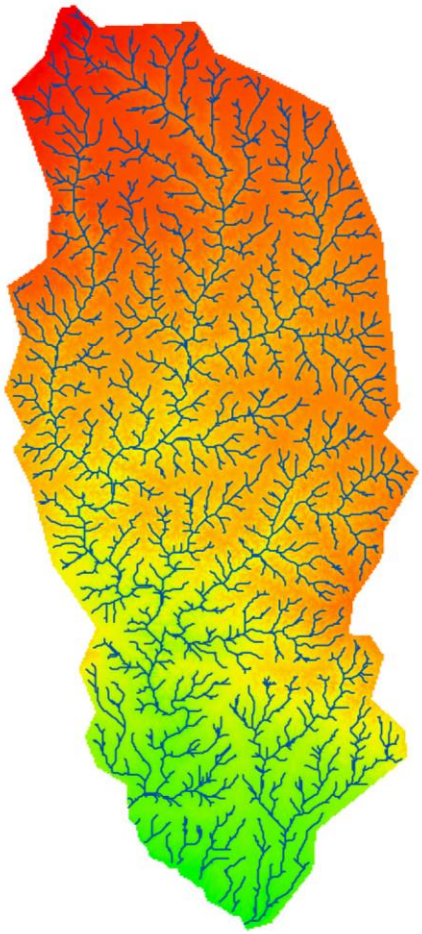
Water-Resource Management of the Devils River Watershed Final Report



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Nathaniel Toll, S. Beth Fratesi, Ronald T. Green, F. Paul Bertetti, and Rebecca Nunu
Earth Science Section
Space Science Division
Southwest Research Institute®

ABSTRACT

The Devils River watershed in south-central Texas has been recognized as one of the remaining pristine rivers in the state. Adding to its importance, the Devils River is a key tributary to the Rio Grande, providing essential freshwater flows to south Texas and the Rio Grande Valley. The Devils River watershed basin is being threatened by proposed large-scale groundwater export projects. This study was undertaken to evaluate what impact groundwater pumping in the upper Devils River watershed would have on downstream discharge in the Devils River.

The watershed is located in a semi-arid environment with modest distributed recharge, oftentimes less than 1-2 cm/year [0.4-0.8 in/year]. The Edwards-Trinity (Plateau) Aquifer of the Devils River watershed is characterized as a karstic carbonate aquifer with preferential flow paths that align with major river channels. Water chemistry, water budget, hydraulics, and geophysical imaging data were used to corroborate this conceptualization.

A coupled surface-water/groundwater model was assembled to replicate the hydraulics of the Edwards-Trinity Aquifer to provide a defensible tool to assess the impact of pumping on river flow. The surface-water model was assembled to determine recharge to the groundwater model. The conduit/diffuse groundwater model replicates both fast conduit flow and slow diffuse flow in the Edwards-Trinity Aquifer. The model provides, for the first time, a numerical groundwater flow model that replicates the hydraulic dominance of preferential flow paths in the karstic Edwards-Trinity Aquifer of the Devils River watershed. The coupled surface-water/groundwater model successfully replicates both flashy flow and low baseflow in the Devils River where it discharges to Amistad Reservoir. In addition, the model exhibits the hydraulic separation of watersheds in the Edwards Plateau, particularly where the aquifer is phreatic.

The coupled surface-water/groundwater model predicted that prior to pumping in the upper Devils River watershed, spring discharge occurred at Beaver Lake which is approximately16 km [10 miles] farther upstream in the Devils River basin from where spring discharge is currently observed (i.e., Pecan or Hudspeth springs). Groundwater pumping in the Devils River watershed is not well constrained and is estimated at 48,000 m^3/day [14,000 acre-ft/year] of which 10,000-24,000 m^3/day [3,000 to 7,000 acre-ft/year] is estimated to occur in the upper portion of the watershed. Decrease in or cessation of spring flow in the Devils River upstream of Pecan or Hudspeth springs is attributed to pumping in the upper Devils River watershed. The impact of additional future pumping near Pecan or Hudspeth springs on the Devils River watershed was found to decrease spring discharge near Pecan or Hudspeth springs and decrease flow in the Devils River where it discharges to Amistad Reservoir. The impact of this potential pumping on Devils River discharge is proportional to the amount of water pumped.

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1 Introduction

The Devils River watershed in south-central Texas has been recognized as one of the remaining pristine rivers in the state (Figure 1). Adding to its importance, the Devils River is a key tributary to the Rio Grande, providing essential freshwater flows to South Texas and the Rio Grande Valley. The 10,259 km^2 [3,961 mi^2] Devils River watershed basin is being threatened by proposed large-scale groundwater export projects. Building on previous work, this project developed an integrated surface-water and groundwater flow model to aid in evaluating how groundwater extractions would impact Devils River flows.

A conduit/diffuse groundwater flow model was previously developed to assess the water resources of the Devils River watershed (Green et al., 2015). Groundwater flow in the karstic Edwards-Trinity Aquifer of the Devils River watershed was conceptualized in this model as dominated by preferential flow paths aligned with the major river channels (Green et al, 2014). This conceptualization has been substantiated using an assessment of stream-flow dynamics, well capacity, subsurface geophysical imaging, water-chemistry, and water-budget analysis. The model provided, for the first time, a numerical groundwater flow model that replicates the hydraulic dominance of preferential flow paths in the karstic Edwards-Trinity Aquifer of the Devils River watershed. In addition, the model exhibited the conceptualized hydraulic separation of watersheds in the Edwards Plateau, particularly where the aquifer is phreatic. This conceptualization is supported by similar conceptualization and modeling of the San Antonio segment of the Edwards Aquifer (Fratesi et al., 2015), a regional karst aquifer whose contributing zone exhibits similar hydraulic relationships to the Devils River watershed.

The conduit/diffuse groundwater flow model developed for the Devils River watershed represents a departure from previous models of the Edwards-Trinity Aquifer that were predicated solely on porous-media groundwater flow (Anaya and Jones, 2004, 2009; Hutchison and Jones, 2010; Hutchison et al., 2011a,b; Eco-Kai, 2014). These porous-media groundwater flow models did not accommodate the rapid and consequential flow dynamics that result from karstic preferential flow within the Devils River watershed nor did they represent the fact that little water flows between adjoining watersheds in the Edwards Plateau as groundwater.

The conduit/diffuse groundwater flow model developed by Green et al. (2015) successfully replicated both conduit and diffuse flow in the Devils River watershed, however it did not accurately replicate Devils River baseflow where it discharges to Amistad Reservoir, particularly during periods of drought or diminished river flow. This limitation in the groundwater-flow-only model is predictable given that virtually all water from Devils River watershed to Amistad Reservoir is discharged as surface water, not groundwater. Although the importance of surface flow to groundwater flow in the Devils River watershed has been previously acknowledged, the inter-relationship between surface-water flow and groundwater flow in the Devils River watershed had not yet been adequately characterized. For these reasons, it is surmised that water-resource management modeling tools applied to the Devils River watershed would benefit if the groundwater-flow model were coupled with a surface-water-flow model. Only when Devils River discharge to Amistad Reservoir is successfully replicated can the model be effectively used to assess the impact of large-scale groundwater pumping on Devils River flow.

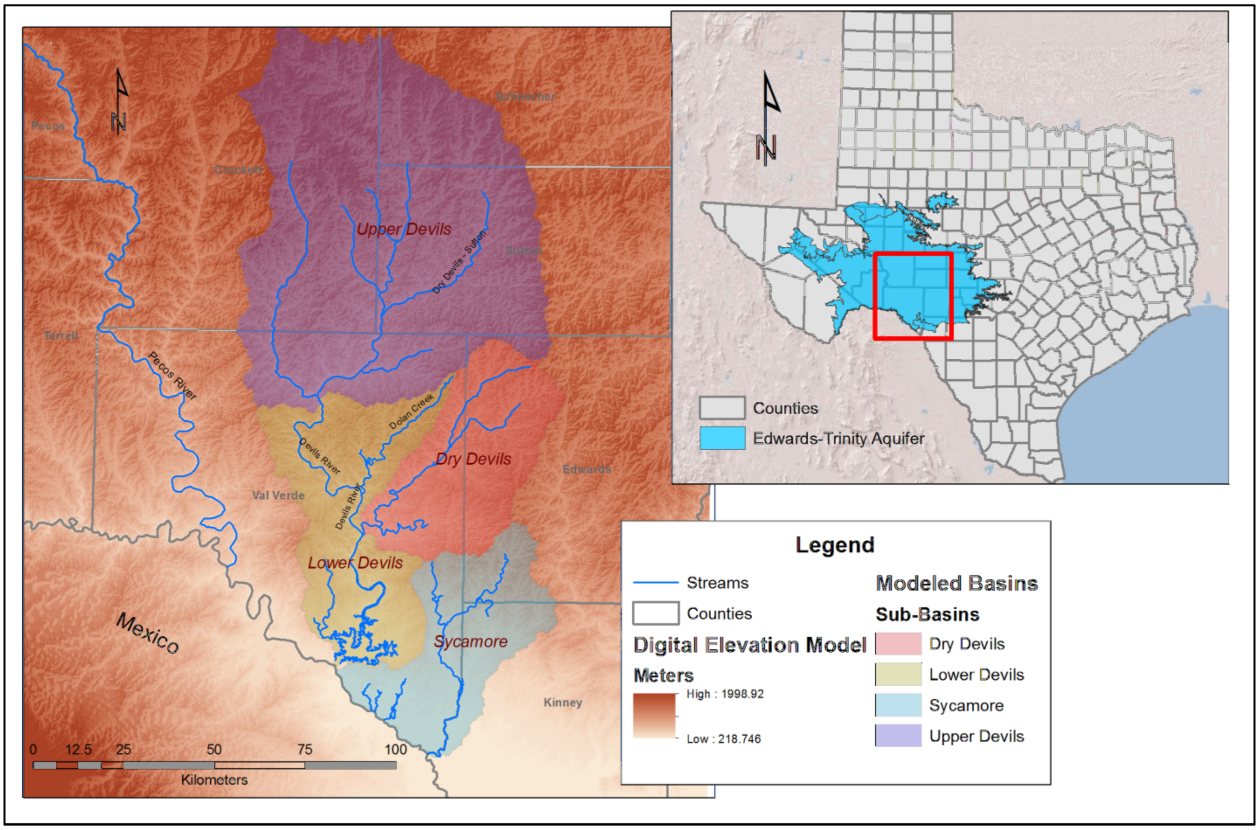


Figure 1. Location map of the sub-basins included in the Devils River basin groundwater model.

This project focused on advancing conceptualization and analysis of the flow dynamics of the Devils River watershed by: (1) development of the surface-water component to the project and (2) refinement in the incorporation of preferential flow paths (i.e., conduits) in the groundwater model. For the model to be an effective tool in simulating integrated groundwater/surface-water flow, it is important that both the surface-water and the groundwater components capture the "flashiness" in river flow where it discharges to Amistad Reservoir and the ability to predict low baseflow during periods of drought.

2 Sustainable Yield

Compounding the challenge of evaluating what impact groundwater extraction from the watershed has on the Devils River is determination of what constitutes the sustainable or safe yield of groundwater extraction from the domain. This concept has been actively discussed and debated for decades (Lee, 1915; Theis, 1940; Bredehoeft et al. 1982; Sophocleous, 1997; Alley and Leake, 2004: Watson et al., 2014; Alley and Alley, 2017). On one end of the debate, development of groundwater is considered safe if the rate of groundwater extraction does not exceed the rate of recharge. The term "safe yield", when defined as the attainment and maintenance of a long-term balance between the amount of groundwater withdrawn annually and the annual amount of recharge, reflects this perspective, but has been discredited as an indicator of sustainability (Sophocleous, 1997). Conversely, sustainable yield can be determined as a function of increased recharge and decreased discharge induced by pumping. A critical aspect to sustainable yield is the effect of pumping on surface-water flow, which highlights the need to effectively characterize both surface water and groundwater in addition to their hydraulic interaction. A general quantitative method to estimate "sustainability" has been elusive, thus sustainable yield is typically calculated using site-specific properties and rates.

3 Background

Significant advances have been achieved in conceptualizing and modeling conduit/diffuse groundwater flow in carbonate aquifers. There are also coupled groundwater/surface-water models in the literature that are successful; however, typically these coupled models have only been used to simulate systems with porous-media aquifers. There are limited documented case studies of coupled groundwater/surface-water models where groundwater is dominated by conduit/preferential flow (Bailly-Comte et al., 2010; Smith et al., 2015; Chen and Goldscheider, 2014; McCormack et al., 2016). The challenge of this project is to develop a coupled groundwater/surface-water model in which groundwater is characterized as a conduit/diffuse flow regime.

Numerical or analytical simulations of groundwater flow through karst media require the ability to accommodate both fast conduit flow and slow matrix flow to effectively replicate the inherent nature of groundwater flow through a karst aquifer (Atkinson, 1977; Jeannin, 2001; Scanlon et al., 2003; Saller et al., 2013). Worthington et al. (2000) gathered data on carbonate aquifers where extensive caves have been found. These data indicated that the matrix provides over 90 percent of the storage of a karst aquifer, whereas, more than 90 percent of the flow is through conduits. Thus, it is important to be able to account for flow in conduit networks and to accommodate mass exchange between conduits and the porous matrix.

Groundwater-flow models for karst carbonate aquifers pose additional challenges compared with models for porous-media aquifers due to the extreme heterogeneity of the hydraulic properties of karst systems, the rapid response of highly conductive karst conduits, and the delayed drainage of the low-permeability fractured matrix after recharge events. The velocity contrast between the least permeable and the most permeable parts in a channeled aquifer is often 6 to 10 orders of magnitude (White and White, 2003). Karst aquifers have been simulated using a variety of approaches such as response functions (Duran et al., 2015) and lumped parameter models (Barrett and Charbeneau, 1997; Halihan et al., 1998; Martinez-Santos and Andreu, 2010), although most approaches are categorized as distributed parameter models. The response function and lumped parameter models do not provide information on potentiometric surfaces and are generally limited to the predictions of spring flows. Distributed parameter models can be classified as continuum models (Harbaugh and McDonald, 1996), double-continuum models (Painter et al., 2006), discrete (Kiŕaly, 2003; Wu et al., 2009), and hybrid models (Abusaada and Sauter, 2013).

Similarly, significant advances in modeling coupled groundwater/surface-water flow regimes have been achieved. Interactions between groundwater and surface water can be complex.

Interactions among climate, landform, geology, and biotic factors need to be synthesized to effectively conceptualize these interactions. Understanding which of these factors and interactions are dominant in the Devils River watershed is critical when conceptualizing groundwater/surface-water dynamics and will facilitate development of numerical tools to simulate flow through the regime.

The state of the science of groundwater/surface-water interactions is discussed in a comprehensive review by Sophocleous (2002). An important characteristic to the Devils River watershed is that the river is gaining throughout virtually its entire reach. Only a small reach south of where perennial flow begins (i.e., near Bakers Crossing) indicates baseflow is losing (Green et al., 2015). Continuous gains in baseflow are attributed to spring discharge fed by preferential flow features. Groundwater is hydraulically connected with surface flow throughout the reach with perennial flow. There is no evidence that a zone of unsaturated flow has formed beneath the riverbed along this reach. Visual inspection of the river indicates limited alluvial sediments are present in the perennial reach of the river. The riverbed is mostly exposed rock with a thin veneer of sediment and limited sand and gravel. There is no evidence that sufficient sediments are available to clog the riverbed. It is unlikely that a disconnected surface-flow regime would form even in the event that dramatic decreases in groundwater elevations were experienced. If groundwater levels were to dramatically decrease, the high degree of hydraulic communication between surface water and groundwater would result in the river going dry.

Devils River baseflow is entirely attributed to groundwater. Baseflow in the Devils River can be responsive to rain events due to the karstic nature of the carbonate aquifer and the presence of preferential flow features. These attributes distinguish the karstic carbonate Edwards-Trinity Aquifer from a classical porous-media aquifer in which transient groundwater flow is subdued. Capturing the dynamic response of baseflow in the river is a prime objective in this project. Conventional or classical conceptual and numerical groundwater/surface-water models developed to simulate subdued changes in baseflow in a porous medium are not equipped to simulate rapid changes in baseflow observed in a groundwater/surface-water flow regime in which groundwater flow is dominated by highly transient conduit flow.

Groundwater Modeling Software (GMS) and Watershed Modeling Software (WMS)(http://www.aquaveo.com/ were used to develop a coupled surface water/groundwater model for the Devils River watershed. The combined GMS and WMS packages are mostly compatible, and offer a range of possibilities to accommodate preferential flow paths in the subsurface, spring discharge into the riverbeds, and flash flow associated with a karst terrain. In addition, the GMS and WMS packages are widely used flow simulators thereby ensuring acceptance by the technical community.

4 Groundwater/Surface-Water Interaction in the Devils River Watershed

As part of the conceptualization that groundwater flow in the karstic carbonate Edwards-Trinity Aquifer in the Devils River watershed is dominated by preferential-flow paths aligned with river channels within the watershed, virtually all discharge from the Devils River watershed to Amistad Reservoir occurs as surface-water flow in Devils River (Green et al., 2014). Discharge as groundwater from the Devils River watershed to Amistad Reservoir is considered negligible. Devils River is recharged by: (i) surface runoff, particularly during large precipitation events and (ii) spring discharge into the riverbed. Thus, during periods of limited or no precipitation when surface runoff is non-existent, all recharge to Devils River is derived from spring discharge. Limited or negligible surface runoff enters the groundwater regime whereas spring discharge is derived from precipitation, which enters the subsurface and eventually arrives at the riverbed via flow through karstic preferential flow paths.

