifers. In: Martin, J. B., Wicks, C., Sasowsky, I. D. (Eds.), Proceedings of the Symposium on Karst Aquifers: Florida and Related Environments. Karst Water Institute, Charles Town, West Virginia, KWI special publication 7. pp. 1-6, 2002.

Romanov, D., Gabrovšek, F. and Dreybrodt, W.: Dam sites in soluble rocks: a model of increasing leakage by dissolutional widening of fractures beneath a dam. Eng. Geol., 70, 17-35, 2003.

Romanov, D., Gabrovsek, F. and Dreybrodt, W.: Leakage below dam sites in limestone terrrains by enhanced corrosion: a modeling approach. Env. Geol., 51, 775-779, 2007.

Romanov, D., Epting, J., Huggenberger, P. and Kaufmann, G.: Karstification of an aquifer along the Birs River, Switzerland – from natural to anthropogenic dominated boundary conditions. EGU General Assembly 2009, Geophysical Res. Abstr., Vol. 11, EGU2009-0, 2009.

Schmassmann, H.: Baselbieter and western Aargauer Tafeljura (in German). In: Jäckli, H., Kempf, T., 1972, Erläuterungen zum Blatt Bözberg-Beromünster 1. Hydrogeologische Karte der Schweiz, 93-100, 1972.

Siemers, J. and Dreybrodt, W.: Early development of karst aquifers on percolation networks of fractures in limestone. Water Resour. Res. 34 (3), 409-419, 1998.

Silliman, S. E. and Booth, D. F.: Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana: J. Hydrol., v. 146, p. 131-148, 1993.

Silliman, S. E., Ramirez, J. and McCabe, R. L.: GHB downflow through creek sediments using temperature time series: One-dimensional solution incorporating measured surface temperature: J. Hydrol., v. 167, p. 99-119, 1995.

Spottke, I., Zechner, E. and Huggenberger, P.: The southeastern border of the Upper Rhine Graben: A 3D geological model and its importance for tectonics and groundwater flow. Int. J. of Earth Sci. 94:580-593, 2005.

Taniguchi, M. and Sharam, M. L.: Solute and heat transport experiments for estimating recharge rate: J. Hydrol., v. 119, p. 57-69, 1990.

Teutsch, G.: Groundwater models in karstified terrains: two practical examples from the Swabian Alb (S. Germany). Proceedings, Solving Ground Water Problems with Models. International Ground Water Modeling Center, Indianapolis, Indiana, 929-953, 1989.

Thrailkill, J., Sullivan, S. B. and Gouzie, D. R.: Flow parameters in a shallow conduit-flow carbonate aquifer, Inner 350 J. J. Quinn et al. / Sedimentary Geology 184 (2006) 343-351 Bluegrass Karst Region, Kentucky, USA. J. Hydrol. 129, 87-108, 1991.

White, W. B.: Geomorphology and Hydrology of Karst Terrains. Oxford Univ. Press, New York, 1988.

2 Summary

The various parts of this thesis illustrate process-oriented methods for water resource monitoring, management and protection. The methods have been applied and tested for specific questions arising in the context of urban hydrogeology within selected areas in the region of Basel, Switzerland. Although the topics of the investigations may differ in terms of objectives and scales, the concept and methods are characteristic for many hydrogeologic problems in urban environments. Figure 3 summarizes the degree of complexity arising in the context of urban hydrogeology. The objectives and the complexity of the system investigated determine the investigative methods required for site characterization and resource management.

