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Corresponding Author: Dr. Ronald Thomas Green, Ph.D.

Corresponding Author's Institution: Southwest Research Institute

First Author: Ronald T Green, PhD

Order of Authors: Ronald T Green, PhD; Ronald Thomas Green, Ph.D.; Paul Bertetti, MS

Abstract: An efficient conveyance system for groundwater is shown to have formed in a karst aquifer within the Devils River watershed 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 high-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.e., conduits) included: (i) a limestone-rich formation, (ii) hydraulic gradients in excess of 0.001, (iii) recharge focused toward the river channels, and (iv) the likely development of the rivers at locations inclined to have enhanced weathering, such as geologic lineaments or zones of high fracture density. Recognition of these preferential pathways in proximity to river channels provides a basis to locate where high capacity wells are likely (and unlikely) and indicate that groundwater flow within the watershed is relatively rapid, consistent with flow rates representative of karstic aquifers. This understanding provides a basis on which better informed decisions can be made regarding the management of the water resources of a semi-arid environment.

Suggested Reviewers: John Brahana PhD
Professor, Geology, U of Arkansas
brahana@uark.edu
John has experience in karst hydrolgy

Calvin Alexander PHD
professor, geology, University of Minnesota
alexa001@umn.edu
Calvin is a recognized expert in karst hydrology

Art Palmer PhD
Professor, Earth Science, State University of New York
palmeran@oneonta.edu
Art is a recognized expert in karst evolution

John Mylroie PhD
Professor, Geology, Mississippi State University

mylroie@geosci.msstate.edu
John is a recognized expert in speleogenesis

Marcus Gary PhD
Research Scientist, Geology, Edwards Aquifer Authority
mgary@edwardsaquifer.org
Marcus is a recognized expert in karst and the Edwards Aquifer

This paper documents a field investigation and analysis of data for a watershed in a karst terrain located in a semi-arid environment. The paper focuses on the evolution of the permeability structure that was influenced by the tectonic history of the area. The result of regional uplift and concurrent faulting resulted in the development of karst conduits coincident with the river channel structure. Assessment of permeability was predicated on well capacity. A strong correlation between well capacity (i.e., interpreted as enhanced permeability) and proximity to river channels was observed. While this assessment is not conclusive by itself, it does make a compelling argument and can be taken as conclusive when interpreted in context of other data and observations. The characterization provided by this interpretation significantly alters the pre-existing conceptualization of the permeability structure of the aquifer.

Highlights (for review)

- A well-developed groundwater/surface water conveyance system in karst was characterized
- The conveyance system developed coincident with the pre-existing river channel system
- A strong correlation between well capacity and proximity to river channels was detected
- Enhanced permeability conduits formed near river channels during uplift
- River gain/loss studies supported the concept of the conveyance system

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Groundwater Conveyance through Karst Aquifers in Semi-Arid Environments

R.T. Green, F.P. Bertetti, and M.S. Miller. Geosciences and Engineering Division, Southwest Research Institute®

Abstract

An efficient conveyance system for groundwater is shown to have formed in a karst aquifer within the Devils River watershed, 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 high-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.e., conduits) included (i) a limestone-rich formation, (ii) hydraulic gradients in excess of 0.001, (iii) recharge focused toward the river channels, and (iv) the likely development of the rivers at locations inclined to have enhanced weathering, such as geologic lineaments or zones of high fracture density. 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 resources management of a semi-arid environment.

Key Words: groundwater; karst hydrology; water-budget analysis; groundwater conveyence; well capacity; arid-land recharge

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Groundwater Conveyance through Karst Terrains in Semi-Arid Environments

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 the resources are limited and stressed is of critical importance. Due to the unique and complex groundwater hydraulics of karst aquifers, special considerations are warranted when characterizing and managing karst aquifer water resources in semi-arid environments.

Understanding the means and mechanisms by which karst 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 regarding hydraulic properties of a karst-dominated aquifer available for adequate characterization.

It can be a challenge to characterize karst-dominated aquifers that exhibit well-developed preferential flow paths and permeability architectures spanning many orders of magnitude. 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; Mouri and Hallihan, 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 speleogenesis, and an empirical assessment of well capacity. The Devils River watershed in south-central Texas is selected to test this method because it conveys significant groundwater in a semi-arid environment and because it is representative of a broad class of karst carbonate aquifers worldwide in semi-arid environments (Figure 1). Accordingly, characterizing key groundwater conveyance mechanisms in the Devils River watershed may help characterize similar karst aquifers in other arid and semi-arid environments.

Geological and Hydrogeological Setting of the Study Area

The carbonate aquifers in central Texas 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, exhibits aquifer and hydraulic characteristics representative of the greater Edwards-Trinity Aquifer and parts of the Trinity Aquifer, but distinct from the Edwards Aquifer (Figure 1).

The Edwards-Trinity Aquifer covers 200,000 km^2 and is the dominant aquifer in west-central Texas (Barker and Ardis, 1996) (Figure 1). This Cretaceous-age karst limestone comprises the younger, more permeable Edwards Group rocks overlying the older and less permeable Trinity Group (Figure 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.

Geologic mapping is useful in characterizing the hydraulic properties of an aquifer when site-specific studies have not been performed and aquifer characterization is 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 (Figure 3) (Hutchison et al., 2011). Although most hydraulic property assignments are consistent with the mapped geology in Figure 3, some assignments of the hydraulic conductivity values are ambiguous (Table 1).

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.

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 limestone aquifer, in which preferential pathways have developed in the carbonate system, 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.

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.

Factors that controlled conduit development were (i) the degree to which rocks are susceptible to dissolution, (ii) the effective hydraulic gradient, and (iii) the focus of the drainage basin (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 (i.e., >0.001). White and White (2001) concur that hydraulic gradients of 0.001 and greater are entirely adequate to enable the development of conduits and distinct groundwater basins. Alternatively, low hydraulic gradients allow multiple alternate flow paths.

