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An online, peer-reviewed journal
published in cooperation with the
Texas Water Resources Institute

Texas Water Journal

Volume 9 Number 1 | 2018

Texas Water Journal

Volume 9, Number 1
2018
ISSN 2160-5319

twj.media

THE TEXAS WATER JOURNAL is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management, research, and policy issues. The journal provides in-depth analysis of Texas water resources management and policies from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. It also provides updates on key state legislation and policy changes by Texas administrative agencies.

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Texas Water Resources Institute
Texas Water Journal
Volume 9, Number 1, December 17, 2018
Pages 129-149

Surface water-groundwater interaction issues in Texas

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Abstract: In Texas, surface water is owned and regulated by the State of Texas, whereas groundwater is owned by respective property owners under the rule of capture. Owners of surface water rights, issued by the state, and groundwater may use and sell their water as a private property right. The Texas Commission on Environmental Quality administers surface water rights, while groundwater conservation districts (where they exist) are primarily responsible for permitting groundwater use. This paper focuses on the complexity of both systems that are designed to manage water resources differently with specific emphasis on where surface water and groundwater interact. Surface water-groundwater interactions have contributed to disputes over the actual ownership and right to water. The available science and the limitations of the models currently used to make water availability and permitting determinations are discussed, as are the investments in field data gathering and interpretation and model enhancements that can lead to better assessments of surface water-groundwater interactions and impacts. More complete science and enhanced models may also help reduce the timeline associated with the permitting of future water supply and use strategies.

Keywords: surface water, groundwater, interaction, availability models, permitting decisions

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Terms used in paper

Acronyms	Descriptive name
BBASC	basin and bay area stakeholder committee
BFI	baseflow index
DORM	Daily Operational Routing Model
DFC(s)	desired future condition(s)
EAA	Edwards Aquifer Authority
ES	Environmental Stewardship
ESA	Endangered Species Act
GAM(s)	groundwater availability model(s)
GCD(s)	groundwater conservation district(s)
GMA(s)	groundwater management area(s)
IHA	Indicators of Hydrologic Alteration
LCRA	Lower Colorado River Authority
LCRB	Lower Colorado River Basin
MAG(s)	modeled available groundwater(s)
MBFIT	Modified Base Flow Index with Threshold
SCOTUS	Supreme Court of the United States
SW-GW	surface water-groundwater
TCEQ	Texas Commission on Environmental Quality
TIFP	Texas In-stream Flow Program
TPWD	Texas Parks and Wildlife Department
TWC	Texas Water Code
TWDB	Texas Water Development Board
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WAM(s)	water availability model(s)
WRAP	Water Rights Analysis Package

INTRODUCTION

The growing use of water resources and greater frequency of droughts, with associated impacts to streamflow, are placing a greater focus on groundwater and surface water interactions in Texas by state agencies (NAS 2005; Scanlon et al. 2005; TWDB 2016a; Toll et al. 2017; Young et al. 2017; Smith et al. 2015; Chowdhury et al. 2010). Among the regulatory issues affected by surface water-groundwater (SW-GW) interactions in Texas are managing water rights along a river, complying with the Endangered Species Act (ESA), implementing environmental flow recommendations, and obtaining bed and banks permits. A question central to all these regulatory issues is how to quantify the impacts of groundwater pumping on the availability of surface water. This question is at the center of several recent studies, conflicts and lawsuits in Texas involving the Rio Grande, San Saba, Colorado, and Brazos rivers. The situation on the San Saba River resulted, in part, in an interim charge for Texas House Natural Resources Committee (85th Legislative session) to evaluate "emerging issues in groundwater and surface-water interaction, in particular in areas of increasing competition for scarce resources"(Straus 2017).

As shown by the recent events associated with pumping groundwater near the four aforementioned rivers, an emerging issue associated with SW-GW interactions is that groundwater permitting and availability must recognize a person's ownership and property interest in water. Sound science is critical to ensuring such protection and determinations.

To properly address questions of how groundwater pumping is affecting surface-water availability, there is a need to properly understand SW-GW interactions (NAS 2005). Several factors contribute to this lack of understanding, including an inadequate number of field studies that address SW-GW interactions, the use of baseflow estimation techniques that do not provide consistent estimates or consider bank flow, and model simulations that do not adequately reflect the physical processes occurring in SW-GW interactions (Parsons 1999; Halford and Mayer 2000; HDR 2007; Mace et al. 2007; Asquith et al. 2005; Scanlon et al. 2005; Partington 2012; Young et al. 2017).

The purpose of this paper is to (1) define key terms and identify statutes in the Texas Water Code (TWC) associated with SW-GW interactions, (2) summarize the role of SW-GW interactions in the management of water resources, (3) present key physical processes that occur in SW-GW interactions, (4) discuss the limitations of currently used techniques to estimate and model SW-GW interactions, and (5) present recommendations to improve the science in relation to SW-GW interactions in Texas. Although this paper is specific to Texas law, management issues, and case studies, the issues raised could be of benefit and application outside of the state for anyone considering SW-GW interactions in their management decisions.

DEFINITION OF GROUNDWATER AND SURFACE WATER

The TWC does not define surface water specifically but rather makes the terms "surface water" and "state water" synonymous. TWC §11.021 defines state water as "The water of the ordinary flow, underflow, and tides of every flowing river, natural stream, and lake, and of every bay or arm of the Gulf of Mexico, and the storm water, floodwater, and rainwater of every river, natural stream, canyon, ravine, depression, and watershed in the state…"

In addition to the surface water features identified in §11.021, the TWC also uses the term "watercourse." The courts have described a watercourse as having (1) a defined bed and banks, (2) a current of water, and (3) a permanent source of supply (Domel v. City of Georgetown, Austin 1999). These criteria are crucial in determining if water is classifiable as state water. Generally, until water reaches a watercourse (where it becomes state water), it is classified as diffuse water. Diffuse water includes rainwater, snowmelt, and overland flow and is the property of the landowner until it joins a watercourse.

Another water feature classified as state water is "underflow," which is generally associated with the presence of subsurface water within the bed and banks of a watercourse. Texas Commission on Environmental Quality (TCEQ) rule §297.1 defines a stream's underflow as "[w]ater in sand, soil, and gravel below the bed of the watercourse, together with the water in the lateral extensions of the water-bearing material on each side of the surface channel, such that the surface flows are in contact with the subsurface flows, the latter flows being confined within a space reasonably defined and having a direction corresponding to that of the surface flow" (30 Tex. Admin. Code §297.1(55)).

In some situations, the TCEQ may classify groundwater as "under the direct influence of surface water." Groundwater classified as under the direct influence of surface water in Texas requires a higher level of treatment for a public water supply than does groundwater that is not under the direct influence of surface water. TWC Chapter 290, Subchapter D defines groundwater under the direct influence of surface water as:

"Any water beneath the surface of the ground with:

(A) significant occurrence of insects or other macroorganisms, algae, or large-diameter pathogens such as *Giardia lamblia* or *Cryptosporidium*;

(B) significant and relatively rapid shifts in water characteristics such as turbidity, temperature, conductivity, or pH which closely correlate to climatological or surface water conditions; or

(C) site-specific characteristics including measurements of water quality parameters, well construction details, existing geological attributes, and other features that are similar to groundwater sources that have been identified by the executive director as being under the direct influence of surface water."

The TCEQ definition above is based on U.S. Environmental Protection Agency regulation (40 CFR 141.2).

Finally, the TWC defines groundwater as "…water percolating below the surface of the earth" (TWC §35.002(5) and §36.001(5)). However, stream underflow has been expressly excluded from being considered groundwater because it is state water. This distinction is important because it grants the TCEQ the legal authority to restrict non-domestic pumping of groundwater near streams if groundwater is present in an underflow zone.

OWNERSHIP AND REGULATION OF SURFACE WATER AND GROUNDWATER IN TEXAS

Texas surface water law has evolved from the Riparian Doctrine to the Prior Appropriation Doctrine. Surface water is owned by the State of Texas held in trust for the public (TWC §11.021, §11.0235). With passage of the Water Rights Adjudication Act in 1967, Texas adopted a unified surface water permit system. Unless the purpose of use is domestic or livestock (exempt uses that remain riparian), anyone wishing to use surface water must receive permission from the state in the form of a "water right." The TCEQ is primarily responsible for granting surface water rights, which then become private property in and of themselves unless forfeited through nonuse.