As described in Green et al. (2014), the preferential flow paths are karst features that developed in alignment with river channels over long periods of time. The specific morphology and alignment of the flow features are not fully defined; however, corroborating evidence indicates the features are located in close proximity (i.e., within 1-2 km [0.5-1.0 miles]) of the rivers and major tributaries and at relatively shallow depths (i.e., 30-45 m [100-150 ft]). It is surmised that the preferential flow features have formed concomitant with depositional bedding (Green et al., 2015).

Stratigraphic units within the watershed have relatively uniform thicknesses that increase and dip to the south (Barker and Ardis, 1996). Riverbed elevation decrease to the south at a rate of 3 m/km [15 ft/mile] (0.3 percent) when measured over a straight line from the inception of the river channel in Schleicher County to the point of discharge at Amistad Reservoir. The actual river gradient is less than 0.3 percent due to the circuitous route taken by the river. Conversely, dip in the surface of the stratigraphic units in the watershed is less than the dip of the riverbed. Because of this discrepancy in dip, the riverbed of the Devils River incises to a greater depth into the stratigraphy in the south compared with the north. Thus, preferential flow features concomitant with bedding form springs where preferential flow features are intersected by the riverbed as the river flows south (Figure 2). This conceptualization is believed to explain the high density of springs in the riverbed of the Devils River. An additional observation supporting this conceptualization is the tendency for springs to be located where the river cuts deeper into the stratigraphy at locations where the river course cuts back into the dip of the layers (Figure 3). Perennial flow in the river begins where preferential flow features that are below the phreatic surface intersect the riverbed. Thereby, the point at which live water is present in the riverbed can migrate upstream and downstream in response to a changing water table.

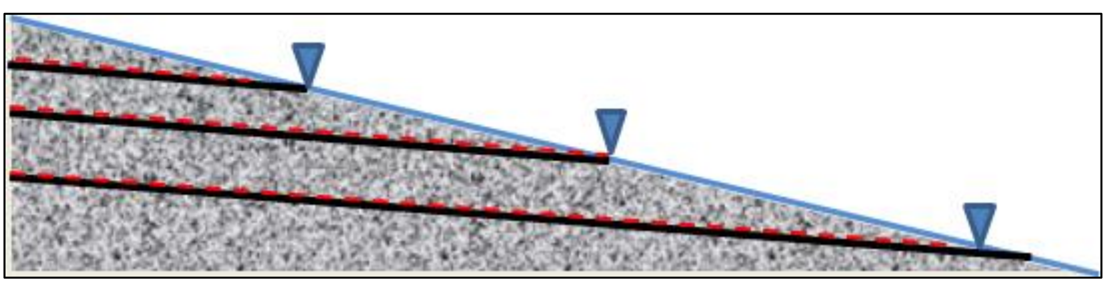


Figure 2. Schematic of hypothesized intersection of preferential flow paths with riverbed at locations where the riverbed incises into the lower stratigraphic units. Black lines denote stratigraphic unit surfaces. Blue line denotes riverbed surface. Red dashed lines denote preferential flow path development along stratigraphic surfaces. Inverted triangles denote spring locations in riverbed. [Not to scale, vertical dimension exaggerated.]

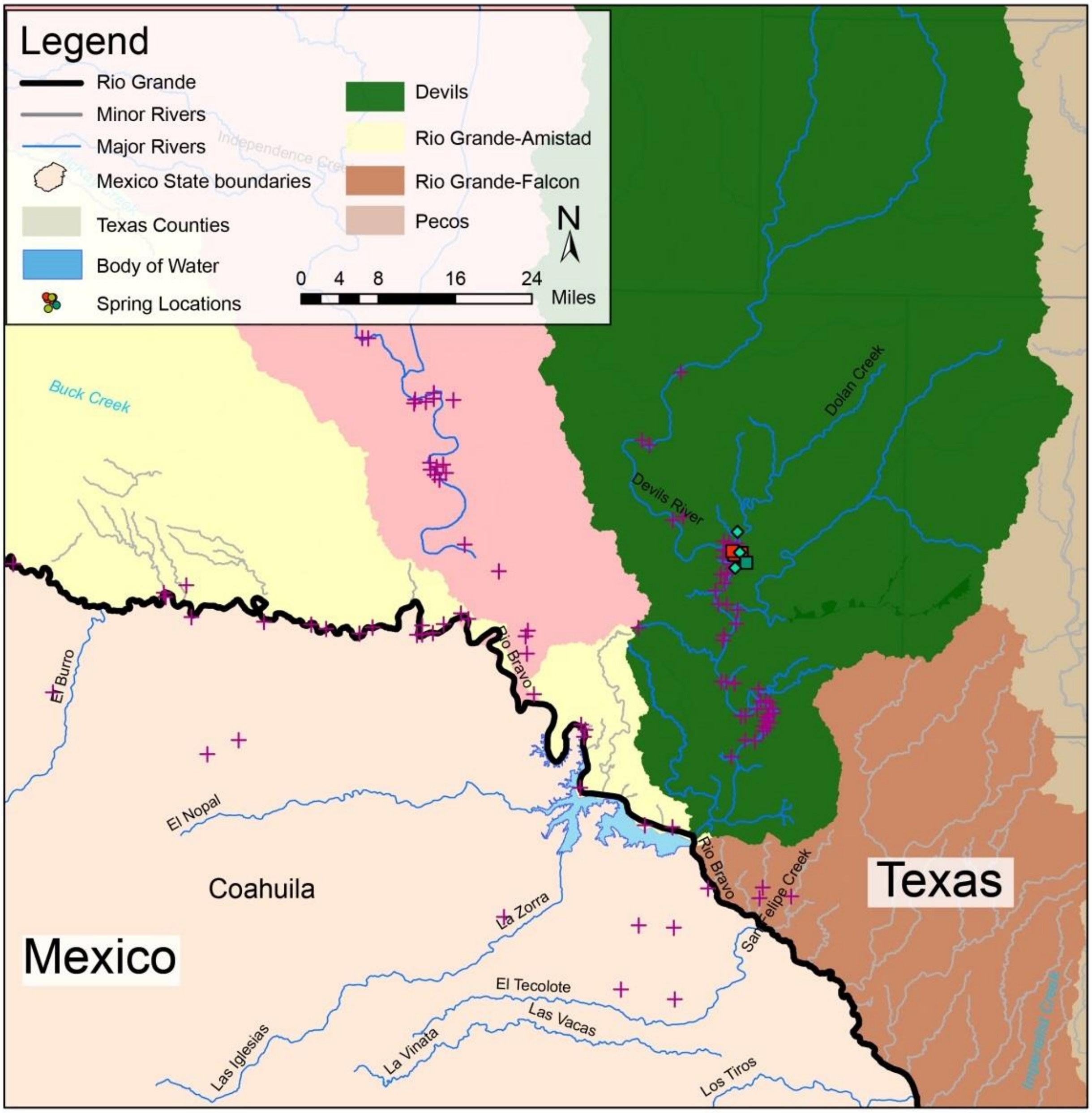


Figure 3. Spring location in the lower Devils River watershed, lower Pecos River watershed, along the Rio Grande, and northern Mexico near Amistad Reservoir. Watershed basins are discriminated by color. Springs are denoted with an +.

The integrated groundwater/surface-water model is built upon the hydrostratigraphic framework developed for the conduit/diffuse groundwater flow model (Green et al., 2015). Coupling groundwater with surface-water flow poses temporal challenges due to vast differences in response times of the different flow mechanisms. Surface-water fluctuations can occur rapidly in response to high-intensity rain events. In these cases, river hydrographs can literally spike in minutes. In contrast, responses in groundwater located distal to preferential flow paths occur over much longer time periods, days to weeks to even months. It is recognized that the hydraulic response of conduit flow in a karst aquifer is much more rapid than the hydraulic response of a porous-media aquifer.

An additional challenge in modeling a karst aquifer is that the time required for water to ingress or egress from the matrix to the conduit is significantly greater than the hydraulic response of flow in a conduit. Thus, three separate timeframes are encountered when modeling groundwater/surface-water interactions in a karst aquifer: (1) the rapid response of surface-water flow in river channels; (2) the relatively quick response of groundwater flow in karst conduits; and (3) the relatively slow response of flow between the matrix and conduits that occurs during the ascending or descending limbs of a hydraulic pulse in a conduit. In summary, the hydraulic response of surface-water flow typically ranges from minutes to hours, the hydraulic response of conduit flow typically ranges hours to days, and the hydraulic response of matrix-to/from-conduit flow typically ranges from days to months.

5 Model Domain

The model domain covers the Devils River watershed (Figure 1). The water resources of the Devils River watershed are relatively abundant for a semi-arid environment. Past investigations of the Devils River watershed were typically included as parts of studies of Val Verde County which includes the lower Devils River watershed. These investigations only included the downstream portion of Devils River watershed (Reeves and Small, 1973; Eco-Kai, 2014). Less common are investigations of the headwaters of the Devils River watershed, which extend north into Crockett, Sutton, and Schleicher counties. Most studies of these headwaters were regional in scale and did not provide insight on individual watersheds (Barker and Ardis, 1992, 1996; Kuniansky and Holligan, 1994; Kuniansky and Ardis, 2004; Green and Bertetti, 2010; Green et al., 2012).

Only the lower Devils River watershed is included in the water-resource assessment of Val Verde County by Reeves and Small (1973). Approximately 24.48 m^3/sec [626,000 acre-ft] is annually discharged to Amistad Reservoir in Val Verde County. This is a significant quantity of water, given the low average annual precipitation (i.e., 450 mm/year [18 in/year]) and correspondingly low recharge. 17.91 m^3/sec [458,000 acre-ft/year] of this is discharged to Amistad Reservoir and the Rio Grande as surface water via the Devils and Pecos rivers (Reeves and Small, 1973 updated with International Boundary and Water Commission and United States Geological Survey river gauge data, [Figure 4] of which an average of 10.29 m^3/sec [263,000 acre-ft/year] is from the Devils River). A total of 6.57 m^3/sec [168,000 acre-ft/year] is discharged from Goodenough and San Felipe springs to the Rio Grande (Reeves and Small, 1973). In contrast, recharge in Val Verde County by precipitation is estimated to be only 2.62 m^3/sec

[67,000 acre-ft/year] (Hutchison et al., 2011b) to 4.25 m^3/sec [108,600 acre-ft/year] (Green and Bertetti, 2010; Green et al., 2014). These approximations suggest that 83 to 89 percent of the water discharged in Val Verde County is sourced from outside the county.

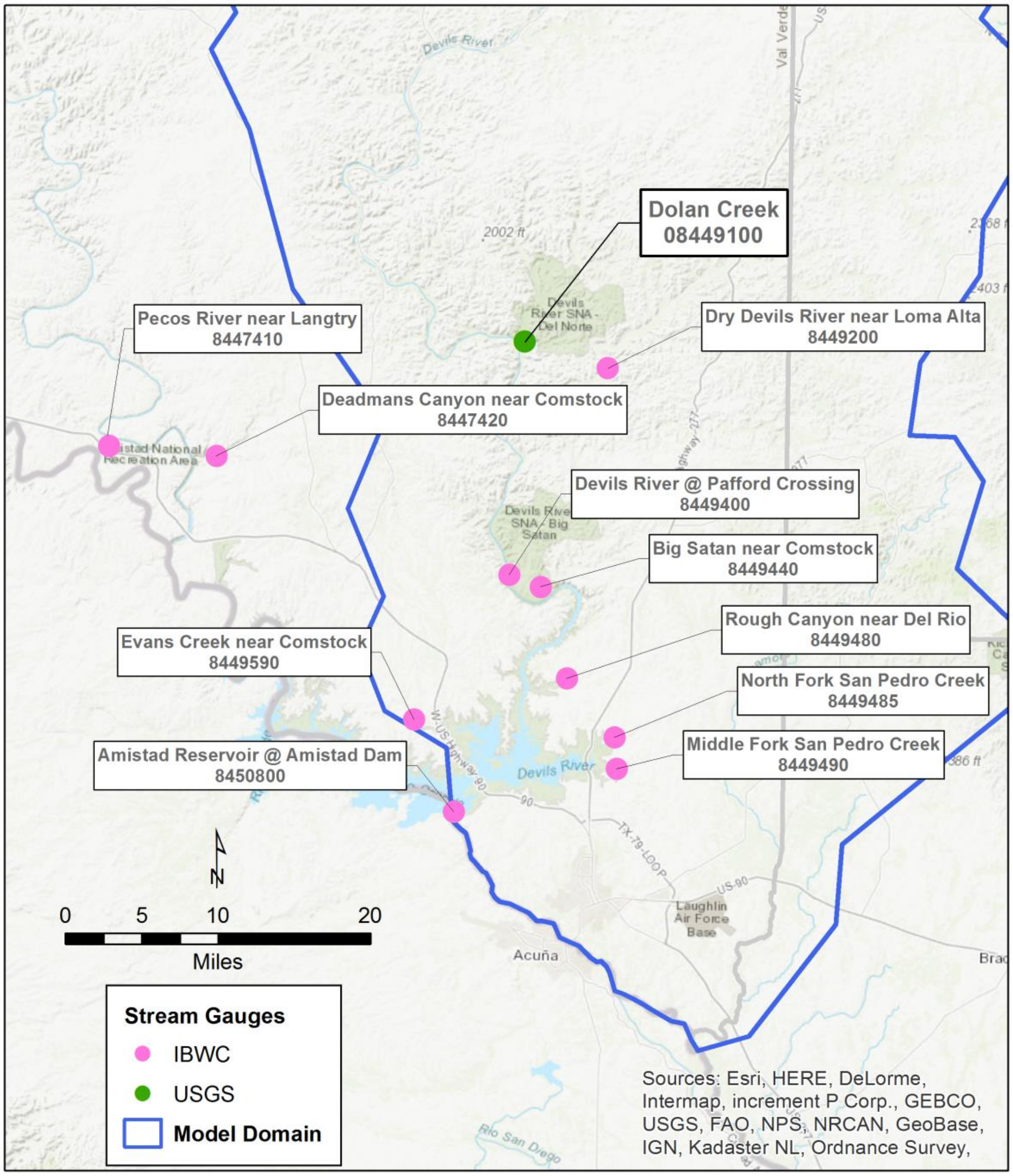


Figure 4. Locations of International Boundary and Water Commission flow gauges within the study domain.

Texas Water Development Board assessments of pumping and recharge in Val Verde County and bordering areas are inconsistent (see Green 2012a, b, c, d for discussions of the inconsistencies in Donnelly, 2007a, b; Hutchison and Jones, 2010; Hutchison et al., 2011a,b; Shi, 2012a, b; French et al., 2012; Veni, and Associates, 1996). Water-resource assessments for Kinney County, in particular, are highly variable. Although Kinney County is not within the domain of this study, this inconsistency is relevant to Val Verde County because many of the models and analyses used to assess the water resources of Kinney County are the same as those used for Val Verde County (Hutchinson and Jones; 2010; Hutchinson et al., 2011a, b). Estimates for historical pumping in Kinney County of less than 0.274 m^3/sec [7,000 acre-ft/year] (Donnelly, 2007a, b) are consistent with Texas Water Development Board calculations based on crop use (documented in Green 2012a, b, c, d), but significantly less than claims of historical pumping, as high as 2.54 to 6.26 m^3/sec [65,000 to 160,000 acre-ft/year] provided to the Texas Water Development Board by the Kinney County Groundwater Conservation District (Hutchison and Jones, 2010; Hutchison et al., 2011a, b; Shi, 2012a, b; French et al., 2012). Groundwater models that incorporate unreasonably high estimates of pumping in Kinney County can provide distorted predictions of aquifer performance that extend into Val Verde County.

Additional information on Crockett, Sutton, and Schleicher counties was extracted from Inglehart (1967), Standen and Kirby (2009), and Muller and Couch (1971). Pumping estimates for Val Verde, Crockett, Sutton, and Schleicher counties were taken from the Texas Water Development Board water-use survey database in its water planning section and planning documents for the Sutton County Underground Water Conservation District (Sutton County Underground Water Conservation District, 2013). With the exception of pumping for domestic and livestock purposes, pumping in the upper reaches of the Devils River watershed is limited to the City of Sonora and a few irrigation wells near Devils River and possibly Johnson Draw in northern Val Verde County and southern Sutton County.

In the coupled surface-water/groundwater model, the groundwater model receives its recharge from the surface-water model. To provide recharge to all parts of the groundwater model, the surface-water model was expanded to nearly match the domain of the groundwater model (Figure 5). The surface-water model domain includes that part of the Devils River watershed south of the gauge station at Pafford (most of which runs off directly into Amistad Reservoir; outlined in yellow, Figure 5), as well as several smaller watersheds to the south of the Devils River watershed, i.e., Sycamore Creek watershed. These areas are included in the groundwater model because of the interest to export groundwater from this region, even though they are not formally in the Devils River watershed. These watersheds are assigned meteorological and hydrological parameters that are consistent with those assigned to the calibrated Devils River watershed. The original surface-water model domain comprised 10,098 km^2 [3,899 mi^2]. The additional nine basins added 2,580 km^2 [996 mi^2], most notably the Sycamore Creek watershed (outlined in purple, Figure 5), so that the final surface-water model domain covers 12,678 km^2 [4,895 mi^2].

