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Focused groundwater flow in a carbonate aquifer in a semi-arid environment

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SUMMARY

An efficient conveyance system for groundwater is shown to have formed in a carbonate aquifer even though it is situated in a semi-arid environment. This conveyance system comprises preferential flow pathways that developed coincident with river channels. A strong correlation between high capacity wells and proximity to higher-order river channels (i.e., within 2.5 km) is used as evidence of preferential flow pathways. Factors that contributed to development of the preferential flow paths: (i) karst development in carbonate rocks, (ii) structural exhumation of a carbonate plateau, and (iii) the requirement that the groundwater regime of the watershed has adequate capacity to convey sufficient quantities of water at the required rates across the full extent of the watershed. Recognition of these preferential pathways in proximity to river channels provides a basis to locate where high capacity wells are likely (and unlikely) and indicates that groundwater flow within the watershed is relatively rapid, consistent with flow rates representative of karstic aquifers. This understanding provides a basis for better informed decisions regarding water-resource management of a carbonate aquifer in a semi-arid environment.

1. Introduction

Urban growth in the arid and semi-arid regions of the United States and other countries places significant stress on water resources, which in many localities are already stressed due to limited recharge and increased water demand. While characterization of water resources is always desirable, accurate assessment of water availability in areas where resources are limited and stressed is of critical importance. Due to the unique and complex groundwater hydraulics of carbonate aquifers, special considerations are warranted when characterizing and managing water resources in semi-arid environments. Carbonate aquifers can serve as the principle source of water in a semi-arid environment as occurs in Spain (Hartmann et al., 2013; Martínez-Santos and Andreu, 2010), Lebanon (Bakalowicz, 2005; El-Hakim and Bakalowicz, 2007) and Texas, USA (Anaya and Jones, 2004, 2009; Hutchison et al., 2011; Green and Bertetti, 2010) and for this reason, accurate characterization of the aquifer system is paramount.

Understanding the means and mechanisms by which carbonate aquifers convey water from the headwaters of the watersheds to their points of discharge is important to the effective management of these valuable resources. The degree of karstification determines whether groundwater flow can be characterized as Darcian or is dominated by conduit flow (Scanlon et al., 2003; Worthington, 2007; Rashed, 2012). Conduit flow can be detected directly with dye tracer tests and indirectly using other hydraulic factors, such as groundwater gradients (i.e., troughs) and aquifer response (i.e., spring discharge) (Schindel et al., 1996; Worthington et al., 2000; Worthington, 2007). Rarely, however, are sufficient site-specific data available to adequately characterize the hydraulic properties of a karst-dominated aquifer to allow for effective management of the resource.

Characterizing karst-dominated aquifers that exhibit well-developed preferential flow paths and permeability architectures spanning many orders of magnitude can be challenging. Practitioners have used various tools to aid in characterizing preferential flow paths in karst systems. Considerable effort has been expended to use lineaments and topographic expressions to discern subsurface hydraulic properties (Lattman and Parizek, 1964; Parizek, 1975; Sander et al., 1996; Magowe, 1999; Mabee et al., 1994, 2002; Moore et al., 2002; Mouri, 2004; Bauer et al., 2005; Mouri and Halihan, 2007).

To characterize the preferential flowpaths of a karst-dominated aquifer, a method is proposed that recognizes the importance of lineaments and topographic expressions, the principles of

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carbonate dissolution, and a surrogate estimate of aquifer permeability. Spatial distribution of well capacity is used to establish a correlation between preferential flow paths in the carbonate aquifer and proximity to river channels. Other spatial relationships were explored, such as correlations between well pumping capacity and geology, geomorphology, or karst features, however, only well pumping capacity and proximity to river channels demonstrated a useful correlation. The ensuing network of preferential flowpaths that are co-aligned with river channels is the foundation for a refined conceptual model in which flow in the watershed is dominated by the preferential flow paths rather than diffuse flow through the inter-stream upland areas. Correlation between karst development and river channels has been observed elsewhere (Abbott, 1975; Woodruff and Abbott, 1979, 1986; Allen et al., 1997; MacDonald and Allen, 2001; Mocochain et al., 2009), however the use of well hydraulics has not been used to quantify the degree of karst development aligned with river channels.

The Devils River watershed in south-central Texas, USA (Fig. 1) is selected to test this method because it conveys significant groundwater in a semi-arid environment and because it is representative of a broader class of carbonate aquifers in semi-arid environments worldwide. Accordingly, characterizing key groundwater conveyance mechanisms in the Devils River watershed may help characterize similar karst aquifers in other semi-arid environments.

2. Geological and hydrogeological setting of the study area

The carbonate aquifers in central Texas, USA are the primary sources of water for a rapidly growing population. Most prominent of these are the Edwards, Trinity, and the Edwards-Trinity aquifers. These aquifers exhibit a broad range of hydraulic characteristics. Of interest is the western Edwards-Trinity Aquifer, an exhumed carbonate aquifer which is the source for significant water resources, although it is located in a semi-arid environment. The Devils River watershed, located in the western Edwards-Trinity Aquifer (Fig. 1), exhibits aquifer and hydraulic characteristics representative of the greater Edwards-Trinity Aquifer and parts of the Trinity Aquifer, but distinct from the Edwards Aquifer (Abbott, 1975; Woodruff and Abbott, 1979, 1986).

