Integrated investigations of karst phenomena in urban environments

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ARTICLE INFO

Article history:
Received 23 February 2009
Received in revised form 20 August 2009
Accepted 31 August 2009
Available online xxxx

Keywords:
Dam site
Subsidence
Karst evolution
Gypsum dissolution
Conduit development
Hydrogeophysics

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 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...
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 Weissner, 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’n et al., 2000). Furthermore, numerous ERT investigations focus on dam leakage (e.g. Al-Saigh et al., 1997) and buried paleochannels (Baines et al., 2002; Mailet 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; Jossin 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 (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 Tomasco, 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
and subsurface water resources during the construction measures an 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 Fig. 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 (Schilfsandstein/Untere Bunte Mergel) and, for most of the investigation area, of Gipskeuper. Gipskeuper is made up of a series of evaporite layers 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 $10^{-14}$ and $10^{-7}$ m s$^{-1}$ (Nagra, 2002). However, with its weathered appearance, Gipskeuper can be considered as a heterogeneous (karstified) aquifer. Areas below the dam and the highway are strongly weathered due to gypsum dissolution in the Gipskeuper rock and are loosened over several meters of thickness.

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

Fig. 1. Investigation area in the urban agglomeration of Basel.
the weathered Gipskeuper (lixivation 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

Fig. 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
Area of investigation

Boundary conditions

Environmental (geological settings, flow regimes, aquifer properties, interaction of surface and subsurface waters, ...)
Anthropogenic/Geotechnical (water engineering projects, operational regimes, ...)

Profiles

Definition and future system profiles for relevant hydraulic and geotechnical boundary conditions

System analysis

Documentation of current system profile (Baseline Scenario)
Data assimilation, preliminary gap analysis, identification of problems, pressures, impacts and requirements

Milestones

Minimization of changes to surface and subsurface waters and safeguarding of water quality issues during water engineering projects
Development of technical solutions guaranteeing sustainable development of surface and subsurface waters

Goals

Sustainable use of surface and subsurface water resources and long-term improvement of groundwater quality
Consideration of long-term impact of geotechnical measures and future changes of use

Conceptualization - Integration of investigative methods - Scenario development

Determination of relevant parameters - Integration of monitoring (e.g. hydrometrical and geophysical) and modeling techniques
Development of tools with predictive character that allow to monitor and model the relevant processes

Fig. 5. Conceptual approach for practical urban hydrogeological applications.

In the investigation, the core elements of this adaptive procedure include the integration and combination of different investigative methods such as setting up of 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.

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.

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 (Loke, 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 analyze the change in system behavior, measurements were carried out both before and after construction measures. The first and second measurements were performed before the construction measures on April 3rd and May 18th, 2007 at river discharges of 27 and 51 m$^3$s$^{-1}$, 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$^3$s$^{-1}$, 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).
Table 1
Compilation of borehole information.