The groundwater conveyance system was developed in the Edwards-Trinity Aquifer during two diverse episodes. The first episode occurred during the middle Cretaceous Period when the

Edwards Group limestones were deposited, subaerially exposed, then buried. The second episode occurred 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). 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. 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). 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 topography channeled water from uplands to the river channels where dissolution was concentrated in the shallow phreatic zone (Abbott, 1975) (Figure 4).

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.

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).

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 branchwork conduits and not maze or multiple-path conduits.

Cave pattern development is also influenced by whether recharge is focused or diffuse (Palmer, 1991). Focused recharge promotes development of branchwork cave patterns with limited limbs. The nature of recharge to the Edwards-Trinity Aquifer is not fully characterized, although the epikarst is hypothesized to contribute to focused recharge in the Edwards and Edwards-Trinity aquifers (Green et al., 2012; Başağaoğlu and Green, 2013). Sinkholes are present in the Devils River watershed basin, which would also contribute to focused recharge. Based on these analyses, conduit formation in the Edwards Group rocks in the Devils River basin would be of the branchwork type with the tendency for few conduits to form.

Speleogenesis and 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). 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 have more poorly developed conduit systems so that groundwater movement is dominated by fracture flow (White and White, 2001).

This variable susceptibility to carbonate dissolution 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 there is greater likelihood of conduit formation in the Edwards Formation 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 rocks of the Trinity Group, particularly where the Trinity Group rocks have increased dolomite content.

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 (Figure 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.

River Channel Groundwater Flow Regime Development

Devils River flow has been measured at two locations at various times during the past 50 years. The Cauthon Ranch gauge located near Juno is in the upper reach near the headwaters. The Pafford Crossing gauge location is located upstream to where surface water has backed up in the

Devils River since the Rio Grande was dammed in 1969, creating the Amistad Reservoir. Tables 2 and 3 list average flow versus drainage area for the two gauge locations for two different periods of record. Table 2 includes all available data at both gauge sites. Table 3 includes data only for the 1964 to 1973 period when data were available for both locations.

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 to 1949 and 1964 to 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 (L/sec)**	**Flow (Mm^3/yr)**
Devils River near Juno	7,164	5,295	168
Pafford Crossing	10,256	10,222	323

Table 3. Average flow (L/sec and mm^3/yr) measured at two gauging locations on Devils River from 1964 to 1973. The Cauthon Ranch near Juno values are the averages of annual measurements. The Pafford Crossing values are the averages for daily measurements.

Gauging Station	**Drainage Area (km^2)**	**Flow (L/sec)**	**Flow (Mm^3/yr)**
Devils River near Juno	7,164	5,295	149
Pafford Crossing	10,256	10,222	294

In both datasets, river flow increased by over 90% (92.6% in Table 1 and 96.5% in Table 2) between the Juno 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 Juno and Pafford Crossing. This observation is consistent with a conceptual model of preferential flow path development in river channels.

Gain/loss surveys can provide a synoptic measure of river flow for the river stage at the time of the survey. A gain/loss survey was conducted under low flow conditions on the Devils River in July 2013 and compared with a published gain/loss survey conducted under relatively higher flow conditions in 2006 (Texas Commission for Environmental Quality, 2006) (Figure 5). With the exception of two minor decreases in measured flow made in 2006 in the upper reach, 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 a monotonic contribution from subsurface channel flow.

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 flow is attributable to contributions from bedrock and not from hyporheic flow through gravel and other riverbed sediments.

Well Capacity Correlated with River Channel Proximity

Well data from the Devils River watershed and an adjoining minor watershed, the Sycamore Creek watershed, were extracted from the Texas Water Development Board driller's database to assess whether the hypothesis of the development of preferential flow paths and enhanced permeability coincident with river channels in carbonate aquifers has merit. The hypothesis is tested by correlating water-well capacity and well proximity to stream channels. This database is the most comprehensive dataset available for the Sycamore Creek and Devils River watersheds that provides some measure of well capacity. Some measure of well capacity is included in 752 of the 2,122 wells in the database . The remaining wells have either no record of capacity or limited capacity. Domestic or stock wells with limited capacity (i.e., less than 75 L/min) are believed to comprise the bulk of the wells with no record of capacity. Limited field checking failed to identify any additional wells with significant capacity that were not included in the subset of 752 wells with a measure of capacity. Locations of the wells in the two watersheds are plotted in Figure 6.

Proper selection of river channels is critical to the correlation of well 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; Rodriguez-Iturbe and Escobar, 1982). Given the high density of incised and intermittent stream valleys within the Edwards Plateau, the correlation of well capacity with proximity to river channels would be biased if stream channels were fortuitously selected to use only those channels proximal to each high capacity well. 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 well capacity was thereby assigned an unambiguous measurement that represented the shortest distance to the closest third-order stream. Wells with no well capacity measurement were excluded from the evaluation.

Well capacity is denoted in Figure 6 by color. The highest capacity wells (> 3,785 L/min) are denoted by a red dot, higher capacity wells (between 1,890 L/min and 3,784 L/min) are denoted by a yellow dot, lower capacity wells (between 378 L/min and 1,889 L/min) are denoted with green dots, and wells with capacity less than 378 L/min are denoted with a purple dot. As illustrated, the majority of wells have capacities less than 378 L/min.

The correlation between well capacity and proximity to rivers is illustrated as a graph in Figure 7. Wells with capacity greater than 1,890 L/min align within 2.5 km of the third-order streams. One exception is a 3,000-L/min capacity well located midway between Devils River and Johnson Draw, with the Devils River being the closest third-order stream at a distance of 4.5 km.

Care must be taken when interpreting well capacity. Although the measured capacity of a well may represent its maximum capacity, it is probably less than the potential maximum capacity of the well at its location. It is possible that a bigger, possibly deeper, well with a larger pump at the well's location would have greater capacity. Regardless, it is significant that out of a dataset of 2,122 wells of which 752 wells were assigned a value for capacity, only one well with capacity greater than 1,890 L/min is located more than 2.5 km from third-order or larger streams. For these reasons, the data in Figure 7 provide compelling evidence that high well capacity is restricted to areas proximal to river channels.

