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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

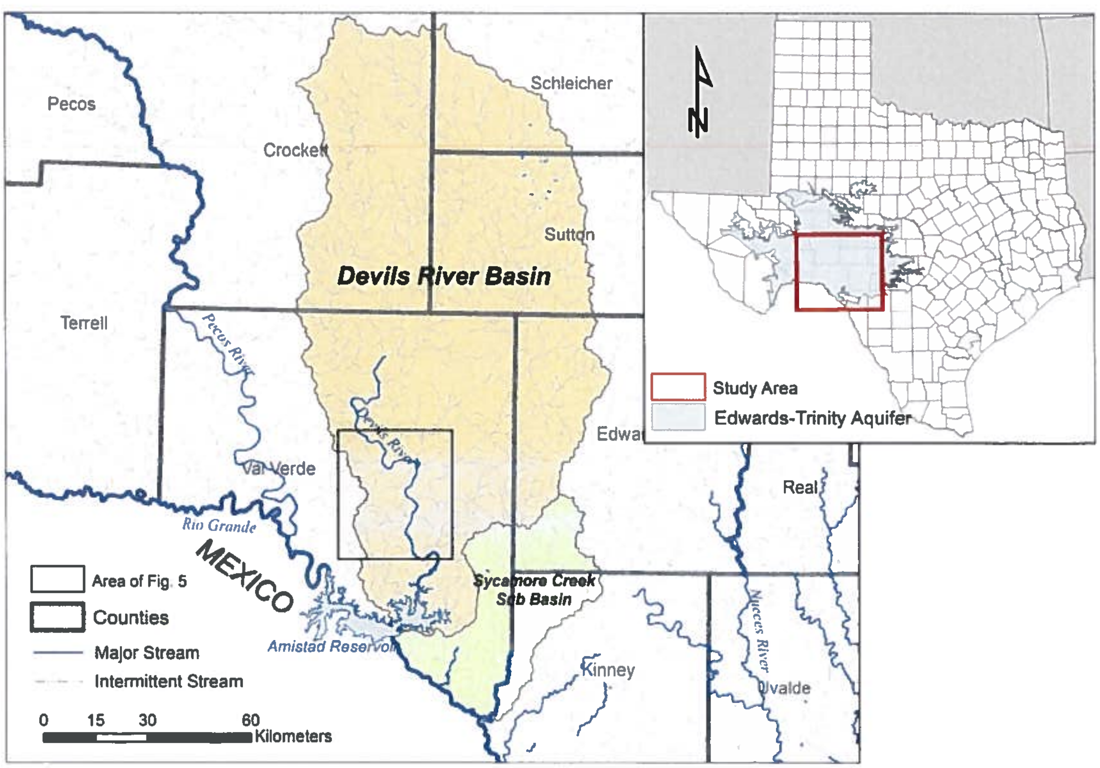

Fig. 1. Location map of the Devils River basin and the Sycamore Creek sub basin in central Texas.

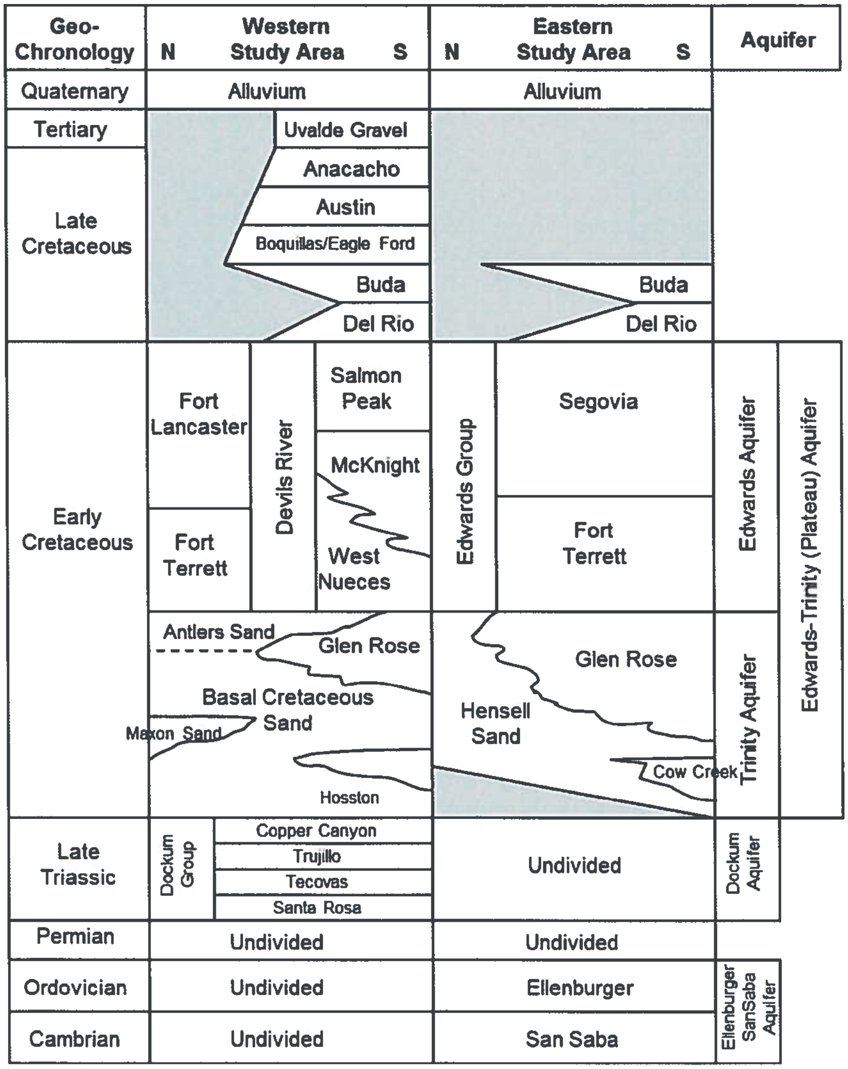

Fig. 2. Stratigraphic column and major aquifer units for the Devils River region and Edwards Plateau.

performed and aquifer characterization data are not available. Conventional characterization of the hydraulic properties of the Edwards-Trinity Aquifer in the Devils River watershed basin has been based on its mapped geology (Anaya and Jones, 2004, 2009; Hutchison et al., 2011). This characterization is well illustrated by the hydraulic conductivity assigned to the current groundwater flow model used to manage the Edwards-Trinity Aquifer (Fig. 3) (Hutchison et al., 2011). Although most hydraulic property assignments are consistent with the mapped geology in Fig. 3, some assignments of the hydraulic conductivity values are ambiguous (Table 1).

Obviously, supplemental hydrogeological information can provide additional insight when characterizing an aquifer than is provided by geologic mapping alone. This is the case with the Edwards-Trinity Aquifer in the Devils River watershed basin. The recognition that the Edwards-Trinity Aquifer is a karst aquifer, in which preferential pathways have developed in the limestone, is paramount. In this case, assigning hydraulic properties to a karst aquifer based solely on geologic maps does not take into consideration the dominating effect of preferential flow paths present in the Edwards-Trinity Aquifer.

3. Preferential flow path development

Refined hydraulic properties are proposed for the Devils River watershed basin based on data and information now available that provide insight regarding preferential pathways in the Edwards-Trinity Aquifer. The interpretation developed in this paper is that preferential pathways have developed coincident with river channels in the Edwards-Trinity Aquifer and that these preferential pathways are the principal means of conveying groundwater from the watershed's headwaters to its points of discharge. The development of organized flow regimes forming in karst systems is not uncommon (Bakalowicz, 2005; El-Hakim and Bakalowicz, 2007; Worthington and Ford, 2009).