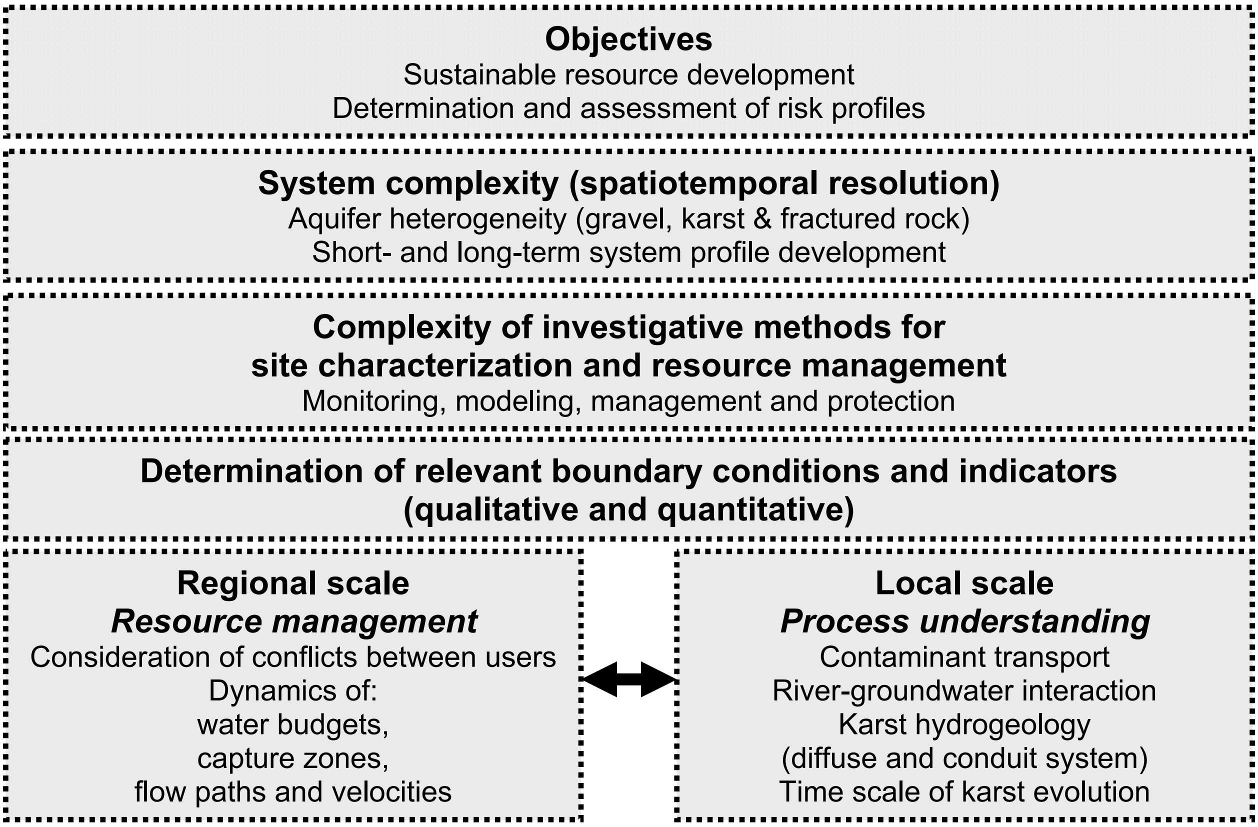

Fig. 3 Complexity of urban hydrogeological investigations.

Results from the various investigation parts

Part I: With the aid of groundwater modeling, the dynamics of the groundwater flow regime under changing spatial and temporal constraints could be simulated and evaluated during the various project phases. In order to avoid a permanent negative impact on the groundwater flow regime, particularly concerning quantitative and qualitative groundwater protection and irreversible deterioration of aquifer systems, recommendations for the optimization of the groundwater management were proposed and constructional arrangements were provided. Modeling results allowed evaluating the effects of groundwater drainage for different excavation techniques. Finally, for this engineering project, a combination of open sump drainage and the dewatering of residual groundwater in areas enclosed was chosen. To maintain city life and safety standards on the construction site, geotechnical measures such as cement injections for subsurface stabilization were used. The optimum dimension, operation and selection of locations, as required for injection wells and culverts, could be evaluated. The modeling results were successfully used to improve the groundwater monitoring system. The latter was adapted to project needs. Next to the management of the various groundwater extractions and injections, the requirements for groundwater protection (groundwater flow regime, groundwater quality) were satisfactorily achieved. The groundwater management system helped to identify changes in groundwater chemistry related to previously polluted industrial areas. Negative consequences for industrial groundwater users could be minimized. It was not necessary to install supplementary injection or interception wells to ensure the supply of groundwater for the industrial users, or to prevent the attraction of contaminated groundwater. After completion, groundwater budgets and groundwater flow velocities are in the same order as observed at the initial state. In summary, the predefined goals could be satisfactorily achieved both at local and regional scales.

