Journal of Contaminant Hydrology 160 (2014) 42–52

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

On the effects of subsurface parameters on evaporite dissolution (Switzerland)

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ARTICLE INFO

Article history:
Received 20 October 2012
Received in revised form 20 February 2014
Accepted 26 February 2014
Available online 6 March 2014

Keywords:
Density driven flow
Discontinuous finite elements
MPFA
Subrosion
Tectonics
Switzerland

ABSTRACT

Uncontrolled subsurface evaporite dissolution could lead to hazards such as land subsidence. Observed subsidences in a study area of Northwestern Switzerland were mainly due to subsurface dissolution (subrosion) of evaporites such as halite and gypsum. A set of 2D density driven flow simulations were evaluated along 1000 m long and 150 m deep 2D cross sections within the study area that is characterized by tectonic horst and graben structures. The simulations were conducted to study the effect of the different subsurface parameters that could affect the dissolution process. The heterogeneity of normal faults and its impact on the dissolution of evaporites is studied by considering several permeable faults that include non-permeable areas. The mixed finite element method (MFE) is used to solve the flow equation, coupled with the multipoint flux approximation (MPFA) and the discontinuous Galerkin method (DG) to solve the diffusion and the advection parts of the transport equation.
Results show that the number of faults above the lower aquifer that contains the salt layer is considered as the most important factor that affects the dissolution compared to the other investigated parameters of thickness of the zone above the halite formation, a dynamic conductivity of the lower aquifer, and varying boundary conditions in the upper aquifer.

1. Introduction

The importance of density driven flow arises due to its significant role in water resources management and engineering (Oude Essink, 2001a,b; Paniconi et al., 2001, and Xue et al., 1995). Simulation of saltwater transport models becomes a real need due to the large number of environmental problems such as intrusion of saltwater in coastal aquifers, landfills leakage, collapse of abandoned salt mines, radioactive waste disposal in salt rock formations and subsurface dissolution of evaporites (Ludwig et al., 2001; Luo et al., 2012; Magri et al., 2011; Oude Essink, 2001a,b). Subsurface dissolution or subrosion occurs when non-saturated groundwater gets in contact with evaporitic rock formations. When carbonate rocks develop cavities over centuries, evaporite rocks can form cavities within days. Therefore, gypsum or rock salt is seen as the most soluble common rock formation (Martinez et al., 1998). The subsurface karst development can create additional groundwater pathways. As a consequence, additional mobilization of the dissolved rock salt solutes can lead to widespread salinization of aquifers. The dissolution of gypsum and/or rock salt could lead to land subsidence. Even comparably small subsidence rates can have an important effect on sensitive urban infrastructures (e.g. dams, buildings, traffic lines, power plants). The dissolution of salt is directly related to the concentration gradient between the mineral salt layer and the bulk water. Groundwater flow in karst aquifers is controlled by several processes. A crucial one is the dissolution kinetics that results in karst void, or rapid fracture enlargement within an aquifer and depends on the saturation level of NaCl. Zechner et al. (2011) studies three possible causes for the observed land subsidence in northwestern Switzerland: (1) natural dissolution of the evaporites of the

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http://dx.doi.org/10.1016/j.jconhyd.2014.02.006
0169-7722/

Middle Muschelkalk (anhydrite and halite), which is related to the tectonic setting of the evaporitic formations within a set of horst and graben structures, (2) salt solution mining, which has been pursued at different locations over the last 150 years and (3) large scale extraction of groundwater in an overlying fissured aquifer with hydraulic connection to the underlying evaporites along fault zones with increased hydraulic conductivity. The authors (Zechner et al., 2011) showed that the most sensitive factor for the dissolution rate is the structure, or dip of the halite formation, which leads to an increase of dissolution rates with increasing dips and that the upcoming process of saline groundwater into the main aquifer occurs under different distributions of subsurface parameters and hydraulic boundary conditions. The authors (Zechner et al., 2011) however considered a well-established homogenous karst with a constant thickness of 10 m on top of the salt layer and do not take into account the process of evaporitic karst evolution.

