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Groundwater balance estimation in karst by using a conceptual rainfall–runoff model

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SUMMARY

A conceptual rainfall–runoff model is proposed for the estimation of groundwater balance components including the influences of time-variant catchment boundaries and intercatchment groundwater flows. Karst underground is considered as a lumped system that contains: (1) soil cover, (2) epikarst zone and (3) vadose and phreatic zones. The soil cover receives an average rainfall in catchment as the input into the system. The epikarst zone is composed of a production store and a routing store. The production store contributes to the loss of water in process of evapotranspiration. The routing store contributes to the retention of percolated water and the lateral distribution of groundwater recharge between internal runoff and diffuse infiltration. The vadose and phreatic zones accumulate groundwater in fissures, fractures and vertical shafts, and produce the vadose seepage, vadose flow and shaft flow components of the karst spring discharge. The parameter estimation and calculation procedure assemble the moisture balance and the groundwater-balance approaches. The rainfall–runoff model is divided in two sub-models. The sub-model based on the moisture balance of soil cover and epikarst production store calculates effective rainfalls. The sub-model based on the groundwater balance of vadose and phreatic zone calculates groundwater recharges. The difference between the effective rainfalls and the groundwater recharges represents the contribution of epikarst zone and non-conservative and time-variant components to the groundwater balance. The proposed methodology is applied to the Jadro Spring located near the city of Split in Croatia. The calculated groundwater balance shows that the Jadro Spring aquifer contains a significant storage capacity in the vadose and phreatic zones. During the year, the aquifer may accumulate up to 140 millions m^3. The variability of calculated catchment area is explained with the time-variant catchment boundary dependent on groundwater levels and the intercatchment groundwater flows from neighboring catchments. The average catchment area of 396 km^2 is estimated by using the average monthly effective rainfalls and the average monthly groundwater recharges.

Introduction

Hydrogeologic and hydrologic characteristics of karst are complex and significantly different from the characteristics of granular media. Underground structures of pores, fissures, fractures and conduits of various size and forms create complex hydrogeologic conditions for groundwater flow. Vertical schematizations of the karst underground usually distinguish four zones (Bonacci, 1987; White, 2002): (1) soil cover, (2) epikarst or subcutaneous zone, (3) vadose or unsaturated zone and (4) phreatic or saturated zone. In addition to the vertical flow, the soil cover and epikarst zone play also a role in the generation of overland flows as well as the underground lateral flow components that precede the process of vertical sinking of water through the vadose zone. The importance of this role depends upon the intensity of precipitation, infiltration capacity and development of karst processes. The main characteristics of the epikarst zone are a substantial storage capacity and a high permeability (Perrin et al., 2003a,b; Aquilina et al., 2006). After precipitation, a part of the water is rapidly transferred through the zone, but the rest of it remains in the zone and subsequently slowly percolates or evaporates. Consequently, the epikarst zone plays dual role: it can be considered as constitutive part of the vadose zone in the groundwater-balance calculations and, at the same time, it contributes to the loss of moisture in process of evapotranspiration. The role of the epikarst zone in the loss of moisture depends on the thickness of soil cover. The role is more important in the bare karst area where the epikarst zone is uncovered. The process of groundwater transmission through the vadose zone can be divided into three components (Bonacci, 1987): (1) shaft flow through the natural and predominantly vertical shafts as a thin film of water flowing along their walls, (2) vadose flow or the flow through the enlarged joints and fractures of the vadose zone with a predominantly vertical direction and (3) vadose

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seepage or very slow sinking through the smallest karst joints and fissures. These three components represent the input mechanism of the phreatic zone, which is characterized primarily as the area of horizontal water circulation toward the network of underground channels that transport water finally to karst springs.

Groundwater recharge represents the portion of total rainfall falling into a drainage basin that reaches firstly the vadose zone and finally the phreatic zone. There are two basic groundwater recharge types in karst terrains: autogenic and allogenic (Lerch et al., 2005). The autogenic recharge can be further separated into a diffuse recharge (entering the aquifer through the soil and fractures and fissures on the karst surface) and a discrete recharge or internal runoff (entering the aquifer quickly through the sinkhole drains). The allogenic recharge to karst aquifers occurs where the surface runoff draining large areas of insoluble rock or low permeability soils flows directly to the adjacent soluble carbonate bedrock. Depending on available data, the groundwater recharge in karst can be estimated with a simple water-balance method using precipitation and actual evapotranspiration, or with more complex and data demanding hydrological models (e.g. Soulios, 1984; Contractor and Jenson, 2000; Bonacci, 2001; Jocson et al., 2002; Petrič, 2002; Jukić and Denić-Jukić, 2004; Geyer et al., 2008). A fluid-mass-balance calculation is a common characteristic of all these methods and models. The fluid-mass-balance can be calculated for the entire karst underground or separately for the soil cover (soil-moisture-balance approach) and the vadose and phreatic zone (groundwater-balance approach). The soil-moisture-balance approach assumes that the initial precipitation left after evapotranspiration is taken up as soil moisture and when the soil is saturated (soil-moisture-holding capacity filled) water begins to form the surface runoff and the percolation through the lower zones. The groundwater-balance approach is generally based on the mass conservation equation of the vadose and phreatic zone, i.e. the recharge for analyzed period is equal to the accumulated groundwater in these zones plus the total discharge.