Water-Budget Analysis

The water budget of the Devils River watershed basin has not been well characterized. Although discharge to Lake Amistad is measured, uncertainty remains regarding the size of the recharge basin and the rate of recharge within the basin. Although the Devils River watershed is located in a semi-arid environment, recharge is relatively significant given the amount of water discharged by the Devils River to Lake Amistad (Reeves and Small, 1973; Veni, 1996; Green and Bertetti, 2010). Flow at the Devils River Pafford Crossing gauge located near Lake Amistad is typically referenced as the measure for average discharge from the Devils River to Lake Amistad. This discharge of 324 Mm^3/yr accounts for approximately 16% of the flow in the lower Rio Grande (1,973 Mm^3/yr) (International Boundary and Water Commission, 2005). Precipitation recharge in counties that cover the Devils River watershed basin has recently been approximated at 7.9 to 12.4 mm/yr by Hutchison et al. (2011) using a groundwater model, and at 16.0 to 33.0 mm/yr by Green and Bertetti (2010) and Green et al. (2012) using water-budget analyses (Table 4).

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).

Average annual precipitation from 1971–2000for the Devils River watershed area is mapped in Figure 8.As illustrated in Figure 8, 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 4).

Recharge estimates by Green et al. (2012) are based on an assessment of the western Edwards-Trinity Aquifer in which recharge was shown to correlate linearly with precipitation, but to become negligible when precipitation is less than 400-430 mm/yr. Given these assessments, and adhering to recharge estimates by Green and Bertetti (2010) and Green et al. (2012), an average annual recharge value for the Devils River watershed is estimated to be 18 mm/yr.

Table 4. 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* (mm/yr)**	**Recharge[#] (mm/yr)**
	Range	**Average[§]**		
Crockett	380-530	530	12.4	8.6
Edwards	580-740	530	11.7	33.0
Schleicher	530-580	560	7.9	20.0

County	Precipitation (mm/yr)		Recharge* (mm/yr)	Recharge[#] (mm/yr)
	Range	Average[§]		
Sutton	530-610	530	10.2	25.4
Val Verde	430-530	510	9.9	16.0

* Hutchison et al., 2011; [#] Green and Bertetti, 2010; [§]average precipitation within the Devils River watershed located within each county

Baseflow and surface runoff were separated from flow measurements using the Devils River Pafford Crossing gauge data collected during the period 1960 to 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 countywide 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 to 50% of the water discharged by the

Devils River to the Amistad Reservoir is sourced from outside of the watershed basin. Unless recharge is greater than approximately 23 mm/yr (a recharge value consistent with a watershed area of 10,260 km^2 and recharge discharge to the Amistad Reservoir of 246 Mm^3/yr), these calculations suggest that the groundwater basin that recharges the Devils River watershed extends beyond the boundary of the surface watershed. 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.

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 speleogenesis using empirical data for aquifer hydraulic capacity. Pre-existing representation of the karst aquifer's hydraulic properties based on geologic mapping is reinterpreted using evidence that indicates a strong correlation between aquifer permeability and proximity to higher order river channels. 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 based on well capacity. Stream and river channels with wells that have capacity greater than 1,890 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 1,889 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., 3,785 L/min) and wells in the interstream areas (i.e., < 115 L/m). A map with the refined permeability assignments is presented in Figure 9.

These proposed values can be refined using modeling to better reflect the flow dynamics of a karst aquifer; however, the permeability architecture of preferential flow paths coincident with higher order river channels is believed to be representative of the actual flow regime. This new framework replaces 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.

Conclusions

An efficient conveyance system for groundwater is shown to have formed in a karst limestone 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 limestone formations. A strong correlation between high-capacity wells and proximity to high-order river channels (i.e., within 2.5 km) was used as evidence of preferential flow pathway presence. Factors that contributed to development of the preferential flow paths (i.e., conduits) include (i) a limestone-rich formation, (ii) hydraulic gradients in excess of 0.001, (iii) recharge focused toward the river channels, and (iv) the likely development of the rivers at locations inclined to have enhanced weathering, such as geologic lineaments or zones of high fracture density.

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 discharge to the Rio Grande. The Devils River watershed basin is representative of a broad class of karst carbonate aquifers worldwide in semi-arid environments. Accordingly, groundwater conveyance mechanisms of importance in the Devils River watershed basin may help characterize similar karst aquifers in other arid and semi-arid environments that also provide significant water resources.