<table>
<thead>
<tr>
<th>OW</th>
<th>Monitoring</th>
<th>Filter section in</th>
<th>Status</th>
<th>From (m a.s.l.)</th>
<th>To (m a.s.l.)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inclinometer</td>
<td>Gipskeuper</td>
<td>Void (filled)</td>
<td>259.48</td>
<td>257.18</td>
<td>2.30</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>Fluvial gravels and Gipskeuper</td>
<td>Connection sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Head, T, EC</td>
<td>Fluvial gravels and Gipskeuper (separate)</td>
<td>Connection unclear, siphon mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Head, T, EC</td>
<td>Fluvial gravels and Gipskeuper</td>
<td>Void, connection</td>
<td>250.92</td>
<td>248.62</td>
<td>2.30</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Gipskeuper</td>
<td>Void (filled), connection sealed</td>
<td>254.20</td>
<td>251.50</td>
<td>2.70</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Gipskeuper</td>
<td>Void (filled), connection sealed</td>
<td>253.60</td>
<td>252.80</td>
<td>0.80</td>
</tr>
<tr>
<td>7</td>
<td>Head, T, EC</td>
<td>Gipskeuper</td>
<td>Sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>Sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Head, T, EC</td>
<td>Fluvial gravels and Gipskeuper</td>
<td>Void (filled), connection</td>
<td>257.05</td>
<td>256.25</td>
<td>0.80</td>
</tr>
<tr>
<td>10</td>
<td>Head, T, EC</td>
<td>Fluvial gravels and Gipskeuper</td>
<td>Connection, siphon mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>Sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Head, T, EC</td>
<td>Fluvial gravels</td>
<td>Siphon mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Head, T, EC</td>
<td>Fluvial gravels and Gipskeuper</td>
<td>Connection unclear, siphon mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Head</td>
<td>Artificial fillings and Gipskeuper</td>
<td>Connection unclear, siphon mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td>Sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Head</td>
<td>Unweathered rock</td>
<td>Dry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>Sealed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Head</td>
<td>Slope clay to Obere Bunte Mergel</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Inclinometer</td>
<td></td>
<td>–</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Head, T, EC</td>
<td>Weathered Gipskeuper</td>
<td>Void</td>
<td>252.17</td>
<td>250.77</td>
<td>1.40</td>
</tr>
<tr>
<td>21</td>
<td>Head</td>
<td>Artificial fillings, Schliffsandstein, Gipskeuper</td>
<td>Void</td>
<td>249.87</td>
<td>249.57</td>
<td>0.30</td>
</tr>
<tr>
<td>66</td>
<td></td>
<td></td>
<td>–</td>
<td></td>
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<td></td>
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<td>69</td>
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<tr>
<td>72</td>
<td></td>
<td></td>
<td>–</td>
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</tr>
</tbody>
</table>

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 where volumetric layers represent hydrostratigraphic sequences (Lemon and Jones, 2003; Epting et al., 2009; Fig. 6).

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). Results of model calibration are discussed in detail in Epting et al. (2009). 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 l s⁻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) average recharge was assumed at 36 – 0.8 m s⁻¹ (areal precipitation 946 mm a⁻¹). 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 (Figs. 1 and 4).

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 two drains. 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. Discussion of 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 (Table 1). 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.

Fig. 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). 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 approximately 500 and 2500 μS cm⁻¹. On the one hand, low electric conductivities are in the range of measured values for river water (450 – 500 μS cm⁻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 (electrolytes). 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 occurs 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 Fig. 8, the operation of the siphon mechanism is illustrated schematically. When the water level in the cave raises 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 the 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 as well as 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).

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 the main directions of joints within the investigation area (Fig. 4). The dye was injected in OW3 and sampled in OW2, 4 and 5 (Fig. 1). Highest concentrations and a second maximum, representing a further preferential pathway, were observed in OW5, which is nearest to the injection well. 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 ms⁻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 m⁻¹ s⁻¹ for an assumed

Please cite this article as: Epting, J., et al., Integrated investigations of karst phenomena in urban environments, Engineering Geology (2009), doi:10.1016/j.enggeo.2009.08.013
4.2. Electric Resistivity Tomography (ERT)

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 features 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
Results of dye tracer test and interpretation.

Table 2

<table>
<thead>
<tr>
<th>Distance</th>
<th>Time</th>
<th>Velocity</th>
<th>Head</th>
<th>Hydraulic gradient</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m)</td>
<td>v (m h⁻¹)</td>
<td>h (m)</td>
<td>dh/dl (m)⁻¹</td>
<td>K (m s⁻¹)</td>
</tr>
<tr>
<td>OW 3</td>
<td>Injection</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OW 2</td>
<td>124</td>
<td>26.8</td>
<td>4.6</td>
<td>111</td>
<td>2.7E-02</td>
</tr>
<tr>
<td>OW 4</td>
<td>116</td>
<td>32.8</td>
<td>3.5</td>
<td>85</td>
<td>3.8E-02</td>
</tr>
<tr>
<td>OW 5</td>
<td>112</td>
<td>26.8</td>
<td>4.2</td>
<td>100</td>
<td>2.9E-02</td>
</tr>
<tr>
<td>Birs R.</td>
<td>137</td>
<td>32.8</td>
<td>4.2</td>
<td>100</td>
<td>2.9E-02</td>
</tr>
</tbody>
</table>

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

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.