Part II: For quantitative groundwater management (see above), aquifer parameters obtained from pumping tests are of prime importance. However, to adequately model groundwater transport, further knowledge of subsurface heterogeneity and the distribution of aquifer parameters is essential. The presented methods, applied to part of the investigation area of Part I, exemplify quantitative data fusion as a practical tool for urban hydrogeology. The applied techniques allow integrating different type and quality data into groundwater models. The dynamics of the groundwater flow regime under changing spatial and temporal constraints were simulated and evaluated on the basis of a regional groundwater model (see above). Furthermore, with regard to contaminant transport on a local scale, the applied techniques present an approach to quantify the effect of groundwater flow budgets and velocities in the individual hydrofacies. Obviously, groundwater flow in heterogeneous media occurs largely through interconnected highly permeable geological aquifer structures. Together with hydrological and operational boundary conditions, they govern the groundwater flow and transport regime. However, the relative amounts of groundwater budgets through the individual hydrofacies do not appear to alter significantly for the various boundary conditions investigated. Moreover, single hydrofacies and their relative occurrence determine the distribution of groundwater budgets.

Part III: Within this part, the implementation of the concept (Fig. 2) and process-oriented approaches for adaptive groundwater management in urban areas was illustrated by selected examples in the region of the city of Basel. The concept focuses on the influence of various water engineering projects on the future development of water resources and associated flow regimes. The changes in interactions between surface and subsurface water systems, when applying engineering measures along rivers often cannot be adequately evaluated based on existing groundwater protection concepts. The present protection concepts basically regard surface and subsurface waters as separate systems, while the transient character of river-groundwater interaction is not considered. Process-oriented approaches should include a comprehensive management on the catchment scale, i.e. surface and subsurface waters, wetlands and terrestrial ecosystems as well as the consideration of issues concerning water quality, water budgets and the structure of aquatic systems. Therefore, instruments have been developed that allow to adequately quantify the cumulative impacts on groundwater resources and to predict the effects of future changes. Together with the setup of extensive groundwater monitoring systems, field experiments and groundwater models that allow the definition of specific groundwater system profiles and scenario techniques, the dynamics of capture zones to groundwater extraction wells should be optimized by paying attention to changing hydrological and operational boundary conditions.

Part IV: This part illustrates an example of how the concept (Fig. 2) could be realized for a project dealing with urban infrastructure maintenance and development at a smaller scale. The case study documents the integration of various investigative methods related to an engineering project and the upgrade of a subsiding highway located next to a river dam. To safeguard surface and subsurface water during the construction measures, an extensive monitoring network was set up. Next to universal measurements and monitoring technologies, investigative methods with predictive character were developed that allow long-term predictions on the future evolution of the system and on further subsidence. An iterative integration and combination of investigative methods together with the analysis of multiple data sets considerably improved the description of the gypsum karst system within the investigation area in southeastern Basel. Extensive groundwater monitoring revealed that, in most observation wells, strong reactions in groundwater heads and electric conductivity were observed during the construction work, and that some of the hydrographs exhibit a siphon mechanism in line with the hydrological characteristics of the river. Hydraulic links within the investigation area were confirmed by a dye tracer test with groundwater flow velocities typical for conduit systems. These results indicate that the karst system is already well developed, whereas solution conduits developed along a system of fractures and interconnected joints. Results from ERT measurements allowed the description of (1) preferential flow in the shallow subsurface; (2) zones that are related to groundwater flow around the dam, including flow dynamics; (3) zones that are related to groundwater flow beneath the dam; (4) drainage phenomena of karst features like voids and conduits; (5) the weathering horizon within the Gipskeuper; (6) near surface faults and fracture zones, and (7) buried paleochannels. Thanks to the multiple data sources, it was possible to partially eliminate ambiguity in data interpretation and to describe the interrelation of observed features in a spatial context. The multiple data sets facilitated the development of comprehensive 3D hydrogeological models. The development of model scenarios facilitated the evaluation of (1) the extension of the weathered Gipskeuper beneath the dam; (2) drain networks within the weathered Gipskeuper and (3) construction measures.

