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Karstification of an aquifer along the Birs river, Switzerland — A modeling approach

Douchko Romanov [a,*], Georg Kaufmann [a], Thomas Hiller [a], Jannis Epting [b], Peter Huggenberger [b]

[a] Free University of Berlin, Institute of Geological Sciences, Section Geophysics, Malteserstr. 74-100, Building D, 12249 Berlin, Germany
[b] Department of Environmental Sciences, Applied and Environmental Geology, University of Basel, Bernoullistr. 32, 4056 Basel, Switzerland

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ABSTRACT

The impact, caused by a construction of a dam site on the Birs river close to Basel (Switzerland), on the evolution of a gypsum-karst aquifer in the vicinity of the hydraulic building, is studied. Several sinkholes provoked subsidence of the dam and the highway nearby. Extensive technical measures had to be conducted in order to prevent further karstification. The numerous geophysical and geological field studies executed in the area, together with a 3D hydrogeological model of the aquifer, provide a very detailed information about the boundary conditions, and the local properties determining the karstification.

In this work, we present a 2D karst evolution model of the aquifer in the vicinity of the dam structure. In contrast to older studies, this time the focus of the research is not the basic processes governing the karst evolution, but modeling the temporal development of the real aquifer. Using the large amount of information about the location, we demonstrate that a detailed knowledge of the local properties of the rock (hydraulic conductivity, solubility) is of crucial importance when modeling real aquifers. From a wide range of possible evolution scenarios, we deduce a warning that solutional features, such as sinkholes, can develop far away from the hydraulic structure and endanger facilities at the surface. Our model is able to reproduce and successfully explain the main geological features revealed by field studies. We suggest a workflow to combine the data from field observations, groundwater modeling, and karst evolution modeling and to study the karstification of real aquifers. We propose a scenario for the evolution of the aquifer and a reasonable range for the values of the basic parameters governing the karstification.

1. Introduction

A small dam site, built a bit more than 110 years ago on the Birs river near Basel (Switzerland), is used to collect water for the power plant nearby. The weir followed an earlier dam construction, utilized to divert water from the river Birs towards the city of Basel (Golder, 1984). During the 1960's a highway was constructed adjacent to the right riverbank. After an initial slow phase of subsidence, during the 1980's several sinkholes developed beneath the highway. Between 2006 and 2007, extensive remediation measures had to be conducted in order to prevent further karstification (Epting et al., 2009a, 2009b). A question arises, whether the change in the flow fields due to the dam construction and the continuous karstification are the reason for the observed subsidence or are there other causes, such as a direct connection between near surface and deeper, already karstified, parts of the gypsum aquifer.

Karst aquifers can be very sensible to variations in the parameters determining their evolution. The heterogeneous distribution of hydraulic conductivities (White, 1988; Ford and Williams, 2007), together with the complexity of chemical reactions governing the rock dissolution (Dreybrodt, 1988; Kaufmann and Dreybrodt, 2007), lead to solutional patterns which are difficult to predict. The time-scales necessary to obtain a mature karst system range from several thousand years for aquifers developing under natural conditions down to less than a year for areas near large hydraulic facilities (Klimchouk et al., 2000; Dreybrodt et al., 2005). Consequently, the aquifers in soluble rocks are very difficult to assess and their future development is difficult to predict. Field studies like boreholes, pump tests, tracer injections, and application of different geophysical methods require dense measurement networks, processing of many samples, and interpretation of a large amount of data. There are many examples in the literature discussing different aspects of the karst evolution, the increased leakage, the mechanical stability, the environmental and the engineering considerations related to dam sites (James and Lupton, 1978; James and Kirkpatrick, 1980; James, 1992; Malkawi and Al-Sheriadeh, 2000; Milanovic, 2000; Mohammadi and Raeisi, 2007; Johnson, 2008; Bonacci and Josip, 2009; Bonacci et al., 2009). There are also several examples of successful development, application, and interpretation of numerical models in order to reveal the basic processes governing the karstification of aquifers in soluble rocks (gypsum or limestone) under natural (Gabrovsek and Dreybrodt, 2001; Romanov et al., 2003a; Bauer et al., 2005; Dreybrodt et al., 2005; Kaufmann, 2005; Gabrovsek and Dreybrodt, 2010; Kaufmann et al., 2010), and man-

* Corresponding author. Tel.: +49 30 838 70682; fax: +49 30 838 70729.
E-mail address: douchko.romanov@fu-berlin.de (D. Romanov).