Previous field investigations (e.g. Ludwig et al., 2001) have shown the importance of hydrological heterogeneities at various scales on density-driven transport. Luo et al. (2012) presented a 2D and 3D modeling study to describe the impact of different engineering solutions and appropriate remedial strategies for an abandoned, flooded deep salt mine in Stassfurt, Germany. Luo et al. (2012) found that the hydrogeological structure in the study area played a significant role in development of the subsurface concentration distribution. Due to the typical lack of knowledge about the hydrogeological structure and properties in field studies, different approaches to study the effect of heterogeneity within the simulations were used. To our knowledge, very few studies have investigated the hydraulic role of subvertical fault zones on the subrosion (subsurface dissolution) process. In addition Magri et al. (2011) studied possible explanations for seawater intrusion in the Seferihisar–Balcova Geothermal system in Turkey. They found, based on data acquisitions and numerical simulations, that groundwater flow and coupled hydrochemical and hydrothermal patterns are strongly controlled by fault tectonics.

In the presented work we investigate the role of varying parameters such as aquifer geometry and transient conductivity on the rate of salt dissolution. The study is conducted on a 2D cross section of 1000 m long and 150 m deep. The effects of density and viscosity due to the salt dissolution are considered to couple the flow-transport numerical model. The effect of gravity is also included in the numerical model. The numerical simulations were run on a 2 GHZ PC with 2 GB-RAM. Aside from the novelty of the presented study, there is an important added feature presented in this work, which is the numerical model that is solved on unstructured mesh and in anisotropic domain. This feature is an introductory account to extend the study to model 3D reactive-naturally fractured reservoir (R-NFR) that is playing a major role today in the oil industry (e.g. oil extraction, CO_2 injection in NFRs, and R-NFRs). The study includes (1) variations of thicknesses of the karst aquifer on top of the salt, (2) a dynamic conductivity of the karst aquifer on top of the salt modified after (Kaufmann, 2002) that relates the hydraulic permeability to the amount of dissolved salt, (3) variations of the imposed hydraulic boundary conditions such as the value of the hydraulic gradient at the right side boundary (ESE), or the depth of the pumping well at the left side (WNW) of the domain (Fig. 2a) and (4) the geometry and the number of normal faults and their effect on the salt dissolution process; in particular, two approaches are studied, the variable width and the heterogeneity of normal faults above the lower aquifer. In the first approach the effect of different fault widths on the dissolution process is studied, whereas in the second approach the single fault is replaced by several thin faults separated by impermeable areas.

2. Model concept

The study site for the 2D simulations is located in northwestern Switzerland to the east of the southeastern border of the Upper Rhine Graben and is part of the Tabular Jura (Fig. 1). Land subsidence has been observed at six different locations, and monitored subsidence rates reached more than 100 mm/year, affecting area ranges from 100 to 1500 m. The study area is underlain by Triassic and Jurassic strata, which slightly dip to the southeast. The subsidence is mainly caused by subsurface dissolution of halite (rock salt), and partly by dissolution of overlaying anhydrite/gypsum formations of the Middle Muschelkalk. Fracture zones causing increased permeability within the Jurassic and Triassic formations are supposed to favor vertical exchange of groundwater also across aquitards.

Existing 3D regional geological and the groundwater models (Spottke et al., 2005) were used to define structural and hydraulical boundary conditions for an approximately 1000 m long and 150 m deep 2D cross section, where a series of 2D density-coupled solute-transport simulations were conducted to study the effect of different parameters on the salt dissolution process. In the following we present a simple but basic description of the adopted model in this study. The model is divided into four different zones. The zones are the upper aquifer, the lower aquifer and two normal faults (Fig. 2a). The normal faults act as the connecting channels between the upper aquifer and the lower aquifer. The permanent regime of the simulation is established under the mere assumption that the dissolution process stops whenever the bulk water in the lower aquifer is completely saturated with salt and it cannot by pumped out to the upper aquifer due to the high density contrast (of water) between the upper aquifer and the lower aquifer.

The simulated piezometric head distribution within the upper aquifer shows the effect of the large-scale industrial pumping in the central part of the model (up to 1.5 m^3/s), where the piezometric head is lowered up to 5 m (Fig. 1). Due to the hydraulic head imposed at the ESE boundary, freshwater invades the domain at the upper aquifer, where it flows from WNW to ESE within the lower aquifer affected by the gravitational forces (Fig. 2b). The freshwater and saltwater mixture is extracted by the pumping well at the WNW side of the upper aquifer.

3. Numerical model

Modeling density driven flow problems requires a nonlinear coupling between flow and transport equations. This nonlinearity is due to the density-viscosity linking between Darcy's flow and the advection dispersion equation. The strong nonlinearity between flow and transport can typically lead to long CPU times. The 2D simulations are conducted using a