Factors that controlled conduit development in the Devils River watershed were (i) the degree to which rocks are susceptible to dissolution, (ii) exhumation of the Edwards Plateau leading to increasing the effective hydraulic gradient, and (iii) the focus of recharge into a defined stable river system (White and White, 2001). Palmer (1991) notes that cave patterns with limited branches tend to form if recharge is focused, the carbonate rock is limestone rich, and hydraulic gradients are at least moderate

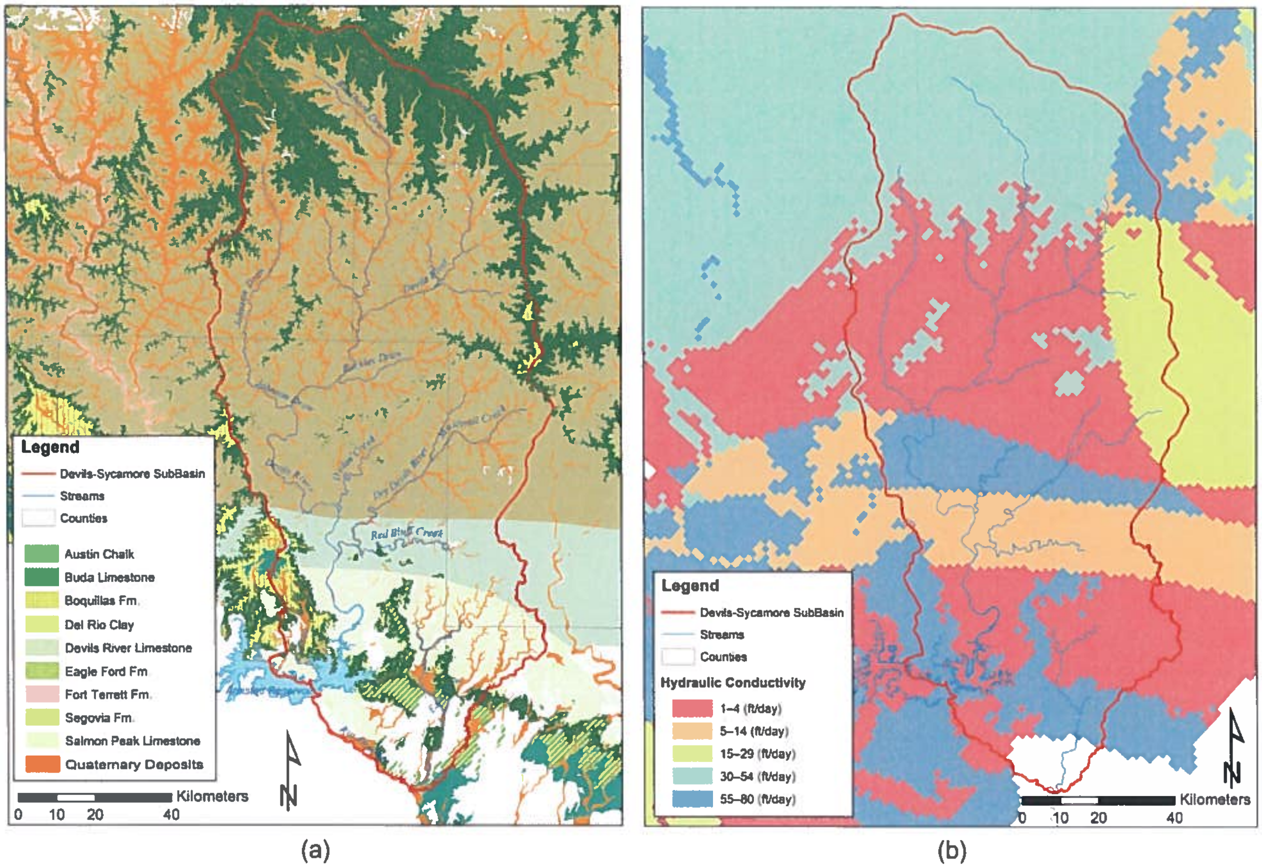

Fig. 3. Map of Devils River watershed illustrating (a) geologic assignments based on State of Texas geologic maps (Fisher, 1977, 1981) (left) and (b) hydraulic conductivity values assignments (taken from Hutchison et al., 2011) (right). The red border denotes the Devils River watershed basin.

Table 1
Assignment of hydraulic conductivity values to Devils River basin rocks based on geologic mapping (extracted from Anaya and Jones, 2004, 2009; Hutchison et al., 2011).

Hydraulic conductivity (m/day)	Geologic formation	Geographical feature
17–24	Buda Limestone, Kbu	Edwards Plateau
0–1.2	Segovia, Ks	Southern end of Edwards Plateau
1.5–4.2	Segovia/Buda Limestone, Ks/Kbu	Eastern Devils River Channel
1.5–4.2	Segovia, Ks	North-central Devils River Channel
4.6–8.8	Del Rio Clay, Kdr	South-central Devils River Channel
9.1–16.5	Salmon Peak, Ksa	Southeast Devils River Channel
0–1.2	Del Rio Clay/Buda Limestone/Eagle Ford, Kdr/Kbu/Kef	South Devils River Channel.

(i.e.,>0.001). White and White (2001) concur that hydraulic gradients of 0.001 and greater are adequate to enable the development of focused conduits. Alternatively, low hydraulic gradients could have led to multiple alternate flow paths.

Exhumation of the Edwards Plateau and the subsequent development of the groundwater conveyance system in the Edwards-Trinity Aquifer occurred during two diverse episodes. The first episode was in the middle Cretaceous Period when the Edwards Group limestones were deposited, subaerially exposed, and then buried. The second episode started during the Miocene Epoch when Balcones faulting eroded the fault-rejuvenated streams and exhumed the Edwards Group limestones (Abbott, 1975; Woodruff and Abbott, 1979, 1986) and is potentially ongoing. Exhumation of the karstic tablelands preserved relict landforms such that streambeds became incised valleys whose evolution was enhanced by increased hydraulic gradients.

During uplift, incipient preferential flow paths formed in the subsurface, coincident with the existing river systems, when mildly acidic precipitation flowed in riverbeds and developed enhanced permeable flow channels in the soluble carbonate rock. The susceptibility of limestone to dissolution is a function of the amount of calcium carbonate in the rock (Dreybrodt and Gabrovsek, 2003; Romanov et al., 2003; Dreybrodt et al., 2005). Solution features, such as conduits and other karst features, developed in carbonate rocks when weak carbonic acid formed from rainwater and organic carbon dissolved calcium carbonate ($CaCO_3$) over geologic time (Ford and Williams, 1989)

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2HCO_3^-$$

Aquifers with greater limestone content tend to have better developed conduit systems, resulting in primarily conduit flow in the aquifer. Conversely, aquifers with higher dolomite [$CaMg(CO_3)_2$] content tend to be less susceptible to carbonate dissolution than aquifers with greater limestone content, although karst development is certainly observed in dolomite-rich formations (White and White, 2001).