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made conditions (Romanov et al., 2003b; Hiller et al., 2011). But there are only few studies dealing with the application of karst evolution models to real aquifers (Romanov, 2003; Kaufmann and Romanov, 2008; Rehrl et al., 2008), because real aquifers require a detailed knowledge of the boundary conditions, the geology, the hydrology, the local rock parameters, and the other properties of the aquifer. Furthermore, this amount of data demands massive computational resources and long calculation and processing times. However, Epting et al. (2009a, 2009b) demonstrate first steps towards a successful integration of field, theoretical and numerical studies.

Our paper presents an attempt to create and study a numerical karst evolution model able to describe the karstification of an evaporite karst system in the context of a dam site on the Birs river in Switzerland. An overview photo of the site is depicted in Fig. 1. The main reasons to select this aquifer for combined field, hydrogeological, and karst evolution modeling studies are:

1. Since the observed subsidence of the highway near the dam during the 1980's, a series of geophysical and geological field studies has been performed in the area. Together with a recently developed 3D hydrogeological model of the aquifer, they provide very detailed information about the boundary conditions and the local properties determining the present karstification processes (Epting et al., 2009a, 2009b).
2. The studied area is small ($<70\,000\ m^2$), allowing a dense discretization of the modeling domain.
3. The geological and the hydrological settings of the region are relatively well known (Fechter, 1856; Golder, 1984; Kirchhofer, 2006).
4. The system of measurement stations (observation network) established at the location to observe the hydraulics and the vertical movements of the dam provide real-time information about the aquifer.
5. The large amount of data allows us to critically evaluate the results of our karst evolution study, verify the approximations, and to improve the numerical representation of the aquifer.

To present the results we follow a step by step approach, starting with a simple model based on the known data and capable to correctly describe the processes in the aquifer. In this way, we are able to interpret the "snapshot" provided by in-situ investigations and groundwater modeling of the aquifer nowadays and evaluate it from the point of view of the temporal evolution of the karst system described by our model. This allows us to narrow the ranges of possible values for the basic parameters, refine or even correct some of our assumptions and/or generalizations, and iteratively reach the "best model", able to satisfactory describe the reality. Consequently, we provide a solid base for more complex models and suggest a workflow for modeling of the karst evolution in aquifers that are not so well surveyed as the one along the Birs river. Our model can be integrated in future large scale theoretical and field studies dealing with the prevention of increasing leakage, the prevention of sinkhole development and the safety of hydraulic facilities in karst regions.

2. Site description

The Birs river joins the Rhine several kilometers East from Basel close to the Swiss–German border. The dam site is located approximately 5 km upstream the Birs river in the flexure zone of the Eastern Edge of the Upper Rhine Graben, within a sequence of alternating marly clays, intercalated within anhydrite, and gypsum layers. The Birs valley is densely populated and urbanized. Park-like environments bound the riverbanks. Few hundred meters before and after the dam the river is flowing within or near the bedrock surface consisting of Triassic and Jurassic sedimentary units, parallel to the western border of the highway H18 (Basel–Delemont) (see Figure 1).

The stratigraphic column, extending from Quaternary river gravels to Triassic Gipskeuper, is depicted in Fig. 2a. Note that only the lithological sequences observed in the vicinity of the dam are colored in Fig. 2a. Fig. 2b depicts a top view of a horizontal cross-section. In order to simplify the figure and better illustrate the complex pattern of lithological variations in the investigation area, we do not plot the Quaternary layer in Fig. 2b, but it is depicted as a pale yellow rectangle on the top the vertical cross-section along the AA′ (Figure 2b) line in Fig. 2c. The quaternary gravels, silty flood deposits, and artificial fillings beneath the highway overlie the Jurassic and Triassic strata on the East bank of the river (Figure 2). These sequences consist of clays (Obstusus Tone), grayish and reddish marls and clays, sandstones (Untere and Obere Bunte Mergel, Schilfsandstein), and for the most of the investigation area Gipskeuper

Fig. 1. An overview photo of the dam structure on the Birs river, Neuewelt, Basel, Switzerland. The gray arrows mark the east and the west bank of the river (left to right on the photo). The camera is directed towards south–south west.