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Karstification of aquifers interspersed with non-soluble rocks: From basic principles towards case studies

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ABSTRACT

We have developed a numerical model able to describe the karstification of aquifers in fractured rocks containing soluble (limestone or gypsum) and insoluble layers. When water is flowing along fractures crossing the soluble layers, it is able to dissolve the material there, to increase the aperture width of the conduit, and consequently to increase the local hydraulic conductivity. Depending on the thickness and the distribution of these layers, the dissolution can be active only for limited periods, or during the whole evolution time. Fractures located in insoluble layers do not change at all. We are interested in the integral effect of these local processes and study four simplified scenarios of karstification along a prominent wide conduit crossing a fractured limestone block. We keep the initial and the boundary conditions the same for all scenarios and vary only in the amount and the distribution of the soluble material. We demonstrate that aquifers in 100% limestone, without any insoluble layers, develop along areas with high hydraulic conductivities and high hydraulic gradients, creating channel like pathways. On the other hand aquifers containing soluble layers with limited thickness develop faster and exhibit diffuse patterns determined by the chemical properties of the rock.

The second part of the paper is a step towards modeling of real karst systems. We present the evolution of an aquifer located in the vicinity of a large hydraulic structure. All initial and boundary conditions, except the amount and the distribution of the soluble rock, remain the same for all scenarios. As a material example for the bedrock, we chose Gipskeuper from an aquifer along the Birs river in Switzerland. This rock consists of soluble gypsum layers and insoluble clays and marls, with typical layer thickness in the range of millimeters to centimeters. The basic processes discussed in the first part of the paper remain valid. We demonstrate that large insoluble zones can impair the karstification process and even completely block it, while areas with thin soluble layers can provide a preferential pathway and decrease the evolution times considerably. Finally we show that the evolution of the leakage rates and the head distribution within the aquifer can sometimes reveal misleading information about the stage of karstification and the safeness of the dam.

Our model can be used not only to study simplified geological settings and basic processes, but also to address some of the complications arising when modeling real aquifers.

1. Introduction

Aquifers located in terrains with soluble rocks exhibit a very inhomogeneous distribution of hydraulic conductivities. The bedrock is characterized by domains with relatively low porosity (0–20%) and hydraulic conductivity (10^{-6}–10^{-11} m/s) (Freeze and Cherry, 1979). These domains are separated by a system of fractures, which are the main pathway for the percolating water. Water is aggressive to limestone and gypsum rocks and is able to dissolve a certain amount of material along its way. Consequently the aperture widths of the fractures are effectively widened, allowing more aggressive solution to penetrate deeper into the aquifer and to increase the dissolution rates there. During the early phase of this *karstification* process a zone of considerably widened fractures is growing towards the outflow area of the aquifer, allowing a slow but steady increase of the amount of flow through. As soon as the widened channels reach the resurgence, the flow rate is increased by few orders of magnitude within a very short time. This *breakthrough* event is marking the end of the initial phase of the evolution (Dreybrodt, 1988). At that time, the outflow part of the aquifer is connected to the inflow side by a well-developed channel. The flow along the karstified area can become turbulent, supporting high dissolution rates. This is a typical scenario for early evolution of aquifers in soluble rocks.

The process of karstification has been intensively studied during the last 100 years and especially during the last quarter of the 20th century (Lowe, 2000; White, 2000; Ford and Williams, 2007). The theoretical and experimental studies published at that time allow us to better understand the flow distribution, the chemistry and the

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transport of the flowing solution, and the chemical reactions active in the aquifer (Klimchouk et al., 2000). The rapid development of numerical methods and computational power during this period enabled numerical modeling of the basic processes governing the karst evolution.

1.1. Modeling of karst aquifers evolution

The first modeling attempts are closely related to the scenario described above — studying the evolution of a channel in a block of soluble rock, typically limestone. The conduit is not exchanging solution with the porous domains along its pathway, and therefore all the water entering at the inflow has to leave at the outflow-1D models. The evolution of the dissolution rates along the fracture is determined by the hydraulic gradient, the calcium concentration at the entrance, the equilibrium concentration with respect to calcite and the dissolution rate law for limestone. The results describe some basic mechanisms governing the karst evolution and are a fundamental part of the knowledge required to create and interpret the more complex 2D and 3D models. The single conduit-1D models (Dreybrodt, 1990, 1992, 1996; Palmer, 1991; Gabrovsek, 2000; Dreybrodt and Gabrovsek, 2000; Kaufmann, 2002) ignore the fact that solution can be exchanged between fractures at the places where they cross each other (*exchange flow*). Therefore, the logical step further was to build complex more realistic 2D systems of channels and study their development (Groves and Howard, 1994a,b; Howard and Groves, 1995; Hanna and Rajaram, 1998; Siemers and Dreybrodt, 1998; Clemens et al., 1996, 1997a,b, 1999; Kaufmann and Braun, 1999, 2000; Gabrovsek et al., 2000; Gabrovsek and Dreybrodt, 2001; Romanov et al., 2002; Kaufmann, 2003a; Gabrovsek et al., 2004; Bauer et al., 2000, 2002, 2005; Dreybrodt et al., 2005; Kaufmann, 2005; Kaufmann and Romanov, 2008; Rehrl et al., 2008). These models resemble the reality much better. They show that the exchange flow is an important karstification process. It can affect the evolution times significantly, sometimes by orders of magnitude. It can also activate the *mixing corrosion* (Bögli, 1964; Gabrovsek and Dreybrodt, 2000; Kaufmann, 2003b; Romanov et al., 2003a; Gabrovsek and Dreybrodt, 2010) in areas where waters with different properties mix. Together with the two dimensional, there are also some well-developed three dimensional karst evolution models (Annable, 2003; Kaufmann, 2009). Their results confirm the basic principles revealed by the 1D and the 2D models.