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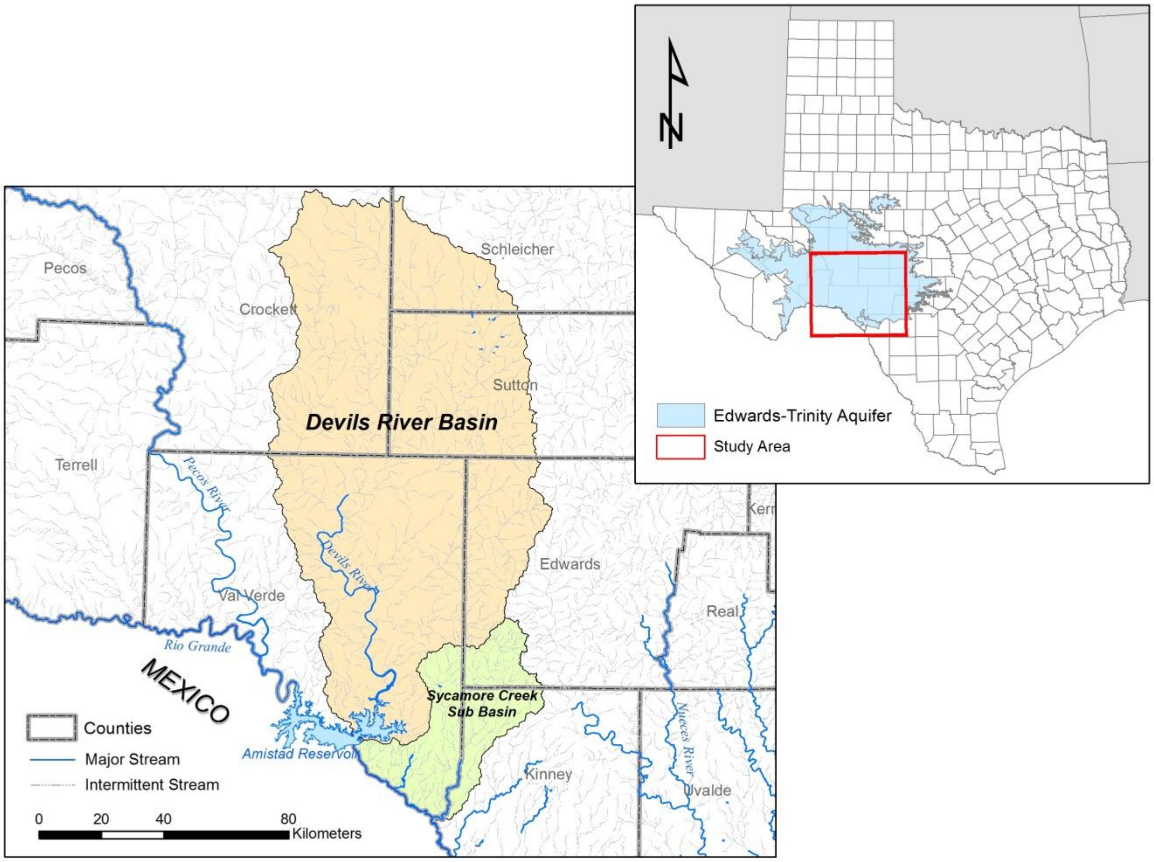

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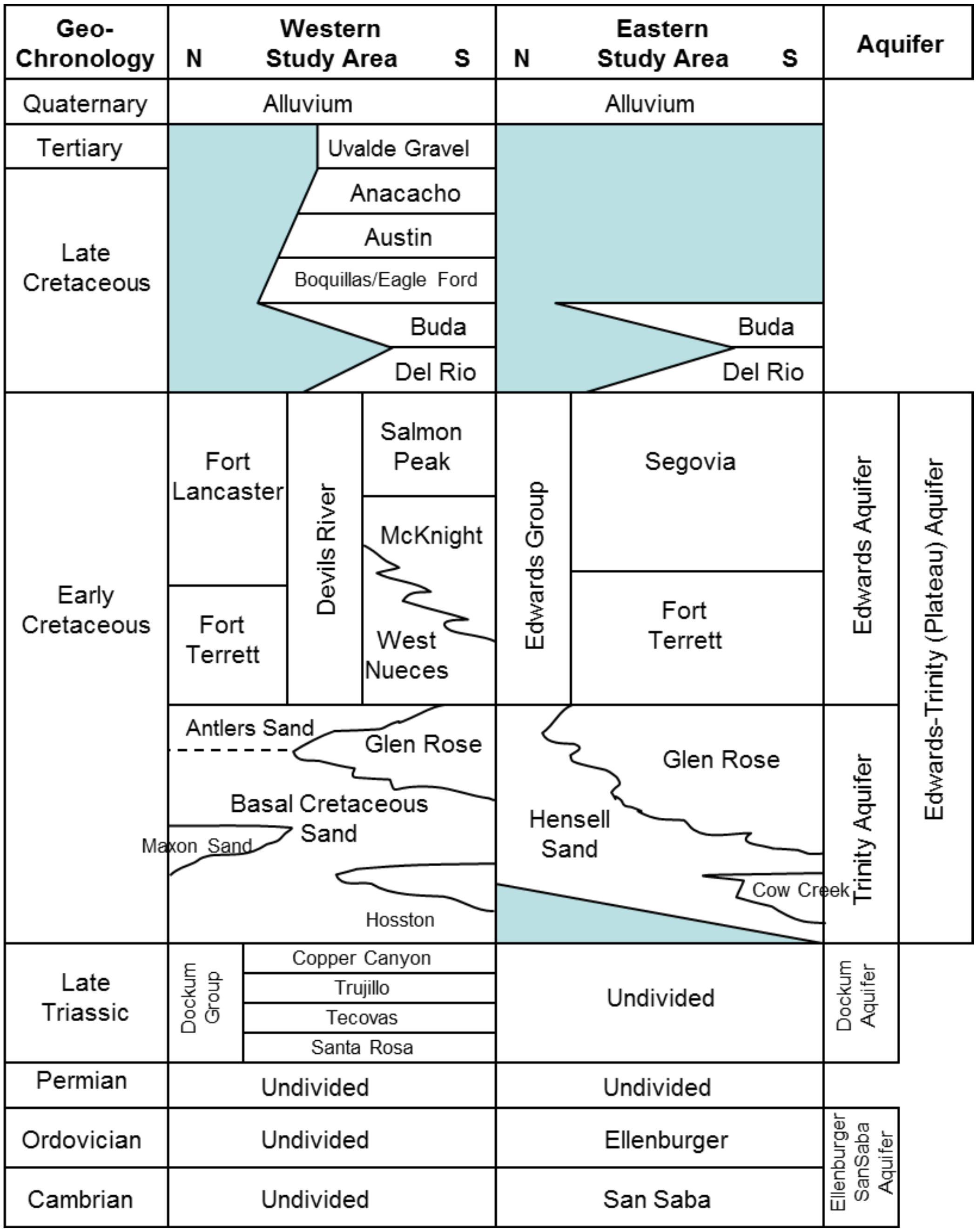