6 Geochemistry

The Edwards-Trinity (Plateau) Aquifer is the primary aquifer in the Devils River watershed. Previous conceptual models of recharge in the area suggest that there is significant influence from the less permeable Buda Limestone that caps the tablelands and that high permeability flow zones have developed preferentially along existing stream channels. Using geostatistical and geochemical models, recent geochemical data collected by the Sutton County Underground Water District and historical data from the Texas Water Development Board's groundwater database have been analyzed in an effort to characterize groundwater chemistry within the Devils River watershed and to test conceptual models of recharge and flow in the region. Plotted data include Total Dissolved Solids, bicarbonate, and calcium (Figures 6-8).

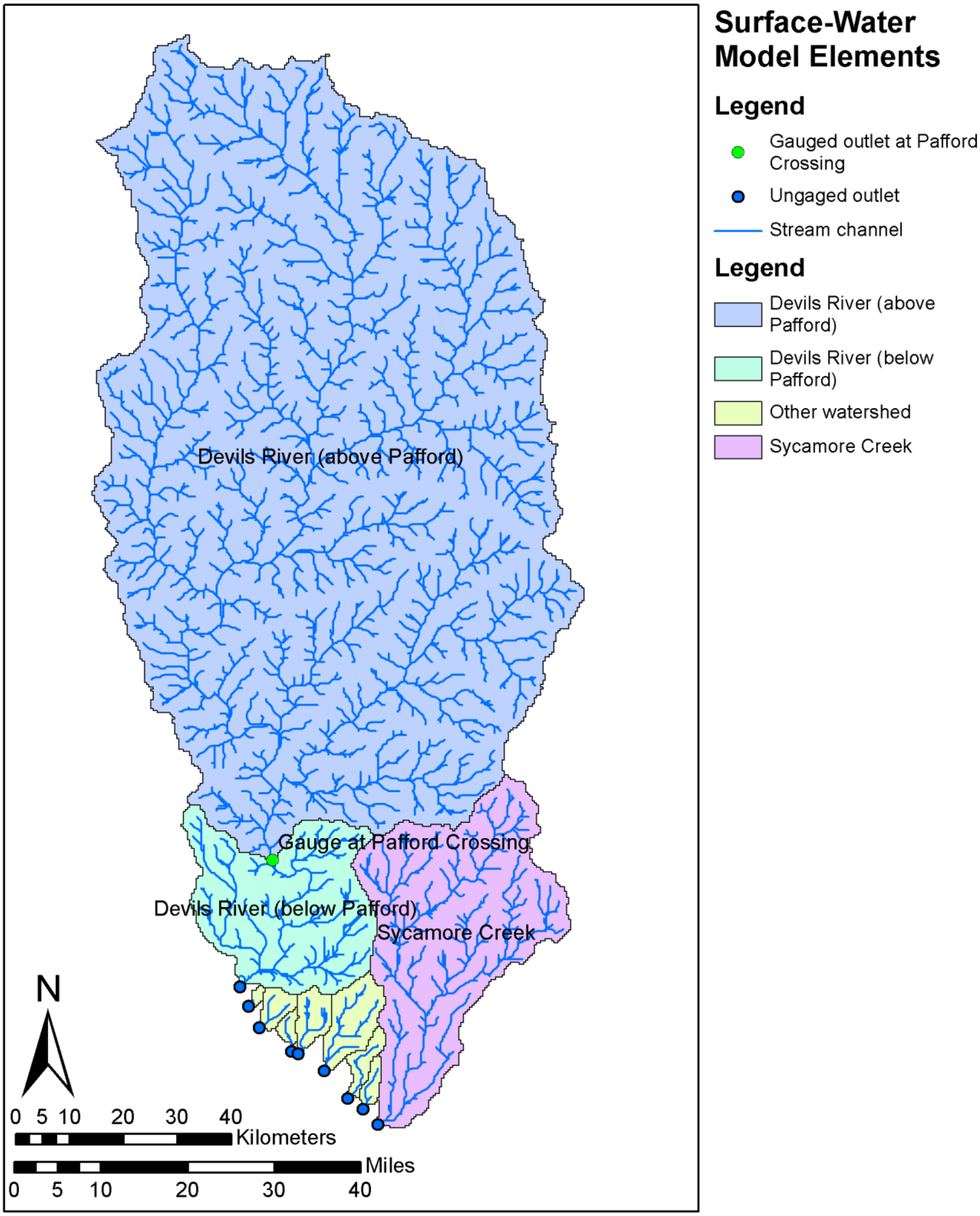


Figure 5. Expanded surface-water model domain, approximating the groundwater model domain.

These water-chemistry plots show distinct variations in geochemistry that are likely related to mechanisms of recharge and potential interactions between the Trinity and Edwards strata. Some of the geochemical trends are counterintuitive. For example, calcium and bicarbonate concentrations are highest in proposed recharge areas and are closely aligned with the Dry Devils River (Sonora), Johnson Draw, and Dry Devils River (Val Verde) channels. The data and analyses can be interpreted to suggest that the Glen Rose Limestone may act as a barrier to interformational flow from deeper groundwater.

Of particular interest to this project, is that water-chemistry variations, particularly evident in bicarbonate concentrations, but also apparent in Total Dissolved Solids and calcium concentrations, align with suspected conduit locations. This independent line of evidence corroborates the conceptualization of conduit placement predicated on geophysical-field survey and dye-tracer test results. Conduit location designation in the groundwater-flow model remains uncertain; however, water chemistry results help reduce the level of uncertainty.

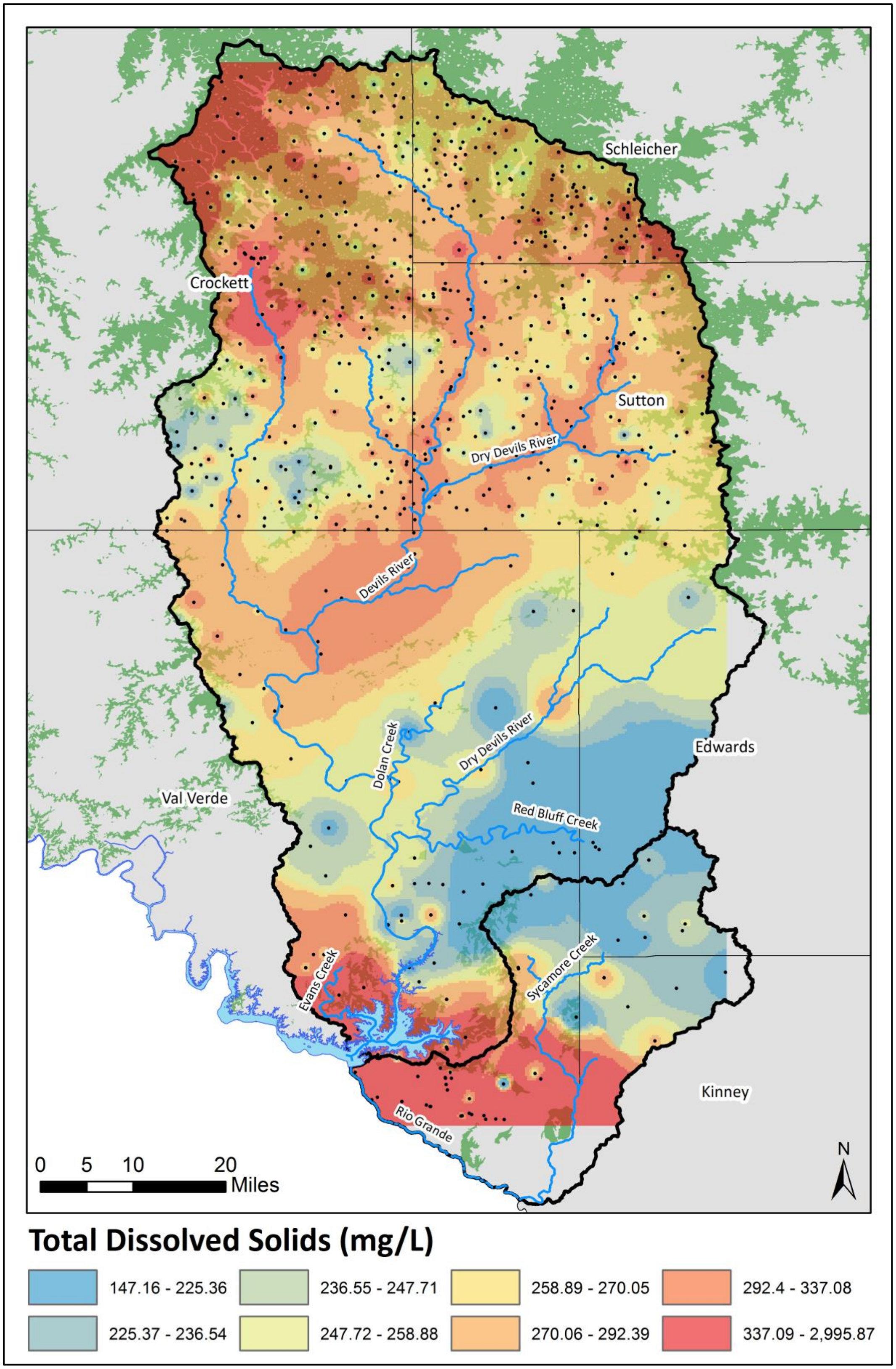


Figure 6. Total dissolved solids concentrations in the study area.

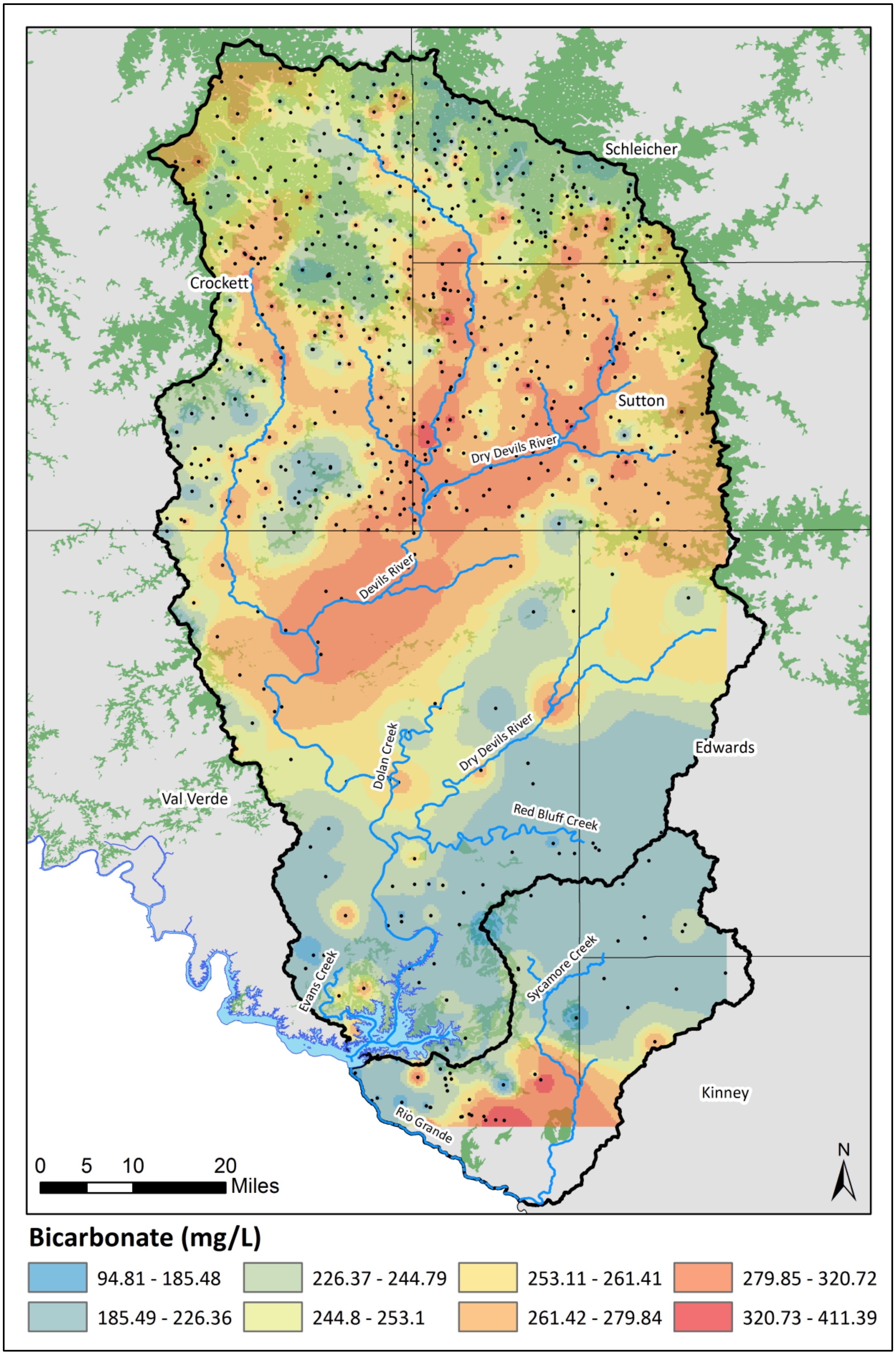


Figure 7. Bicarbonate concentrations in the study area.

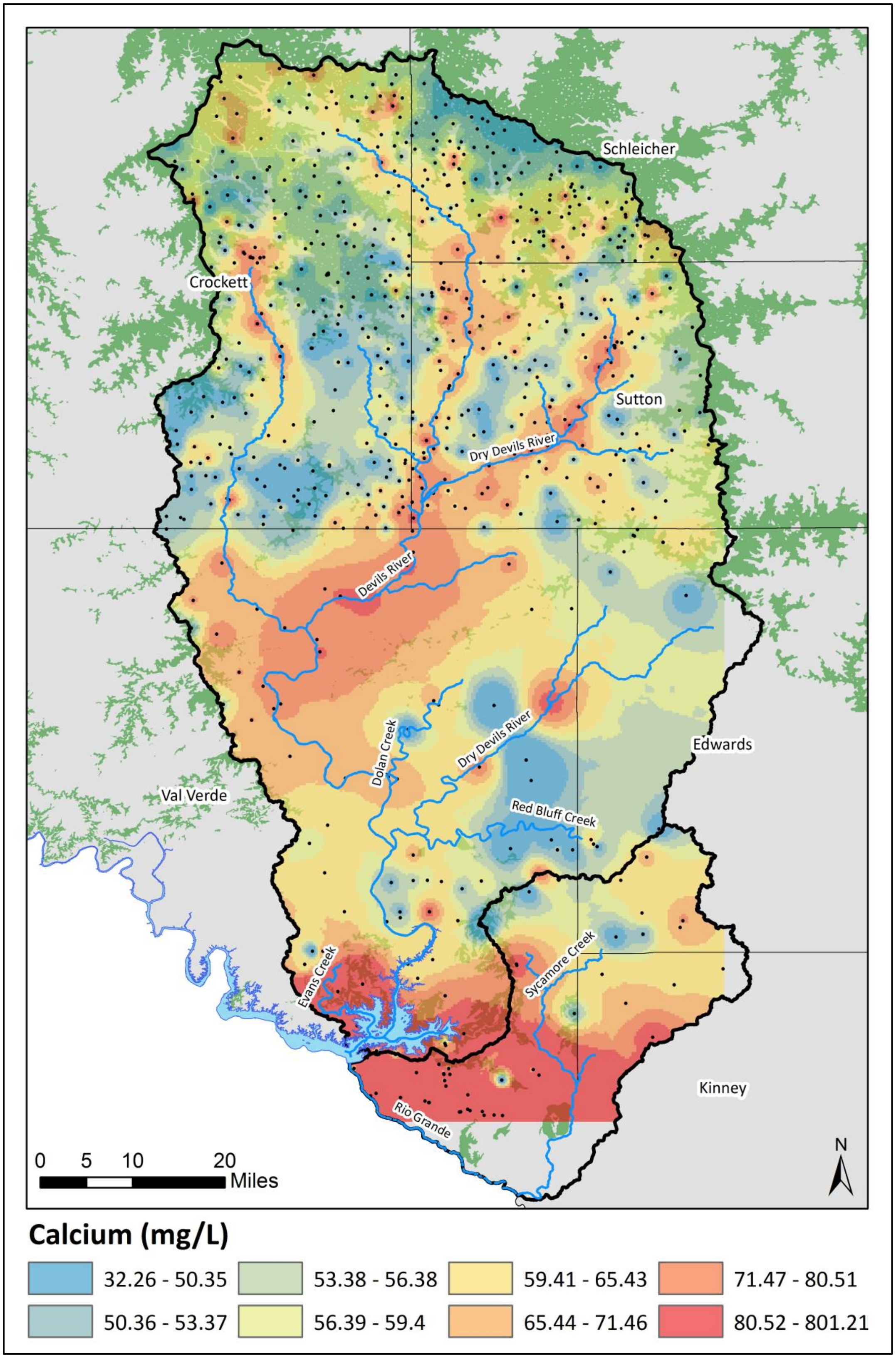


Figure 8. Calcium concentrations in the study area.

7 Development of Surface-Water Model

The surface-water model was developed to capture river-flow conditions and model land-surface processes, providing recharge to the groundwater model. The surface-water model covers the same domain as the groundwater model, coinciding closely with the extent of the Upper Devils River, Lower Devils River, Dry Devils River, and Sycamore Creek subbasins (Figure 1). The target for the surface-water model calibration is the direct discharge of the Devils River at the Pafford Crossing gauge (Figure 4). Direct discharge is that portion of river flow attributed to runoff, excluding the baseflow component. Recharge to the groundwater model is also calibrated indirectly via the groundwater model and is considered the more critical calibration target.

