SURFACE WATER AND GROUNDWATER—TOGETHER AGAIN?

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CHAPTER 9.1

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I. INTRODUCTION

Everybody learns about the Earth's water cycle in grade school: how water evaporates from the ocean, condenses into clouds, and returns as rainfall. The water from that rainfall then flows over the land surface, into and through the ground, and back into the oceans to start the cycle all over again. Because the movement of water over and in the Earth is a cycle, each part is, to a certain degree, connected to and dependent upon the other parts. This is certainly the case between surface water and groundwater, which share an interface—the land surface.

Although the connection between surface water and groundwater is scientifically recognized, the acknowledgment of this connection is arguably limited in statute and law in Texas. And although current water availability models and groundwater availability models consider the connection between surface water and groundwater, there is much room for improvement. Furthermore, the models, for the most part, do not "talk" to each other.

One reason for the tenuous connection between surface and groundwater in Texas law is that surface water law and groundwater law have, for the most part, progressed on separate tracks. Part of the reason for this division may be that many people early in the history of Texas did not fully understand the movement of water in nature. For example, the Texas Supreme Court case that established the rule of capture in Texas (*Houston and Texas Central Railroad Co. v. East*, 81 S.W. 279, 280, Tex. 1904) noted that the flows of groundwater were "*…so secret, occult, and concealed that an attempt to administer any set of legal rules in respect to them would be involved in hopeless uncertainty…*" despite the fact that the science at the time understood the physical laws governing groundwater flow (Mace and others, 2004). Surface water, on the other hand, is easier for a layperson to understand since it rests on the land surface for all to see.

Scientists that study groundwater and surface water tend to come from different disciplines—groundwater scientists tend to be geologists, and surface water scientists tend to be engineers, although there are those that straddle the interface and focus on how surface water and groundwater interact. This disciplinary division has led to some good-natured ribbing between the two groups. An old joke among groundwater scientists is that surface water is simply rejected groundwater. And, of course, surface water scientists joke that the opposite is true.

The bottom line is that there is a known physical connection between surface water and groundwater, a connection that is particularly important in Texas because many streams and aquifers interact with each other. This connection will become more important with time as the need for water grows and as potential conflicts develop. The purpose of this paper is to present scientific and legal definitions for surface water and groundwater and to describe how surface water and groundwater interact, how their interaction is currently handled in Texas' surface water and groundwater availability models, and what could be done in the future to better consider this interaction.

II. SURFACE WATER AND GROUNDWATER: DEFINITIONS

Scientifically speaking, as indicated by their names, surface water is water on the land surface, and groundwater is water in the ground, below the land surface. Surface water includes water in surface streams; lakes, reservoirs, and wetlands; seas and oceans; and ice and snow. Groundwater includes water in aquifers and other geologic formations and water flowing downward into them.

The Texas Water Code does not specifically define surface water. Instead, the code defines state water, which is described as "*[t]he 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 is the property of the state.*" (Tex. Water Code §11.021, Vernon's 2006). For the most part, state water is surface water, although underflow—water flowing beneath the bed or through the sediments of a river or stream (after Wilson and Moore, 1998, and Jackson, 1997)—is technically, as defined previously, groundwater. The Texas Water Code defines groundwater as "*…water percolating below the surface of the earth*." (Tex. Water Code §36.001(5), Vernon's 2006).

III. SURFACE WATER - GROUNDWATER INTERACTION

Surface water-groundwater interaction is the interplay between water on and beneath the land surface. This interaction includes the flow of surface water into the groundwater system and the flow of groundwater into the surface water system. The flow of surface water into the groundwater system is defined as infiltration, which includes the flow of water into rock or soil at the land surface and the flow of water from a surface stream into its streambed (Wilson and Moore, 1998). This flow also includes the flow of water from a lake or any other surface water body into the ground. Water flowing in the other direction, from groundwater to surface water, includes spring flow and baseflow to surface streams and lakes (baseflow, in this context, is the seepage of groundwater into a stream). In the case of a stream overlying an aquifer, water can flow from the stream into the groundwater system (a losing stream) or from the groundwater system to the stream (a gaining stream; Figure 1). It is not uncommon for a stream to be gaining in one reach and losing in another, depending on how the stream interacts with the groundwater system.