The Edwards-Trinity Aquifer covers 200,000 km^2 and is the dominant aquifer in west-central Texas (Barker and Ardis, 1996) (Fig. 1). This Cretaceous-age limestone comprises the younger, more permeable Edwards Group rocks overlying the older and less permeable Trinity Group (Fig. 2). The Edwards-Trinity Aquifer has significant vertical and lateral spatial variability (Rose, 1972). The climate varies from humid subtropical in the east to arid and semi-arid (steppe) in the west. The Devils River watershed conveys an average of 324 Mm^3/yr of water from the Edwards Plateau to the Amistad Reservoir and the Rio Grande in the south. This amounts to over 15% of the total flow of the lower Rio Grande (United States Geological Survey, 2013)—an impressive quantity of water delivered from a semi-arid area where average precipitation is less than 500 mm/yr over a surface watershed comprising 10,260 km^2.

Most of the Edwards Plateau is mantled by the Edwards Formation with a tableland geomorphological surface that exhibits a stair-step topography formed by differential weathering of strata with variable resistance. More resistant layers form "treads" which are gently sloping surfaces with minimal (i.e., <0.5 m) soil overburden. Less resistant layers weather to form "risers", step-like features with clay-rich, low-permeable soils with a thickness of less than 1.0 m to as much as 3.0 m (Woodruff and Wilding, 2008; Wilcox et al., 2007). The Devils River is incised through the tableland surface exposing steep cliffs in places. Aside from the incised river and stream channels there are few karst features such as sinkholes or other solution cavities exposed at the surface.

Geologic mapping is useful in characterizing the hydraulic properties of an aquifer when site-specific studies have not been

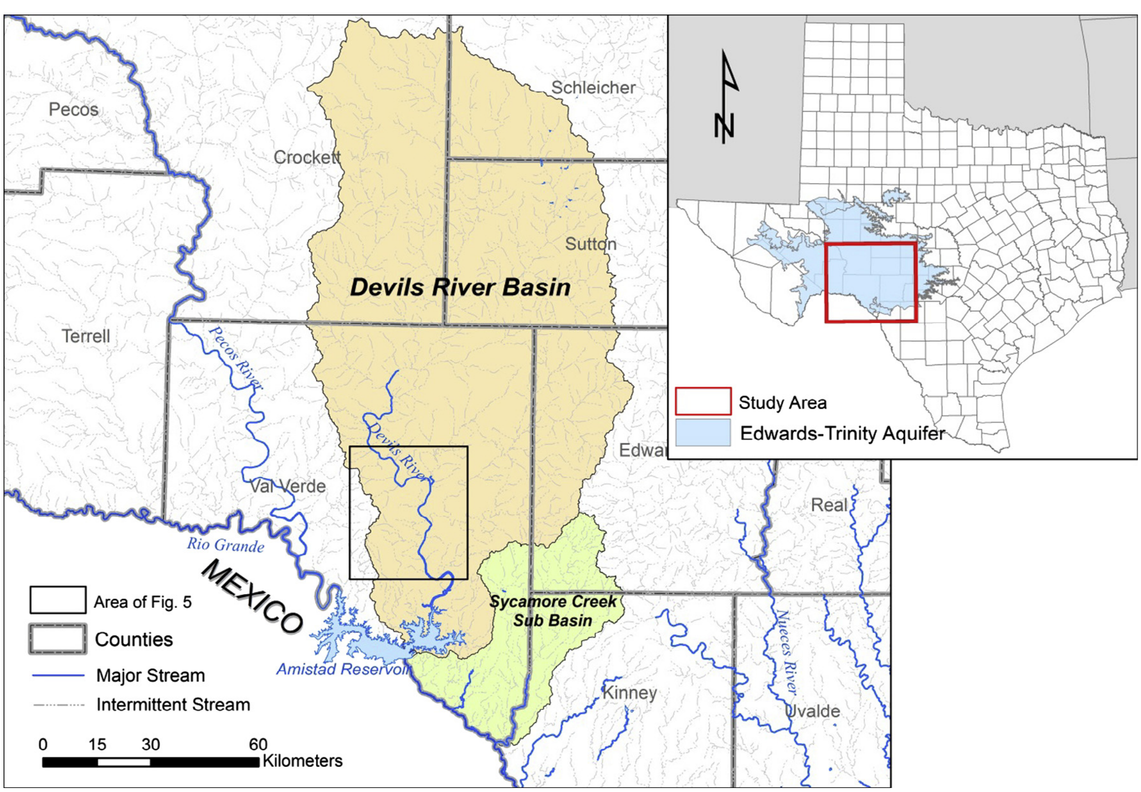

Fig. 1. Location map of the Devils River basin and the Sycamore Creek sub basin in central Texas.