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Surface–groundwater interactions in hard rocks in Sardon Catchment of western Spain: An integrated modeling approach

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SUMMARY

The structural and hydrological complexity of hard rock systems (HRSs) affects dynamics of surface–groundwater interactions. These complexities are not well described or understood by hydrogeologists because simplified analyses typically are used to study HRSs. A transient, integrated hydrologic model (IHM) GSFLOW (Groundwater and Surface water FLOW) was calibrated and post-audited using 18 years of daily groundwater head and stream discharge data to evaluate the surface–groundwater interactions in semi-arid, ~80 km^2 granitic Sardon hilly catchment in Spain characterized by shallow water table conditions, relatively low storage, dense drainage networks and frequent, high intensity rainfall. The following hydrological observations for the Sardon Catchment, and more generally for HRSs were made: (i) significant bi-directional vertical flows occur between surface water and groundwater throughout the HRSs; (ii) relatively large groundwater recharge represents 16% of precipitation (P, 562 mm·y^{-1}) and large groundwater exfiltration (~11% of P) results in short groundwater flow paths due to a dense network of streams, low permeability and hilly topographic relief; deep, long groundwater flow paths constitute a smaller component of the water budget (~1% of P); quite high groundwater evapotranspiration (~5% of P and ~7% of total evapotranspiration); low permeability and shallow soils are the main reasons for relatively large components of Hortonian flow and interflow (15% and 11% of P, respectively); (iii) the majority of drainage from the catchment leaves as surface water; (iv) declining 18 years trend (4.44 mm·y^{-1}) of groundwater storage; and (v) large spatio-temporal variability of water fluxes. This IHM study of HRSs provides greater understanding of these relatively unknown hydrologic systems that are widespread throughout the world and are important for water resources in many regions.

1. Introduction

Hard rock systems (HRSs) widely occur in various parts of the world and cover about 20% of the land surface (Singhal, 2008). HRSs are known to be quite modest in groundwater productivity because of relatively low permeability and storage. However, because HRSs are wide spread, they provide an important source of water for humans and groundwater dependent ecosystems (Singhal and Gupta, 2010). Hard rock geology can broadly be described as consisting of weathered unconsolidated rocks near surface, and transitioning to fractured rocks underlain by massive non-fractured rock. Subsurface structure in HRSs is typically affected by local and regional tectonics resulting in faults, dykes, and other discontinuities, as well as lithological changes. Hydrogeology of hard rocks is highly heterogeneous in the horizontal and in the vertical directions, creating large contrasts in hydraulic properties that make it difficult to characterize and simulate the flow of groundwater in these systems.

The dynamics of surface–groundwater interactions in HRSs is largely unknown and these interactions generally have not been well described as HRSs are structurally complex, affected by preferential flow along faults and fractures and by interactions with surface water. In HRSs, there is a large amount of uncertainty in the partitioning of precipitation into evapotranspiration, runoff, and net groundwater recharge. Furthermore, there is evidence that in HRSs, there is large variability in groundwater residence times, including local and regional groundwater flow paths that discharge groundwater to the surface and support groundwater dependent ecosystems (Huntington and Niswonger, 2012). Groundwater discharge that occurs in close proximity to recharge areas of the upland HRSs makes it difficult to discern groundwater recharge that contributes to aquifer storage versus recharge that very quickly discharges back to surface and becomes runoff. Where

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recharge and discharge occur in close proximity (i.e., short groundwater flow paths), the concept of net recharge is important and better reflects changes in groundwater storage as compared to simply using recharge, as is done in many conventional groundwater resource assessments following the work of Tóth (1963). Therefore, in HRSs, it is particularly important to simulate the recharge and discharge processes using integrated hydrologic models (IHMs) that internally integrate surface and groundwater exchange processes rather than calculating recharge externally applying it as a boundary condition in a groundwater model. Accordingly, IHMs are useful for assessing water resources in HRSs because they are able to simultaneously simulate evapotranspiration, runoff, recharge, and discharge using precipitation, temperature and boundary conditions. Besides, they provide a better estimate of groundwater storage, streamflow, and the effects of climate on water resources than standard groundwater models (Hunt et al., 2013; Surfleet and Tullos, 2013a,b; Surfleet et al., 2012).

IHMs can be divided into two groups depending on the governing equations used for simulating saturated and unsaturated flow, including: (1) models based on Richards' equation (Richards, 1931) such as Hydrogeosphere (Therrien et al., 2006), CATHY (Weill et al., 2011), MODHSM (Panday and Huyakorn, 2004); and PARFLOW (Maxwell et al., 2009); and (2) models relying on simpler equations, such as GSFLOW (Groundwater and Surface water FLOW, Markstrom et al. (2008)) used in this study, where vertical unsaturated flow is simulated using a kinematic wave (KW) equation and lateral unsaturated flow is neglected beneath the soil zone (Charbeneau, 1984; Chen et al., 1994; Colbeck, 1972; Harter and Hopmans, 2004; Mantoglou, 1992; Niswonger and Prudic, 2004; Smith, 1983; Smith and Hebbert, 1983). The KW equation assumes that unsaturated flow occurs in response to gravity potential gradients only, ignoring negative potential gradients. The KW equation was implemented in the UZF1 package (Niswonger et al., 2006) for MODFLOW-2005 and its variant called MODFLOW-NWT (Niswonger et al., 2011) along with PRMS (Precipitation Runoff Modeling System, Leavesley et al. (1983)) forms GSFLOW. A simpler representation of unsaturated flow is used in GSFLOW because Richards' equation is highly nonlinear, so its solutions are computationally demanding and require fine spatial and temporal discretization (Downer and Ogden, 2004; Sheikh et al., 2009; Vogel and Ippisch, 2008). At the catchment scale simpler equations for unsaturated flow, such as used within the UZF1 package, are advantageous for modeling as the errors introduced by averaging or upscaling soil hydraulic parameters for regional scale models makes the KW and Richards' equations comparable in accuracy, while the KW equation requires less input data and much less computations (Bailey et al., 2012; Morway et al., 2013).