Regardless of the selected approach, due to the complexity of hydrologic and hydrogeologic characteristics and unavailability or limitation of groundwater monitoring data, conceptual or black-box models are usually applied in order to simulate the process of water transport through the karst underground. The conceptual models are based on very simplified physical interpretations of the process of transforming input into output (White, 2002), usually taking into account separately the effects of different recharge sources (e.g. allogenic recharge, internal runoff and diffuse infiltration), permeability (e.g. fissures, fractures and conduits) and discharge sources (e.g. one or several springs). Series of linear or nonlinear reservoirs are applied for the mathematical description of the role of different karst aquifer zones in the generation of karst spring discharge (e.g. Halihan and Wicks, 1998; Fleury et al., 2007; Padilla and Pulido-Bosch, 2008; Le Moine et al., 2008). Among the black-box models, Rainfall–Runoff (RR) models based on the convolution integral have an important role. Linear or nonlinear forms of the convolution integral can be applied (e.g. Dreiss, 1982, 1983; Labat et al., 1999, 2000; Long and Derickson, 1999; Pinault et al., 2001; Denić-Jukić and Jukić, 2003; Jukić and Denić-Jukić, 2006). The solution of the linear form is the transfer function representing the unit response function of the karst aquifer.

Karst catchments are characterized with the time-variant boundaries that are dependent on fluctuations of groundwater levels. Only in exceptional cases do the topographic and subsurface watershed lines coincide and only in those places where the boundaries between catchments are located in impermeable rocks. In addition, groundwater exchanges with adjacent catchments through underground piracy routes are common in karst. The resulting leaking/gaining flows named Intercatchment Groundwater Flows (IGF) undermine the determination of groundwater-balance for karst aquifers. Consequently, the karst aquifers express seemingly a non-conservative behavior that is still unsolved problem for RR modeling (Le Moine et al., 2008). The estimation of catchment area for a non-conservative catchment is very difficult because the influences of different non-conservative and time-variant factors are hidden in the value of catchment area calculated by water balance, especially if a short time period is analyzed. Le Moine et al. (2007) give a review of solutions that may numerically account non-conservative behaviors in a RR model. The results of practical application to a karst spring are presented in the case study Le Moine et al. (2008), where an empirical function from GR4 J model (Perrin et al., 2003a,b) is applied for the estimation of daily IGF. This paper proposes a conceptual RR model for the estimation of groundwater balance components and the identification, quantification and characterization of the contributions of time-variant catchment boundaries and IGF. The proposed model uses the meteorological and spring discharge monitoring data. The mathematical background and parameter estimation procedure is based on the theories of linear and nonlinear reservoirs (e.g. Singh, 1988) (Appendix A) and Composite Transfer Functions (CTF) (Denić-Jukić and Jukić, 2003) (Appendix B). Gauss–Newton and Levenberg–Marquardt optimization algorithms (Levenberg, 1944; Marquardt, 1963) are used for the determination of optimal values of parameters. The model is applied on the Jadro Spring located near the city of Split in Croatia (Fig. 1).

Study site and data

The Jadro Spring catchment is situated in the Dinaric karst mainly formed of carbonate rocks and partly of impermeable flysch. Except the several small karst fields, the catchment area is practically without soil cover and with poor vegetation. Groundwater system is well developed in limestone and dolomites. There is no reliable hydrological delineation of the catchment area. The results of investigations show significant variations of the calculated catchment area by using water balance methods (e.g. Bonacci, 1987; Denić-Jukić and Jukić, 2003). The north boundary of the catchment is presented with complete hydrogeologic barrier northern from the Mućko polje. The tracer tests of the ponor Jablan located near the town Muć (Fig. 1) revealed fast connection between this area and the Jadro Spring. The injected tracer appeared also at the neighboring smaller spring Žrnovnica. The catchment boundary on the west is not well determined, i.e. it is determined on the basis of less important hydrogeologic indicators and in fact presents a hypothetical delineation. The tracer tests of the ponor Postinje show that the western part of the Mućko polje is shared with adjacent catchments. The southern boundary is the coastal barrier formed on the contact between permeable rocks of hinterland and impermeable rocks of the coastal area. The outlet of the Jadro Spring is situated in the lowest part of this contact area at the elevation of 35 m a.s.l. The eastern boundary of the catchment is situated in the area of complex hydrogeology. The assumed eastern limit is near the perennial Cetina River flowing through a carbonate formation at elevations above 272 m a.s.l. The tracer tests of the ponor Grabov Mlin located near the Cetina River riverbed that were performed in 1963 revealed the direct connection between the Cetina River and the Jadro Spring (Bonacci, 1987). About 96% of the injected tracer appeared at the spring 23 days after the tracer had been injected into the ponor, which indicates the existence of IGF from the neighboring catchment of the Cetina River. This IGF is explained with the location of the spring. Namely, the Jadro Spring is located at the elevation of 35 m a.s.l., whereas the catchment of the spring and the neighboring Cetina River are situated at the