Part V: This part illustrates that the proposed concept and methods can be used for the setup of monitoring networks and the development of adaptive water management tools on the one hand, but also can be applied for basic research on the development of gypsum karst systems on the other hand. This case study presents comprehensive research within a gypsum karst site in southeastern Basel. The following approach provided a better understanding of the karst system hydraulics: (1) determination of the extension of weathered and non-weathered rock and definition of pre-existing discontinuities; (2) identification of the relevant processes (transient character of system inflow, description of slow and fast flow components); (3) evaluation of episodic major flood events, accompanied by the flushing of conduit fillings and the inflow of more aggressive water and (4) investigations of the long-term development of the system.

Comprehensive studies of transient 3D hydrogeological models allowed evaluating relevant groundwater hydraulics, illustrating the dynamic character of the hydrogeologic flow regime during low frequency flood events, including river infiltration as well as diffuse and conduit components of model outflow. Temperature measurements and the applied heat pulse method is an attractive approach for monitoring time-variant infiltration rates through losing stream reaches, whereas results can be incorporated into hydrogeological models to describe transient hydraulic conductance. 3D hydrogeological models facilitate current state descriptions of karst systems and provide sufficient information for: (1) estimating the transient composition of water budgets; (2) describing the transient character of the hydrogeologic flow regime and (3) simulating and evaluating ***short-term impacts*** on processes, like during episodic flood events. However, ***long-term evolution*** of karst systems and prognosis can only be accomplished by the setup of models that consider the change of hydraulic properties with time. The results presented show how 2D karst evolution modeling can be calibrated to describe the current state of karst systems and can be used for prognosis of system development and subsidence risk assessment in the nearby future. 2D karst evolution modeling results illustrate that the amounts of gypsum within soluble rock can inhibit karstification and the development of connected percolation pathways necessary for system breakthrough. Moreover, local breakthrough events can lead to delimited subsidence events as can be observed in the real world. The described models require a step-wise approach, can have predictive character and allow the optimization of investigative methods of similar subsidence problems and the development of effective long-term strategies within ***transient hydrogeological environments***.

Scientific achievements

The scientific achievements of this thesis include: **(1)** the implementation of a concept for adaptive and integrated water resource management (AWM and IWRM); **(2)** the demonstration of integrating different methods and tools for process-oriented investigations in urban areas (monitoring, modeling, hydrogeophysics, etc.); **(3)** the fusion of qualitative and quantitative geological and hydrological information of different quality to describe aquifer heterogeneity; **(4)** the revision of existing protection concepts and approaches for risk assessment; **(5)** the application of karst evolution modeling based on genuine field data; **(6)** novel iterative approaches for the setup and combination of groundwater and karst evolution modeling techniques; **(7)** methods applied to characterize short-term impacts and long-term development of flow regimes in karst areas and **(8)** suggestions for monitoring strategies, including the development of tools that can be used for prediction.

(1) The concept proposed for practical urban hydrogeologic applications (Fig. 2) allows determining appropriate strategies for the qualitative and quantitative management of water resources. This includes the development of scenarios of possible future profiles and the investigation of short- and long-term consequences related to parameter changes. As a result, an integrated perception of water resources helps in predicting the consequences of management plans, engineering measures and environmental scenarios (e.g. urbanization, climate change). The results of the case studies led to the development of strategies used for the process of decision-making in water resource management and protection in urban areas with complex and contradicting interests.