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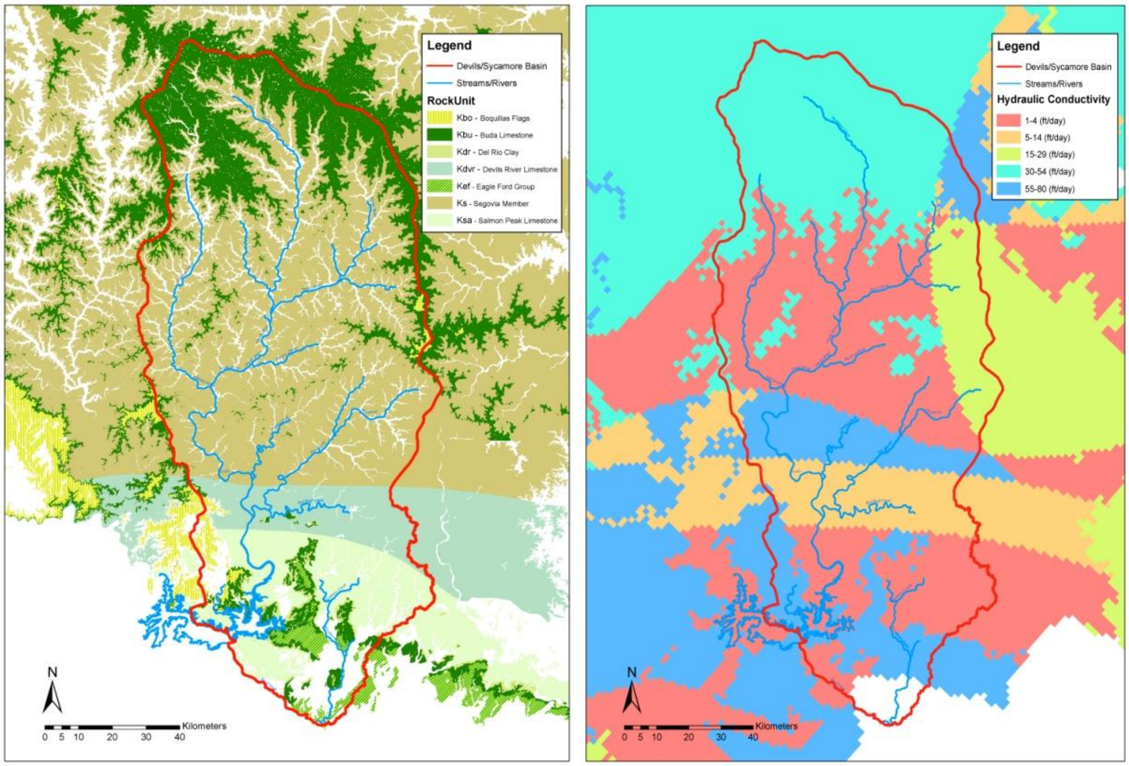

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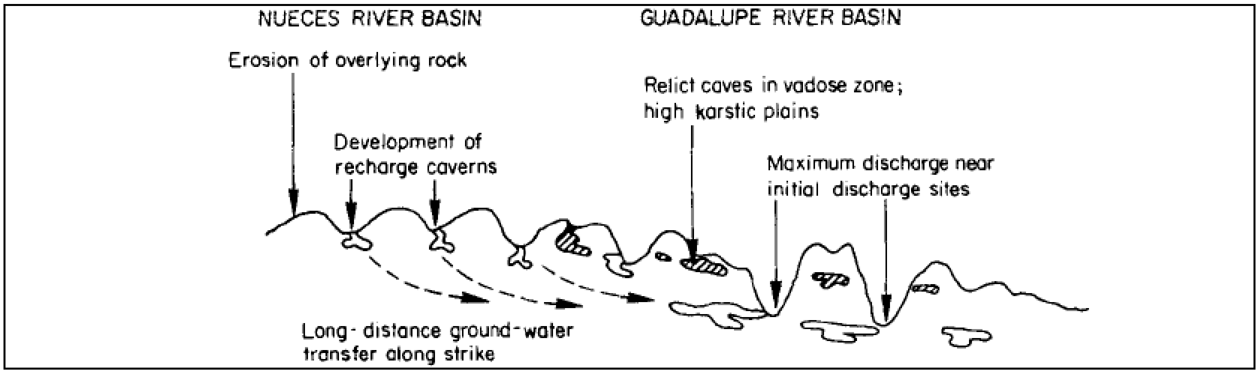