The surface-water model is constructed using Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), a semi-distributed, surface-water modeling program developed by the U.S. Army Corps of Engineers. Aquaveo's Watershed Modeling System (WMS) program allows HEC-HMS to easily incorporate distributed model parameters, resulting in increased ability to control contributions from different areas of the catchment. Rainfall, land-use, ground slope, and soil-type data are imported on a gridded basis. Surface-water hydrologic parameters, losses to evapotranspiration, and groundwater recharge are calculated on a gridded basis by the model. This allows recharge to be exported to the groundwater model as spatially distributed data.

Prior to development of the final surface-water model, six month-long preliminary models with spatially homogeneous parameters were constructed and calibrated to test the loss methods and initial parameters for the final model. The model domain for these models was the portion of the watershed that feeds the stream gauge at Pafford Crossing. A final surface-water model covering the years 2000-2015 was constructed with spatially varying parameters and was coupled with the groundwater model by designating infiltration from the surface-water model as recharge to the groundwater model.

7.1 Loss Method

The rainfall-runoff model first separates out that part of the precipitation that is "lost" to processes such as interception by vegetative canopy, surface ponding, infiltration, evapotranspiration, and percolation. The conceptual model of loss used here incorporates two elements: an initial abstraction and a continuous loss (Figure 9). The initial abstraction accounts for wetting of soil and vegetation and pooling of water in surface depressions. No runoff occurs until this initial abstraction is completely filled. A small rainfall event may, therefore, not generate any runoff. Some loss methods treat this initial loss as a storage "bucket" that can be reset by evapotranspiration; these loss methods are useful for modeling multiple storm events.

After the initial abstraction is fulfilled, runoff begins. Continuous loss is then applied. This loss represents water that ultimately goes to evapotranspiration or percolation to groundwater. Not all of the loss methods explicitly accommodate these individual components.

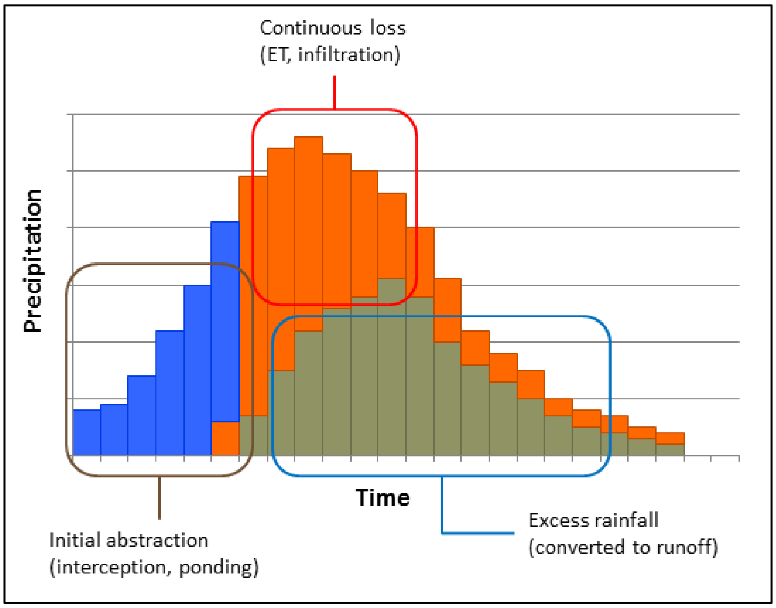


Figure 9. Illustration of loss method applied to precipitation hyetograph.

7.1.1 SCS Curve Number Method

The preliminary surface-water models incorporate the SCS Curve Number method as a comparison for selection of a loss method for the final model. Developed by and named after the Soil Conservation Service (SCS, now the United States Department of Agriculture Natural Resources Conservation Service [USDA NRCS]), the method is an empirical method developed by extensive study of small catchments and experimental plots (USDA NRCS, 2004a,b).

In the SCS Curve Number method, runoff is calculated as follows (USDA NRCS):

$$\boldsymbol{Q} = \frac{(\boldsymbol{P}-\boldsymbol{I_a})^2}{(\boldsymbol{P}-\boldsymbol{I_a})+\boldsymbol{S}} \quad \textbf{(1)}$$

where:

Q = runoff (cm)
P = rainfall (cm)
S = potential maximum retention after runoff begins (cm), and
I_a = initial abstraction (cm).

I_a represents precipitation that is "lost" before runoff begins and is in fact subtracted first during the calculation of runoff. Equation 1 applies only if $P > I_a$. Where $P \leq I_a$, then $Q = 0$ and no runoff occurs. I_a represents such processes as vegetation interception, infiltration to the aquifer, evaporation, and transpiration. I_a has been estimated or assumed to equal approximately 0.2S in most non-urban environments.

The SCS Curve Number (CN) is related to *S*:

$$\boldsymbol{S = \frac{1000}{\mathrm{CN}} - 10.} \quad \textbf{(2)}$$

Coupling the relationships described above results in a relationship between rainfall and runoff that follows a set of index curves widely used to calculate runoff.

7.1.2 Selection of Parameters for the SCS Curve Number Method

Published tables of SCS CNs allow hydrologists to choose a CN based on land use and soil type (Table 1). The CN is often adjusted during calibration of the surface-water model. The value of CN can range from 30 to 100, with higher CNs indicative of increased runoff.

The soil type is linked to the Hydrologic Soil Group, a measure of the runoff potential of soils (USDA NRCS 2004a). The soil groups are labeled imaginatively A, B, C, and D, with group A representing the soils with the least runoff potential and D representing soils with the most runoff potential. In this classification, runoff potential is tied to the ability of soils to transmit water when wet, allowing infiltration and subsequent “loss” of precipitation to runoff.

Land use implies a certain type of land cover, which impacts runoff potential. For instance, industrial lands often have a high percentage of paved land with 100% runoff potential, resulting in high CNs not greatly dependent on hydrologic soil group. The runoff potential of cropland and pasture, in contrast, depends greatly on hydrologic soil group. Although it is not usually incorporated into land-use code tables, the condition of the vegetation matters as well; healthy vegetation lowers runoff potential by intercepting rainfall before it reaches the ground and by slowing runoff and allowing the water more time to infiltrate.

The results of the land-use and soil-type analysis in the study area are presented in Table 2 and Figure 10 through Figure 12. The study area comprises mostly rangeland, forest land, and pasture, with some scattered industrial lands (Figure 10 and Table 2). The soil-survey data indicate that the soils in the study area are mostly unweathered bedrock, clays, and loam (Figure 11), and that these soils have relatively high runoff potential, belonging mostly to Hydrologic Soil Groups C and D (Figure 12). The individual CN values in Table 2 are weighted by area to produce a CN of 74 for the entire Devils River basin. The basin CN is a calibration variable.

Table 1. – Table used in current surface-water model for calculation of SCS CN from land use and hydrologic soil group. The hydrologic soil groups indicate potential for runoff. A – low runoff potential; B – moderately low runoff potential; C – moderately high runoff potential; D – high runoff potential. Water bodies have a very low CN, indicating no runoff potential. Tundra, snowfields, and glaciers have been excluded from this table. This table is modified from Chow, et al., 1988.

Land Use Code	Description	Hydrologic Soil Group			
		A	B	C	D
		Curve Number			
11	Residential	51	68	79	84
12	Commercial and Services	66	78	85	89
13	Industrial	81	88	91	93
14	Transportation, Communications, and Utilities	94	96	98	100
15	Industrial and Commercial Complexes	81	88	91	93
16	Mixed Urban or Built-up Land	66	78	85	89
17	Other Urban or Built-up Land	66	78	85	89
21	Cropland and Pasture	39	61	74	80
22	Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas	39	61	74	80
23	Confined Feeding Operations	39	61	74	80
24	Other Agricultural Land	64	75	82	85
31	Herbaceous Rangeland	58	64	72	77
32	Shrub and Brush Rangeland	52	59	67	74
33	Mixed Rangeland	52	59	67	74
41	Deciduous Forest Land	61	65	72	78
42	Evergreen Forest Land	63	68	74	79
43	Mixed Forest Land	63	67	71	74
51	Streams and Canals	1	1	1	1
52	Lakes	1	1	1	1
53	Reservoirs	1	1	1	1
54	Bays and Estuaries	1	1	1	1
61	Forested Wetland	1	1	1	1
62	Nonforested Wetland	1	1	1	1
71	Dry Salt Flats	98	98	98	98
72	Beaches	70	75	80	85
73	Sandy Areas Other than Beaches	70	75	80	85
74	Bare Exposed Rock	98	98	98	98
75	Strip Mines, Quarries, and Gravel Pits	70	75	80	85
76	Transitional Areas	70	75	80	85
77	Mixed Barren Land	70	75	80	85
83	Bare Ground	70	75	80	85

Table 2. Results of land-use analysis in the study area and resulting SCS CNs. These data are for the surface-water basin that feeds into the stream gauge at Pafford Crossing.

Hydrologic Soil Group	Land Use Description	Curve Number	Area (km^2)
D	Shrub and Brush Rangeland	74	7466.43
D	Evergreen Forest Land	79	1148.04
D	Mixed Rangeland	74	613.06
C	Shrub and Brush Rangeland	67	383.79
C	Mixed Rangeland	67	120.45
D	Cropland and Pasture	80	104.67
D	Herbaceous Rangeland	77	55.66
C	Herbaceous Rangeland	72	52.34
C	Evergreen Forest Land	74	40.70
D	Industrial	93	34.89
D	Mixed Forest Land	74	34.89
C	Cropland and Pasture	74	14.95
D	Transportation, Communications and Utilities	100	11.63
C	Residential	79	5.81
D	Commercial and Services	89	4.15
C	Mixed Forest Land	71	1.66
D	Residential	84	1.66
C	Commercial and Services	85	1.66
D	Other Agricultural Land	85	0.83
D	Nonforested Wetland	1	0.83
C	Transportation, Communications and Utilities	98	0.83
D	Orchards, Groves, Vineyards, and Nurseries	80	0.83
C	Industrial	91	0.83
D	Lakes	1	0.83

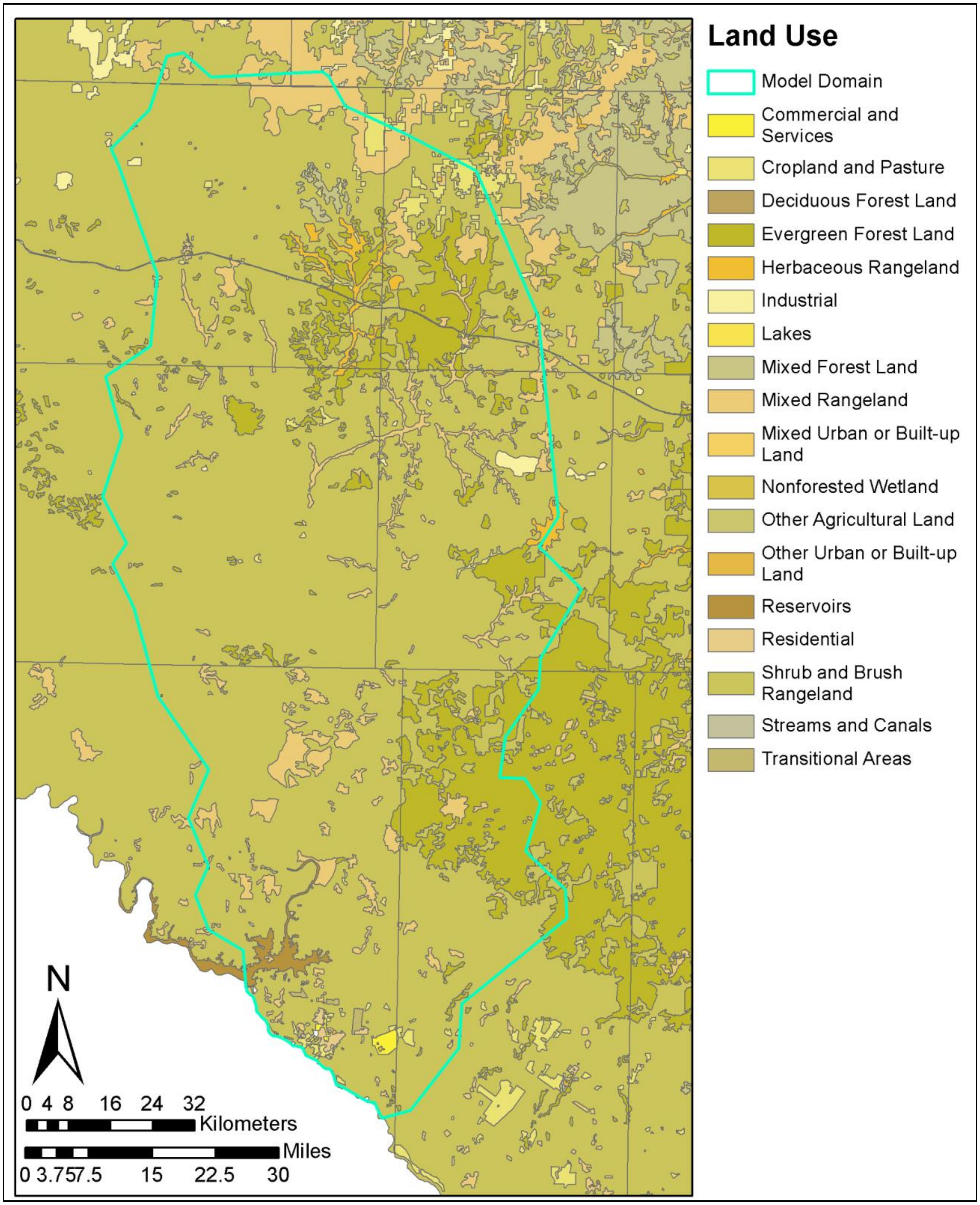


Figure 10. Distribution of land use in the study area. Data from USGS Land Use and Land Cover database (http://edcwww.cr.usgs.gov/products/landcover/lulc.html).

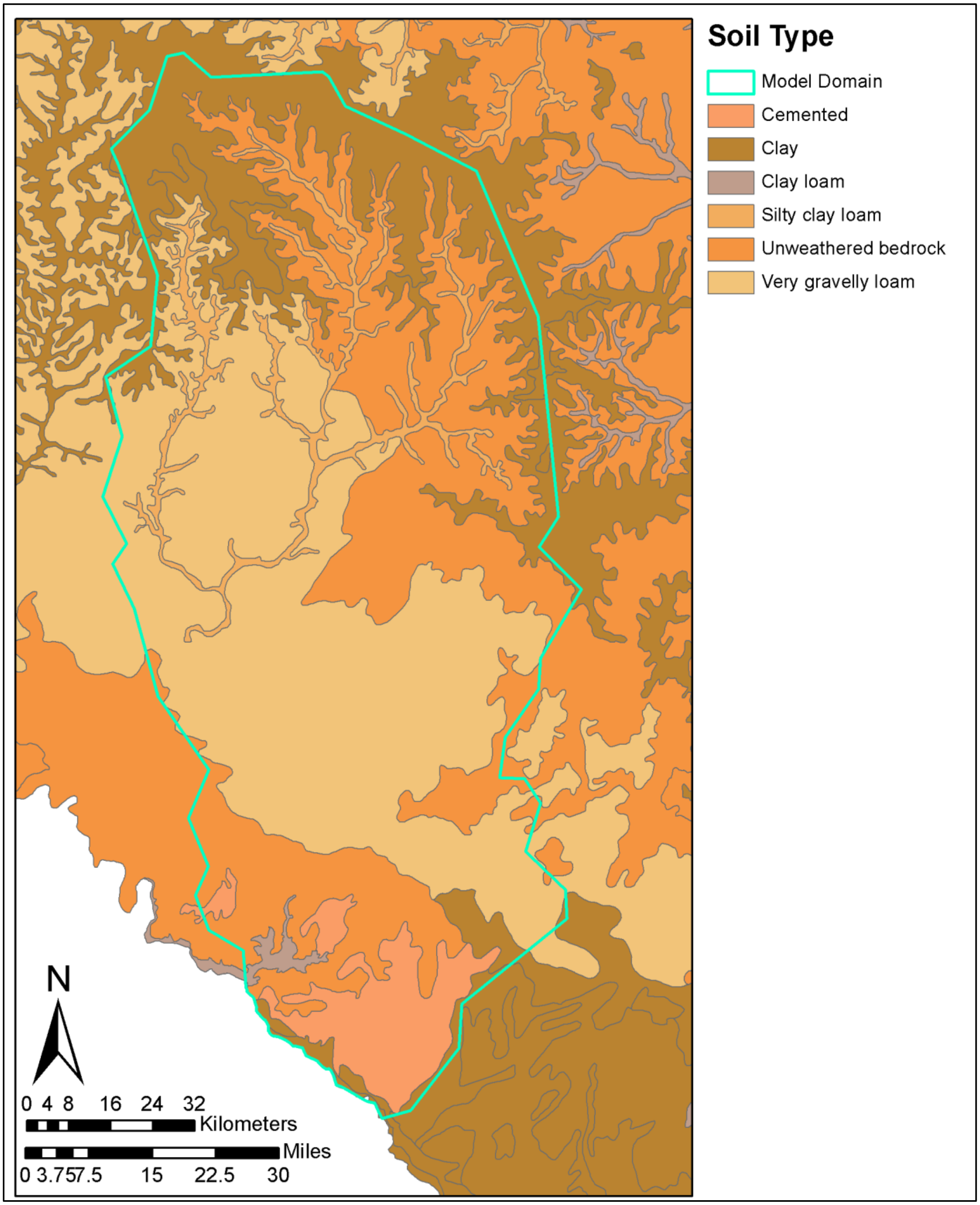


Figure 11. Distribution of soils in the study area. Data from USDA NRCS STATSGO database (http://soils.usda.gov/sdv).