(2) Regarding selection and setup of appropriate monitoring and modeling tools, it is important to ensure that the chosen methods and tools are capable of answering relevant questions. When applying hydrogeologic models, one of the key requirements is high-quality, site-specific data (National Research Council 1990). The iterative integration and combination of investigative methods, together with the analysis of multiple data sets, considerably improved the description of the water resources and flow regimes investigated within the two case study areas (Fig. 1). Furthermore, it could be demonstrated that hydrogeophysical methods can result in a more comprehensive and detailed site characterization than could be achieved by drilling alone. Especially, in complex environments, such as karst areas, and unstable sites, where invasive techniques (e.g. drilling) cannot be carried out. The multiple data sets facilitated the development of comprehensive 3D hydrogeological models, which were continuously adapted and calibrated. The magnitude of calibrated parameters corresponds to regional hydrogeological investigations and field experiments. Together with the hydrometrical investigations and the results of hydrogeological models the temporal and spatial dynamics of the systems could be interpreted in the context of the groundwater flow regimes. Physical-based models describing water systems are useful in conceptional understanding and all phases of the planning process, but particularly in (a) the assessment of current and future system profiles including the effects of anthropogenic activities; (b) the establishment of monitoring strategies (optimal design of monitoring systems and quality assurance of data); (c) setting up and implementation of programs of measures and (d) the development and optimization of water management and protection strategies, including the definition of risk profiles for water resources. Furthermore, the development of methods is important for uncertainty assessment (e.g., data uncertainty, inverse modeling and parameter estimation, sensitivity analysis, multiple model simulation and scenario analysis) because they need to be taken into consideration when making model-based decisions and for evaluating the ranges of controlling factors. Additionally, current research confirmed that groundwater recharge in many river valleys, especially in northwestern Switzerland, is dominated by infiltrating river water (Huggenberger et al. 2006). Methods were developed that allow quantifying the transient conductance across river beds and river banks. This includes a riverbed conductance model, which was derived from temperature data analysis of riverine groundwater. Results facilitate the evaluation of changing infiltration patterns and their consequences on regional water balances as well as the time-variant vulnerability of water resources.

(3) Groundwater investigations generally focus on the required drawdown and dimensioning of construction site drainages. However, this approach is unsatisfactory as contamination is an additional factor to be considered in urban areas. To adequately evaluate potential mobilization of contaminants, focus should be placed on aquifer heterogeneity. Furthermore, with regard to contaminant transport on a local scale, the applied techniques present an approach to quantify the effect of groundwater flow budgets and velocities in the individual hydrofacies. Obviously, groundwater flow in heterogeneous media occurs largely through interconnected highly permeable geological aquifer structures. The described integrated approach, incorporating sedimentological and geostatistical analyses as well as groundwater modeling, may assist in meeting the challenges presented by sensitive urban environment and lead to more target-oriented remediation strategies. These include an evaluation of contaminated sites, risk assessment of waste disposal and parameterization of numerical groundwater models, leading to the development of new approaches for complex practical problems.

(4) Many engineering projects along rivers that could affect riverine groundwater production lack efficient groundwater protection concepts. Often, protection concepts basically have a monitoring character, while collected data represent historiography. Therefore, the extension of current protection concepts by means of process-oriented approaches is of great importance. In some cases the goal is to work out options that provide adequate space for groundwater usage as well as for river systems. Consequently, the spatial context is not only restricted to the vicinity of planned impacts on water systems, but can often concern system dynamics covering large areas of the floodplain (Huggenberger et al. 2006). These challenges increase the requirements for investigation and assessment methods (Regli and Huggenberger 2007). A clear definition of present water system profiles, including its transient character, helps to define realistic goals and targets for site-specific conditions. Such approaches should involve a comprehensive management on both local and catchment scales (i.e. surface and subsurface waters, wetlands and terrestrial ecosystems) as well as the consideration of issues concerning water quality, water budgets and the structure of aquatic systems. The dynamics of capture zones of groundwater extraction wells can be optimized with the setup of extensive water monitoring systems, field experiments and hydrogeological modeling. This allows the definition of specific resource profiles and scenario techniques, but also the change of hydrological and operational boundary conditions.