Geologic lineaments and zones of fracture concentration have been shown to act as avenues for enhanced weathering and increased permeability, thereby facilitating vertical and lateral groundwater movement (Siddiqui and Parizek, 1971; Parizek, 1975; Lattman and Parizek, 1964; Sharpe and Parizek, 1979; Klimchouk and Ford, 2000a,b). Once initiated, the preferential flow paths were further enhanced by a positive-feedback growth mechanism in that an increased volume of mildly acidic water was available to promote solution cavity development. This preferential flow-field development converged in river channels because the topography channeled water from uplands to the river channels where dissolution was concentrated in the shallow phreatic zone (Abbott, 1975) (Fig. 4). Similar genesis of enhanced permeability near river channels has been observed in the unconfined Chalk Aquifer in England (Allen et al., 1997; MacDonald and Allen, 2001).

Uplift and contemporaneous faulting at the boundary of the Edwards Plateau increased hydraulic gradients that incised into the limestone plateau. The incised valleys often led to topographical low points, providing for spring discharge. Watershed piracy from cut-off streamflow and fault-induced watershed interconnection in the eastern Edwards Aquifer allowed for more direct surface flow paths with increased hydraulic gradients (Woodruff, 1974, 1977; Woodruff and Abbott, 1986). Because the same conditions existed south of the Edwards Plateau that existed in the eastern Edwards Aquifer, similar evolution of surface-water flow regimes in the Devils River watershed basin would also have led to increased hydraulic gradients.

Using the potentiometric surface of the Edwards-Trinity Aquifer (Kuniansky and Holligan, 1994; Barker and Ardis, 1992, 1996; Bush et al., 1993; Ardis and Barker, 1993), current hydraulic gradients have been measured in proximity to the Devils River watershed basin. The gradients are 0.0016 in Sutton County, 0.0013 in Reagan County, 0.0012 in Crockett County, and 0.0038 in Val Verde County. These measured hydraulic gradients are sufficiently large to support the development of preferential flow paths focused in river channels rather than expansive solutionally enhanced flow spread over broad paths.

There is evidence that another form of piracy, in which groundwater basins extend farther upgradient than the overlying surface watersheds, exists in the western Edwards Aquifer (Woodruff and Abbott, 1979, 1986; Green and Bertetti, 2010). The resulting enhanced flow regime, whether due to a longer flow path or to an increased hydraulic gradient, increases the degree of positive feedback in the development of solution features in the karstic limestone. This in turn leads to further development of the karstic flow regime and enlargement of lower level conduits at the points of discharge (Woodruff and Abbott, 1986). The hypothesis proposed here is that a number of smaller conduits have formed proximal to river channels rather than one large conduit or even a small number of larger conduits. The ensemble of the smaller conduits has resulted in high preferential flow paths formed concurrent with river channels.

The variable susceptibility of carbonate dissolution in the formations of the Edwards Plateau has important implications with regard to how conduits form in the Edwards-Trinity Aquifer. The Upper Glen Rose member of the Trinity Group has been categorized as predominantly a thin- to medium-bedded sequence of nonresistant marl alternating with resistant beds of dolostone, lime mudstone, and bioclastic limestone (Stricklin et al., 1971; Barker et al., 1994). Lower units in the Trinity Group also tend to be less rich in limestone relative to the Edwards Formation and to the Upper Glen Rose member; thus dissolution of the carbonate rocks in the Edwards Formation is likely to be more rapid or more developed relative to the Trinity Group. In brief, carbonate dissolution is going to occur preferentially in the limestone-rich Edwards Limestone portions of the Edwards-Trinity Aquifer rocks relative to the less limestone-rich and low-permeability rocks present as interbeds in the Trinity Group.

The upper Edwards Group limestone (i.e., Segovia Member) is mostly exposed at the surface in the Edwards Plateau, an area that includes the Devils River watershed (Fig. 3). There are limited occurrences of the overlying Buda Limestone, in which cases the full thickness of the Edwards Group is preserved. Elsewhere, erosion has removed all formations that overly the Edwards Group and part of the upper Edwards Formation leaving only a variable thickness of the Edwards Group present. Although the upper Edwards Group has been eroded over most of the Edwards Plateau, at no place in the Devils River channel has the Edwards Group been fully eroded to expose the Trinity Group (Fisher, 1977, 1981). This factor is important because the limestone-rich Edwards Group limestone is available to provide for conduit development throughout the entire reach of the Devils River channel.

4. River channel groundwater flow regime development

Flow in the Devils River has been synoptically measured twice and has had continuous measurements taken at two locations at various times during the past 50 years. The Cauthon Ranch river gauge located near Juno is in the upper reach near the headwaters. The Pafford Crossing gauge location is located at the Devils lower reach, slightly upstream from where surface water has backed up in the Devils River since the Rio Grande was dammed in 1969, creating the Amistad Reservoir. Table 2 lists average flow versus drainage area for the two gauge locations for two different periods of record.

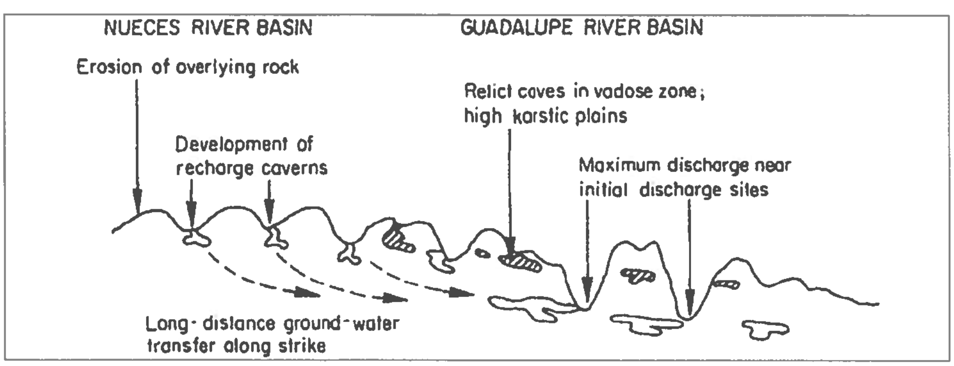

Fig. 4. Schematic cross section of the development of recharge caverns coincident with incised river channels in the western Edwards Aquifer (taken from Woodruff and Abbott, 1979, 1986).

Table 2
Average flow (L/min and Mm^3/yr) measured at two gauging locations on Devils River. The Cauthon Ranch near Juno values are the averages of annual measurements for the periods of 1926–1949 and 1964–1973. The Pafford Crossing values are the averages of data of daily measurements for the period 1/1/1960 to 12/31/2011.

Gauging station	Drainage area (km^2)	Flow (Mm^3/yr)	Flow (Mm^3/yr)
Cauthon Ranch	7164	168	149
Pafford Crossing	10,256	323	294

Over both time periods, river flow increased by over 90% (92.6% in column 4 and 96.5% in column 5) between the Cauthon Ranch river gauge and the Pafford Crossing river gauge, even though the drainage area only increased by 43%. The obvious source of increased flow between these two gauging stations is due to emergent flow in the river channel, not to the incremental increase in the size of the watershed between the Cauthon Ranch and Pafford Crossing river gauges. This observation is consistent with a conceptual model of preferential flow path development in river channels and that the preferential flow is increasingly discharged to the river in downstream reaches.

Synoptic flow surveys, also referred to as gain/loss surveys, have been completed twice on the Devils River. Synoptic flow surveys are valuable for several reasons, one of which is to identify which river reaches are gaining and which are losing. A synoptic survey conducted under low flow conditions on the Devils River was completed in July 2013 and compared with a published synoptic survey conducted under relatively higher flow conditions during an unspecified time in 2006 (Texas Commission for Environmental Quality, 2006) (Fig. 5). With the exception of two minor decreases in measured flow made in 2006 in the upper reach and one reading of 1198 L/s in the upper reach during the 2013 survey, the entire reach of the Devils River was gaining from its headwaters to its outfall into the Amistad Reservoir. This is particularly obvious downstream from the confluence of Dolan Creek with Devils River. In addition, the river gains at a rate in excess of the increase in watershed area. This excess in increased flow is attributed to contributions from subsurface channel flow mostly attributed to discrete discharge at spring locations.