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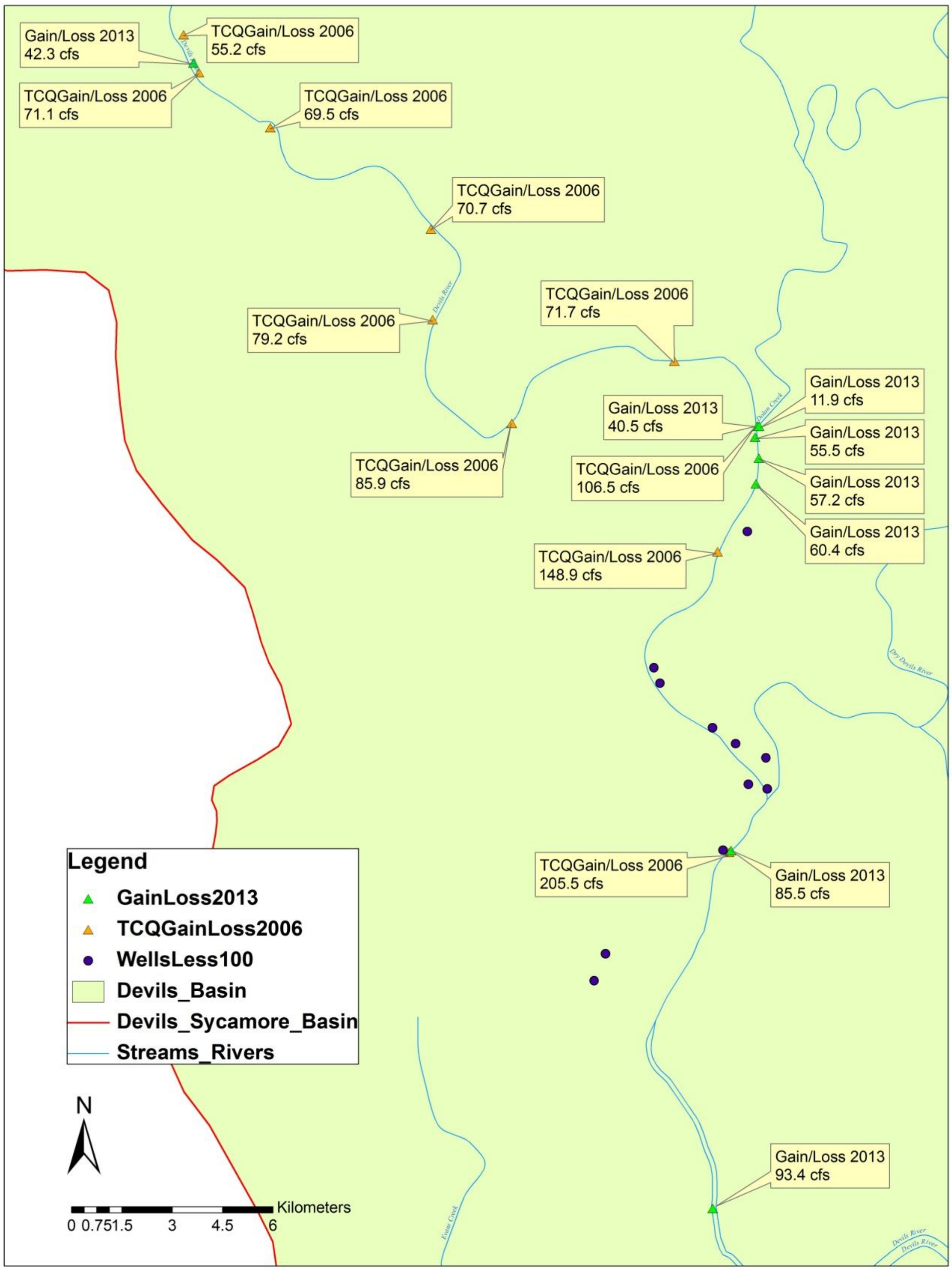

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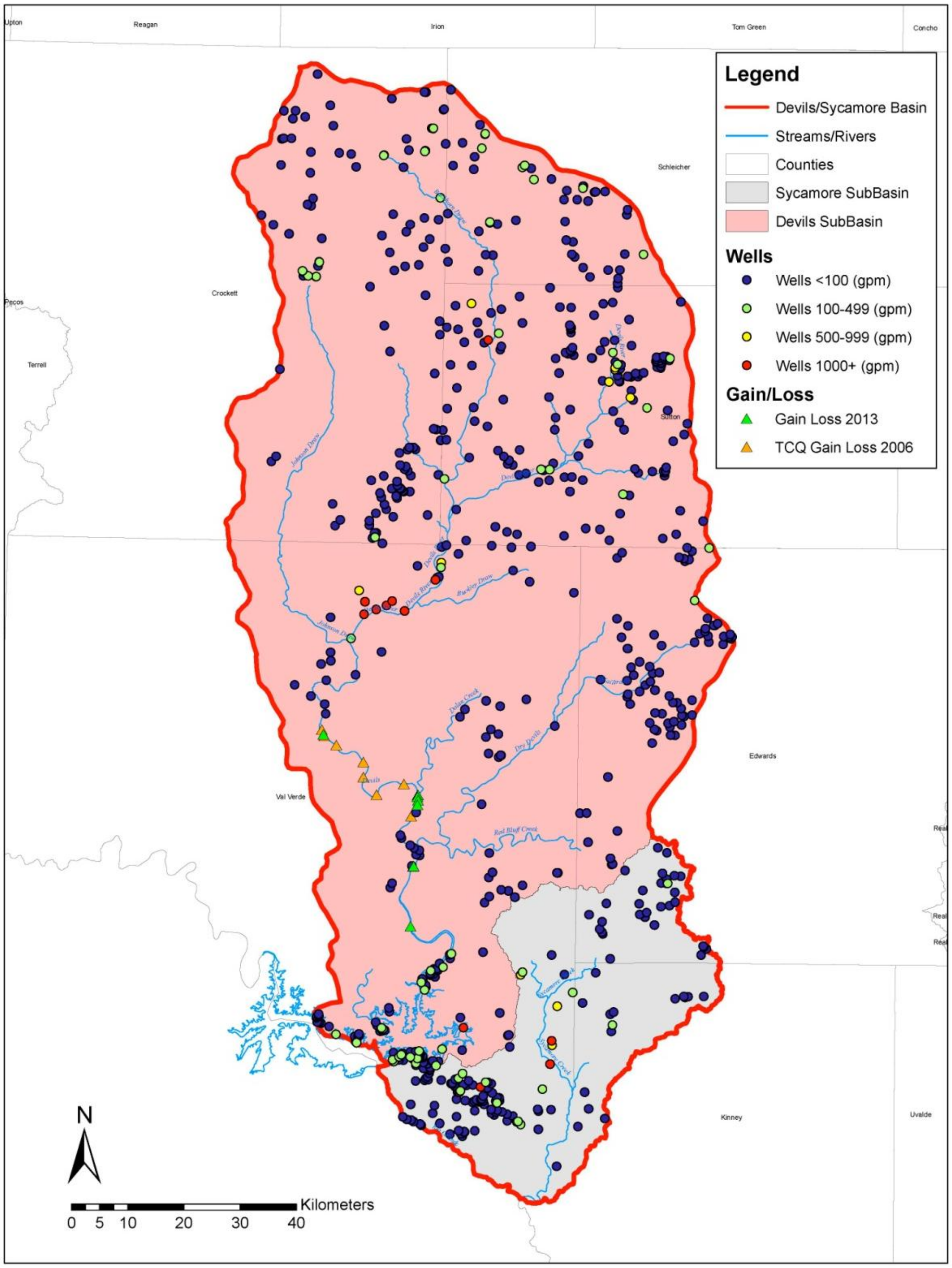