Surface water-groundwater interaction is important because what happens in one resource can, and often does, affect the other. Humans often affect this interaction. For example, wells pumping an aquifer may cause spring flows and baseflows to decline or even cease, affecting flow in surface streams. In extreme cases, pumping of an aquifer can cause the interaction between the aquifer and the stream to reverse: before pumping, water flowed from the aquifer to the stream; after pumping, water flowed from the stream into the aquifer. Similarly, streamflow intercepted before it can infiltrate into an aquifer affects water levels and flow in the aquifer.

A. Examples in Texas

Because Texas has many streams and aquifers, there is great potential for surface water-groundwater interaction (Figure 2). There have also been many studies quantifying these interactions (see, for example, compendiums by Slade and others, 2002, and Scanlon and others, 2005). Based on 91 streamflow gages spread across Texas, Scanlon and others (2005) found that baseflow—presumably from groundwater—ranged from 0 to more than 90 percent of streamflow.

There are also many examples of human influence on those interactions. Perhaps most dramatic is Brune’s (1981, 2002) contention that most springs in Texas have failed or are failing due to increased pumping, which has affected surface water resources. Several examples, such as Comanche Springs, Lake Amistad, and the Rio Grande at El Paso, illustrate surface water and groundwater interactions and the importance of these interactions on water resources in Texas.

1. Comanche Springs

Comanche Springs, located in Fort Stockton, was a water resource for humans for at least 10,000 years, from the Native Americans to the Spanish explorers to the Texans who migrated to the area in the 1800s and 1900s (Brune, 1981). Besides providing water for wildlife, recreation, and a U.S. Army fort, the springs were also used to irrigate about 6,000 acres of crops. By 1948, a severe drought led a farmer to drill and pump a well field nearby, “upstream” of the springs. Before that time, Comanche Springs flowed about 19,000 gallons per minute; by 1962, Comanche Springs stopped flowing altogether (Figure 3). After Comanche Springs dried up, the irrigators downstream of the springs sued the farmer with the well field. The trial court and the court of civil appeals (*Pecos County WCID No. 1 v. Williams*, 271 S.W.2d503, Tex. Civ. App.-El Paso 1954) sided with the farmer with the well field, citing the East case, and the Texas Supreme Court declined to take the case on appeal (Brown, 2001). Today, the springs usually flow only during the winter and early spring months before the irrigation season starts.

2. Lake Amistad

Lake Amistad is a manmade lake constructed on the Rio Grande upstream of Del Rio for flood control, water supply, power, and recreation for Texas and Mexico. Construction on Lake Amistad began in December 1964 and was completed and filled with water by November 1969. When the lake began filling, groundwater levels in the bordering Edwards-Trinity (Plateau) Aquifer rose significantly, as much as 150 feet (Figure 4). Groundwater level changes could be seen at least 10 miles away from the lake (based on hydrographs in Boghici, 2002). Spring flow at San Felipe Springs has increased since completion of Lake Amistad (Brune, 2002) from about 41,000 gallons per minute to about 63,000 gallons per minute (based on data presented in Brune, 2002). The lake has had the opposite effect on another group of springs, the Goodenough Springs, once the third largest group of springs in Texas. After the lake inundated them, the pressure from 150 feet of water now overlying the springs has reduced the spring flow.

Groundwater levels have increased because of the water level in the lake. Before the lake was filled with water, groundwater flowed toward and discharged at and near the Rio Grande and its tributaries in the area. After construction of the dam, the water level in the lake was, in places, more than 150 feet higher than the streams. Therefore, groundwater is now flowing toward a higher level, which caused water levels in the aquifer to rise. The increase of flow at San Felipe Springs also suggests that the lake has changed groundwater flow in the aquifer.