(5) The application of karst evolution modeling to real world settings improved the understanding of the complex processes underlying natural and anthropogenic induced karstification. The results presented show how 2D karst evolution modeling can be calibrated to describe the current state of karst systems and can be used for prognosis of system development and subsidence risk assessment in nearby future. 2D karst evolution modeling results illustrate that the amount of gypsum within soluble rock can inhibit karstification and the development of connected percolation pathways necessary for system breakthrough. Moreover, local breakthrough events can lead to delimited subsidence events as observed in nature.

(6) The investigation of water resource management problems requires the consideration of many interacting processes. Therefore, one goal is to link the most appropriate modeling software components. These components may be from various domains and operate at different temporal and spatial resolutions. Nevertheless, it was possible to iteratively couple and combine groundwater and karst evolution modeling techniques. The application of different modeling techniques, employed by independent modeling teams, allowed both capturing different aspects of the hydrologic processes and defining the required level of model complexity. Generally, the transferability of the two modeling approaches could be confirmed. In this way the strength of each individual model could be exploited. This allowed the identification of sources of associated uncertainties and the determination of relevant parameters governing the processes within complex geological settings including varying properties of the formations with regard to hydraulic conductivity and solubility.

(7) It could be demonstrated that various investigative methods for karst aquifer characterization are complementing each other and allow the interpretation of short-term impacts and long-term development on system-dynamics. This includes the description of the transient character of the flow regime during and after episodic flood events (surface-groundwater interaction, diffuse and conduit flow) as well as the evaluation of time scales for karstevolution. 3D hydrogeological groundwater modeling facilitated current state descriptions of the karst system and provided sufficient information for: (1) estimating the transient composition of water budgets; (2) describing the transient character of the hydrogeologic flow regime and (3) simulating and evaluating ***short-term impacts*** on processes, like during episodic flood events. By contrast, ***long-term evolution*** of karst systems and prognosis were simulated by the setup of karstevolution models that assess the change of hydraulic properties with time (see above).

(8) In addition to long-term strategies in groundwater monitoring, process-oriented monitoring programs were set up during the engineering measures. Process-oriented experiments allowed to test hypotheses and to complete the knowledge on water resources. Such adapted programs encompass (a) the installation of supplementary observation wells, (b) the set up of high-frequency measurement intervals, and (c) more detailed programs to analyze the groundwater chemistry. The monitoring programs could be adapted to the progress of the various engineering measures, to the current management requirements and to the results obtained from current investigation results. Results allow the optimization of investigative methods, leading from general measurements and monitoring technologies to tools with predictive character. Transferability of all tools to areas with similar questions is, in principle, possible. In addition, urban and industrial development in areas prone to subsidence requires special sets of rules and regulations to minimize potential problems related to present and future impacts. Such perceptions are also needed in the domain exploration and use of geothermal energy, which is increasing rapidly. The tools described require a step-wise approach and can have predictive character that allow the optimization of investigative methods of similar subsidence problems and the development of effective long-term strategies within ***transient hydrogeological environments***.

3 Conclusions

Integrated and adaptive surface and groundwater monitoring, management and protection in urban areas require innovative process-oriented approaches. The impacts of major engineering projects on water resources must be viewed from a holistic perspective. Currently, our knowledge of subsurface processes is incomplete. The setup of concepts, tools and process-oriented experiments allow to test hypotheses and to fill knowledge gaps. It is also necessary to consider the various impacts simultaneously and to recognize that they are often not locally limited and can have effects on a regional scale. The implementation of sustainability concepts during engineering projects is a key objective of urban hydrogeology.

Obviously, the processes must be first understood on a local or project scale. In addition, engineering projects requiring the development protection schemes and geotechnical investigations often provide ***windows of opportunity***. They may result in changing perceptions for a sustainable development of water resources and in coordinating future measures.