Visual inspection of the Devils River indicates the river bed is mostly exposed bedrock with minimal evidence of gravels or other floodplain sediments. This observation supports the hypothesis that the increase in surface flow in the Devils River is attributable to contributions from bedrock and not from hyporheic flow through gravel and other riverbed sediments.

5. Well capacity correlated with river channel proximity

The principle hypothesis proposed in this paper is that preferential flow paths and enhanced permeability are coincident with river channels in the Devils River watershed. A similar correlation, in terms of high transmissivity aligned with River Lambourn and River Kennett, was discerned in the unconfined Chalk Aquifer in Berkshire County, England (Connorton and Reed, 1978; Morel, 1980; Allen et al., 1997; MacDonald and Allen, 2001). The high transmissivity/river correlation of the Chalk Aquifer was discerned using geomorphological evidence. The hypothesis is tested on the Devils River watershed by correlating water-well pumping capacity and well proximity to river channels. Well data from the Devils River watershed and an adjoining minor watershed, the Sycamore Creek watershed, were extracted from the Texas Water Development Board Submitted Driller's Report and Groundwater databases (TWDB, 2012a,b) to assess whether the hypothesis of the development of preferential flow paths and enhanced permeability coincident with river channels in carbonate aquifers has merit. These databases are the most comprehensive datasets available for the Sycamore Creek and Devils River watersheds that provide some measure of hydraulic capacity. Unfortunately, hydraulic capacity information is limited to well pumping capacity. A more useful measure, such as specific capacity, is not included in either database. Information on pumping capacity is included for 751 of the 2122 wells in the database for the Sycamore Creek and Devils River watersheds. The remaining wells have either no record of pumping capacity or limited pumping capacity. Domestic or stock wells with limited pumping capacity (i.e., less than 75 L/min) are believed to comprise the bulk of the wells with no record of pumping capacity. Limited field checking failed to identify any additional wells with significant pumping capacities that were not included in the subset of 751 wells. Locations of the wells with measured pumping capacity in the Devils River and Sycamore Creek watersheds are plotted in Fig. 6.

Proper selection of river channels is critical to the correlation of well pumping capacity with proximity to stream channels. Watersheds, such as that of the Devils River, with low annual rainfall totals, high intensity rains, and sparse vegetation have high drainage density (Gregory, 1976; Rodríguez-Iturbe and Escobar, 1982). Given the high density of incised and intermittent stream valleys within the Edwards Plateau, the correlation of well pumping capacity with proximity to river channels would be biased if stream channels were fortuitously selected to use only those channels proximal to each well with high pumping capacity. Only stream segments with a Horton–Strahler number of three or greater as classified in the National Hydrography Dataset, Version 2 (United States Geological Survey, 2013) were included in this analysis to avoid selection bias.

The ArcGIS geoprocessing tool ***Near*** was used to calculate distances between wells and third-order and greater streams. This computation was facilitated by entering shape files for the third-order and greater streams (United States Geological Survey, 2013) and locations of all wells that had documented values for well capacity. Each well with a documented pumping capacity was thereby assigned an unambiguous measurement that represented the shortest distance to the closest third-order stream. Wells with no pumping capacity measurement were excluded from the evaluation.

The correlation between well pumping capacity and proximity to stream channels is presented in Fig. 7. A strong correlation between well capacity and proximity to higher-order river channels is clearly illustrated in the graph. Care must be taken when interpreting well pumping capacity. Although the measured pumping capacity of a well may represent its maximum capacity, it is probably less than the potential maximum pumping capacity of the well at its location. It is possible that a large, possibly deeper, well with a larger pump at the well's location would have greater pumping capacity. Regardless, it is significant that out of a dataset of 2122 wells of which 751 wells were assigned a value for pumping capacity, only one well with pumping capacity greater than 1890 L/min is located more than 2.5 km from third-order or larger streams.

Because of the uncertainties associated with the well pumping capacities in the Driller's Report database, it is fruitful to analyze the relationships between the total number of wells with available pumping data and distances to the nearest higher-order river channel. A histogram of the well pumping capacity data in terms of $\log_{10}$(L/min) is shown in Fig. 8. The data are adequately represented by a log-normal distribution with a mean (μ) of 1.83 (67 L/min) and standard deviation (σ) $\pm$ 0.65. Four classes of well pumping capacity were defined using the distribution parameters μ and σ: low $\leqslant \mu$ (67 L/min); $\mu >$ med $\leqslant \mu + \sigma$ (68–300 L/min); $\mu + \sigma >$ med-high $\leqslant \mu + 2\sigma$ (301–1300 L/min); and high $> \mu + 2\sigma$

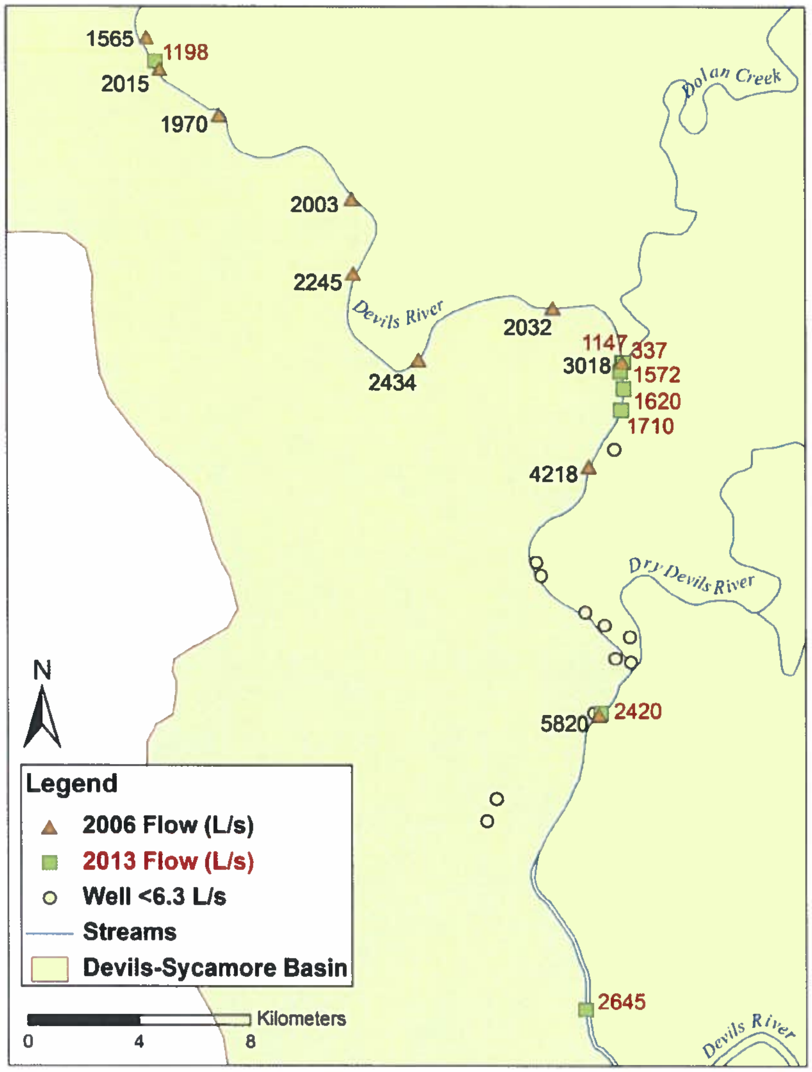

Fig. 5. Locations of flow measurements along the Devils River during relatively high flow conditions in 2006 (TCEQ, 2006) and low flow conditions in 2013.