Texas groundwater law is rooted in the rule of capture. Texas landowners own the water beneath their property (TWC §36.002) and may use or sell the water as private property. The Texas Legislature, however, has authorized the establish-

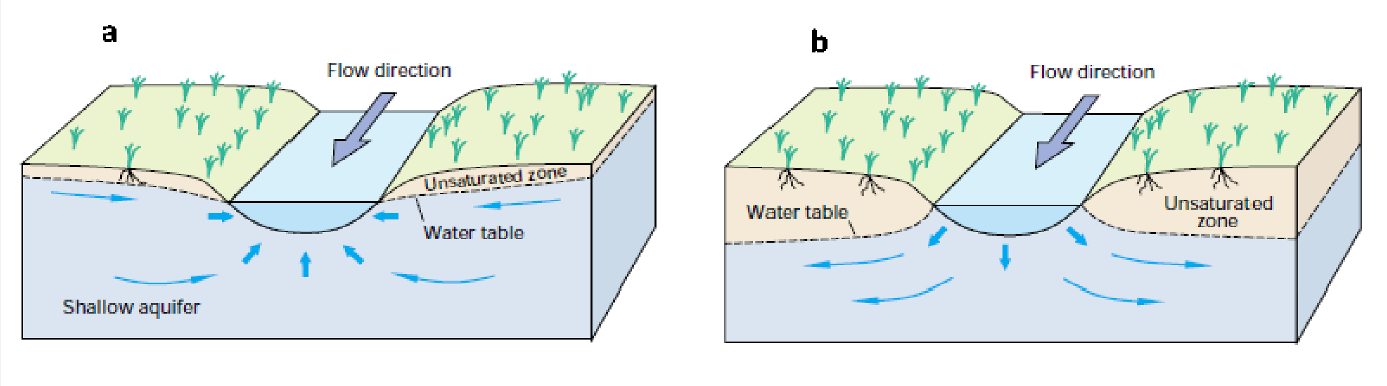

Figure 1. Schematic showing groundwater flow toward a gaining stream (a) and groundwater flow away from a losing stream (b) (modified from Winter et al. 1998).

ment of groundwater conservation districts (GCDs), which generally have the authority to modify the rule of capture by promulgating rules for conserving, protecting, recharging, and preventing waste of underground water. TWC §36.0015 states that GCDs "are the State's preferred method of groundwater management in order to protect property rights, balance the conservation and development of groundwater to meet the needs of this state, and use best available science in the conservation and development of groundwater." There are currently 100 GCDs that cover about 70% of the area of Texas. GCDs operate though a board of directors, whose members are either elected or appointed, generally by elected officials, per the conditions established in the legislative act that created the district or TWC if the district was through petition. GCDs may choose to recognize SW-GW interaction through the adoptions of management goals to maintain springflow and/or stream baseflow.

The TCEQ cannot authorize or regulate groundwater pumping via permit, just as a GCD cannot regulate the permitting and diversion of surface water. Consequently, an inherent statutory conflict is created by having these separate regulatory mechanisms, particularly as it relates to SW-GW interaction. The differences in the regulatory agencies, technical disciplines, and ownership issues associated with surface water and groundwater have led to the development of programs to develop regulatory tools for evaluating groundwater availability and surface water availability but few tools for evaluating SW-GW interactions.

SURFACE WATER-GROUNDWATER INTERACTION

Traditionally, surface water and groundwater have been treated independently when managing these resources in Texas. However, it is well understood that these two resources are often hydrologically connected. In some instances, surface water serves as a source of flow that can change the chemistry and availability of groundwater. Conversely, groundwater can increase the flow volume and affect the chemistry of surface water. In some cases, the same stretch of river may lose flow to the aquifer in one season and gain flow from the aquifer in another season. As the demand for water and the need for new water supplies increase in Texas, understanding the hydrologic connection between surface water and groundwater becomes integral to developing appropriate legislation and strategies to effectively use and manage these two resources.

Gaining and losing streams

A stream that receives water emerging from a submerged spring or other groundwater seepage through its streambed is a gaining stream (Winter et al. 1998). A stream that loses water to groundwater by outflow through the steambed is called a losing stream (Winter et al. 1998). Figure 1 illustrates the dynamics of gaining and losing streams. A stream may always gain water from an aquifer (perennial streams) or always lose water to an aquifer (intermittent or ephemeral streams). The flow conditions in a stream might also vary over time and across space, such that it is characterized as both gaining and losing. The conditions that cause these variances can be natural, such as flood events, or anthropogenic, such as pumping.

An important metric for evaluating SW-GW interactions is the difference in elevation between the water table in an aquifer and the water level in a stream. For a gaining stream, the water-level elevation in the stream is lower than the water level in the immediate aquifer. Under these conditions, the aquifer discharges water to the stream, increasing the stream's flow. For a losing stream, the water-level elevation in the stream is higher than the water-table elevation in the aquifer. Under these conditions, the stream recharges water to the aquifer.

Groundwater contribution to a stream can originate from unconfined aquifers or from confined aquifers. For the case of an unconfined aquifer, groundwater flow typically exits an aquifer and flows to the stream as diffuse flow. In coastal aquifers such as the Gulf Coast Aquifer System, the majority of groundwater contribution to streams occurs as diffuse flow. For the case of a confined aquifer, pressured groundwater flows through preferential flow pathways created by faults, fractures, and karstic features until it exits at a spring location and enters a stream. In the Texas Hill County, the confined section of the Edwards Aquifer produces some of the biggest springs in Texas. These springs include Barton Springs, San Marcos Springs, Comal Springs, Las Moras Springs, and San Felipe Springs.

The Texas Water Development Board (TWDB) (2016a) made several key points regarding SW-GW interactions in Texas:

- An estimated 9.3 million acre-feet of groundwater flows from major and minor aquifers to surface water in an average year. This represents about 30% of the average surface water flow in Texas.
- Aquifer interactions with surface water vary regionally and within each aquifer. Between 14% and 72% of streamflow over aquifer outcrop areas is due to groundwater discharge from major and minor aquifers.
- The largest groundwater contributions to surface water occur in East Texas, the Hill Country, and around major springs in West Texas.
- The aquifer with the most groundwater discharge to surface water is the Gulf Coast Aquifer, with an estimated 3.8 million acre-feet per year.

Besides indicating that SW-GW interactions can significantly affect streamflow, the TWDB (2016a) shows that local geology and meteorological conditions are important factors that affect SW-GW interactions.

Baseflow and bank flow

TCEQ Rule §297.1 defines baseflow as "[t]he portion of streamflow uninfluenced by recent rainfall or flood runoff and is comprised of springflow, seepage, discharge from artesian wells or other groundwater sources, and the delayed drainage of large lakes and swamps." This definition implies that bank flow is not a part of baseflow. As discussed by Freeze and Cherry (1979), bank storage effects and bank flows can complicate the process of defining and determining baseflow. Bank storage refers to the variable amount of water stored temporarily in the stream banks during rising flood stage (Todd 1955). Bank flow is the release of bank storage back to the stream that occurs following high river stage. Despite being potentially important to characterizing SW-GW interactions, bank flow and bank storage are not recognized in TCEQ rules and are not considered in the water balance simulated by water availability models (WAMs) and groundwater availability models (GAMs).

Bank flow is the flow of water into and out of the banks along a stream (Figure 2). Figure 2A shows water levels under conditions for a gaining stream where the water level is higher in the aquifer than in the stream. Figures 2B and 2C show the effects of a rainfall event on water levels in the stream, causing them to become temporarily higher than the water level in the aquifer that is in contact with the stream. During this time, stream water flows into the aquifer and is stored in the banks of the aquifer as bank storage. After the flood event has passed and the stream becomes a gaining stream again (see Figure 2D and 2E), the water held as bank storage returns to the stream and mixes with the water that originated from the aquifer. After bank flow has ceded, the stream and aquifer water levels eventually return to conditions typical for a gaining stream.

Significant bank storage and flow occurs when (1) a stream reach is subject to stage increases, (2) bank materials have a high permeability, and (3) sufficient volumes of permeable bank material or alluvium provide storage (Rassam and Werner 2008). The abundance of high permeability alluvium will also promote the occurrence of underflow. In general, downstream reaches are more favorable to bank storage than headwater reaches (Kondolf et al. 1987) because they have greater drainage areas that produce large flood peaks and are more likely to be flanked by alluvium with a large capacity to store water relative to streamflow. Kunkle (1962) showed, in some cases, annual discharge from a groundwater basin can be less than the annual discharge from bank storage.

The identification and calculation of bank flow requires at a minimum measured water-level elevations and water quality parameters from a river gage and wells in the aquifer underlying and adjacent to the stream. Figure 3 shows water levels measured in 2007 at a Colorado River gage and a water well located about 200 feet from the Colorado River (URS and Baer Engineering 2008). These data are from a monitoring program performed by the Lower Colorado River Authority (LCRA) to investigate SW-GW interactions near the City of Wharton from 2006 to 2008. Over that period, the groundwater level in the aquifer was higher than the stream water level in the Colorado River over 80% of the time, which means the Colorado River was a gaining stream (see Figure 1) over 80% of the time. However, during multiple high stream stage events, the increase in stream water levels caused significant increases in the groundwater level that represent bank storage in the aquifer (as illustrated in Figures 2B and 2C). On several occasions, the bank storage became great enough to cause a reversal of groundwater flow direction 200 feet from the stream. Following the peak stream stage and the accumulation of bank storage, bank flow (as illustrated in Figures 2D and 2E) occurs as water levels recede in both the aquifer and the stream until another high stage ensues.