Multiple interests concerning water use and protection challenge the intentions of water engineering and protection schemes that can only be solved by simultaneously considering all of the various interests. Previously, decisions concerning impacts on urban water resources were typically taken at the level of the individual project. However, it is the sum of all impacts, and their interaction in time and space, that has to be considered. To accomplish this, it is necessary to develop instruments that facilitate the adequate quantification of the consequences resulting from cumulative effects of numerous decisions concerning water resources. At the same time, system boundaries and profiles must be identified. They represent the current state of the system and allow identifying deficits and knowledge gaps. The definition of future profiles and specific targets lead to defined overall goals for specific water resources.

The clear definition of system profiles and goals fosters an optimal evaluation of the impact of individual measures in the context of urban development as it relates not only to current issues, but also to future demands. Extended monitoring systems combined with field experiments as well as modeling and scenario techniques provide tools that increase the understanding of system behavior and the dynamics of water flow regimes. Furthermore, these methods help to predict the long-term behavior of the system and the performance of the infrastructures affected. The cost of setting up such a monitoring system, including a series of ERT profiles and integrated hydrogeological modeling, is relatively low compared to the total cost of the engineering project.

It was possible to demonstrate that integrated conceptual approaches incorporating methods of adaptive water management can help to meet challenges originating from major constructions in sensitive urban environments. Applying methods of scenario development facilitates the assessment of effects of water engineering measures on water resources. Extending current protection concepts with process-oriented approaches that consider the interaction between surface and subsurface waters enhance the sustainable development of water resources. Knowledge of the composition of water quality, including an adequate consideration of variable hydrologic, operational and technical boundary conditions, is therefore of upmost importance.

In addition, the way in which the different elements of the approach were accepted by the stakeholders of the project was investigated. Their implementation during major urban development projects requires close cooperation with the general public, civil engineering planners, supervisors of the construction and industrial sites, consulting and geotechnical engineers, environmental bureaus and geoscientists. To reconcile the various individual and often conflicting interests, groundwater protection as well as policy and management aspects should already be considered at the early stages of urban planning.

A systematic consideration of water resources in urban development and the implementation of water management systems can serve as a decision tool for project planners and official departments. This allows ongoing adaptation dealing not only with current issues, but also with future demands. The results and methods can serve as guidelines for future projects. They can also assist in taking effective and optimum measures for groundwater protection and improve the sustainability of resource exploitation. Short-term and long-term strategies can result in improved sustainable management during engineering measures and also facilitate controlled sustainable development thereafter. While some of this work may be specific to the case studies presented, the concept and the methodologies are directly transferable to other urban areas.

References

Altshuler A, Luberoff D (2003) Mega-projects: the Changing Politics of Urban Public Investment. Brookings, Washington, DC Bedford B (1996) The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecol Appl 6:57-68

Bedford B (1996) The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecol Appl 6:57-68

Burke JJ, Sauveplane C, Moench M (1999) Groundwater management and socioeconomic responses. National Resources Forum, 23, 303-313

BUWAL (2004) Wegleitung Grundwasserschutz. Vollzug Umwelt. Bundesamt für Umwelt, Wald und Landschaft, Bern, 1-141

Carmon N, Shamir U, Meiron-Pisther S (1997) Water Sensitive Urban Planning, Journal of Environmental Planning and Management, 40(4), 413-434

EEA (1999) Groundwater quality and quantity in Europe – Environmental assessment report No 3, In S. Nixon (Ed.), European Environmental Agency, Luxembourg. ISBN 92-9167-146-0

Eiswirth M, Hötzl H, Cronin A, Morris B, Veselič M, Bufler R, Burn S, Dillon P (2003) Assessing and improving sustainability of urban water resources and systems. RMZ Mater Geoenviron 50:117-120

Eiswirth M, Wolf L, Hötzl H (2004) Balancing the contaminant input into urban water resources. Environ Geol 46:246-256