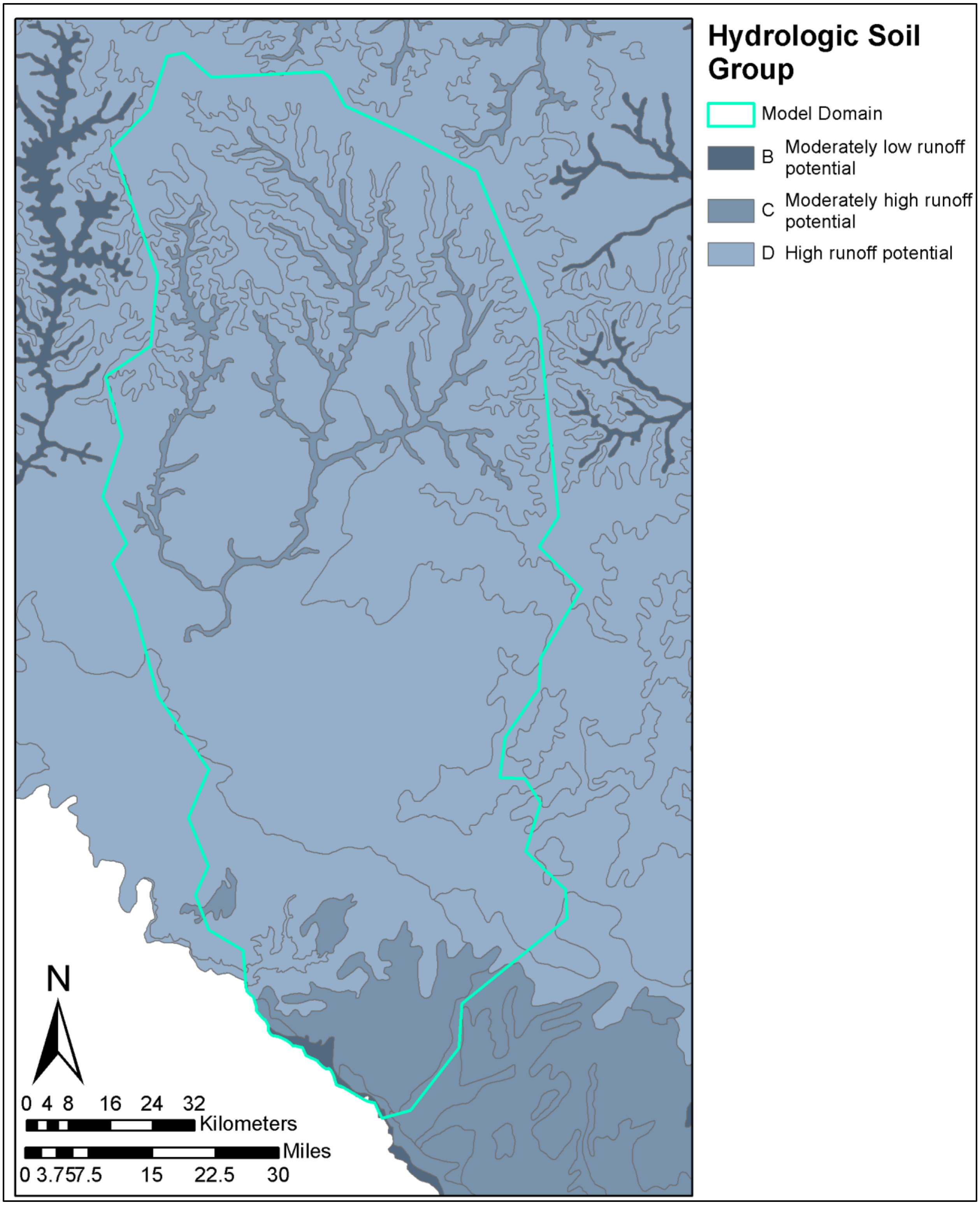


Figure 12. Hydrologic soil groups in the study area. Data from USDA NRCS STATSGO database (http://soils.usda.gov/sdv).

7.1.3 Deficit and Constant Loss Method

A loss method appropriate for continuous modeling and whose percolation can be output on a gridded basis to the groundwater model was incorporated into the preliminary models and the final model. Two loss methods that meet these criteria are available. (i) The first method is the soil moisture accounting (SMA) method (Bennett, 1998). This method is a storage-based system in which the canopy (vegetation), surface depressions, two-soil layers, and groundwater layers all gain and lose moisture at different specified rates based on precipitation, evapotranspiration, overflow, infiltration and percolation between the different storage compartments. (ii) The second method is the deficit and constant loss (DCL) method (USACE, 1992) which, in its simplest formulation, represents only a single-soil layer. This is a more parsimonious method suited for separation of long-term precipitation records into surface runoff, evapotranspiration, and downward percolation to the groundwater table.

The SMA loss method has been reported to compare favorably to the DCL method on the basis of relatively short model periods (e.g., Razmkhah 2016). The major benefit to the SMA loss method is its incorporation of a baseflow component; however, this benefit is not significant in this modeling effort since baseflow is modeled separately using MODFLOW. The DCL method is therefore appropriate for the Devils River coupled surface-water flow/groundwater flow model.

The DCL method comprises a theoretical “bucket” (deficit) of water that represents storage of water in the soil zone. The deficit can range from zero up to a specified maximum volume of moisture, measured in inches of rainfall. Deficit varies with time. Rainfall decreases the deficit by saturating the soil layer. During times without precipitation, percolation and evapotranspiration increase the deficit.

When rainfall occurs, the upper storage layers fill first, then overflow into the lower storage layers. Water then fills the deficit (saturates the soil layer) and only after the deficit is filled will runoff begin. The water in the soil zone is vulnerable to direct evaporation and to uptake by plants and subsequent transpiration (i.e., evapotranspiration). During evapotranspiration, the upper storage layers empty first, then the soil dries. Evapotranspiration ceases after either (i) all of the moisture is gone, or (ii) during precipitation.

Both evapotranspiration and percolation are represented in the model by specified constant rates. The maximum storage deficits, evapotranspiration rate, and percolation rate are all adjusted during calibration. The practical implementation is more complex than this when including canopy interception (water that falls onto the leaves of the vegetation), as well as water ponding on the surface. These processes are considered additional storage “buckets” and are treated similarly to soil storage. These processes are obviously also vulnerable to evapotranspiration.

7.1.4 Selection of Parameters for Deficit and Constant Loss Method

The DCL method (including the canopy and evapotranspiration functions) requires parameters to be set for maximum storage deficits, maximum percolation rate, and monthly evapotranspiration rate. Initial parameters for the long-term, surface-water model were selected based on the short-term, surface-water model calibration. The calibrated parameters for the long-term model are given in Table 3. Pan evaporation rates used in the long-term model are taken from USGS Quandrangle 706, which covers a large part of the model area (Table 4).

Table 3. Parameters used in DCL method.

	Calibrated Value
Maximum upper layer storage deficit (in)	3.6
Maximum lower layer storage deficit (in)	0.5-4
Maximum percolation rate (in/hr)	0.05
Time of concentration (hr)	12
Storage coefficient (hr)	12

Table 4. Average monthly total pan evaporation (inches) for the two model time periods. Data from Texas Water Development Board (http://www.twdb.texas.gov/surfacewater/conditions/evaporation/).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1981-1999	2.53	2.93	4.41	5.72	6.21	7.27	8.75	8.15	6.26	4.82	3.32	2.60
2000-2015	2.81	2.99	4.87	5.74	6.25	7.87	8.01	8.23	6.03	5.00	3.40	2.57

7.2 Transform Method

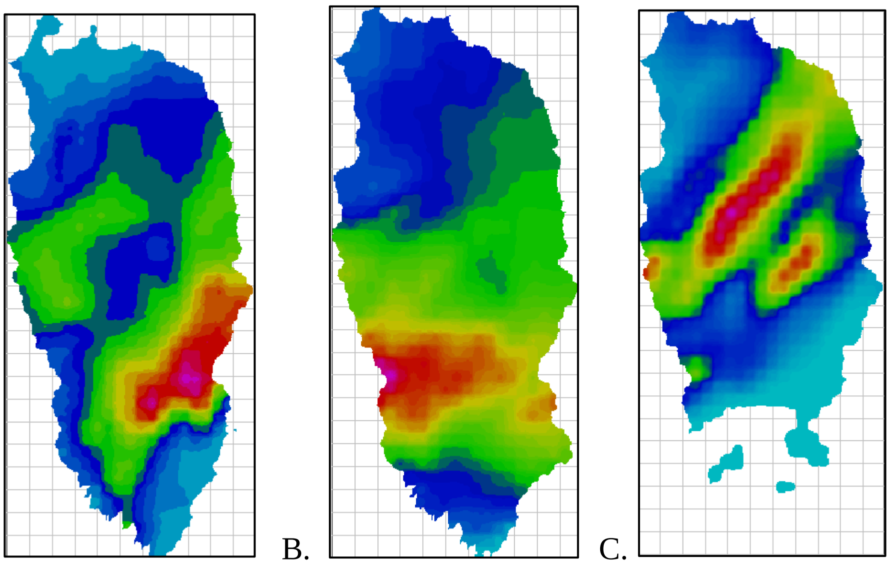
In rainfall-runoff modeling, the transform model represents movement of excess rainfall from the place where it fell to the outlet point at the river gauge. The choice of transform model and parameters partially determines how the runoff volume is distributed, when peak flow occurs, and magnitude of peak flow.

The modified Clark transform model is a distributed parameter model that accounts for spatial variability of parameters (Kull and Feldman, 1998; Peters and Easton, 1996). It transforms the precipitation signal into a discharge signal by accounting for the time required for water to travel from different parts of the watershed to the outlet (represented by a parameter known as "time of concentration") and by accounting for storage of water in various parts of the watershed (represented by a storage coefficient).

The choice of transform model can be critical when modeling single storm events with short time steps. The model is less sensitive to the choice of transform model and parameters with a 24-hour time step than it would be with a time step of one hour or less. The preliminary models use a one-hour time step and the long-term, surface-water model uses a 24-hour time step. The modified Clark transform model For the watershed discharging into the stream gauge at Pafford Crossing, the calibrated time of concentration and storage coefficient for the long-term model were both 12 hours.

7.3 Precipitation Data

Daily precipitation data from the PRISM Climate Group at Oregon State University spanning the period from 2000 to 2015 were used as input for the long-term surface-water model. Precipitation during the 2000-2015 model time period 47 cm/year [18.4 inches/year]. Examples of pixelated NEXRAD precipitation data illustrating the high degree of spatial variability in precipitation intensity are presented for February, April, and July of the year 2000 in Figure 13.



A. B. C.

Figure 13. Examples of pixelated NEXRAD precipitation data illustrating the high degree of spatial variability in precipitation intensity for three days in 2007. Rainfall intensity is depicted ranging from low (blue) to high (red and pink). (A) June 11, 2007. Maximum rainfall 5 cm [2 inches]. (B.) May 1, 2007. Maximum rainfall 11.5 cm [4.5 inches]. (C.) August 17, 2007. Maximum rainfall 25 cm [10 inches].

The continuity of the PRISM data, their relatively small size in relation to the extremely bulky NEXRAD Stage III 1-hour and 3-hour datasets, and their nationwide coverage (allowing for simple import into any U.S. model) make it a reasonable and cost-effective precipitation product.

The distribution and magnitude of PRISM rainfall in specific storms of interest have been compared with one-hour and three-hour NEXRAD Stage III data to check against errors in production or conversion of the PRISM dataset. The NEXRAD data generally align with the overall magnitude of the PRISM data, which is not unexpected, as the PRISM data are derived from the NEXRAD data. The single exception was a storm on September 22, 2013 that was completely absent from the PRISM data, but present in other NEXRAD data and resulted in 396 m^3/s [14,000 cfs] of observed discharge.

8 Surface-Water Model Results

8.1 Short-Term Surface-Water Models

The six short-term surface-water models with spatially homogenous parameters were constructed to compare the SCS curve number and the DCL methods. The parameters determined during calibration of the six, month-long models were then used in calibration of the final long-term model. Each month was selected because it experienced a specific rainfall event. Precipitation events ranged from small to large so that the ensuing model would be robust and appropriate for both dry- and wet-climatic conditions. Surface-water model calibration was conducted on months containing target storm events of varying sizes that occur under both high-baseflow and low-baseflow conditions. Target months were February 1997, August 1998, June 2000, May 2001, May 2002, and October 2002. A large (approximately 2,265 m^3/s [80,000 cfs]) discharge event occurred during the month of August 1998. Moderately large (approximately 226-340 m^3/s [8,000-12,000 cfs]) discharge events occurred during the months of February 1997 and October 2002 (Figure 14). Smaller (~28 m^3/s [1,000 cfs]) discharge events occurred during the months of June 2000, May 2001, and May 2002 (Figure 15).

The six month-long, surface-water-flow models were calibrated to the discharge data from the Pafford Crossing stream gauge on the Devils River. Discharge data were collected on a daily basis and were arbitrarily assigned to a time of 00:00, or midnight, at the beginning of each day. In some cases, this arbitrary time assignment caused the discharge peak to occur before the actual rainfall event. To prevent the discharge peak from occurring before the rainfall peak, thus making calibration impossible, the entire discharge record was shifted 24 hours later to midnight at the end of each day. Preliminary results for the calibration months are presented in Figures 13 and 14. In these figures, discharge refers to direct discharge – that portion of total discharge that is due to runoff and excludes baseflow.

Results for the February 1997 moderately large storm event are excellent for both loss methods (Figure 14). Results for the large storm event in August 1998 are ambiguous (Figure 14). Although it was possible to calibrate peak flow using a reasonable parameter set, manual calibration of both the SCS and DCL methods resulted in a hydrograph with a double peak not observed in the actual discharge data (Figure 14). The initial discharge event in October 2002 was well matched using both loss methods, but the SCS CN method was unable to then reproduce the lack of discharge later in the month (Figure 14). Smaller (<28 m^3/s [1,000 cfs]) discharge events illustrated in Figure 14 show a similar response to the two loss methods, with DCL more likely to overestimate the initial event, but SCS CN unable to then reproduce the lack of discharge later in the month.

These results are generally as expected, indicating the limitations of the SCS CN method with regards to continuous modeling and demonstrating the ability of the DCL method to model different-sized storms. The calibrated DCL parameters for the six short-term surface-water models are given in Table 5. The parameters were consistent enough to provide a guide to initial parameter values for the long-term, surface-water model. It should be noted, however, that overcalibration is a distinct danger when calibrating short-term, surface-water models, and the longer-term model will not be as easy to calibrate.

Table 5. Calibrated DCL parameters for short-term surface-water models.

Month	Initial Deficit	Maximum Deficit	Constant Rate	Time of concentration	Storage Coefficient
February 1997	0.4	2	0.1	15	20
August 1998	0.5	2	0.05	15	25
June 2000	2	2.3	0.1	15	25
May 2001	1.2	2.3	0.1	15	25
May 2002	0	2.3	0.1	15	25
October 2002	2	2	0.28	15	25

8.2 Long-Term Surface-Water Model Results

The long-term surface-water model was calibrated for the period of 2000 to 2015, with parameters input spatially distributed. The DCL loss method was used with a 24-hour timestep. Output from the long-term surface-water model consisted of infiltration, which was input as recharge to the groundwater model. During calibration, priority was given to calibrating recharge to the groundwater model rather than calibrating direct runoff to high flows. The results of direct runoff calculations in the surface-water model are given in given in Figure 16. The largest discharge events in the model time period occurred in November 2000 (447 m^3/s [15,800 cfs]), November 2004 (1,100 m^3/s [35,700 cfs]), and June 2007 (660 m^3/s [23,300 cfs]). A discharge event of 396 m^3/s [14,000 cfs] was recorded in September 2013 that had no corresponding rainfall data; this storm was ignored during calibration.

In general, the fit of the long-term surface-water model discharge to observed high flows is moderate. Agreement of the high-discharge events in October 2003 and November 2004 is good. The model overestimated the discharge event on August 2007 and underestimated discharge events in November 2000, June 2007, and April 2010. Small to moderate discharge events were more likely to be underestimated than overestimated, for example those in November 2001, October 2002, and October 2011.

There are several sources of uncertainty inherent to large-scale direct runoff events that likely impact the direct runoff calculations of this model.