(>1301 L/min). The well pumping classes were then binned in 1-km increments with respect to their calculated distance to the nearest higher-order river channel. A bar graph of the results is shown in Fig. 9. Data in the figure demonstrate that both well pumping capacity (i.e., frequency of greater capacity well classes) and the total number of wells increase dramatically as the distance to the nearest river channel decreases. A majority of the wells fall into the ⩽67 L/min classification, but these wells are also located within a few km of the higher-order stream channels. Fig. 10 presents the same data plotted on a $\log_{10}$-$\log_{10}$ scale. The data are separated into two groups, one that includes all the analyzed wells and a second that excludes the ⩽67 L/min pumping capacity wells. Both data sets are well characterized by a power function fit of the form $Count = a \cdot (Distance)^b$, where a and b are constants. The observation that distance from river channels is a reasonable predictor of well pumping capacity and well count is similar to trends observed in other studies of carbonate aquifer properties (e.g., MacDonald and Allen, 2001). When combined with data in Fig. 7, these trends provide compelling evidence that wells with a high pumping capacity are restricted to areas in close proximity to river channels.

6. Water-budget analysis

Having an understanding of the water budget of the Devils River watershed can help constrain the groundwater/surface water flow conceptual model. Historically, the water budget of the Devils River watershed basin has not been well characterized. Although discharge from the Devils River to Amistad Reservoir is measured, uncertainty remains regarding the size of the Devils River recharge basin and the rate of recharge within the basin. Accurate calculation of recharge is obviously central to meaningful determination of the water budget in any environmental setting and carbonate aquifers in a semi-arid climate are no exception. A variety of approaches has been used to calculate recharge in semi-arid environments. Baseflow separation has been used to estimate recharge when spring or stream discharge measurements are available (Arnold et al., 1995; Arnold and Allen, 1999; Green and Bertetti, 2012; Green et al., 2012). Chemical analysis of spring or stream discharge has been shown to be useful to either assist in baseflow separation (Doctor et al., 2006) or to discern seasonal contributions to recharge and, ultimately, discharge (Aquilina et al., 2005). Another approach to determine recharge is to evaluate the spatial

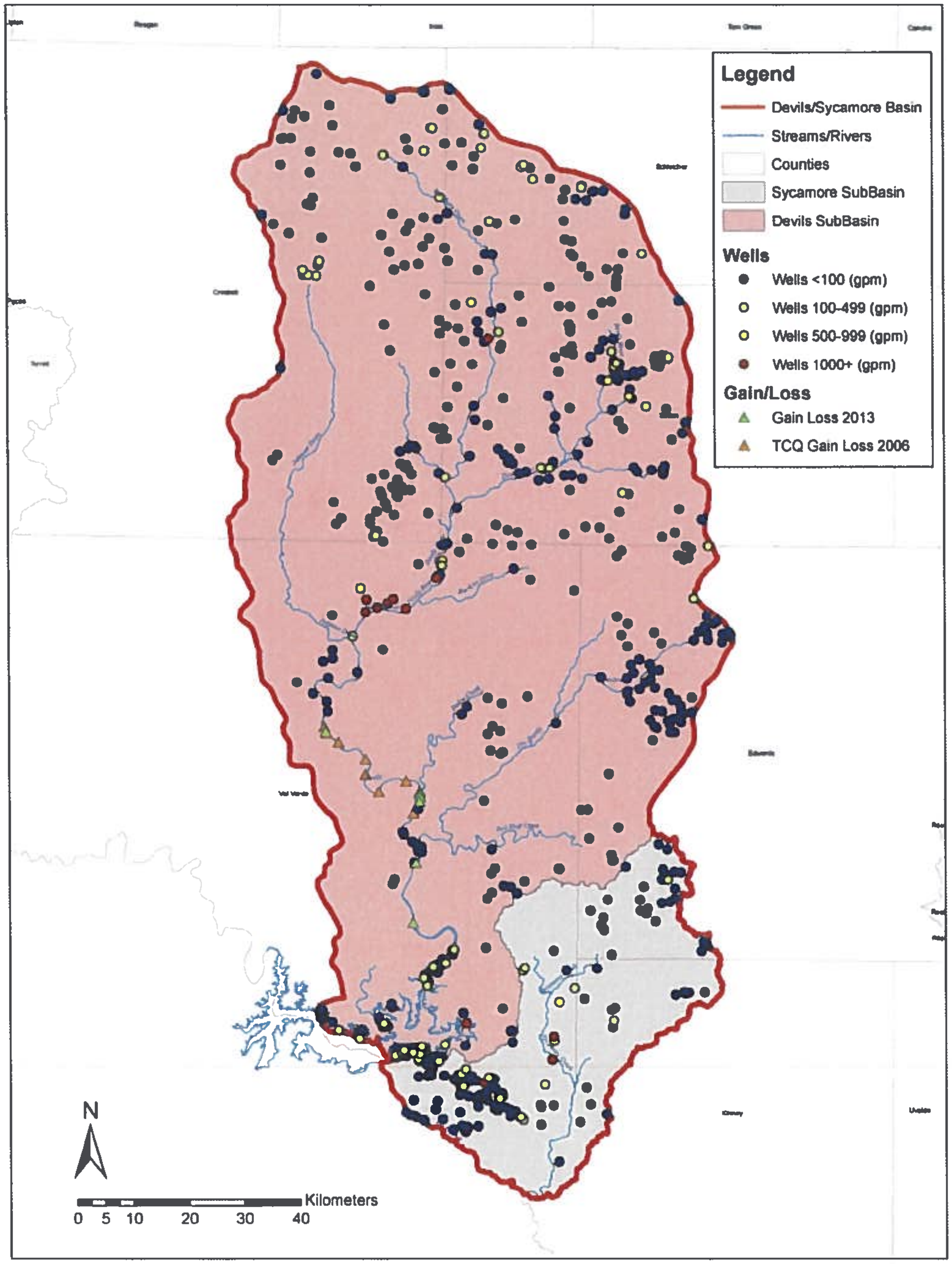

Fig. 6. Map of the Devils River watershed with well locations. Highest capacity wells [>3785 L/min (1000 gpm)] are denoted by a red dot, higher capacity wells [between 1890 and 3784 L/min (500 and 999 gpm)] are denoted by a yellow dot, lower capacity wells [between 378 and 1889 L/min (100 and 499 gpm)] are denoted with green dots, and wells with capacity less than 100 gpm are denoted with a purple dot. As illustrated, the majority of wells have capacities less than 378 L/min (100 gpm).

and temporal variability of recharge using aquifer response (Hughes and Mansour, 2005; Hartmann et al., 2012, 2013).