GSFLOW has already been applied in several basins around the world, to simulate hydrological processes of surface–groundwater interactions, climate change impact assessment and other applications (e.g., Hunt et al., 2013; Surfleet and Tullos, 2013a,b; Surfleet et al., 2012; Yimam, 2010); it has also been applied in hard rocks by Ely and Kahle (2012) and Huntington and Niswonger (2012). However, to our knowledge, neither GSFLOW nor any other integrated HRSs modeling study did transient model calibration of groundwater heads along with streamflows over long-time calibration period required to analyze dynamics of HRSs drainage processes as in this study. A more complete understanding of that dynamics is needed to assess surface-groundwater interactions in HRSs and water resources susceptibility to changes of climatic conditions.

Conceptualizing and modeling HRSs is challenging because of geologic heterogeneity and uncertainty in permeability associated with bedrock fracturing, weathering and tectonic processes (Sánchez-Vila et al., 1996). Different models can be conceptualized for HRSs, e.g., dual porosity models (e.g., Barenblatt et al., 1960; Gringarten, 1982; Streltsova-Adams, 1978), discrete fracture network (DFN) models (e.g., Lee and Farmer, 1993; Long et al., 1982), parallel plate models (e.g., Bear, 1993; Lee and Farmer, 1993), and equivalent porous medium (EPM) models (e.g., McDonald and Harbaugh, 1984). The EPM concept, applied in this study, assumes that by averaging highly fractured and interconnected rocks over a large volume, the average flow resembles flow through a porous medium with equivalent, statistically distributed hydraulic parameters represented in the groundwater flow equation. The EPM models are an attractive option for catchment scale modeling because they require much less data input and computational resources than DFN models. Generally, the EPM models are applicable if: (a) fractures are dense and interconnected within the representative elementary volume (REV) corresponding with model grid size, (b) apertures are constant rather than varying, (c) orientations are distributed rather than constant, (d) sufficiently large volumes dependent on the grid size are considered (Long et al., 1982), and (e) the interest is mainly on volumetric flow, such as for groundwater supplies (Singhal and Gupta, 2010).

Hard rock hydrogeology research proposed in this study has two main objectives: (1) to improve understanding of the dynamics of surface–groundwater interactions in HRSs with emphasis on drainage processes; and (2) to provide long-term integrated, quantitative water balance in a hard rock catchment. In this study, we addressed these objectives applying a transient IHM of the Sardon Catchment in Spain using GSFLOW. We selected GSFLOW because: (i) it is integrated, multi-compartment, hydrologic-flow model that dynamically integrates surface, unsaturated, and saturated zones; (ii) it is a MODFLOW based model, so it is comparable to many other groundwater modeling studies, including a former study in the same Sardon Catchment by Lubczynski and Gurwin (2005); (iii) it relies on a simplified equation for simulating unsaturated flow, and therefore, it is less data and computationally demanding and more suitable for regional applications (such as the Sardon Catchment) than Richards' equation based models; and (iv) it is a public domain code with very good documentation and support. We selected the Sardon Catchment in Spain as a test site because: (i) it is representative of similar HRSs around the world, i.e., consists predominantly of weathered and fractured aquifers with generally low storage and low to medium permeability; (ii) it has minimal human impact because of very low population and water supply in the catchment from the artificial Lake Almendra located outside the catchment; (iii) there is monitoring network with 18 years of hydrologic data available; and (iv) a de-coupled groundwater modeling study of the same Sardon Catchment was done by Lubczynski and Gurwin (2005) that can be used for comparison to evaluate the differences of using a IHM and a non-IHM approaches.

2. Methods

2.1. Study area and conceptual model

The Sardon Catchment is located in the central-western Spain about 40 km to the west of Salamanca city (Fig. 1). It has a hilly landscape and is mainly composed of weathered and fractured granites. Its altitude varies from 860 m above sea level (a.s.l.) at the southern catchment boundary to 733 m a.s.l. at the Sardon River outlet at the northern boundary. The topographic boundaries of the Sardon Catchment are marked by locally outcropping and shallow sub-cropping massive non-fractured rocks composed of granites and impermeable schists at the southern, western, and northern boundaries and quartzite intrusion in granite along the eastern boundary. The upland boundary areas are relatively flat Tertiary planations in contrast to the central lowland areas, characterized by steeper slopes due to the incision of the centrally located Sardon River and its tributaries (Fig. 1).