- While gauge data are thought to be accurate to ±5% (Rantz, 1982), this is only for the baseflow component. Flow during flash floods in semi-arid regions can generate measurement errors –50% to +100% during flash floods in semi-arid regions. (Lerner et al., 1990).
- NEXRAD calculations result in rainfalls that are too high for typical semi-arid convective storms (Yatheneedras et al., 2008). Depending on the exact nature of this bias, it can potentially exaggerate the difference between large storms and small storms, creating the same disconnect between calibration of larger storms and small storms observed in this model.
- Uncertainty in initial soil-moisture conditions for each storm, caused by the extreme spatial variability of rainfall events in this semi-arid environment. In a continuous model,

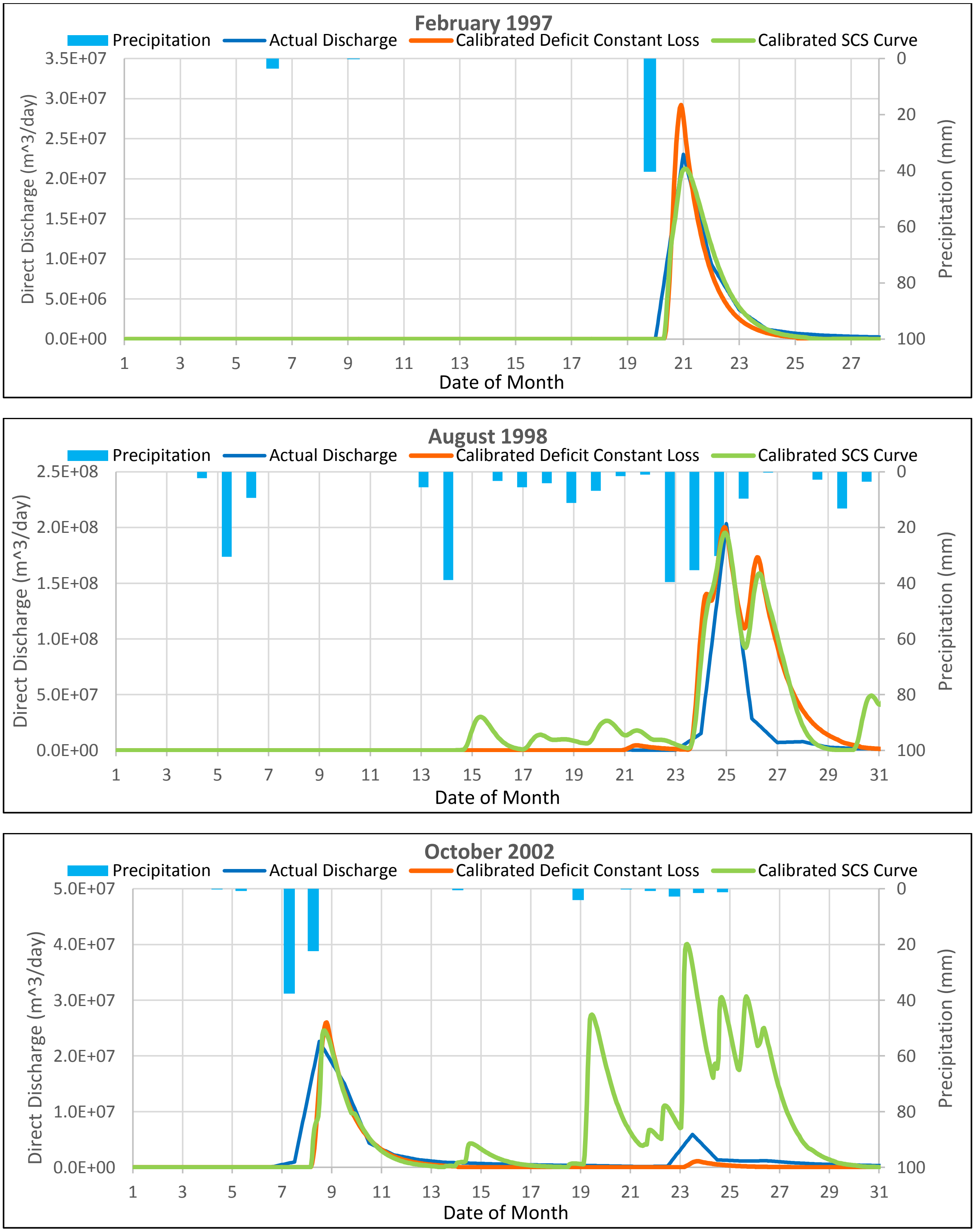


Figure 14. Short-term surface-water model results for moderate to large discharge events for target months of February 1997, August, 1998, and October 2002.

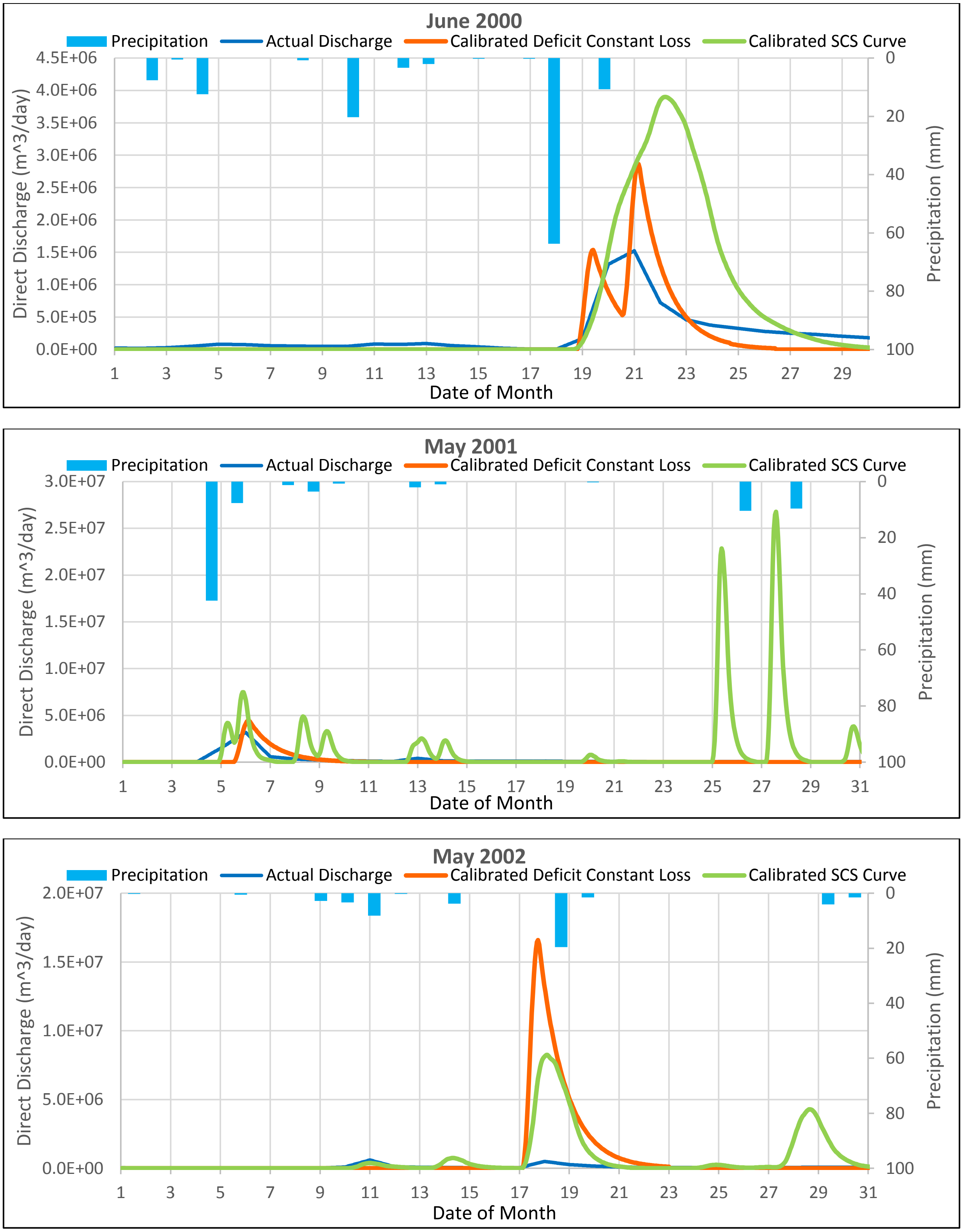


Figure 15. Short-term surface-water model results for small discharge events for target months of June 2000, May 2001, and May 2002.

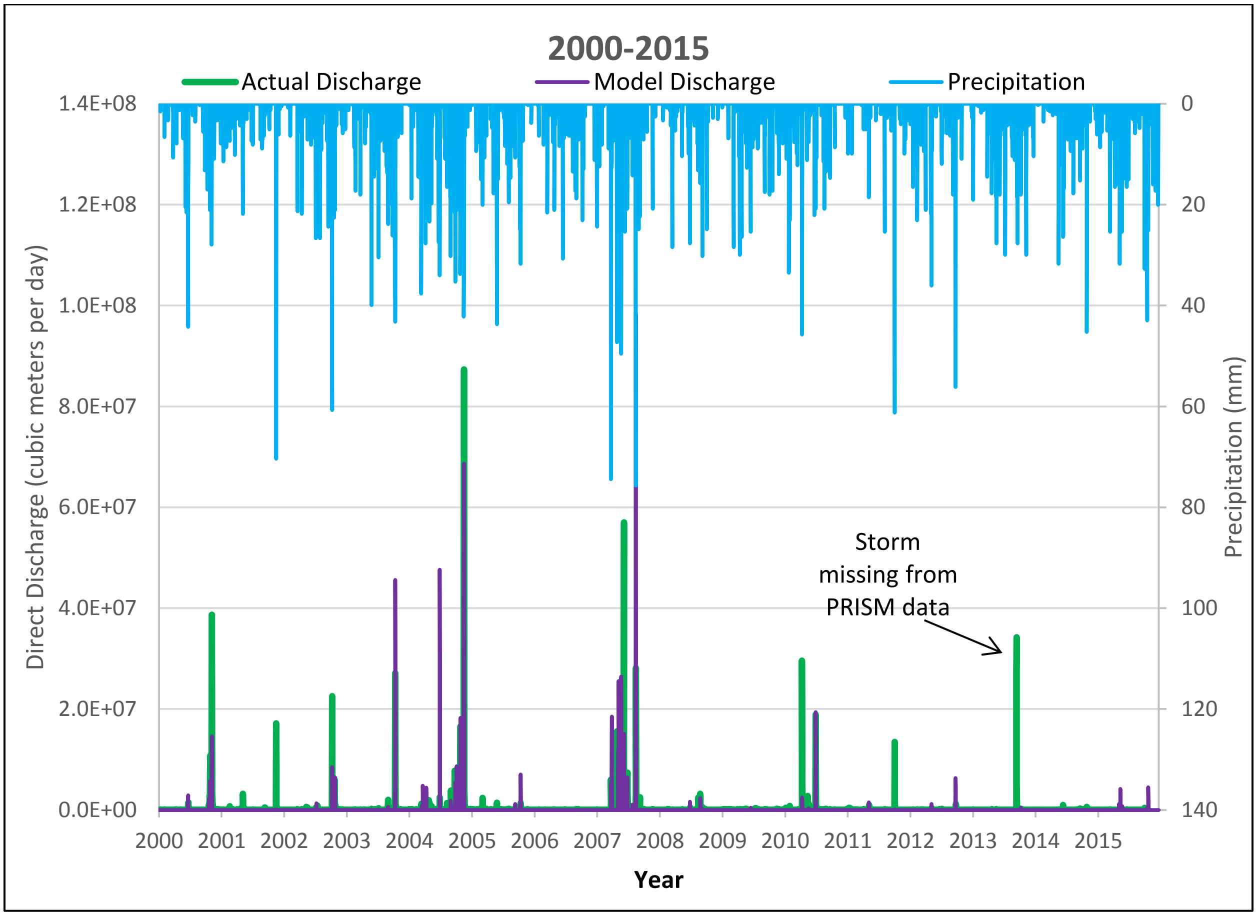


Figure 16. Results of direct runoff calculations in the long-term surface-water model.

- especially in a large watershed, small errors in soil moisture will be magnified to large errors in direct discharge.

For direct runoff in a large watershed, these small errors are often magnified during the transform method calculation. Groundwater recharge, on the other hand, should be less susceptible to such error.

9 Groundwater Model Development

Green et al. (2014) describe the conceptual model on which the groundwater model of the Devils River watershed is based. The conceptualization that groundwater flow in the Edwards-Trinity Aquifer is dominated by preferential flow paths that align with the river channels and major tributaries is supported by groundwater-elevation and water-chemistry data analysis, hydraulic analysis, dye traces, and results from geophysical surveys.

9.1 Refinement of the Conduit Network

The groundwater-flow model described by Green et al. (2015) was predicated on this conceptualization, however that model did not fully capture the flashiness in river flow where it discharges to Amistad Reservoir, nor was it able to replicate low river baseflow during times of drought. Although coupling of a surface-water model to the groundwater-flow model was undertaken to help mitigate these limitations, expansion of the conduit network was also believed to be necessary. Motivation for the conduit network enhancement is found in theoretical assessments of speleogenesis (i.e., karst conduit development) (Király , 1998, 2003; Dreybrodt et al., 2005). The approach used here to designate conduit location relies on a combination of empirical and speleogenetic methods.

Designating location and extent of a karst network is challenging even when supporting data are abundant. Uncertainty in location and extent is high when characterizing karst systems with limited data. Jeannin et al. (2007) suggest using statistical, fractal, empirical, and speleogenetic methods to extrapolate karst networks in carbonate aquifers. Numerical analysis has been used to theoretically generate karst networks in carbonate rocks (Annable, 2003). Borghi et al. (2016) discuss the use of inverse methods to improve designation of the likely locations of conduits using numerical methods. Borghi et al. (2016) designated likely conduit locations based on knowledge of recharge (i.e., sinkholes or sinking streams) and discharge (i.e., springs) that were determined by tracer test. Borghi et al. (2016) recommends not to attempt to designate conduit location by a manual trial and error approach when recharge and discharge are known, but no other information is available. In our case, we have evidence that conduits are aligned with river channels, that discharge occurs within the river channels, but are uncertain whether recharge is distributed (i.e., applied to the rock matrix), funneled directly to river channels, or some combination of the two sources of recharge.

The extent of conduit development is highly dependent on whether recharge is distributed or focused. In general, the maturity of conduit development will progress from less dense networks (i.e., Figure 17b) to more mature networks (such as Figure 17c and eventually 17d) as a function of boundary conditions (i.e., spatial distribution of recharge) and system inputs (i.e., precipitation and water chemistry). The current state of the maturity of the conduit network in the Devils River watershed is not well defined. This technical uncertainly is resolved by a multi-facet evaluation which is a function of the recharge model, maturity of conduit development, and coupling of surface-water flow with groundwater flow. The discrete-feature network used in the 2015 model is illustrated in Figure 18. The conduit network is expanded to better represent a karst conduit network similar to one hypothesized in Figure 17 (Kaufman, 2005). Conduit locations assigned to the groundwater model (Figure 19) were designed to mimic surface-water morphology (Figure 20).

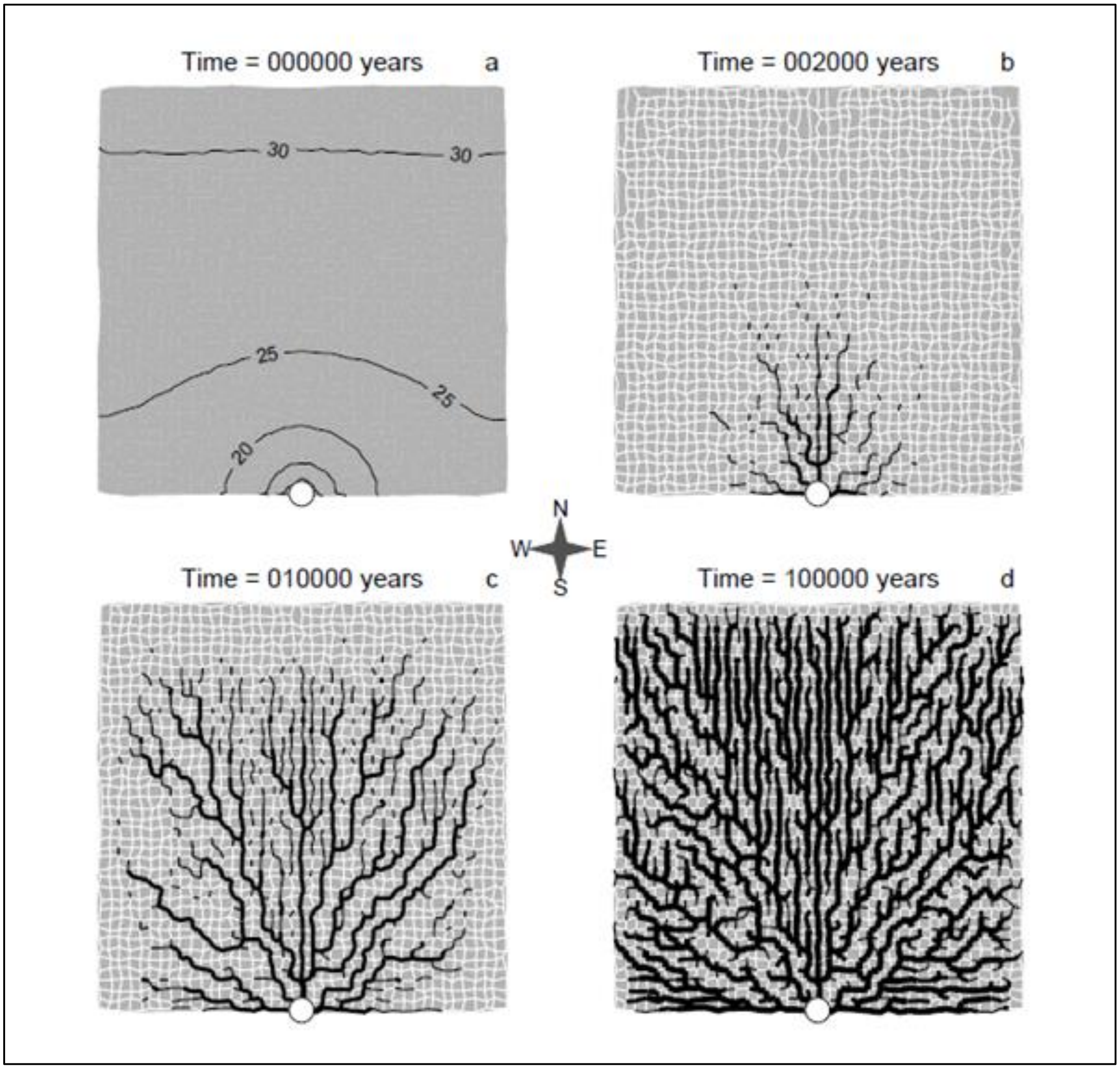


Figure 17. Conduit development simulated for a medium with uniform distributed recharge and uniform hydraulic boundaries (Kaufman, 2005).