Recharge to the Devils River watershed is relatively significant given the amount of water discharged by the Devils River to Amistad Reservoir even though the watershed is located in a semi-arid environment (Reeves and Small, 1973; Veni, 1996; Green and Bertetti, 2010). Flow at the Devils River Pafford Crossing gauge located near Amistad Reservoir is typically referenced as the measure for average discharge from the Devils River to Amistad Reservoir. This discharge of 324 Mm^3/yr accounts for approximately 15% of the flow in the lower Rio Grande (1973 Mm^3/yr) (International Boundary and Water Commission, 2005). Precipitation recharge in counties that cover the Devils River watershed basin has been approximated at 7.9–12.4 mm/yr by Hutchison et al. (2011) using a groundwater model (Table 3). Recharge in Val Verde County was previously estimated at 38.1 mm/yr by Reeves and Small (1973) and in the Dolan Creek tributary to the Devils River watershed in Val Verde County at 55.4 mm/yr by Veni (1996).

Recharge can also be established using precipitation measurements. Average annual precipitation from 1971 to 2000 for the Devils River watershed area is mapped in Fig. 11. As illustrated in Fig. 11, the average annual precipitation for each county within the Devils River watershed varies from less than 400 mm/yr in the west to about 585 mm/yr in the east (Table 3). Recharge for the

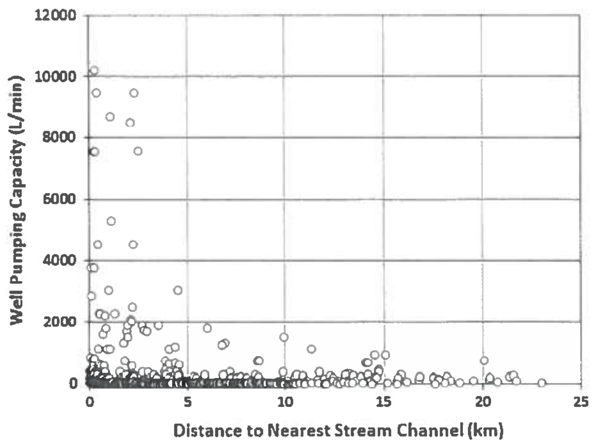

Fig. 7. Graph of well capacity versus distance to the nearest third-order or greater stream channel. The data suggest a strong correlation between distance and well pumping capacity, especially for higher capacity wells (>2000 L/min).

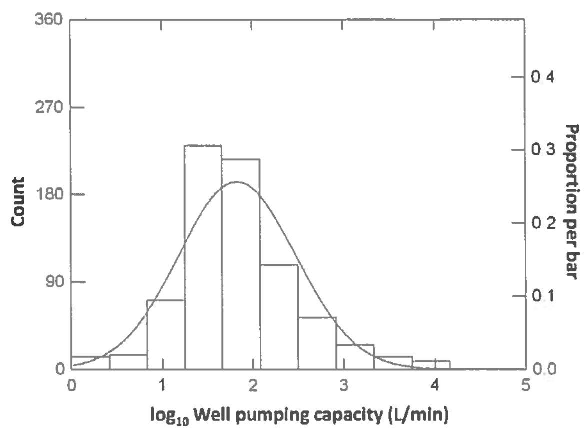

Fig. 8. Histogram and fit of normal distribution for $\log_{10}$-transformed well pumping capacity data for Devils River region wells. The data are reasonably represented by a log-normal distribution with $\log_{10}\mu$ of 1.83 L/min and $\log_{10}\sigma$ of ±0.65.

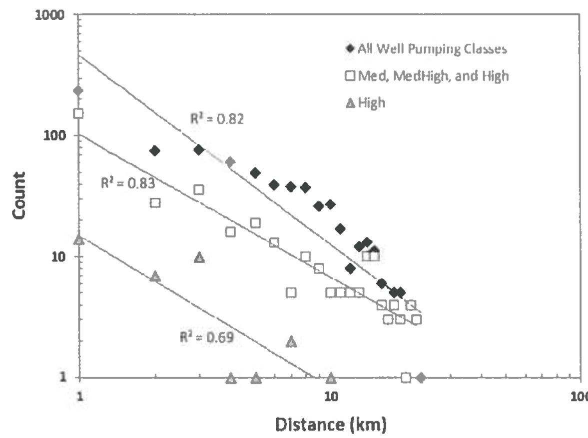

Fig. 10. Scatter plot of classified well pumping capacity data versus distance to the nearest third-order or greater stream channel. The data indicate distance from stream channels is a good predictor of well pumping capacity and the number of wells. The lines represent least-squares best fits of power functions to each of the data sets and are presented with their respective R^2 values.

Devils River basin has been estimated based on an assessment of the western Edwards-Trinity Aquifer in which average recharge was shown to correlate linearly with average precipitation, but to become negligible when precipitation is less than 400–430 mm/yr (Green and Bertetti, 2010; Green et al., 2012). This threshold is important when assessing recharge; however it must be recognized that it is a long-term average and that factors such as antecedent moisture, storm duration and intensity, and seasonal factors such as temperature and humidity have a significant impact on actual recharge rates. Using the approach by Green and Bertetti (2010) and Green et al. (2012), average recharge is estimated to range from 16.0 to 33.0 mm/yr by), for an average annual recharge value for the Devils River 20 mm/yr. It is important to recognize this rate has significant spatial and temporal variability given the fact that the watershed is near this calculated threshold for negligible distributed recharge and that average precipitation varies significantly across the watershed (Fig. 11).

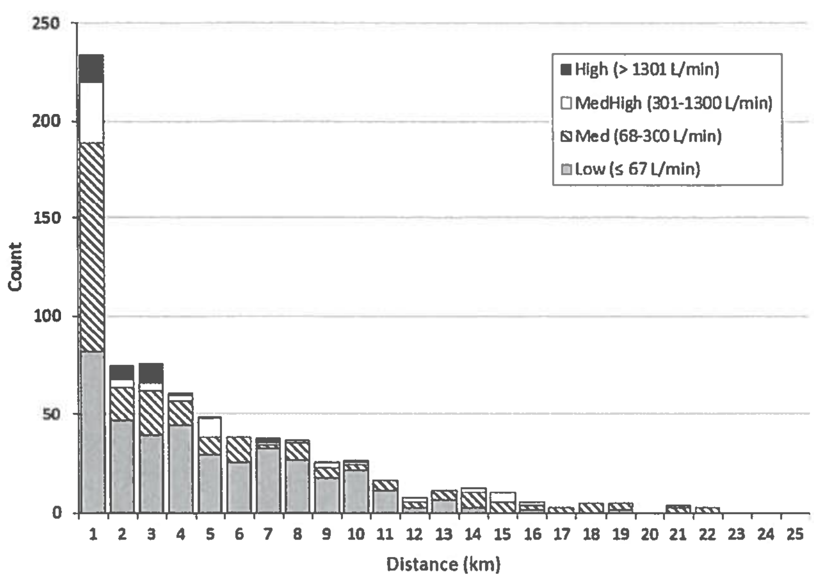

Fig. 9. Number of wells in each pumping capacity class plotted by distance to the nearest third-order or greater stream channel. Wells classes are based on mean and standard deviation values for the log-normally distributed pumping capacity data for wells in the Devils River region.

Table 3
Comparison of recharge by Hutchison et al. (2011) and Green and Bertetti (2010) for counties within the Devils River watershed.

County	Precipitation (mm/yr)		Recharge[a] (mm/yr)	Recharge[b] (mm/yr)
	Range	Average[c]		
Crockett	380–530	530	12.4	8.6
Edwards	580–740	530	11.7	33.0
Schleicher	530–580	560	7.9	20.0
Sutton	530–610	530	10.2	25.4
Val Verde	430–530	510	9.9	16.0

[a] Hutchison et al. (2011).
[b] Green and Bertetti (2010).
[c] Average precipitation within the Devils River watershed located within each county.