Although the data in Figure 3 can be used to demonstrate the occurrence of bank storage and bank flow to SW-GW interactions, additional information is needed to determine the amount of water transferred between the stream and the

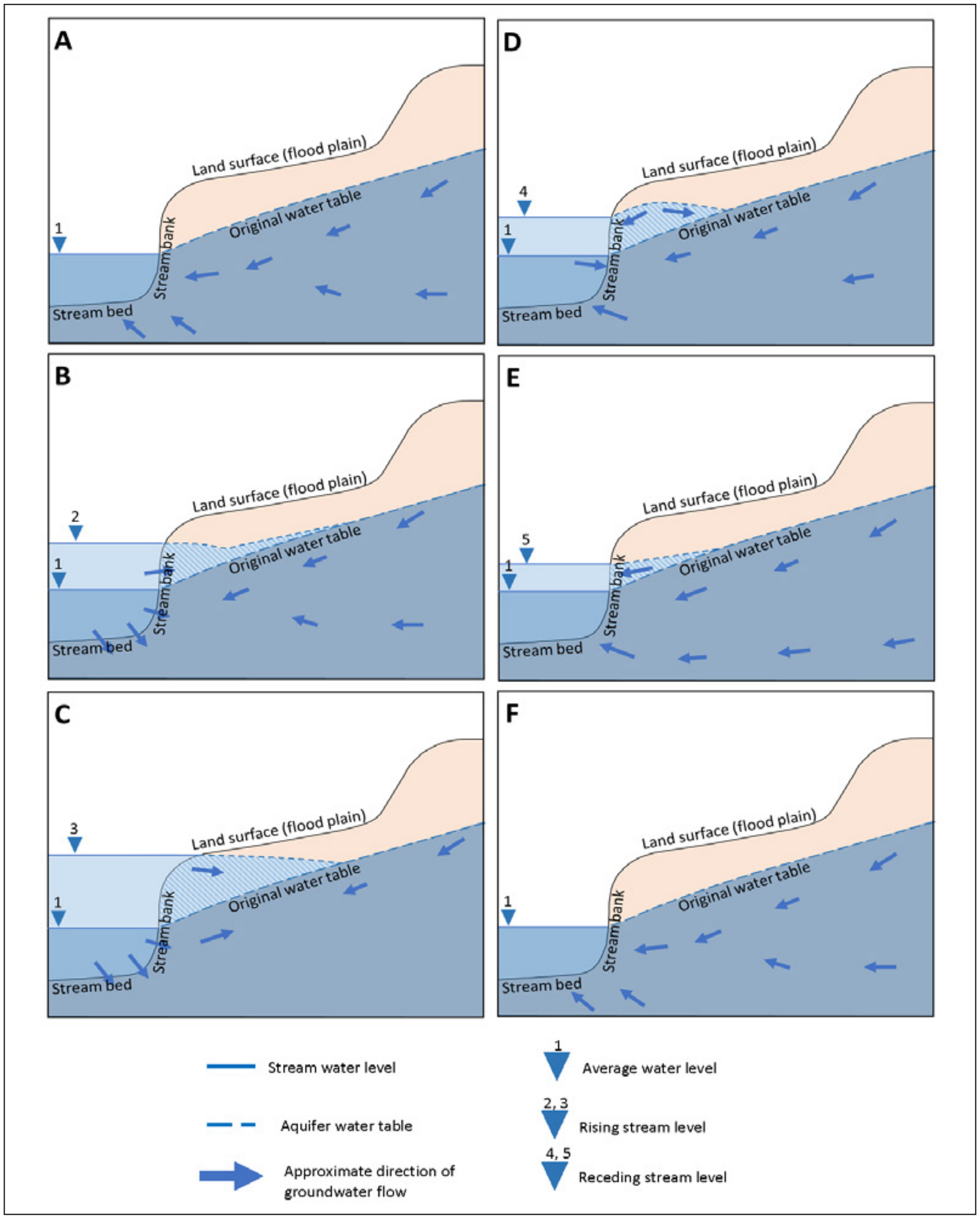

Figure 2. Schematic showing groundwater flow toward a stream at sequential times. Water levels during average flow conditions at a gaining stream (A). Increase in stream elevation during a flooding event causes hydraulic gradient reversal at stream-aquifer interface. Streamflow enters aquifer and becomes bank storage in stream bank (B and C). Decrease in stream elevation after a flooding event. Bank storage flows back to the stream as water level in the streams lowers over time (D and E). Water levels in stream and aquifer return to conditions that existed prior to flood event (F).

aquifer. Among the additional information required to make such a determination are hydraulic properties of the aquifer and measurements of water quality parameters. The chemical data is used to partition flow based on mass-balance considerations. Numerous studies have successfully used geochemical analysis of stable isotopes, anions, and salinity to estimate baseflow (Boulton et al. 1999; Porter 2001; Oxtobee and Novakowki 2002; Brodie et al. 2005; SKM 2012; Scholl et al. 2015; Rhodes et al. 2017; Cook et al. 2018).

The importance of bank storage to SW-GW interactions is difficult to assess in most Texas rivers because of the sophisticated level of analysis and large quantity of data required to derive definitive answers. In order to thoroughly quantify bank storage effects, evaluations of flow exchange should include both

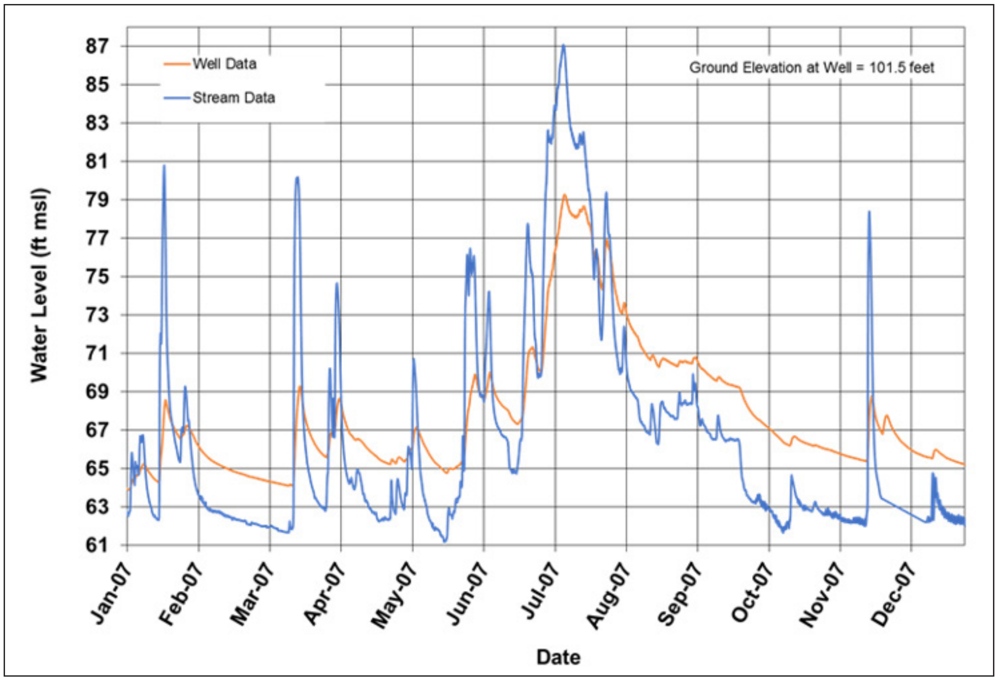

Figure 3. Comparison of measured water levels in the Colorado River and in the Colorado River Alluvium near the City of Wharton in 2007 (from URS and Baer Engineering 2007).

calculations based on hydraulic data and geochemical data. One Texas river that has a relatively large amount of permeable bank material is the Brazos River. A recent study by Rhodes et al. (2017) that includes both hydraulic and geochemical analysis demonstrates that bank storage can be a significant component of groundwater flow to the Brazos River. During a four-month river stage recession following a high stage event, less than 4% of the water discharged from the subsurface resembled the chemical fingerprint of the alluvial aquifer. Instead, the chemistry of the discharged water closely resembled the high stage event river water. Rhodes et al. (2017) concluded that the Brazos River is well connected to rechargeable bank storage reservoirs but disconnected from the broader alluvial aquifer.

SURFACE WATER AND GROUNDWATER AVAILABILITY IN TEXAS

In 1997, Senate Bill 1 of the 75th Texas Legislature directed the TCEQ (then called the Texas Natural Resource Conservation Commission) to develop WAMs for river basins in Texas. A WAM "is a computer based simulation program used to evaluate the amount of surface water in a river or stream that would be available to existing or proposed water rights under specified basin operations and hydrologic conditions"(HDR 2007). WAMs consist of two parts: the modeling program called the Water Rights Analysis Package (WRAP)(Wurbs 2001) and the text files that contain basin-specific information for the WRAP to process. WAMs do not explicitly simulate water fluxes associated with stream-aquifer interactions, but they can indirectly account for the effects of a losing stream through a channel loss function or a naturalized flow adjustment file (HDR 2007). As noted by HDR (2007), however, the majority of WAMs do not include channel losses because the losses are typically small relative to streamflows.

The authors believe that a potentially more valuable surface water model for investigating SW-GW interactions than WAMs are flow-routing models for the stream basin. Flow-routing models solve hydrologic equations that describe how a pulse of water moves downstream. Flow-routing models calculate flow as a function of space and time using equations based on flow continuity and momentum. Two examples of routing models are the LCRA's Daily Operational Routing Model (DORM) (Carron et al. 2010) and the Upper Rio Grande Water Operation Model (Boroughs 2013). These and other routing models can be used to estimate SW-GW interactions by performing water budget calculations that account for all losses and gains along a stream reach except for those associated with SW-GW interaction. Data used by DORM for its water budget calculations include hourly data from gaged tributaries, return flows, releases from Lake Travis, releases from Lady Bird Lake, and known diversions. Working with LCRA to find two- to four-week periods of stable low-flow conditions with high quality data, Young et al. (2017) found that DORM simulations provided credible estimates of SW-GW interaction for low-flow periods in 2012, 2013, 2014, and 2015. Based on DORM results that were generally consistent with previous estimates of SW-GW interactions (Saunders 2009, 2012), Young et al. (2017) recommends that DORM simulations be incorporated into field studies aimed at measuring SW-GW interaction along the Colorado River.