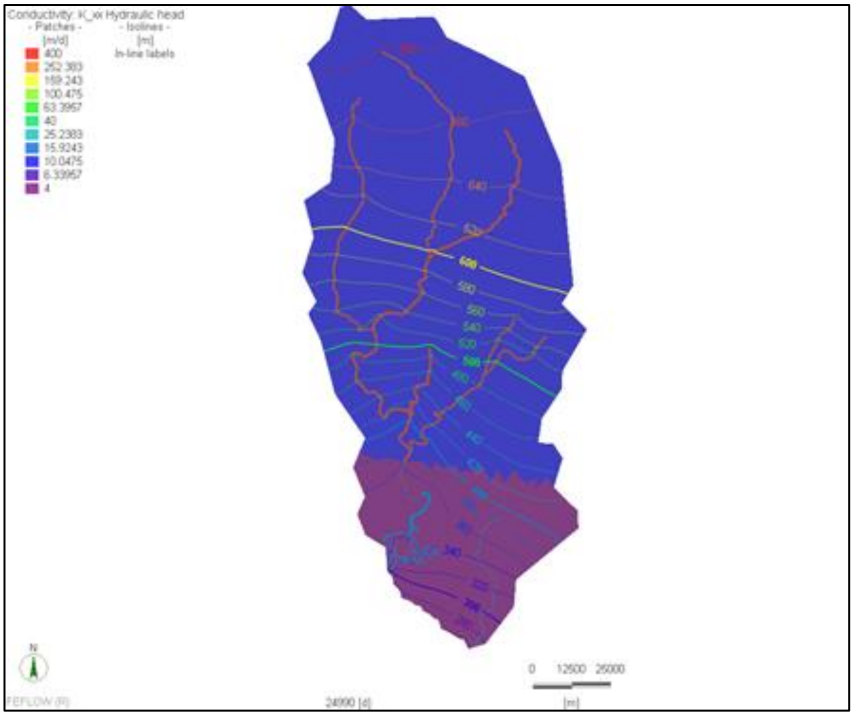


Figure 18. 2015 Finite Element Model Conduits. Solid lines denote the location and extent of discrete features aligned with the major river channels in the groundwater flow model (Green et al., 2015)

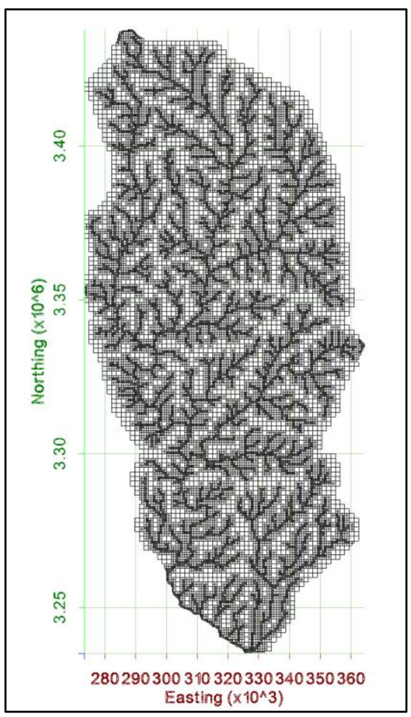


Figure 19. Plan view of MODFLOW-USG quadtree grid. Note the full discretization of the dense stream network.

Figure 20. Flow Accumulation Network. Solid blue lines indicate the location of stream channels in the surface-water model, delineated based on the digital elevation model.

9.2 Configuration of the Groundwater Model

The groundwater-flow model comprises two layers representing the Edwards and the underlying Trinity formations (Figure 21). The top layer contains the karst conduit network. Layer 1 extends from the ground surface to 40 meters below the bottom of the incised stream channels. Based on known existence of conduits below the streambeds (Green et al., 2015) supplemented with recent groundwater water-chemistry data analysis (Section 2), the initial conduit distribution matches the stream accumulations calculated in the surface-water model (Figure 20). The final location and parameters assigned to the conduits were determined during calibration. The MODFLOW-USG software package was used to create an unstructured grid in which resolution was higher around the conduit features and lower in areas distal to the conduits (Figures 19 and 21). In this way, reasonable run times were achieved while incorporating the fine discretization needed to calculate conduit flow.

Cells intersected by the flow accumulation lines are designated as drain cells. Drain conductance was set at 10,000 m/day [32,800 ft/day]. Hydraulic conductivity was set at 2 m/day [6.6 ft/day] for the matrix of layer 1. The hydraulic conductivity of cells within 200 m of flow accumulation lines was set to 100 m/day [328 ft/day] for low-order stream tributaries and 1,000 m/day [3,280 ft/day] for the higher order streams. The hydraulic conductivity for the matrix of layer 2 was set to 1 m/day [3.3 ft/day]. Model parameters are illustrated in Figure 22 and summarized in Table 6.

Table 6. Summary of hydraulic properties assigned to the groundwater model

Layer/Feature	Hydraulic Conductivity (m/day)	Specific Yield (dimensionless)	Specific Storage (1/m)	Conductance (m/day)
1	2	0.012	N/A	-
2	1	0.012	0.00001	-
Stream conduit (high order)	1000	0.0001	-	10,000
Stream conduit (low order)	100	0.0001	-	10,000

9.3 Coupling of Surface-Water and Groundwater Models

The model of surface-watershed processes spanning the years 2000-2015 was coupled with the groundwater model. Constructing a rainfall-runoff model of this duration is remarkable in that many of the most popular and well-documented methods used in rainfall-runoff modeling were developed to model single events, usually by civil engineers, in order to predict the timing and magnitude of peak flood waters so that flood structures can be optimally designed. The aim of this surface-water flow model is different; it is the long-term impact of groundwater extraction on surface-water flow over the course of days, months, and decades, not minutes and hours that is of interest. The additional computational and labor cost of modeling at an hourly timestep would return little, if any, additional information. Therefore, methods and calculations appropriate for continuous modeling of decades-long surface-flow at a daily timescale were used.

9.4 Steady-State Model Calibration

The steady-state groundwater-flow model was constructed and calibrated to water-well data spanning years 2000-2015. The comparison of the steady-state model prediction with water-well data was satisfactory (Figure 23). Simulated groundwater elevations were compared with measured groundwater elevations at 13 wells spaced across the model domain. Simulated groundwater elevations were within 7-9 m [25-30 ft] of observed groundwater elevations with few exceptions.

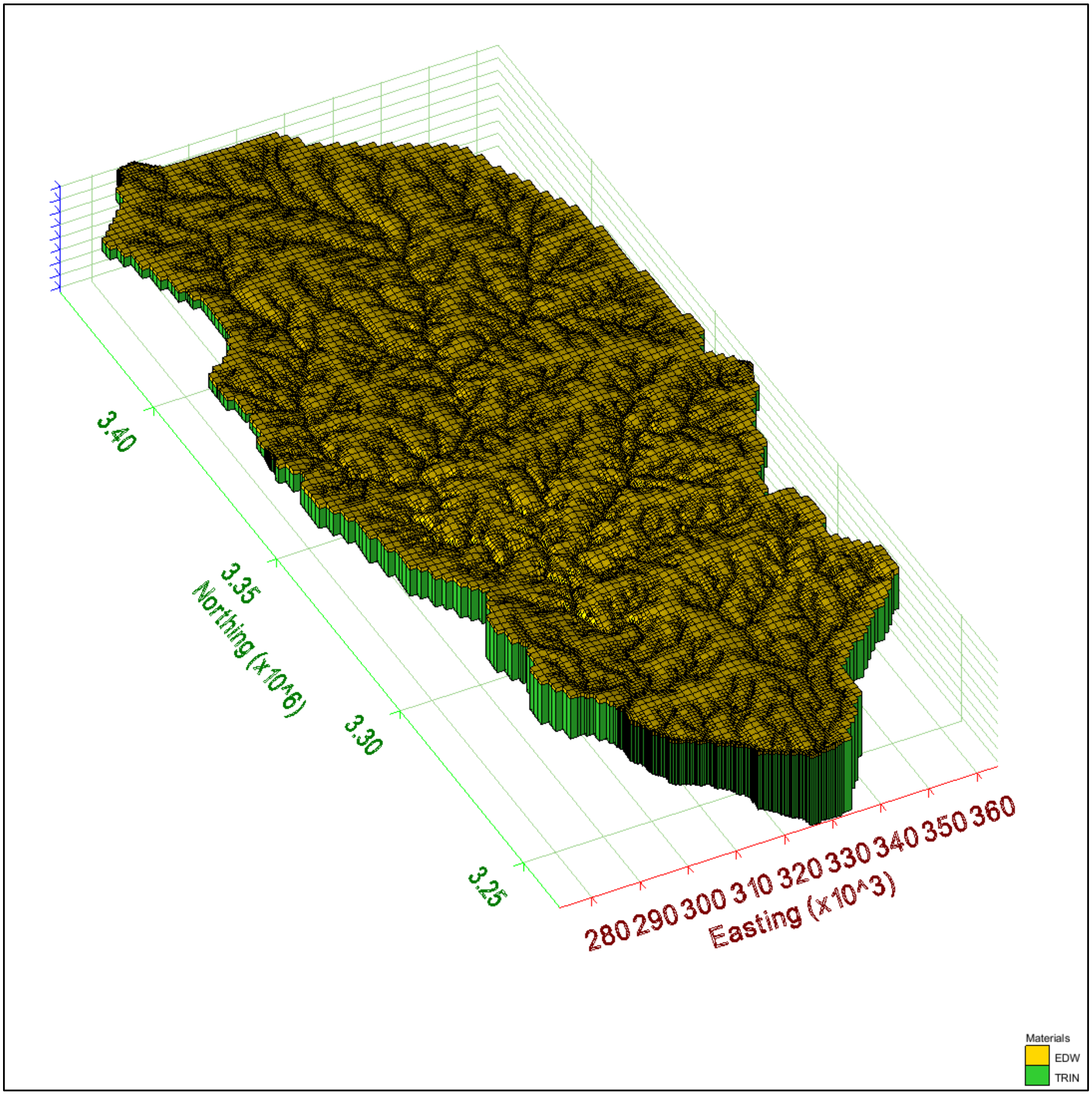


Figure 21. Oblique view of the refined groundwater-flow model.

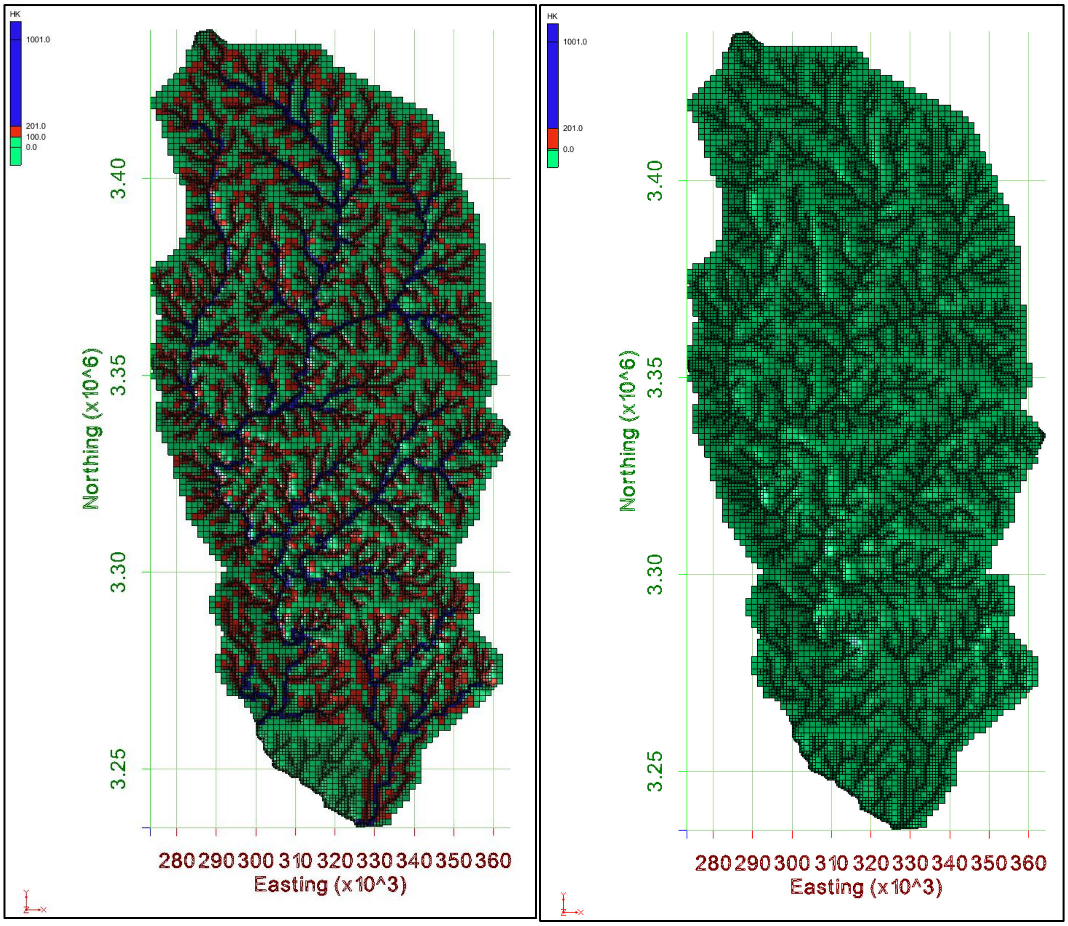


Figure 22. Hydraulic Conductivity field for layer 1(left) and layer 2 (right). Note the higher conductivity of the stream channels to simulate conduit flow in layer 1.

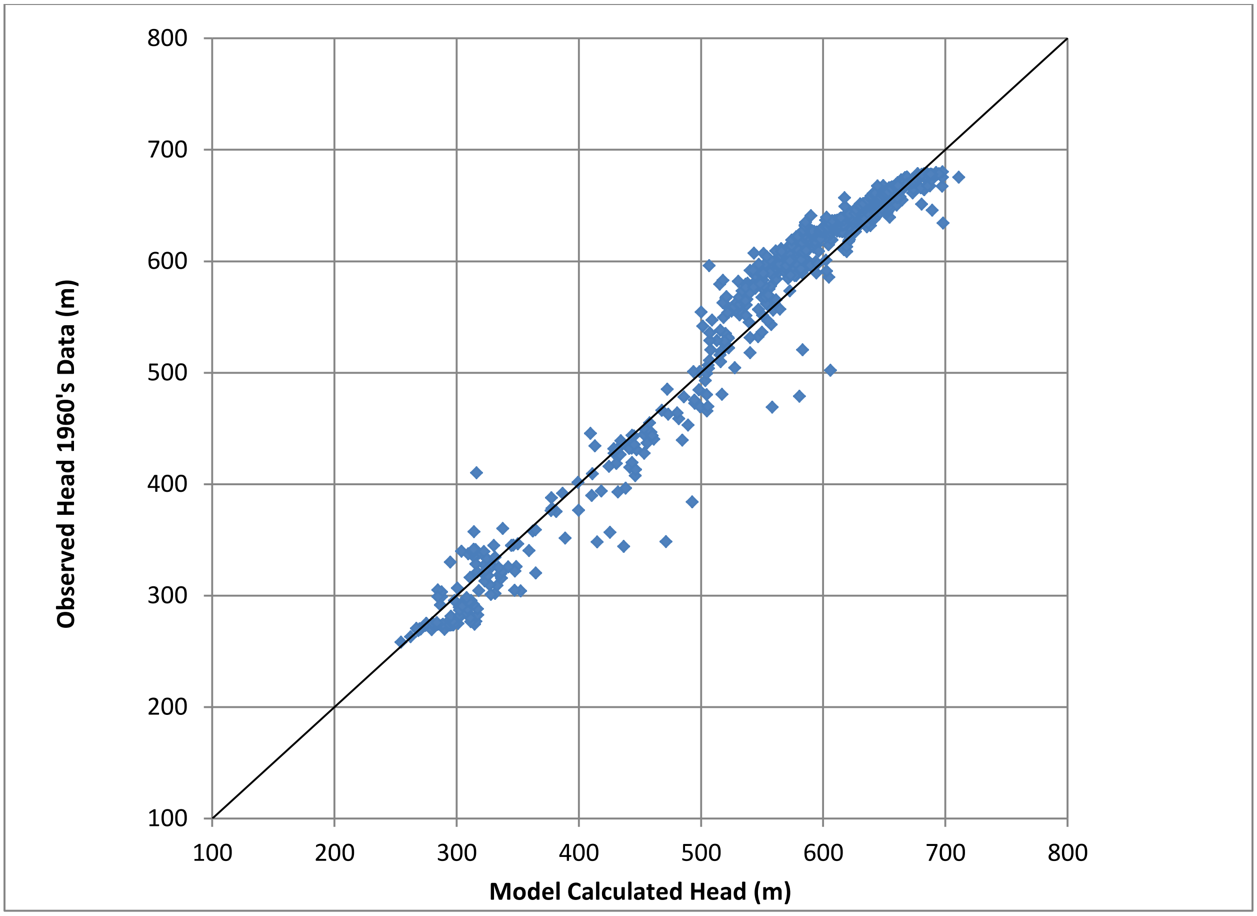


Figure 23. Steady-State Calibration plot of observed heads versus modeled heads. A perfect fit is when every point falls on the X-Y line shown in the plot.