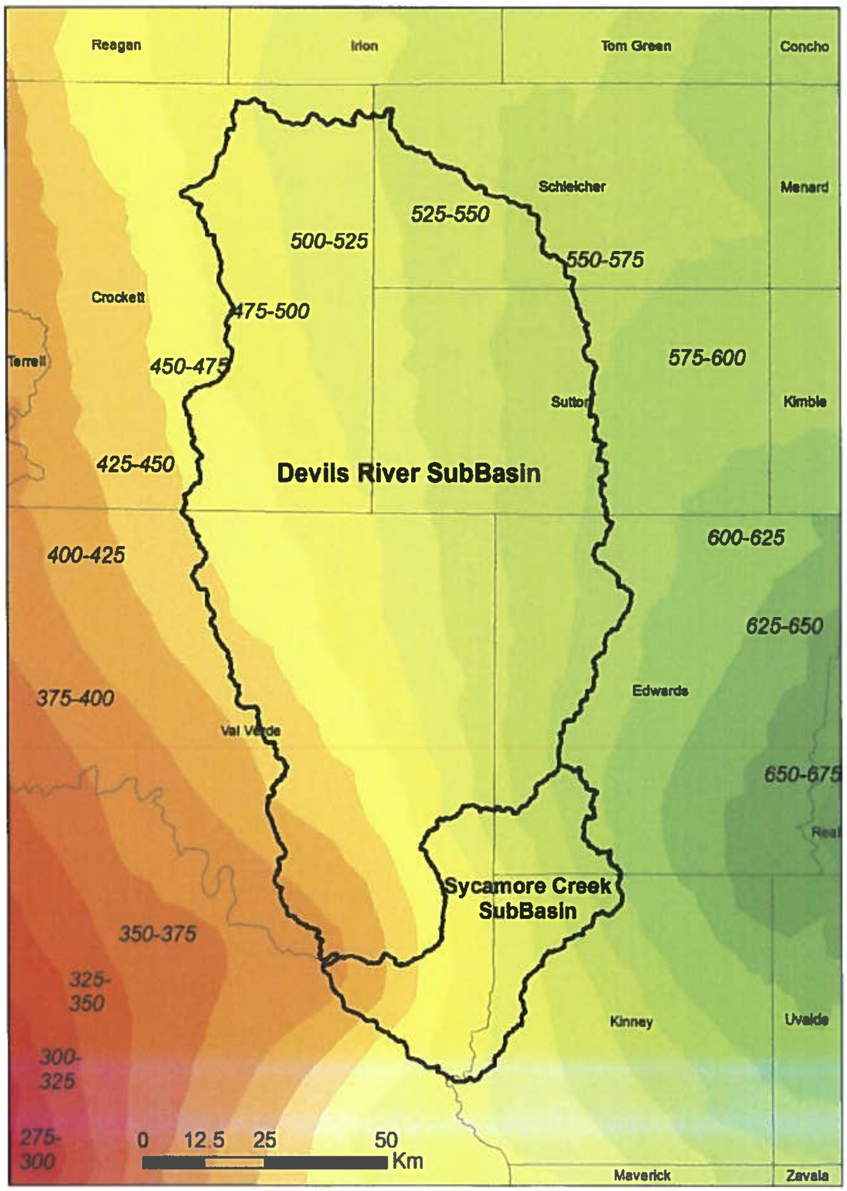

Fig. 11. Average annual precipitation (mm/yr) in the Devils River region over the period 1971–2000. Precipitation data are courtesy of PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 06 December 2006.

Baseflow and surface runoff were separated from flow measurements using the Devils River Pafford Crossing gauge data collected during the period 1960–2009 (Arnold et al., 1995; Arnold and Allen, 1999). Baseflow was calculated to be 76% of total flow with the remaining 24% contributed by surface runoff (Green and Bertetti, 2010; Green et al., 2012). Thus, 76% of the 324 Mm^3/yr (or 246 Mm^3/yr) the Devils River discharges to the Amistad Reservoir is attributed to baseflow and, hence, recharge (White and White, 2001; White, 1999, 2006).

If recharge for the Devils River watershed basin is estimated at 11.4 mm/yr (areal average of recharge for the Devils River watershed basin estimated using countywide recharge values by Hutchison et al., 2011), then 21,583 km^2 of watershed is required to account for the amount of recharge water discharged via the Devils River. If recharge is estimated at 20 mm/yr (areal average of recharge calculated using basin-wide recharge estimates by Green and Bertetti, 2010), then 12,121 km^2 of watershed is required to account for the amount of water discharged via the Devils River. Because the area of the Devils River watershed basin is 10,260 km^2, this suggests that 15% of the water discharged by the Devils River to the Amistad Reservoir is sourced from outside of the watershed basin. An average recharge rate of approximately 23 mm/yr, however is consistent with a watershed area of 10,260 km^2 and discharge rate of 246 Mm^3/yr to the Amistad Reservoir. These calculations suggest that the groundwater basin that recharges the Devils River watershed may extend beyond the boundary of the surface watershed if the average recharge rate is less than 23 mm/yr. Additional assessment is needed to reduce the uncertainty in the estimates for recharge and the baseflow fraction to ascertain the full extent of the Devils River groundwater basin.

Long-term average-flow measurements for rivers that discharge to Amistad Reservoir were calculated by Green and Bertetti (2010) using data from the International Boundary and Water Commission website (http://www.ibwc.state.gov/Water_Data/histflo1.htm). The surface water inputs to Amistad Reservoir are 1322 Mm^3/yr from the upper Rio Grande, 240 Mm^3/yr from the