In 2001, Senate Bill 2 tasked the TWDB with developing GAMs of all major and minor aquifers in Texas. The TWDB defines groundwater availability modeling as "the process of developing and using computer programs to estimate future trends in the amount of water available in an aquifer and is based on hydrogeologic principles, actual aquifer measurements, and guidance from persons with interest in the models and the program" (TWDB 2016b). The goal of the GAM program "is to provide useful and timely information for determining groundwater availability for the citizens of Texas" (TWDB 2016b). GAMs are constructed using the family of USGS MODFLOW codes that simulate groundwater flow (McDonald and Harbaugh 1988; Harbaugh and McDonald 1996; Harbaugh et al. 2000; Harbaugh 2005; Niswonger et al. 2005; Panday et al. 2013).

GAMs, in their current capacity, simulate water movement based on the physics of water flow and can simulate the exchange of water between aquifers and streams. Among the factors that limit the ability of GAMs to accurately simulate SW-GW interactions is that they were developed to address water issues at a relatively large spatial scale and are not readily suitable to simulate SW-GW interactions at a local scale of a few miles and less (Scanlon 2005; HDR 2007; Kelley et al. 2008). Another issue that limits GAMs' capability for accurately simulating SW-GW interaction at the local scale is that they use time periods of months to years; whereas, accurate modeling of SW-GW interaction will usually require time periods of hours to days (Scanlon 2005). Besides having the limitations associated with spatial and temporal scales that are large compared to scales that drive SW-GW interactions, GAMs are also limited because GAMs cannot simulate unsaturated flow, which can be an important process for accurate modeling of SW-GW interaction. Recognizing that these are GAM limitations and not necessarily a limitation of MODFLOW, as packages to include unsaturated flow processes exist, highlights one of the ways to enhance GAMs, or a modification of a GAM, to improve simulations of SW-GW interactions.

Despite the inherent limitations with GAMs for simulating SW-GW interaction at the local scale of a few miles, GAMs will not necessarily provide reasonable estimates of SW-GW interaction even at the regional scale unless considerable care is taken with its development. Specifically, the model calibration process for a GAM is particularly important because of the wide range of factors affecting SW-GW interactions. These factors include how recharge, evapotranspiration, streamflow, stream channel geometry, stream-bed hydraulic properties, and runoff are represented in the model. Additionally, another major issue affecting GAM simulation of SW-GW interaction, discussed by Mace et al. (2007), is the vertical resolution (i.e., the layer thicknesses) of the groundwater model:

> "One of the difficulties in accurately representing surface water-groundwater interaction is the vertical resolution in the groundwater availability model. The interaction of a stream and an aquifer is an intimate affair that occurs locally on the order of feet to tens of feet. In many cases, the current groundwater availability models are too coarse, both laterally and vertically, to accurately represent surface water-groundwater interaction. The difference between a gaining stream and a losing stream can be the difference of a few feet of groundwater level change, especially for the aquifers along the Gulf Coast where there is not much topography."

The importance of vertical resolution (inclusion of shallow model layers) at the regional scale is twofold. One reason is that the vertical resolution affects a GAM's capability to represent a shallow groundwater flow zone. This shallow flow zone is the primary conduit in the real physical aquifer system for much of the recharge that enter the groundwater system to move relatively quickly to discharge locations in the aquifer's outcrop, which includes seeps, springs, and surface water bodies. A second reason is that the vertical resolution prevents deep pumping wells that are nearly hydraulically isolated from water table near ground surface from being represented in the same model layer that is a river or a lake.

One of the first applications of shallow model layers to represent a shallow, local flow system in a regional groundwater model was the Lower Colorado River Basin (LCRB) model (Young et al. 2009). The LCRB model sought to improve the accuracy of both recharge and SW-GW interaction by including a shallow and relatively thin model layer near the water table to represent the shallow groundwater flow system. The incorporation of the shallow groundwater layer was made with considerations toward improving how the model represents the aquifers and alluvium. The geology representation was guided by using maps of surface geology including alluvium developed by Barnes (1974).

Figure 4 shows that the county-scale LCRB model provides a significantly better match to historical estimates of groundwater contributions to the Colorado River than the regional-scale Central Gulf Coast GAM (Chowdhury et al. 2004). With regard to the source for pumped groundwater for Matagorda, Wharton, and Colorado counties from 1980 to 2000, the Central Gulf Coast GAM predicts that 66% is leakage from streams whereas the LCRB model predicts 71% is from recharge from precipitation (Young et al. 2009). The large differences in the source for the pumped groundwater illustrate that at a regional scale, model layering can have a significant effect on simulated SW-GW interactions. Among the GAMs that include a thin model layer near the water table to represent shallow ground-

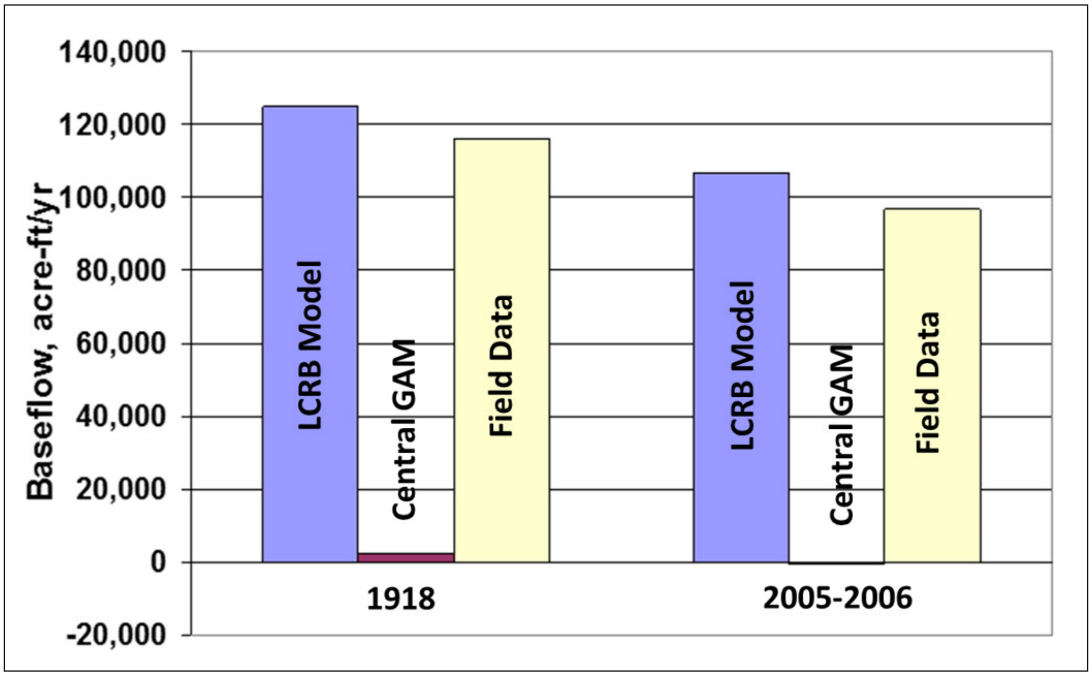

Figure 4. Comparison of measured baseflow along the Colorado River (Field Data) with simulated baseflow values from the LCRB groundwater model and from the Central Gulf Coast Groundwater Availability Model (data from Young et al. 2009; LCRB = Lower Colorado River Basin, GAM = groundwater availability model). The Field Data includes gain-loss studies performed with river gage data reported by Slade (2002) and Saunders (2006).

water flow system are a GAM for the Yegua-Jackson Aquifer (Deeds et al. 2010), a GAM for the Northern Trinity and Woodbine Aquifers (Kelley et al. 2014), and a GAM for the central portion of the Sparta, Queen City, and Carrizo-Wilcox aquifers (Young et al. 2018).

Independent studies funded by the TWDB (HDR 2007) and the TCEQ (Scanlon et al. 2005) have investigated the ability of models to predict SW-GW interactions. Both studies emphasized that there is a critical need for field data that can be used to develop appropriate conceptual models and guidelines for developing GAMs to help standardize and improve the approaches used to simulate SW-GW interactions. Before significant improvements in simulating SW-GW interactions with GAMs and other groundwater can occur, additional field studies need to be conducted. Scanlon et al. (2005) recommended that additional field studies be performed that include (1) co-locating groundwater monitoring wells with stream gages, (2) characterizing stream morphology and aquifer hydraulic properties, (3) collecting water-level and water quality data, (4) evaluating streamflow gains and losses and aquifer bank storage and bank flow, (5) conducting aquifer tests near streams, and (6) evaluating the time it takes water to travel between streams and wells.