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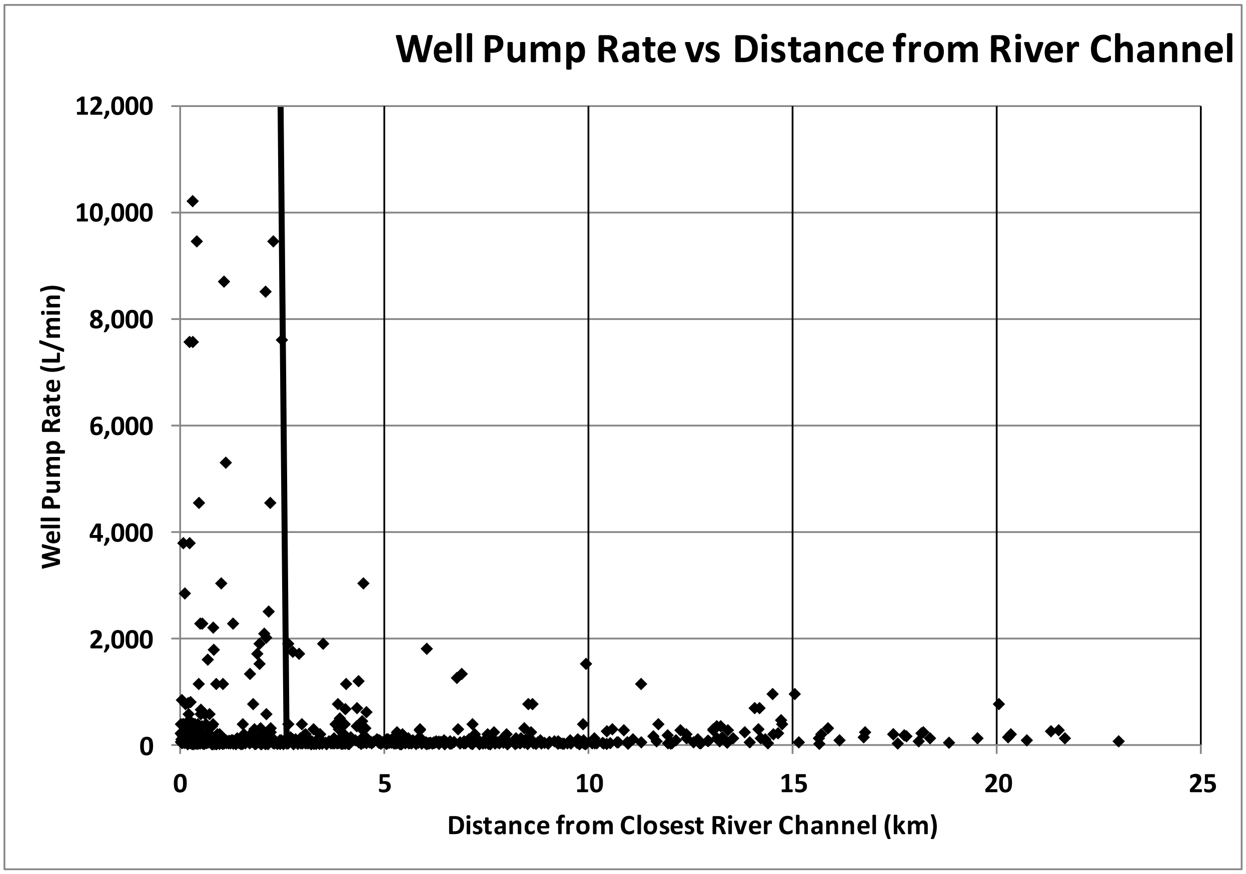