Eiswirth M, Hötzl H (1994) Groundwater Contamination by leaky sewer systems. Water Down Under, National Conference of Institution of Engineers, Adelaide, Australia, November 1994, 111-114

Fatta D, Naoum D, Loizidou M (2002) Integrated environmental monitoring and simulation system for use as a management decision support tool in urban areas. J Environ Manage 64:333-343

Foster SSD, Morris BL (1994) Effects of urbanisation on groundwater recharge. In WB Williamson (Ed.), Groundwater Problems in Urban Areas, Proceedings of ICE conference London, June 1993, Thomas Telford, 43-63

Foster S, Lawrence A, Morris B (1998) Groundwater in urban development: assessing management needs and formulating policy strategies. World Bank Technical Paper No390

Foster SSD (2001) The interdependence of groundwater and urbanization in rapidly developing cities. Urban Water 3:185-192

Hufschmied P (2006) Hydrogeological and geotechnical problems during construction of traffic lines in Central Berlin. Presentation at the Swiss Hydrogeological Society, Geneva, 12-13 May 2006

Huggenberger P, Epting J, Regli C, Spottke I, Zechner E (2006) Fluss-Grundwasser Interaktion. MoNit: Modellierung der Grundwasserbelastung durch Nitrat im Oberrheingraben. INTERREG III A-Projekt. Landesamt für Umwelt, Messungen und Naturschutz Baden-Württemberg, Karlsruhe, 110 Seiten

Ku HFH, Hagelin NW & Buxton HT (1992) Effects of Urban Storm-Runoff Control on Groundwater Recharge in Nassau County, New York. Ground Water, 30(4), 507-514

Lawrence AR, Stuart ME, Barker JA, Tester DJ (1996) Contamination of chalk groundwater by chlorinated solvents: A case study of deeps penetration by non-aqueous phase liquids. Journal CIWEM, 10, 263-272

Lerner DN, Issar SI, Simmers I (1990) Recharge due to Urbanisation. Groundwater Recharge, A guide to understanding and Estimating Natural Recharge - International Contributions to Hydro geology, 8, IAH publication. Verlag Heinz Heise Publishers, 201-204

Lerner DN (1996) Urban groundwater: An asset for a sustainable city. European Water Pollution Control, 6(5), 43-51

Loucks DP, Gladwell JS (1999) Sustainability Criteria for Water Resources SystemsInternational Hydrology Series, Cambridge University Press. UNESCO, Cambridge (1999), p. 144

Kirchhofer RT (2006) GeoData. Geological Data-base of the city of Basel and northwestern Switzerland

National Research Council (1990) Groundwater models: scientific and regulatory applications. National Academy Press, Washington, DC

National Research Council (1992) Global environmental change.: understanding the human dimensions. Stern PC, Young OR, Druckman D (eds) Committee on the Human Dimensions of Global Change; Commission on Behavioral and Social Science and Education. National Academy Press, Washington, DC

Nazari MN, Burston MW, Bishop PK & Lerner DN (1993) Urban Groundwater Pollution: A Case Study from Coventry, UK. Ground Water, 31(3), 417-424

Pahl-Wostl C (2006) NeWater Newsletter No. 1: new Approaches to Adaptive Water Management under Uncertainty. NeWater at the World Water Forum in Mexico. Mexico City, March 2006, http://www.newater.info. Cited June 2006

Pahl-Wostl C, Möltgen J, Sendzimir J, Kabat P (2005) New methods for adaptive water management under uncertainty–the NeWater project. Paper accepted for the EWRA Conference 2005, Menton, France, September 2005

Prokop G (2003) Sustainable management of soil and groundwater resources in urban areas. Proceedings of the 2nd IMAGETRAIN Cluster Meeting, Krakow, Poland, 2-4 Oct 2002

Regli C, Huggenberger P (2007) Grundwasserschutz bei wasserbaulichen Eingriffen in Fliessgewässer - Hydrogeologische Aspekte, gwa 7, 261-272

WCED (1987) Our Common Future. World Commission on Environment and Development, Oxford (England)

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