STREAM HYDROGRAPHS

Besides using models that simulate the movement of surface water or groundwater, SW-GW interactions can be estimated by using hydrograph-separation methods. Stream hydrographs show changes in measured water levels (that is, stream height or stage) at river gages as a function of time. Hydrograph-separation methods (sometimes called baseflow separation) aim to distinguish a streamflow hydrograph into two components:

1) Quickflow – flow in direct response to a rainfall event including overland flow (runoff) and direct rainfall onto the stream surface (direct precipitation).
2) Baseflow – the steady flow derived from groundwater discharge to the stream and lateral movement in the soil profile (interflow).

Many hydrograph-separation methods have been developed to estimate the baseflow and runoff components of streamflow, and these methods have been implemented in a number of computer programs that facilitate the estimation process (Pettyjohn and Henning 1979; Nathan and McMahon 1990; Wahl and Wahl 1995; Sloto and Crouse 1996; Rutledge 1998; Arnold and Allen 1999; Eckhardt 2005; Lim et al. 2005; Piggott et al. 2005). Although each of the methods is based on formalized algorithms for identifying the baseflow component

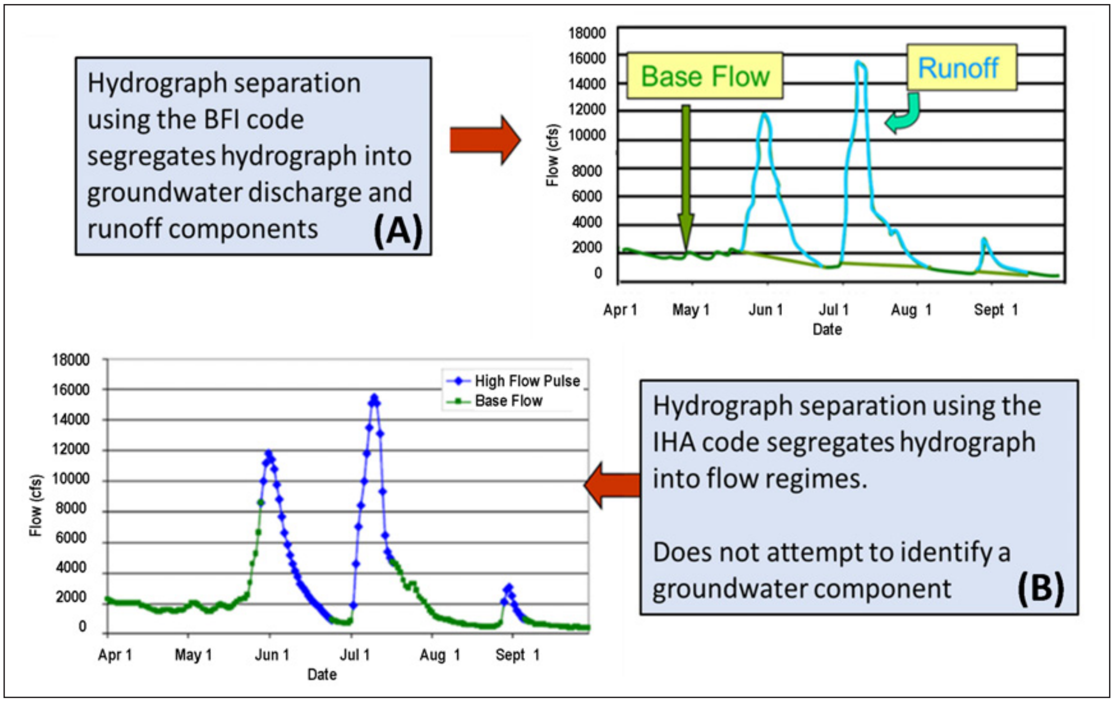

Figure 5. Analysis of a stream gage hydrograph by a surface water hydrologist using the IHA software (A) and by a groundwater hydrologist using the BFI software (B) (IHA = Indicators of Hydrologic Alteration; BFI = baseflow index).

of total streamflow, they can differ substantially in their underlying assumptions and degree of freedom in their application. Because of the different underlying assumptions with the different methods, there are advantages to using more than one hydrograph-separation method to analyze a streamflow record to assess uncertainty.

Hydrograph-separation methods have been widely used to estimate SW-GW interaction and recharge across watersheds in Texas (Young and Kelley 2006; Deeds et al. 2010; Scanlon et al. 2012; Kelley et al. 2014; Ewing et al. 2016; TWDB 2016a; Young et al. 2018). Most of these Texas studies have used either the Base-Flow Index (BFI) Program (Institute of Hydrology 1980; Wahl and Wahl 1995) or the Baseflow Program developed for use with the Texas A&M University's Soil and Water Assessment Tool (Nathan and Mahon 1990; Arnold and Allen 1999). A potential concern with these two methods and other hydrograph-separation techniques is that they do not explicitly account for discharge that did not originate from the groundwater basin (Scanlon et al. 2005) and thus will likely overestimate baseflow. Scanlon et al. (2005) identify these sources as in-stream detention and subsequent discharge of surface water, alluvium aquifer recharge such as bank storage/release following flood events, perched groundwater zones, or fractured zone recharge/discharge in the near subsurface.

In addition to the type of hydrograph-separation programs used by hydrogeologists to identify groundwater contribution to a stream, there are other types of hydrograph-separation programs used by surface water hydrologists to identify flow regimes. These type of hydrograph separations are performed to support the Texas Instream Flow Program (TIFP). The purpose the TIFP is to perform scientific and engineering studies to determine flow conditions necessary for supporting a sound ecological environment in the river basins of Texas (TCEQ, TPWD, TWDB 2008). To identify flow regimes, surface water hydrologist use either the Indicators of Hydrologic Alteration (IHA) program (Richter et al. 1996) or the Modified Base Flow Index with Threshold (MBFIT) (Brandes et al. 2011) to class a portion of a hydrograph into one of four flow regimes: subsistence flow, baseflow, high flow pulses, or overbank flows.

Figure 5A shows the results of a stream hydrograph analysis performed using the BFI program. The BFI program is used to partition a streamflow into a runoff component comprising diffuse surface water flow and a baseflow component comprising groundwater flow into a stream. Figure 5B shows results from applying IHA to the same stream hydrograph in Figure 5A to identify baseflow regimes and high flow pulse regimes. The application of the BFI and the IHA programs illustrate the different type of results produced by each program. Because the two programs use very different sets of underlying assumptions, there is not a common set of information on which the two disciplines can rely to develop a shared understanding and quantification of SW-GW interactions.

Halford and Mayer (2000) share some of the same concerns that Scanlon et al. (2005) state regarding the reliability of the hydrograph-separation techniques without some type of third-party dataset or analysis to ground truth the estimated groundwater contribution calculated from the hydrograph separation. Halford and Mayer (2000) question the accuracy of the hydrograph-separation technique when the underlying assumptions of the technique have not been validated. Based on their analysis of 14 studies in nine states, Halford and Mayer (2000) say that:

- "The recession-curve displacement method and other hydrograph-separation techniques are poor tools for estimating groundwater discharge or recharge when major assumptions of the methods are violated."
- "The identification of groundwater discharge in stream discharge records can be ambiguous because drainage from bank storage, wetlands, surface water bodies, soils, and snowpacks also decreases exponentially during the recession period."

USGS (2017) noted that an important limitation of the BFI program, as well as other hydrograph-separation methods, is that "In general, the method [BFI program] interprets most regulated releases as baseflow. If the program is used for regulated streams, the effects of regulation must be carefully accounted for thorough manual adjustment of the program output." Even when underlying assumptions of the baseflow separation methods are met, the applications of the methods can still be problematic. This situation is illustrated by results from Partington et al. (2012) who analyzed numerically simulated river hydrographs with automated baseflow separation techniques. Partington et al. (2012) found that the automated baseflow separation underestimates the simulated baseflow by as much as 28% or overestimates it by up to 74% during rainfall events. They also concluded that no separation method was clearly superior to the others, as the performance of the various methods varies with different soil types, antecedent moisture conditions, and rainfall events.

Some of the concerns documented by Halford and Mayer (2000) and Scanlon et al. (2005) are confirmed by Young et al. (2018) who estimated baseflow from 35 stream gages in Groundwater Management Area 12. For the 35 stream gages, the average recharge rate across the watershed estimated using the BFI method and the program developed for use with the Texas A&M's Soil and Water Assessment Tool was 2.70 inches and 3.78 inches, respectively, which is about a 140% difference. Such a large difference is evidence that additional work is needed to vet and ground truth the applications of baseflow-separation techniques to quantify SW-GW interaction.

In our opinion, TWDB (2016a) further illustrates the importance to vet and ground truth the approaches used for interpreting stream hydrographs in Texas. This study, prepared in response to House Bill 1232 of the 84th Texas Legislature, estimated the volume of flows from aquifers to surface water in Texas. TWDB (2016a) used the results from several U.S. Geological Survey (USGS) studies (Wolock 2003a, 2003b; Wolock et al. 2004) to spatially distribute groundwater contributions to surface water for the outcrop areas of the major and minor aquifers. Wolock (2003a) analyzed hydrographs from approximately 19,000 stream gages across the United States using the BFI program (Wahl and Wahl 1995). One output of the BFI program is the BFI Index, which is the average percentage that groundwater contributes to streamflow. Figure 6 shows the BFI values from Wolock (2003a) for the Lower Colorado River downstream of Tom Miller Dam in Austin. These nine values indicate that average annual groundwater contributions range from 40% to 65% of the total surface water flow in the Colorado River. Among other SW-GW studies performed in the region are stream low-flow gain-loss studies by Saunders (2009, 2012). Results from these studies can be used to generate BFI values. The analysis of Saunders' data produces BFI values that are up to four times smaller than those presented by Wolock (2003a) at some of the gages shown in Figure 6.

