



Integrated investigations of karst phenomena in urban environments

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ABSTRACT

Theories that describe karst systems are often limited to conceptual models. However, engineering projects within complex karst systems demand the development of tools that allow site-specific descriptions of the hydrogeologic settings and calibrating the processes of karst evolution.

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

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. Investigative 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.

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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. 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.

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, 2008). However, these concepts have rarely been applied successfully in urban planning.

Infrastructures that are constructed on soluble geologic formations are prone to subsidence (Gutiérrez, 1996; Lamont-Black et al., 2002). Especially when found within gypsum-bearing formations, karst features develop much more rapidly than in carbonate formations. While the characterization and modeling of flow in heterogeneous and fractured media has been investigated intensively, there are no

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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, a monitoring 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 presented approach included the integration and continuous adaptation of field measurements and modeling techniques. The establishment of a groundwater monitoring 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 hydrogeological models.

Geophysical 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). 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. Šumanovac and Weisser, 2001; McGrath et al., 2002; van Schoor, 2002; Kaufmann and Romanov, 2009), 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 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 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 (Bitterli-Brunner et al., 1984; Bitterli-Brunner and Fischer, 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 fractures are mapped and then studied (Long et al., 1982; Long and Billaux, 1987); and (5) open channel equivalents (Thraillkill 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. Subsequently with the calibrated hydrogeological model scenarios could be developed to evaluate different hydraulic and geotechnical boundary conditions.

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 hydroelectric 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).

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).

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 m³ of supplementary cement, in order to plug all existing underground water channels and stabilize the ground beneath. To safeguard surface

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