Some of the models presented above have been compared by a common benchmark scenario and have shown very similar results (Romanov et al., 2002; Bauer et al., 2003; Kaufmann, 2003c; Kaufmann et al., 2010). This gives a confidence, that the models can be used not only to study the basic processes governing the evolution of highly idealized karst aquifers, but also to describe the development of real karst systems and become an integrated tool for many case studies.

Most of the studies so far have been concentrated mainly on the effects of the boundary conditions and some structural features on the evolution of aquifers. This is a very good way to reveal basic mechanisms and timescales for karst evolution, and the obtained results are generally valid. The problem is that these results still cannot be applied directly to any real karst aquifer. Local parameters such as distribution of hydraulic conductivities, rock types, blocked fractures, periodical variations in the boundary conditions, effects caused by human activities, are only part of the reasons that can give a preference of a certain process and/or impair others during the different periods of the evolution.

In this paper, we present an attempt to address some of the complications that arise when modeling real aquifers. Fig. 1 depicts a part of Gipskeuper from an aquifer along the Birs river in Switzerland (Epting et al., 2009a,b). The bright areas in the sample are gypsum layers and are soluble in water. The dark gray ones are clays and marls that are insoluble. The dimensions of this sample are 37 × 23 × 11 mm.

Fig. 1. Rectangular (37 × 23 × 11 mm) rock block, taken from a Gipskeuper horizon in an aquifer near the Birs river in Switzerland (Epting et al., 2009a,b). The white parts are few millimeters wide and are the only soluble (gypsum) parts of this sample.

A fracture going through a gypsum layer in this rock will not be able to widen more than the width of the gypsum layer — few millimeters, up to few centimeters. On the other hand, if the conduit is going through the clay then there will be no dissolution at all. Note, that all models discussed so far do not take into account such limitations. The conduits building their networks are allowed to widen until they merge with each other if they are crossing soluble rocks, or are insoluble during the whole evolution if they go through insoluble layers. Our first goal will be to build a model able to describe the evolution of a karst aquifer in a rock formation containing soluble layers with a limited thickness, similar to the sample depicted in Fig. 1.

The paper is structured in the following way: In the next part, we present a model that is a modification of one of the widely used 2D karst evolution models (Gabrovsek and Dreybrodt, 2001; Romanov, 2003; Dreybrodt et al., 2005). The modifications allow us to address local solubilities as the one discussed above. In order to reveal the effect on the evolution, we compare the karstification of an aquifer in a rock similar to the one from Fig. 1 and the same aquifer, with the same boundary conditions, but evolving in 100% soluble bedrock. After that, we turn our attention to the evolution of an aquifer close to a large hydraulic structure and discuss different aspects that have to be taken in account when modeling scenarios relevant to real aquifers.

2. Model description

The modeling approaches, discussed in the Introduction, use a conduit (rectangular or cylindrical) as a basic building element. When a solution aggressive to the soluble rock (limestone or gypsum) is flowing along the fracture, dissolution takes place and the aperture width (diameter) is increased. As already mentioned, we use a 2D karst evolution model. All details about this modeling approach have been published in the literature (Dreybrodt et al., 2005) and will not be discussed here. We will shortly go only through the main points. Fig. 2 depicts our modeling domain — a 2D horizontal cross-section of a soluble (gypsum or limestone) bedrock. There is a system of fine fractures (blue in the online/light gray in the printed version of the paper, area) and one prominent fracture (green/darker gray line) connecting the inflow and the outflow sides. The hydraulic conductivity of the domain depends on the fracture's aperture widths and the distance between them. The dark gray square depicts a magnified view of the network. Every fracture has a rectangular cross-section, connects two nodes, and is defined by its length L[cm], aperture width a[cm], and aperture height b[cm]. These parameters, together with all chemical properties of the rock, can be applied to every single conduit of the model, independently. The water is moved along the fissures by the head difference ΔH[cm] between the input (left hand side) and