Comparisons of studies involving SW-GW interaction that provide different water budgets show that the variability is not only caused by using different types of data over varying time periods but also by using different assumptions for interpreting the data. Among the assumptions that could be important to an analysis are those related to flow diversions, flow returns, regulated flows upstream, seeps from perched groundwater tables, pumping in or near the alluvium, alluvial recharge, and bank storage/bank flow. The need for well documented and vetted approaches for interpreting stream hydrographs is cited in previous studies funded by TWDB (HDR 2007; Young et al. 2017) and TCEQ (Scanlon et al. 2005) as an important and necessary step toward improving the understanding and modeling of SW-GW interaction in Texas.

WATER RESOURCE MANAGEMENT DECISIONS AFFECTED BY SW-GW INTERACTION

The TWC recognizes that surface water and groundwater resources are hydrologically connected, at least locally, and requires that regulatory authorities consider this when issuing permits. TWC §36.113(d)(2) requires that GCDs, when evaluating groundwater permits, consider whether "…the proposed use of water unreasonably affects existing groundwater and surface water resources or existing permit holders…" Similarly, TWC §11.151 states "in considering an application for a permit to store, take, or divert surface water, the commission [TCEQ] shall consider the effects, if any, on groundwater or groundwater recharge." Statute recognizes the potential inter-

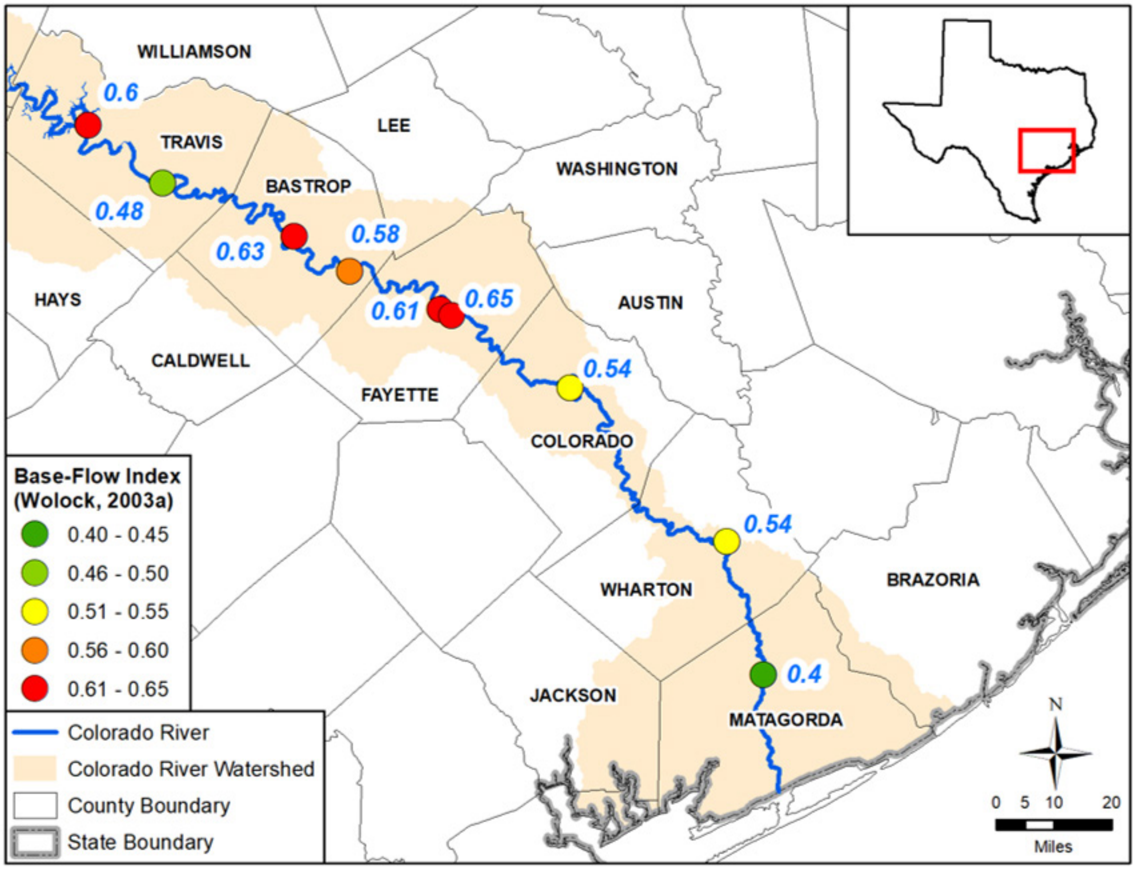

Figure 6. Baseflow index (BFI) from Wolock (2003a) for stream gages on the lower reach of the Colorado River. The BFI figures are percentages of groundwater contribution to streamflow.

connectivity between groundwater and surface water but (1) doesn't specify what level of interaction would spark action on a permit, (2) doesn't require any action by the regulating body, and (3) doesn't coordinate the regulatory realms of TCEQ from the surface water perspective or GCDs from the groundwater perspective.

Pumping near streams

In Texas, there are thousands of shallow wells with depths less than 100 feet that are located near streams. Some of these wells, and those located in the river alluvium within a few hundred feet of the river, pump sufficient water to impact the flow between the stream and the aquifer. Historically, there have been relatively few cases where regulators curtailed pumping. The general lack of action by parties affected is likely the result of a combination of several factors including (1) the lack of clarity in the TWC with regard to how to characterize underflow and how to assess pumping impacts, (2) the dearth of field measurements characterizing SW-GW interactions, (3) the absence of a demonstrated and standardized approach for analyzing stream hydrographs, (4) the reluctance of GCDs to require well owners to meter and report water use, and (5) the inaccuracies associated with many historical gain/loss studies on stream reaches and the inability of WAMs and GAMs to evaluate SW-GW interactions.

The drought-induced periods of lower surface water availability during the last decade have created conditions such that affected parties or stakeholders have requested regulatory assistance to protect state waters from adverse impacts caused by groundwater pumping. This has occurred on the Rio Grande, San Saba, Brazos, and Colorado rivers.

Rio Grande in New Mexico

In January 2013, Texas submitted a complaint to the Supreme Court of the United States (SCOTUS) alleging that New Mexico was in violation of the 1938 Rio Grande Compact. Specifically, Texas alleged that New Mexico had violated the Compact by allowing the diversion of surface water through the pumping of groundwater that is hydrologically connected to the Rio Grande, thereby diminishing Texas' ability to obtain the water the Compact apportioned to it. The New Mexico wells, which are estimated to number 3,000, pump as much as 270,000 acre-feet/year (TLO 2018). In addition, New Mexico has permitted wells that will facilitate additional water use in the future. In January 2017, New Mexico requested that SCOTUS dismiss the complaint from Texas and dismiss a request from the United States to intervene as a party to the litigation. The Special Master appointed by the Supreme Court on this case ruled against New Mexico's motion to dismiss Texas' complaint and to hear oral arguments for the United States complaint. In early 2018, SCOTUS heard arguments by the United States to intervene as a party and to essentially make the same claims as Texas. In March 2018, the SCOTUS ruled that the United States can be a party to the litigation. Litigation will likely proceed well into 2019 to discovery, motions, and eventually a hearing of the merits before the Special Master. The Special Master will then make recommendations to SCOTUS on the merits of the case (SCOTUS 2013).

San Saba River

Since 2011, the TCEQ has received complaints alleging shallow groundwater wells are being used to pump surface water in the form of underflow from the San Saba River. The area identified is a 40-mile reach between Menard and Brady (House Committee on Natural Resources 2018; Sadasivam 2017; 2018), where numerous wells within one mile of the river are completed in the alluvial deposits, which are believed to be a lateral extension of the river. Before 2000, the San Saba River was never known to cease flowing—not even during the record drought of the 1950s. From July to October in six of the past 15 years, and for every summer from 2011 to 2015 (House Committee on Natural Resources 2018; Sadasivam 2017; 2018), the river has gone dry along the 40-mile reach. In 2015, TCEQ Investigation Report Number 1254241 (TCEQ 2015) presented findings from its hydrogeological investigation and determined that some of the groundwater wells were illegally capturing state waters and that, for future pumping to continue, the well owners needed to obtain the appropriate surface water rights. In May 2018, the Texas House Natural Resources Committee conducted a public hearing in Brady, Texas that included both local and statewide perspectives on issues related to SW-GW interactions. During the hearing, arguments were heard from upstream users that natural climate changes and decreased springflows are reasons for the low surface water flows whereas the downstream users claim that wells drilled close to the rivers are pumping the San Saba dry. Among the factors that could affect future actions is the threat of federal regulation. The San Saba is home to five species of mussels that the U.S. Fish and Wildlife Service (USFWS) is considering listing as endangered. If any one of those mussel species is found to be endangered, it could mean restrictions on water use from the San Saba.