9.5 Transient-Model Calibration

16-year-long transient runs were performed. Precipitation for the initial surface-water model is in hourly increments, averaged across the basin. The degree of flashiness of hydraulic response was captured at some, but not all, monitoring wells. Simulations of wells located near inferred preferential flow paths or conduits appeared to correctly replicate the hydraulic response of the aquifer proximal to the preferential flow paths. Transient runs indicate that the coupled surface-water and groundwater model produces a baseflow that responds much better with regards to the variation in magnitude of discharge than the Green et al. (2015) groundwater model (Figure 24). This is attributed to the improved representation of recharge and conduits in the new model.

The transient calibration of the groundwater flow model predicted that spring discharges occur further upstream in the Devils River basin then currently observed. However, historical accounts of the Devils River watershed indicate that continuous discharge was observed at Beaver Lake prior to development (Dearen, 2011). Beaver Lake is approximately 16 km (10 miles) upstream from Pecan or Hudspeth springs, the current headwaters of live water in the Devils River. This difference is attributed to pumping that has altered river flow compared with pre-development conditions.

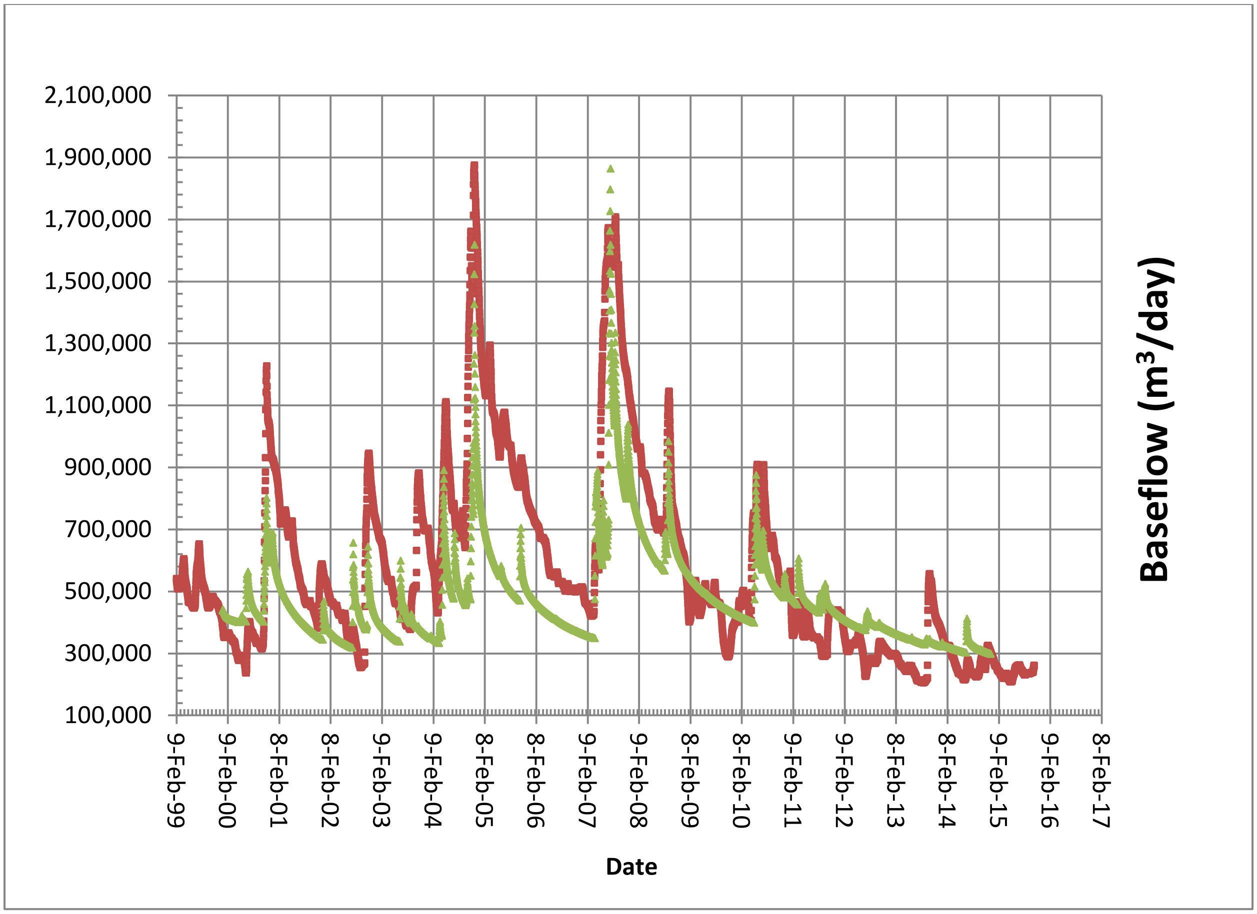


Figure 24. Model predicted base flow (green triangles) versus observed baseflow (red squares) at Pafford Crossing, 2000-2015.

The average annual extraction of groundwater in Devils River watershed is not well constrained due to un-metered wells and un-reported water pumping by the oil and gas industry. Total pumping in the watershed is estimated to be 48,000 m^3/day [14,000 acre-ft/year] to account for this uncertainty. After implementing pumping of 48,000 m^3/day [14,000 acre-ft/year] throughout Devils River watershed in the model, the springs near Beaver Lake in the upper Devils River watershed vanished (Figure 25).

The impact of pumping from a hypothetical wellfield near Juno at 1,817 m^3/hour [8,000 gpm or 12,900 acre-ft/year] was also simulated. Pumping at this rate has the effect of depleting additional springs and causing the onset of live water in the river to migrate downstream. If additional groundwater resources are exploited in the basin, a proportional decrease in the flow to the Devils River would potentially result in a decrease of live water in the Devils River (Figure 26).

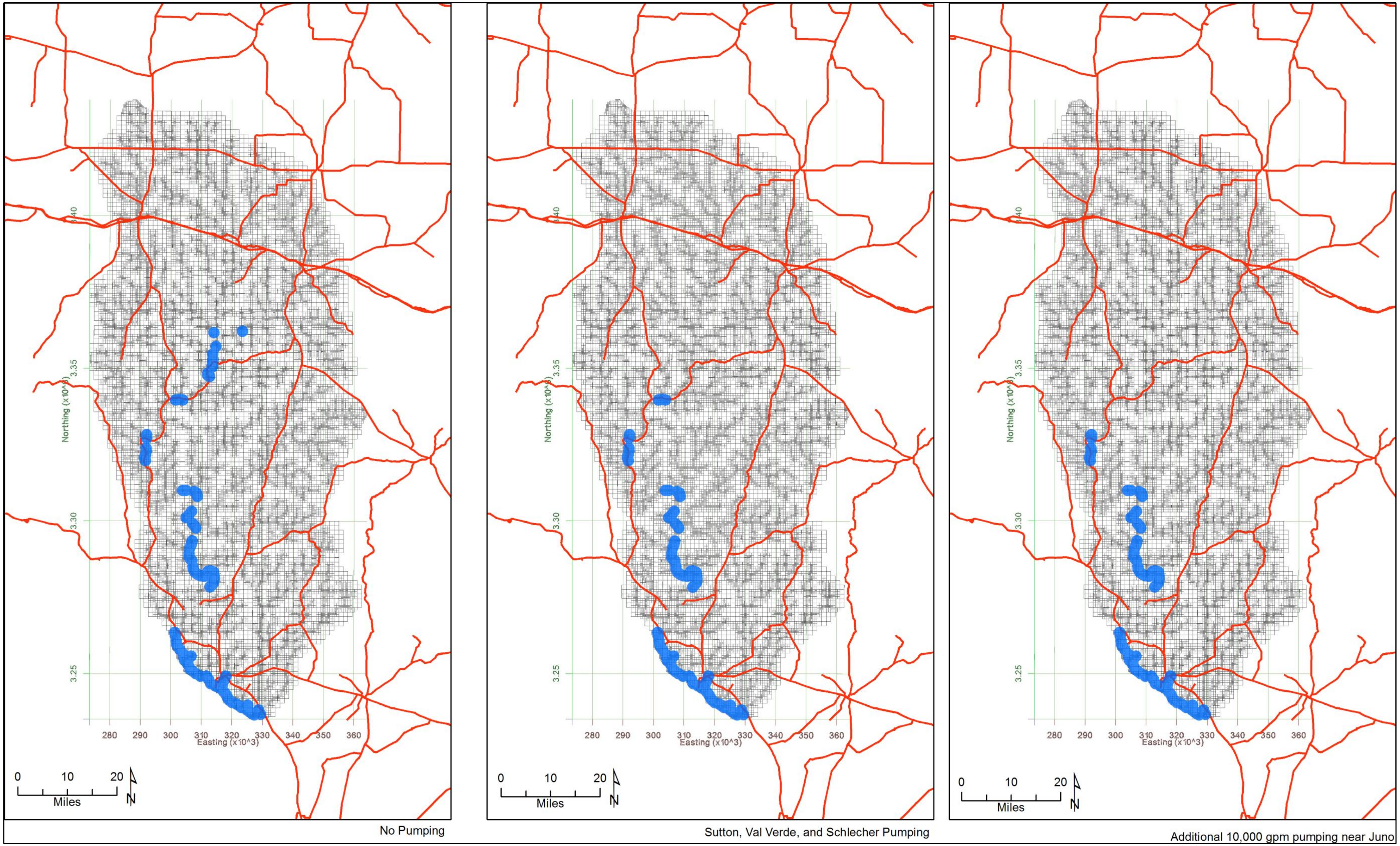


Figure 25. Model predicted spring locations. From left to right: Spring locations with no pumping, pumping as estimated by the Texas Water Development Board in Sutton, Val Verde, and Schlecher Counties, and additional pumping for export from a well field near Juno. Blue marker symbols are predicted spring locations.

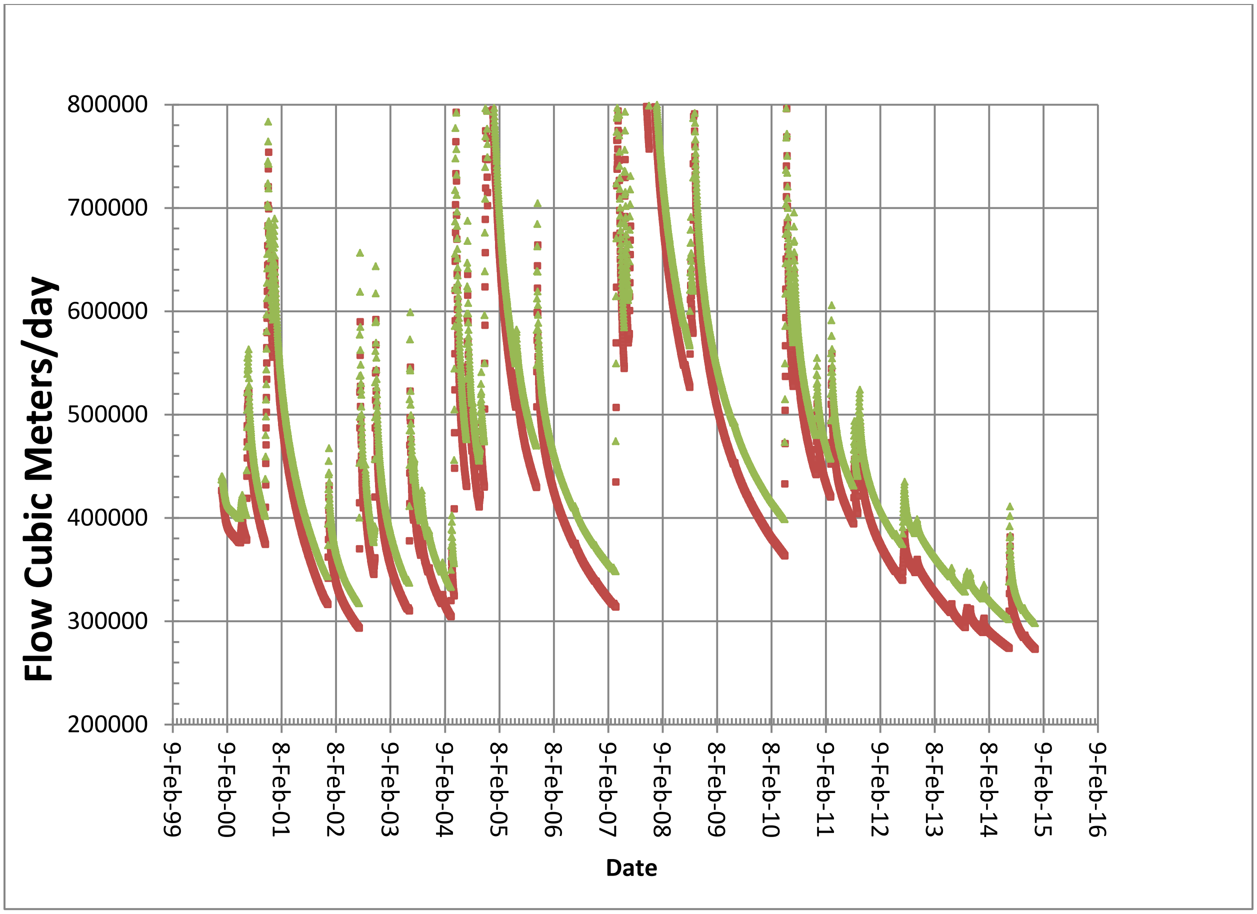


Figure 26. Modeled baseflow for a scenario where 8,000 gpm of groundwater is exported from Juno (red squares) compared to a simulation without groundwater export (green triangles).

10 Discussion and Conclusions

The Devils River watershed in south-central Texas has been recognized as one of the remaining pristine rivers in the state. The Devils River is also a key tributary to the Rio Grande, providing essential freshwater flows to south Texas and the Rio Grande Valley. The Devils River watershed basin is being threatened by proposed large-scale groundwater export projects. This study was undertaken to evaluate what impact groundwater pumping in the upper Devils River watershed would have on downstream discharge in the Devils River.

The watershed is located in a semi-arid environment with modest distributed recharge, oftentimes less than 1-2 cm/year [0.4-0.8 in/year]. The Edwards-Trinity Aquifer of the Devils River watershed is characterized as a karstic carbonate aquifer with preferential flow paths that align with major river channels. Water chemistry, water budget, hydraulics, and geophysical imaging data were used to corroborate this conceptualization.

A coupled surface-water/groundwater model was assembled to replicate the hydraulics of the Edwards-Trinity Aquifer to provide a defensible tool to assess the impact of pumping on river flow. The surface-water model was assembled to determine recharge to the groundwater model.

The conduit/diffuse groundwater model replicates both fast conduit flow and slow diffuse flow in the Edwards-Trinity Aquifer. The model provided, for the first time, a numerical groundwater flow model that replicates the hydraulic dominance of preferential flow paths in the karstic Edwards-Trinity Aquifer of the Devils River watershed. The coupled surface-water/groundwater model successfully replicates both flashy flow and low baseflow in the Devils River where it discharges to Amistad Reservoir. In addition, the model exhibits the hydraulic separation of watersheds in the Edwards Plateau, particularly where the aquifers are phreatic.

The coupled surface-water/groundwater model predicted that prior to pumping in the upper Devils River watershed, spring discharge occurred at Beaver Lake which is approximately16 km [10 miles] farther upstream in the Devils River basin from where spring discharge is currently observed (i.e., Pecan or Hudspeth springs). Groundwater pumping in the upper Devils River watershed has ranged from 10,000-24,000 m^3/day [3,000 to 7,000 acre-ft/year] since 1960 (Hutchison et a., 2011b; Sutton County Underground Water Conservation District, 2013). There is uncertainty in actual pumping amounts due to un-metered wells and un-reported water pumping by the oil and gas industry.

Decrease in or cessation of spring flow in the Devils River upstream of Pecan or Hudspeth springs when compared with pre-development conditions is attributed to pumping in the upper Devils River watershed. The impact of additional future pumping near Pecan or Hudspeth springs on the Devils River watershed was found to decrease spring discharge near Pecan or Hudspeth springs and decrease flow in the Devils River where it discharges to Amistad Reservoir. The impact of this potential pumping on Devils River discharge is proportional to the amount of water pumped (Figure 26).

Several important observations were made during assembly and execution of the models.

- Groundwater flow and sustainability in the Devils River watershed appears to be controlled by the morphology of the area more than the bulk hydraulic properties of the rocks. The ability of the model to replicate Devils River discharge was only achieved when the groundwater model attained the apparently correct distribution, morphology, and alignment of conduits relative to the watershed topography. This model was relatively insensitive to assignment of hydraulic properties.

- Even with a dense conduit network as conceptualized in this model, wells must be installed in or adjacent to stream cells to achieve significant flow without destabilizing the model. This observation mimics the reality of well placement in the Edwards-Trinity Aquifer. Wells with capacity greater than 110- 220 m^3/hour [500-1,000 gpm] are only found proximal to river channels. Wells located at a distance greater than about 3 km (2 miles) from a river channel typically have a capacity less than 11- 22 m^3/hour [50-100 gpm].

- Production of groundwater in the basin will result in a proportional reduction in the flow in the Devils River. The impact is most pronounced during low flow conditions.

- While less than a 5% reduction in baseflow may not seem significant, a reduction of baseflow of this magnitude has the potential to shift the location of "live water" farther downstream. The ecology of the system could be impacted as discharge points in the river are extinguished.

Development of a surface-water/groundwater flow model of the Devils River watershed that successfully replicates baseflow in the Devils River provides the ability to evaluate the impact of groundwater extraction from the watershed on Devils River discharge to Amistad Reservoir. This model clearly demonstrates the strong linkage of groundwater extraction from the watershed on Devils River flow. This model is available to evaluate future water-resource management scenarios to be able to ascertain what impact groundwater extraction would have on downstream river flow.

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