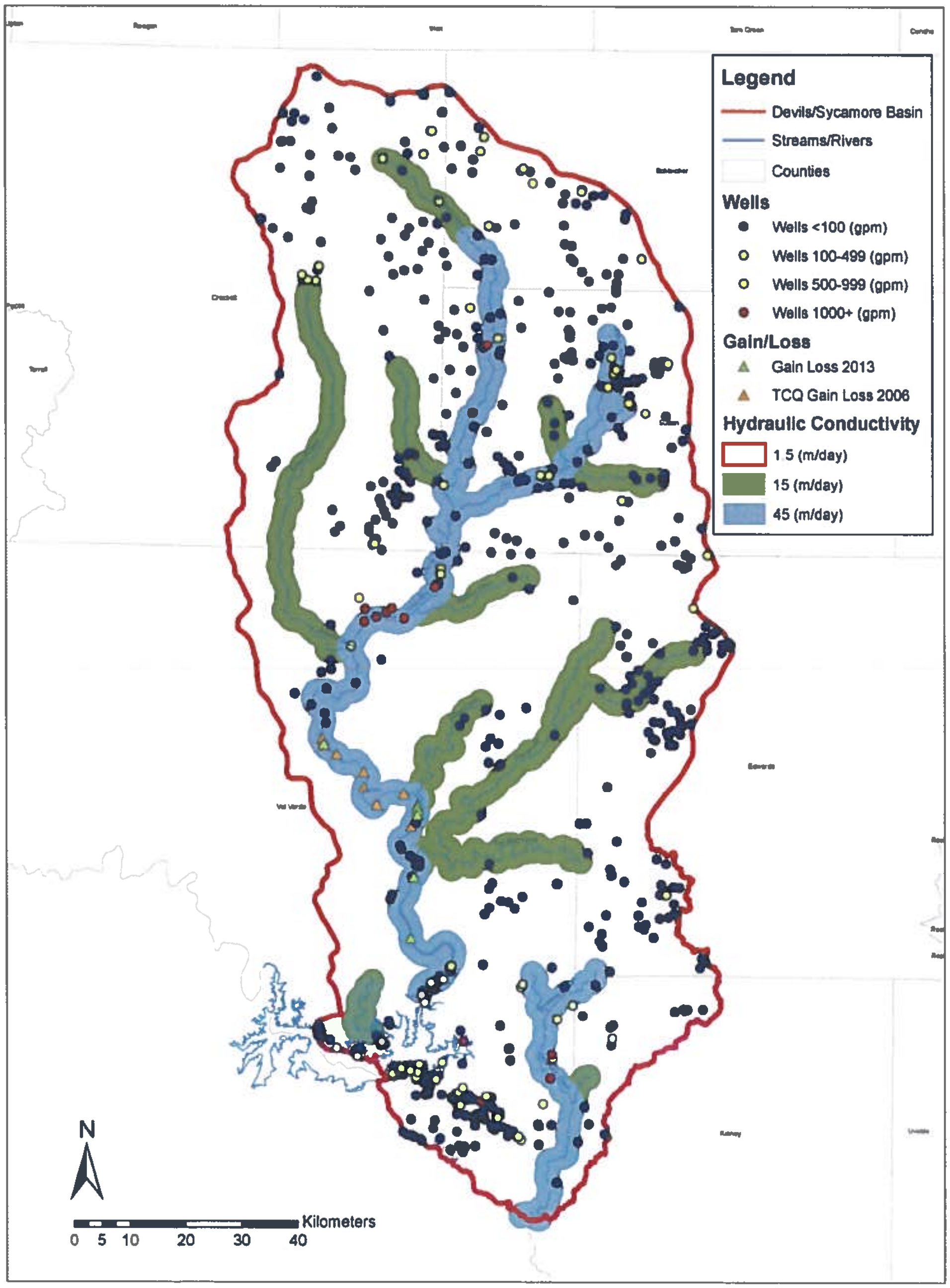

Fig. 12. Map of Devils River watershed basin with refined hydraulic conductivity assignments.

Pecos River, 325 Mm^3/yr from the Devils River, and an estimated 125 Mm^3/yr from Goodenough Spring now located within Amistad Reservoir (Brune, 1975). The total of this input to Amistad Reservoir (i.e., 2012 Mm^3/yr) compares well with the measured discharge of 2049 Mm^3/yr from Amistad Reservoir. This self-consistent, water-budget analysis indicates that recharge to Amistad Reservoir occurs essentially as surface flow and that there is negligible inflow to the reservoir as river-channel underflow or interformational flow. This suggests that most of the underflow in the Devils River channel has discharged from the preferential flow paths to surface flow upstream of the Pafford Crossing river gauge.

7. Groundwater conveyance in a semi-arid karst terrain

A refined conceptualization of groundwater conveyance in a semi-arid karst terrain is proposed based on fundamental processes of dissolution and using surrogate data for aquifer hydraulic capacity. Using evidence that indicates a strong correlation between aquifer permeability and proximity to higher-order river channels, pre-existing representation of the carbonate aquifer's hydraulic properties of the Devils River watershed (Anaya and Jones, 2004, 2009; Hutchison et al., 2011) is reinterpreted. The refined conceptualization of the permeability architecture of the karst aquifer is proposed in which high-capacity preferential flow pathways coincide with higher order river and stream channels.

Gradational hydraulic property values are assigned to these preferential flow paths in the Edwards-Trinity Aquifer in the Devils River watershed based on well pumping capacity. Stream and river channels with wells that have capacity greater than 1890 L/min are assigned a hydraulic conductivity of 45 m/day. Stream and river channels with wells that have capacity in the range of 378 L/min to 1889 L/min are assigned a hydraulic conductivity of 15 m/day. All river valleys with enhanced hydraulic conductivity have widths of 5 km, consistent with the correlation distance estimated in the well capacity/proximity to river assessment. Interstream areas are assigned a hydraulic conductivity of 1.5 m/day, a value that is a factor of 30 less than the hydraulic conductivities assigned to the highest capacity river channels. This relative difference in hydraulic conductivity is comparable to the difference in well capacity between wells in the higher order river channels (i.e., 3785 L/min) and wells in the interstream areas (i.e., <115 L/min). A map with the refined permeability assignments is presented in Fig. 12.

A significant source of uncertainty in these recharge estimates is determination of the extent of the Devils River watershed basin. Differences between the extents of surface water and groundwater basins can be significant in karst systems (Maréchal et al., 2008). Consistent with this generalization, the extent of the Devils River groundwater basin is not well defined and may differ from the extent of the surface watershed. Groundwater modeling can be used to estimate recharge in karst aquifers (Dörfliger et al., 2009; Fleury et al., 2009), however, successful completion of a model would be challenging given that both recharge and basin size are poorly constrained. Nonetheless, recharge, and basin extent, and the flow dynamics of the karst aquifer can be refined using a permeability architecture of preferential flow paths coincident with higher-order river channels. This new framework would replace one in which the permeability architecture is based primarily on geologic mapping. The refined conceptualization is fundamentally consistent with (i) karst development in carbonate rocks, (ii) structural evolution of the Edwards Plateau, and (iii) the requirement that the groundwater regime of the Devils River watershed has sufficient capacity to convey sufficient quantities of water at the required rates across the full extent of the watershed.

8. Conclusions

An efficient conveyance system for groundwater is shown to have formed in a karst carbonate watershed located in a semi-arid environment. This conveyance system comprises preferential flow pathways that developed coincident with river channels whose locations appear to date to the early days of regional uplift and exhumation of the carbonate formations. A strong correlation between wells with high pumping capacity and proximity to higher-order river channels (i.e., within 2.5 km) was used as evidence of preferential flow pathway presence. The principle factors that contributed to development of the preferential flow paths are the presence of a limestone-rich formation and recharge that has been geomorphologically focused toward river channels. A secondary factor that may have contributed to the development of these preferential flow paths is the relatively large hydraulic gradient (i.e., in excess of 0.001) enhanced as the Edwards Plateau was exhumed.

Flow measurements in the Devils River measured under relatively high- and low-flow conditions supports the hypothesis that the river is gaining in downstream reaches at a rate that exceeds the added size of the watershed. This characteristic leads to perennial river flow being restricted to only the lower reach of the river. Lastly, water-budget analysis of the Devils River watershed supports the interpretation that essentially all of the recharge to Amistad Reservoir that is derived from the Devils River watershed is contributed as surface flow from the river and that there is minimal underflow or cross-formational flow from the watershed at the point the watershed abuts the reservoir. Recognition of these preferential pathways in proximity to river channels provides a basis to determine where high capacity wells are likely (and unlikely) and suggests that groundwater flow within the watershed is relatively rapid, consistent with flow rates representative of karstic aquifers (Worthington, 2007). This understanding provides a basis for better informed decisions regarding water-resources management in a semi-arid environment.

The Devils River watershed basin in the Edwards-Trinity Aquifer system in south-central Texas was selected to evaluate this interpretation and conceptualization. Although the climate of the Devils River watershed is semi-arid, the watershed is the source for significant water resources that contribute to the Rio Grande. The Devils River watershed basin is representative of a broad class of karst carbonate aquifers in semi-arid environments worldwide. Accordingly, groundwater conveyance mechanisms of importance in the Devils River watershed basin may help characterize similar karst aquifers in other semi-arid environments that provide significant water resources.

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