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Research papers

Water exchange, mixing and transient storage between a saturated karstic conduit and the surrounding aquifer: Groundwater flow modeling and inputs from stable water isotopes

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ABSTRACT

Water exchanges between a karstic conduit and the surrounding aquifer are driven by hydraulic head gradient at the interface between these two domains. The case-study presented in this paper investigates the impact of the geometry and interface conditions around a conduit on the spatial distribution of these exchanges. Isotopic ($\delta^{18}O$ and δD), discharge and water head measurements were conducted at the resurgences of a karst system with a strong allogenic recharge component (Val d'Orléans, France), to estimate the amounts of water exchanged and the mixings between a saturated karstic conduit and the surrounding aquifer. The spatio-temporal variability of the observed exchanges was explored using a 2D coupled continuum-conduit flow model under saturated conditions (Feflow®).

The inputs from the water heads and stable water isotopes in the groundwater flow model suggest that the amounts of water flowing from the aquifer are significant if the conduit flow discharges are less than the conduit flow capacity. This condition creates a spatial distribution of exchanges from upstream where the aquifer feeds the conduit (recharge area) to downstream where the conduit reaches its maximum discharge capacity and can feed the aquifer (discharge area). In the intermediate transport zone no exchange between the two domains takes place that brings a new criterion to delineate the vulnerable zones to surface water.

On average, 4% of the water comes from the local recharge, 80% is recent river water and 16% is old river water. During the November 2008 flood, both isotopic signatures and model suggest that exchanges fluctuate around this steady state, limited when the river water level increases and intensified when the river water level decreases. The existence of old water from the river suggests a transient storage at the aquifer/conduit interface that can be considered as an underground hyporheic zone.

1. Introduction: Water exchanges between a karst conduit and the surrounding aquifer

Water from karstic aquifers is largely used for water supply. In these systems the quantity and quality of outflowing water are highly variable, changing with time following the climatic conditions on the watershed (White, 1999). To help water supply managers, it is fundamental to understand the mechanisms that drive these temporal changes in water quality.

The main known reason for these water quality changes is the huge range of water velocities observed in karst systems. The water flows in three types of porosity: inter-granular porosity within the rock matrix, small aperture fracture porosity, and large cavernous conduit porosity (White, 1999). The matrix porosity and the small fracture porosity around the conduit can be subsumed under the term of aquifer porosity. If the conduits are connected to the surface, the system will be highly vulnerable to the River water dynamics, Intensifying the surface water-groundwater interactions (Sophocleous, 2002).

As these porosities are connected, water can flow from one to the other, causing exchanges or pulses of water that affect the quality of water at the outlet of the karst system. In the literature, existing approaches are conducted at the global scale (Grasso et al., 2003; Butscher and Huggenberger, 2008; Hartmann et al., 2013) with varying degrees of process representation of the matrix/conduit exchanges. These exchanges are explained hydrodynamically

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by time changes in water pressure in the conduit that create pressure and mass transfer to/from the aquifer. Bailly-Comte et al. (2010) used mathematical models of karst resurgence recession to show that karst resurgence hydrographs can be interpreted according to pressure transfer between two distinct porosities within the aquifer, conduit and aquifer porosity, which induce two distinct responses at the resurgence. Water exchanges between conduits and aquifer porosity are governed by hydraulic head differences between conduits and matrix, head gradients within conduits, and the permeability difference between conduits and the aquifer (Kovács et al., 2005). If the hydraulic head changes over time are the only driver, it follows that the exchanges must take place under saturated conditions and that the intensity of the exchanges decreases to zero when the system tends to a steady state pressure condition (Bailly-Comte et al., 2010). The water exchange is considered as a transient process.

The use of stable water isotopes has enriched groundwater conceptual models and has evidenced the physical phenomena taking place in karst systems, such as the differentiation of the catchment areas of the main springs (Andreo et al., 2004), the importance of the recharge elevation gradient (Binet et al., 2006), or the existence of water storage in the epikarstic zone (Lee and Krothe, 2001; Perrin et al., 2003). In their examination of water mixing deduced by water chemistry at the spring, Charmoille et al. (2009) observed that the regional hydraulic gradient and the mixing of water estimated by hydrochemistry could differ, suggesting dynamic local flows in the opposite direction to the regional hydraulic gradient. This suggests that the amount of water exchanged, estimated at the regional scale, may differ from the amount of water mixed between the two kinds of porosities. The use of stable water isotopes or water chemistry in hydrological studies improves the conceptual models of groundwater surface water interactions (Charlier et al., 2010; Doctor et al., 2006; Marfia et al., 2004), making it possible to estimate the relative proportions of the conduit, intermediate, and diffuse flow components (Long and Putnam, 2004). More generally, mixing models from hydrochemistry analysis suggest that in these karst systems 75% of the water can come from the aquifer (Martin et al., 2003). These mixings take place throughout the year and are significant even if the system tends to a pseudo hydrodynamic steady state in low water periods.