Brazos River

In 2009, surface water rights holders in the Brazos River Basin were subject to the first of several calls from the Dow Chemical Company to exercise its senior priority water right. These water calls sparked a series of water diversion curtailments and associated actions that led the TCEQ to, in response to a petition from affected water right holders, establish a watermaster program to regulate diversion from the Brazos River starting in 2015. Curtailments have heightened awareness that groundwater pumping in the Brazos River Alluvium could be affecting surface water availability. Within Robertson, Brazos, and Burleson counties, the GCDs have issued permits totaling more than 130,000 acre-feet/year, and the TWDB has reported pumping greater than 100,000 acre-feet/year for several years in the Brazos River Alluvium. Recently, the TWDB (Wade et al. 2017) used the Brazos River Alluvium GAM (Ewing and Jigmond 2016) to establish 210,536 acre-feet/year as the minimum modeled available groundwater (MAG) for Groundwater Management Area (GMA) 12 between 2013 and 2070. The concern that groundwater pumping could affect surface water availability can be investigated by evaluating the water budget for the TWDB GAM simulations (Wade et al. 2017) and additional GAM simulations that involved no pumping. The joint analysis of these GAM simulations indicate that nearly all of the groundwater pumped from the Brazos River Alluvium wells originates from the Brazos River.

Colorado River

During the first joint planning cycle, Environmental Stewardship (ES) petitioned GMA 12 (ES 2011) to argue that the desired future conditions (DFCs) did not adequately consider SW-GW relationships and did not include protection for the Colorado River, Brazos River, and associated streams and springs. During the second joint planning cycle, ES (2016) presented results from GAM and WAM simulations to argue that future groundwater pumping would lead to declines in Colorado River flow to impact over 1,100 water rights. ES (2016) stated:

> "Critical environmental flow standards for the Colorado and Brazos rivers are threatened by groundwater pumping and must be considered and mitigated in establishing DFCs for aquifers that impact the Colorado and Brazos rivers and their tributaries."
>
> "There are logical arguments and credible evidence that the groundwater pumping in the proposed DFCs will have an adverse impact on surface water permits making it proper that the impact on surface water rights be considered under Section 36.108(c)(7)."

In finding that the GMA 12's DFCs were reasonable and GMA 12 did not need to account for SW-GW interactions, the TWDB (2012) stated the following:

1. "Senate Bill 3 does not place the responsibilities discussed by Environmental Stewardship on the Districts. Before granting or denying a permit, a district must consider, among other things, whether 'the proposed use of water unreasonably affects existing groundwater and surface water resources or existing permit holders.' But that requirement is part of the permitting process; there is no explicit requirement in the statutes under which this petition was brought for the Districts to consider impacts on spring flow and other interactions between groundwater and surface water."
2. "A number of factors affect instream flow and outflows from the Colorado and Brazos rivers and technical work remains to be done to better monitor, analyzed, and manage that interaction."…"But, the issue at hand is whether the DFCs are reasonable as expressions of the desired future conditions of the aquifers."

An overarching concern expressed by ES (2011) is that GMA 12 did not use the science and technology necessary and appropriate to simulate SW-GW impacts and evaluate groundwater pumping impacts on streamflows. During the second joint planning session, ES (2016) maintained that the DFCs are not protective of the environment and recognized that the currently adopted DFCs are the current legal standard and, as such, should not be significantly changed until the GAM has been improved and better data are available to assess SW-GW interactions. To help correct this situation, ES, the LCRA, the Brazos River Authority, and the GCDs in GMA 12 have worked with the TWDB to update the GAM for the central portion of the Queen City, Sparta, and Carrizo-Wilcox aquifers (Young et al. 2018), which includes improved SW-GW interactions.

The GAM update included several modifications to better represent a shallow groundwater flow system. One of these modifications was to explicitly represent the Colorado River Alluvium and the Brazos River Alluvium as independent hydrostratigraphic entities with thicknesses and hydraulic properties based on hydrogeological studies and with pumping rates based on wells screened across the alluviums. Another modification was to represent aquifers using two model layers instead of a single model layer where they outcrop and receive recharge from rainfall. In addition, the GAM grid spacing in the vicinity of the Colorado River and Brazos River was changed from 1 mile by 1 mile to as small as 0.25 mile by 0.25 mile in order to more accurately represent well locations and the location and bathymetries of the Colorado and Brazos rivers.

Rio Grande at El Paso

While pumping near El Paso has not recently been a concern for regulatory agencies with regard to SW-GW interactions, it has been historically and may likely be in the future. In the first half of the 1900s, estimated pumping from deep wells in the El Paso area increased from about 2,200 acre-feet/year in 1910 to about 31,000 acre-feet/year in 1953 (Knowles and Kennedy 1956). This caused a reversal of flow between the Rio Grande Alluvium and the deeper aquifers. Hutchison (2006) noted that in the El Paso area, groundwater flow was generally toward the alluvium until about 1940, then away from the alluvium after 1960. Hutchison (2006), using the groundwater model developed by Heywood and Yager (2003), showed groundwater pumping in the El Paso area caused a switch from an overall flow of groundwater to surface water of about 3,000 acre-feet/year to 5,000 acre-feet/year before 1925 to an overall flow of surface water to groundwater after 1925. Over the last 20 years, the net losses from the Rio Grande have stabilized at about 33,000 acre-feet/year (Mace et al. 2007). With regard to the reported SW-GW interaction for the Rio Grande at El Paso, it is important to recognize that these fluxes contain biases introduced by the uncertainties associated with using regional models.

Bed and bank permits, environmental flows, endangered species and desired future conditions

Besides surface water rights, other regulatory issues that could be affected by SW-GW interactions are environmental flows, habitat for endangered species, bed and bank permits, and desired future conditions.

Environmental flows

Senate Bill 2 passed into law by the 77th Texas Legislature in 2001 established the TIFP. TIFP is jointly administered by the Texas Parks and Wildlife Department (TPWD), the TCEQ, and the TWDB in collaboration as appropriate with other entities. The goal of the TIFP is to identify flow regimes (quantity and timing of flow) that are adequate to maintain an ecologically sound environment, conserving fish and wildlife resources while also providing sustained benefits for other human uses of water resources. One of the objectives of the instream flow program is to mimic the natural flow regime as closely as possible.

Streamflow requirements (standards) for particular locations in specific stream systems are defined in terms of flow regimes. TWC §11.002.16 defines an environmental flow regime as "quantities that reflect seasonal and yearly fluctuations that typically would vary geographically, by specific location in a watershed, and that are shown to be adequate to support a sound ecological environment and to maintain the productivity, extent, and persistence of key aquatic habitats in and along the affected water bodies." The development of an instream flow regime includes four components: subsistence flows, baseflows, within-bank high flow pulses, and overbank high pulse flows.

For some streams, SW-GW interactions can become an important process that impacts the quantity and quality of streamflow during subsistence flows or baseflows. Subsistence flows occur during drought or very dry conditions. The primary objective of subsistence flow standards is to maintain tolerable water quality conditions to provide minimal aquatic habitat space for the survival of aquatic organisms. Baseflows represent the range of average or normal flow conditions without the effects of recent rainfall. A primary objective of baseflow standards is to provide adequate habitat for the support of diverse, native aquatic communities and maintain groundwater levels to support riparian vegetation.

Endangered Species Act

The ESA took effect in 1973. Its purpose is to conserve and recover listed endangered species and the ecosystems upon which they depend. SW-GW interactions are potentially important to the ESA in the execution of ESA's Section 9—the taking provision. This section makes it a felony to "take" a threatened or endangered species without specific authorization from the USFWS. The ESA provides for both civil and criminal prosecution for illegal "takes." The U.S. Supreme Court has expanded a "take" to include activities that disrupt the habitat of the threatened or endangered species or interfere with usual feeding and breeding activity. Species in Texas that have protection under the ESA are listed in the Texas Parks and Wildlife Code 68.002 and the Texas Administrative Code. The aquatic animals under ESA protection includes birds, fish, and amphibians. The Texas hornshell mussel is under ESA protection in Texas (Federal Register 2018) and 11 other freshwater mussel species are currently under review by the USFWS for ESA listing (Ingram 2017).

As a result of legal threats of a federal takeover of the Edwards Aquifer under the ESA, the Texas Legislature adopted the Edwards Aquifer Authority (EAA) Act in 1993 (Votteler 1998). The EAA was created to preserve the Edwards Aquifer while protecting threatened and endangered species in the aquifer-fed Comal and San Marcos springs. The creation of the EAA clearly demonstrates that SW-GW interactions can be important to maintaining habitat for endangered species.

The ESA was also a key component of lawsuits involving the deaths of an unknown number of whooping cranes in Aransas Bay during the drought of 2008 and 2009 (USCA 2014; Votteler 2017). Plaintiffs argued that the deaths were indirectly a result of insufficient freshwater flows into Aransas Bay caused by diversion of water, authorized under water rights issued by the TCEQ, from the San Antonio and Guadalupe river basins. An initial court ruling by a Corpus Christi district judge stated that the ESA had been violated by TCEQ's administration of water rights, but a later ruling by the 5th Circuit Court of Appeal in 2014 stated that the TCEQ did not violate the ESA based on the narrow issue of proximate cause. Proximate cause is a legal concept providing that a person should only be held liable for that sequence if the outcome would have been reasonably foreseeable. Despite the 5th Circuit ruling exonerating the TCEQ of violating the ESA, the ruling confirms that ESA considerations need to be properly evaluated as part of water resource planning.