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).

4.2.1. 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.

4.2.2. 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 approximately 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 than for the first two measurements. 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 Fig. 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 geometrical 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 course of the bedrock surface that was interpolated based on geological information derived from boreholes and reports made during the installation of the piles.

4.2.3. Groundwater flow beneath the dam

The inversion models of the first two measurements before the construction measures show very high resistivities above 200 Ohm 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, for the second measurement this zone of high resistivity values does not reach as deep as for the first measurement. This decrease in resistivity indicates elevated undercurrent below the dam during flood events and 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 Ohm are highlighted. This limiting value was adopted from Schön (1983) assuming that resistivity values above 140 Ohm are not typical for rocks of the Keuper sequence. Additionally, in the inversion model of the third measurement conducted after the installation of the piles, a region with elevated resistivity values can be observed in the central part where subsurface structures of the dam are located.

4.2.4. 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 Ohm 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 maximum resistivity values within this zone migrate towards the void. 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 Ohm 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 m³ 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.

4.2.5. Delineation of the weathering horizon within the Gipskeuper

Results of the ERT measurements could not be used for detecting sharp boundaries between weathered and non-weathered zones, as could be derived from the detailed 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.

4.2.6. Faults and fracture zones

The investigation area is characterized by an intense tectonic segmentation into compartments. Both ERT profiles proceed 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 dip direction of the fault is indicated at 20 to 30° North.

4.2.7. Buried paleochannels

In 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

Fig. 11 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. Fig. 12 illustrates the divergence of measured

![Image](image_url)

**Fig. 11.** 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). The covering water layer on top of the weathered Gipskeuper upstream of the dam is indicated by two colors.

Please cite this article as: Epting, J., et al., Integrated investigations of karst phenomena in urban environments, Engineering Geology (2009), doi:10.1016/j.enggeo.2009.08.013
and calibrated groundwater heads at the observation wells ranging between 0.14 and 2.38 m; one observation well falls dry. 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 3, 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 l s⁻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 l s⁻¹.

4.4. Integration of the investigative methods

Fig. 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 (Figs. 4 and 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 (Figs. 9 and 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.

Fig. 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 abandoned river channels, and is delimited by the occurrence of more resistant rocks to the east (cf. Fig. 4). 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 bended river to the east. The longitudinal cross section in Figs. 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 bended 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.

Table 3

<table>
<thead>
<tr>
<th>ZONE</th>
<th>Kind, Dircichet</th>
<th>Kind, Cauchy</th>
<th>Drains</th>
<th>ZONE 1</th>
<th>ZONE 2</th>
<th>ZONE 3</th>
</tr>
</thead>
<tbody>
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<td>10.2</td>
<td>0.0</td>
<td>5.6</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>OUT</td>
<td>2.2</td>
<td>13.4</td>
<td>6.1</td>
<td>5.4</td>
<td>2.1</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Water budgets (in l s⁻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).
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 $1E-02$ l s$^{-1}$; low flow cells $1E-02$ to $E-02$ l s$^{-1}$; medium flow cells $2E-02$ to $3E-02$ l s$^{-1}$; high flow cells $>3E-02$ l s$^{-1}$) (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).
connected conduits that lie along a direct path between recharge and discharge locations and cascade along a hydraulic gradient.

5. Conclusions

The integration of monitoring data with field experiments as well as modeling and scenario techniques facilitated the determination of the relevant parameters governing the gypsum karst system and an understanding of the fundamental governing processes. The developed process-oriented tools 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.

Since the construction of the dam the hydraulic gradient within the investigation area has been increased, resulting in accelerated karst evolution. 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.

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. 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.

Acknowledgements

The authors would like to thank Susan Braun-Clarke, Christoph Butscher, and the anonymous reviewers for providing valuable comments on the manuscript, as well as Ralph Henz from PNP (Pfrüter, Nyfeler & Partner) and Hanspeter Keller from the IWB (Industrielle Werke Basel) for their excellent collaboration. Financial support from the FAG (Freiwillige Akademische Gesellschaft Basel) is also gratefully acknowledged.

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