Thus, if the exchanges are driven by pressure transfer, which local conditions (geometric or intrinsic to the karst properties) could induce a steady state pressure disequilibrium between a conduit and the aquifer?

Analysis of the driving mechanisms of water exchanges using coupled models (groundwater flow and transport) is rarely carried out in karst systems because it is very difficult to make the correct assumptions to describe their complexity. This approach is only possible with models that have a high degree of process representation and a high spatial resolution. However, in recent years, the coupled continuum-conduit flow model has enabled the identification of mechanisms that control karst flow. Jeannin (2001) demonstrated the feasibility of using this kind of model to describe actual karst systems. Reimann et al. (2011) provided theoretical evidence of the significance of turbulent flows in the conduit on the exchanges between conduits and the aquifer, and introduced the notion of conduit flow capacity. Depending on the amount of water collected by the conduit compared to its overall flow capacity, a hydraulic gradient at the interface between the conduit and matrix can be determined and will drive the direction and the intensity of the exchanges.

The divergence between exchanges and mixing led the above-mentioned authors to consider this interface as a hyporheic zone, defined as an area where water infiltrates from the conduit into the aquifer and returns to the conduit after relatively short pathways. The hyporheic zone was first evidenced using water isotopes between Rivers and Alluvium (Mengis et al., 1999). This raises the possibility of transient storage in the aquifer (Gooseff et al., 2003), showing the existence of water with residence times bounded between conduit and aquifer residence times. The existence of this zone was evidenced by modeling (Cardenas et al., 2008) and by a laboratory analog study (Wu and Hunkeler, 2013) but little evidence from a saturated karstic conduit itself has yet been provided.

To study the conditions controlling the exchanges between a conduit and the aquifer, and their spatial significance and relative variability from recharge to discharge areas, we observed a karstic system connected to a sinking river. This paper describes the water exchanges observed in an allogenic karst, the Val d'Orléans aquifer, deduced from stable water isotope signatures and a coupled continuum-conduit flow model calibrated from water head measurements.

In the proposed model, particular attention was paid to the spatial variability of these exchanges, from recharge point to discharge area. The role of the conduit interfaces, pressure transfer and karst geometry on the exchanged water was explored by validating groundwater model with stable water isotopes. Analysis of the November 2008 flood event evidenced the existence of transient storage in this karst system.

2. Study area: hydrogeology

The Val d'Orléans is a vast depression in the Loire River main flow, 37 km long and from 4 to 7 km wide (Fig. 1).

The karst aquifer is hosted within a carbonate lacustrine deposit called the Beauce limestone with a high porosity overlain by the Quaternary alluvia of the Loire River. In some places, a clay layer is interbedded, creating a confined area in the limestones. This geological setting creates a multi-layered aquifer system with significant flux between the alluvia and the limestones (Lepiller, 2006). The Loire River feeds more than 80% of the water hosted in the carbonate karst aquifer (11 m^3/s during low water periods) (Martin et al., 2003). The groundwater flows from the city of Jargeau where the Loire River sinks providing significant recharge to the groundwater system. Water outflows toward several resurgences of the Loiret River (e.g. the Bouillon) through the karst networks (Fig. 1) (Lepiller, 2006). The Bouillon is the main resurgence of the river water infiltrated from the Loire River (from 0.1 to 5 m^3/s). The complexity of the system is highlighted by backflooding phenomena (Albéric, 2004), whose frequency of occurrence varies with time (Joigneaux et al., 2011). Backflooding suggests that surface water and groundwater heads are close to the equilibrium, and the direction of the hydraulic gradient between surface and groundwater can be inversed.

Conduit flows of the Val d'Orléans karst system were characterized with 10 dye tracer tests conducted between the recharge points S1 or S2 and the outlet resurgences (Fig. 1). Using a straight line distance between input and output points, the flow velocity was found to range between 0.030 and 0.045 m/s for hydraulic gradients between 0.13‰ and 0.32‰ inside the conduit respectively. The average of the 10 tests gave a velocity of about 0.037 m/s for a hydraulic gradient of about 0.2‰ (Joodi et al., 2010).

The flow converges from S1 and S2 toward the Bouillon resurgence and the average water residence time is about 100 h and 45 h respectively, suggesting an average residence time of the water in the conduit of about 89 h (about 3.5 days). Downstream tracers diverge as evidenced by the number of resurgence points observed along the Loire River.

The mixing between local aquifer and regional (Loire) flows was documented using hydrochemical analysis (Le Borgne et al., 2005). The water balance showed that 15% of the water flows from the aquifer (Gutierrez and Binet, 2010). Based on chloride mass bal-