Bed and banks permits

TWC §11.042 and TCEQ Rule §295 allow the bank and bed of any flowing natural stream in Texas to convey water from the place of storage or discharge to the place of use or diversion. This can include wastewater discharges that are derived from a groundwater source where ownership may be maintained. A bed and bank permit requires the applicant to indicate the source, amount, and rates of discharge and diversion (TCEQ 2017). This information is necessary for the agency to calculate conveyance losses that may result from the bed and banks transfer. Per TCEQ §295.114(b)(6) conveyance losses include the loss to transportation, evaporation, seepage, channel, or other associated carriage losses from the point of discharge to the point of diversion. SW-GW interactions are important to conveyance losses where streams lose flow to the adjacent aquifer. Such losses would occur where the stream stage is at a higher elevation than the water table and the amount of conveyance losses would depend on the geometry of the stream channel, the hydraulic gradient away from the stream, the hydraulic properties of the streambed, and the hydraulic properties of the aquifer.

Desired future conditions

House Bill 1763 of the 79th Texas Legislature requires joint planning among GCDs in a GMA to establish DFCs every five years. TWDB rules define DFCs as "[t]he desired, quantified condition of groundwater resources (such as water levels, water quality, spring flows, or volumes) at a specified time or times in the future or in perpetuity…" TWC §36.1008 (2)(d)(4) requires that, as part of the process for setting DFCs, GMAs consider "environmental impacts, including impacts on spring flow and other interactions between groundwater and surface water" among other factors. GMAs have different interpretations of what "consider" means, which have generally been informed by overall management goals. For example, the GCDs in GMA 9 have developed a DFC in the Edwards Group of the Edwards-Trinity (Plateau) Aquifer that "provides maximum, reasonable and achievable protection for springs and baseflow to creeks and rivers (GMA 9 et al. 2016). Other GMAs have chosen DFCs that do not maintain baseflow and springflow.

In GMA 12, GCDs, river authorities, and the Colorado-Lavaca Basin and Bay Area Stakeholder Committee (BBASC) co-funded work on the Central Sparta-Queen City-Carrizo-Wilcox GAM to improve the capability of the GAM to simulate SW-GW interactions. The improved capability is primarily achieved by creating a shallow groundwater flow zone in the aquifer outcrops, through the addition of model layers, which interacts with streams independently of the deeper groundwater flow zone. To help address their concerns with improving the management of the shallow groundwater flow system, the GCDs in GMA 13 have adopted a DFC that limits drawdown in the outcrop of the Carrizo-Wilcox Aquifer (Hutchison 2017).

DEVELOPING BETTER SCIENCE

A number of activities could be accomplished to improve the science—and thus the regulatory tools—for quantifying SW-GW interactions.

Conduct field studies

Lack of field data is perhaps the greatest obstacle to improving the capability of GAMs to simulate SW-GW interactions, as data are required to develop and validate approaches for modeling this interaction. Field studies are lacking because they are relatively expensive and no state programs currently mandate these studies. As part of a TCEQ study concerning SW-GW interactions, Scanlon et al. (2005) recommended that future studies include (1) co-locating groundwater monitoring wells with stream gages, (2) evaluating streamflow gains and losses, (3) evaluating stream channel morphology, (4) conducting aquifer tests near streams, and (5) evaluating the time it takes water to travel between streams and wells.

An important aspect of any field study is that it collects the necessary information to support the development and testing of models that can be used by state agencies, river authorities, private or public utilities, and hydrogeological consultants to simulate SW-GW interactions. Specifically, field studies should be evaluated in light of anticipated statutory issues that could be before the Texas Legislature in future sessions. Such studies should include the measurements of water levels and water quality parameters, the evaluation of stream hydrographs, the quantification of bank storage and bank flow, and the modeling of SW-GW interactions.

Vet approaches for calculating baseflow using hydrograph separation

Because of the wide range of conditions that exists along rivers and the relatively simple algorithms used by most hydrograph-separation techniques to estimate baseflow, there is considerable opportunity in the analysis for introduction of error into the estimate for baseflow. As such, when estimates of baseflow are important to understanding SW-GW interactions, the baseflow estimate should be properly vetted and uncertainties should be identified and quantified. The vetting process should include a thorough discussion and analysis of factors that could affect the application such as return flows, diversions, dam flows, groundwater pumping, and bank storage. This discussion should quantify, to the extent possible, the potential for each of these factors to impact the stream hydrograph and to introduce uncertainty into the calculated baseflow. The analysis should include multiple and even alternative methods for estimating baseflow in order to help account for the uncertainty associated with any one technique and the sensitivity of the calculated baseflow to the actual mechanics used to implement a particular technique.

Update and improve groundwater availability models

GAMs were originally designed to address large regional-scale groundwater issues and provide information to regional water planning groups and for GCD management plans. Since the start of joint planning, there has been increased interest on the part of GCDs and other stakeholders to use GAMs to address groundwater management issues at the local scale. Among the reasons for the expanded interest are that GAMs are generally considered to represent the best available science, and the prolonged periods of low surface water availability in 2009 and 2011 created additional interest in using groundwater as a water supply. The application of GAMs to evaluate the impacts of specific well fields usually requires discretization and additional field data to better represent site conditions. Such modifications increase the costs for developing a GAM and can complicate its use in regional planning.

Given that GAMs are increasingly being used for much more than what the original TWDB GAM program intended, we make two recommendations to improve the GAMs. The first is to evaluate whether the mission of the GAM program should be modified to better address issues associated with SW-GW interactions. The second is to develop more standardization among the GAMs, where appropriate, for representing interactions that occur in aquifer outcrops such as recharge, evapotranspiration, and SW-GW interactions. Along with this standardization comes the case-by-case analysis of which analytical and numerical methods best represent SW-GW interaction and whether these representations can be accurately included in appropriately-scaled GAMs. The better science derived from WAMs and GAMs as well as increased capabilities may result in less contested issues relative to water permitting activities.

Develop science to better define baseflow, bank flow, underflow

Among the key needs for improving the regulation of SW-GW interactions are the science and data necessary to define the terms used to characterize SW-GW interactions. These terms include baseflow, bank flow, and underflow. There are two significant technical problems associated with defining these terms. The first problem is that these three terms define quantifies that are transient and spatially variable. The second problem is the lack of science to demonstrate how to appropriately accommodate temporal and spatial variability into the measurement of each term. Because of these two technical problems, regulatory agencies called upon to mitigate disputes involving SW-GW interactions may not have, or in most cases do not have, sufficient information to make appropriate regulatory distinctions and determinations.

With respect to developing a science program to better characterize SW-GW interactions, there are two important considerations. One consideration is that the environmental conditions, which include geology, hydrogeology, and meteorology, have a significant impact of SW-GW interactions. As a result, there is no need to study every stream because streams with similar environmental conditions should have similar type of SW-GW interactions. A second consideration is that because SW-GW interactions are not equally important across Texas, a science program should prioritize the critical areas for study based in part on their environmental conditions.

CONCLUSIONS

SW-GW interactions can be important for managing water rights along a river, complying with the ESA, implementing environmental flow recommendations, and obtaining bed and banks permits. A key issue to these regulatory and management concerns is how to quantify the exchange of water between streams and aquifers and to what extent does groundwater pumping impact this exchange and the availability of surface water. Currently, Texas does not possess a sufficient understanding of SW-GW interactions to readily address these concerns at the granularity necessary to facilitate permitting determinations.

The uncertainties associated with quantifying SW-GW interactions have contributed to disputes regarding actual ownership and rights to water. Locations where these disputes have recently occurred or are occurring include the Rio Grande, the San Saba River, the Colorado River, and the Brazos River. To help effectively integrate, regulate, and manage surface water and groundwater resources in Texas, recommendations include conducting field studies focused on quantifying SW-GW interactions, performing additional vetting and ground truthing on hydrograph-separation techniques, improving the capability of GAMs to simulate SW-GW interactions, and developing the science and tools necessary to define and quantify underflow, bank flow, and baseflow.

Communication and cooperation among river authorities, GCDs, the TCEQ and TWDB must also be improved. Such cooperative efforts recently occurred while updating the GMA 12 Carrizo-Wilcox GAM, for which appreciable funding was contributed by the LCRA and Brazos River Authority and by the Post Oak Savannah GCD and Brazos Valley GCD to specifically address SW-GW interactions in the GAM. This jointly funded project clearly shows that proper modeling of SW-GW interactions is a concern and an interest for both river authorities and GCDs.

ACKNOWLEDGMENTS

The authors would like to thank Post Oak Savannah Groundwater Conservation District for its encouragement to write the paper and the Texas Water Development Board (TWDB) for its helpful review. The authors also would like thank House Natural Resources Committee (HNR) Chair Representative Lyle Larson, HNR Director Shannon Houston, TWDB Water and Science Deputy Executive Administrator John Dupnik, and TWDB Groundwater Director Larry French for sharing their insights on the importance of SW-GW interactions and comments on early drafts of the article.

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