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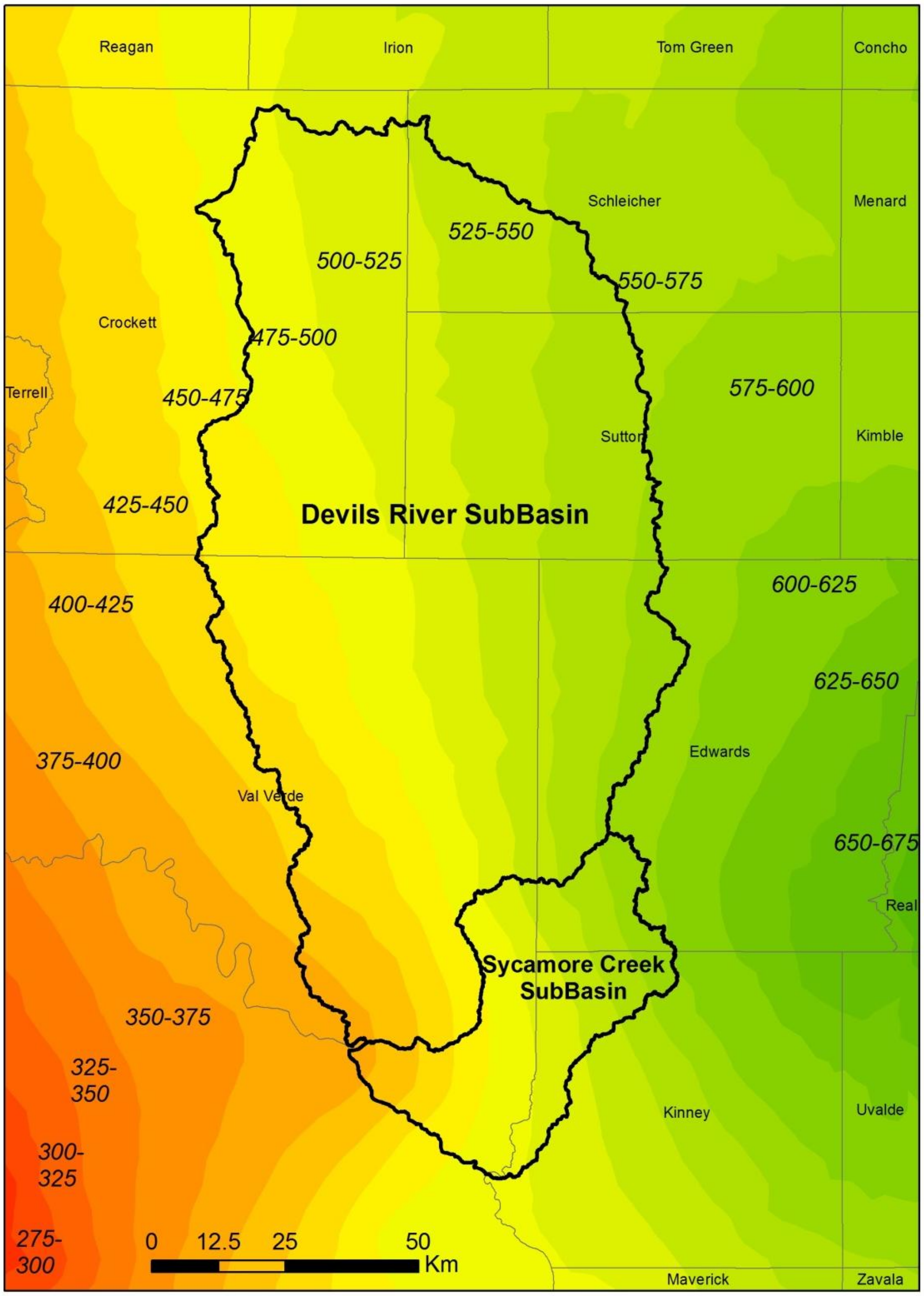

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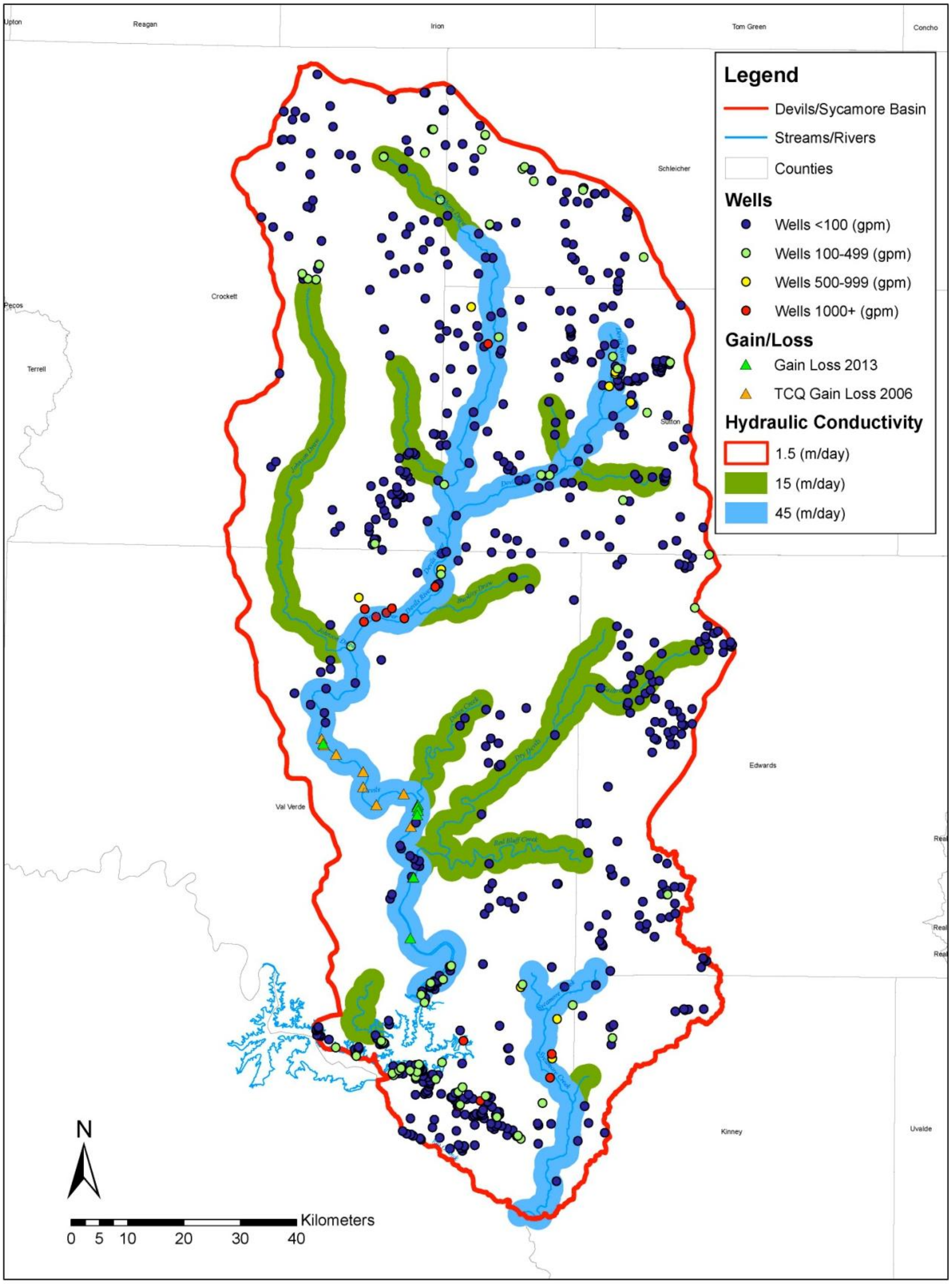

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