3. Rio Grande at El Paso

In 1849, Anson Mills platted the city of El Paso on the northern shore of the Rio Grande across from El Paso del Norte, now Ciudad Juarez (Handbook of Texas, 2007). Up until 1920, about 6,800 acre-feet per year of water flowed from the Hueco Bolson Aquifer into the Rio Grande for Texas and Mexico (Meyer, 1976) through the Rio Grande alluvium. However, as El Paso grew, so did its use of groundwater. The city dug its first water supply well in 1892 a few hundred feet from the Rio Grande (Sayre and Livingston, 1945). By 1904, the International Water Company was drilling wells on the mesa north of Fort Bliss (Knowles and Kennedy, 1956). In the first half of the 1900s, estimated pumping from deep wells in the El Paso area in Texas increased from about 2,200 acre-feet per year in 1910 to about 31,000 acre-feet per year in 1953 (Knowles and Kennedy, 1956). This caused a reversal of flow between the Rio Grande alluvium and the Hueco Bolson Aquifer—water from the alluvium was now flowing into the aquifer. Lippincott (1921) noted that the city wells he studied were being fed from the Rio Grande; however, he was unable to determine how much water the river contributed.

Meyer (1976) estimated that the overall flow reversal point occurred in 1936 (Lippincott, 1921, was probably seeing a local capture of surface water). Bredehoeft and others (2004) noted that the current numerical model for the Hueco Bolson Aquifer (Heywood and Yager, 2003) shows a flow of about 50,000 acre-feet per year from the river to the underlying aquifer in Mexico and Texas. Hutchison (2006, p.164–165) noted that groundwater flow was, in general, upward until about 1940, neutral from 1940 to 1960, and then downward after 1960 in the El Paso area. Huchison (2006), using the groundwater model developed by Heywood and Yager (2003), shows for the El Paso area in Texas an overall flow of groundwater to surface water of about 3,000 to 5,000 acre-feet year before 1925 and an overall flow of surface water to groundwater after 1925 that, over the past 20 years, has stabilized at about 33,000 acre-feet per year (Figure 5).

B. Surface water - groundwater interaction in statute and rules

Texas statute and rules partially recognize the interaction between surface water and groundwater. As previously mentioned, the definition of state water includes underflow in a streambed. The Texas Commission on Environmental Quality rules define underflow of a stream 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)). This suggests, in combination with the definition of state water that includes underflow, that if someone puts a shallow well near a stream where the groundwater is flowing in the same direction as the stream, the water coming from that well may be state water. The Commission's rules also define baseflow, or normal flow, 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. (Accountable effluent discharges from municipal, industrial, agricultural, or other uses of ground or surface waters may be included at times.)*" (30 Tex. Admin. Code §297.1(6)) which includes contributions from groundwater.

Statute also recognizes that surface streams may contribute water to underlying aquifers. In granting permits to surface water, the Texas Commission on Environmental Quality is required to consider the effects on groundwater and groundwater recharge (Tex. Water Code §11.151). This provision was added with the passage of Senate Bill 1 in 1997 (Brown, 2001). Statute also allows unappropriated state water to artificially recharge the Edwards (Balcones Fault Zone) Aquifer and become non-state groundwater (Tex Water Code §11.023(c) and (d)). Artificially recharging the aquifer involves altering the natural flow of surface water such as through diversions or recharge dams (dams built to increase the potential for infiltration into the aquifer) to increase recharge to the aquifer. In addition, statute allows the use of state waterways for transporting groundwater or wastewater whose source was groundwater (Tex. Water Code §11.042(b), Vernon's 2006). Statute also allows the storage of appropriated surface water in groundwater reservoirs (that is, aquifer storage and recovery; Tex. Water Code §11.154).

Statute recognizes that groundwater pumping may affect surface water and requires that groundwater conservation districts, when evaluating groundwater permits, consider whether "…the proposed use of water unreasonably affects existing groundwater and surface water resources or existing permit holders…" (Tex. Water Code §36.113(d)(2), Vernon's 2006). Groundwater conservation districts are also required to coordinate with surface water management entities when developing their groundwater management plan (Tex. Water Code §36.1071(a), Vernon's 2006).

The state explicitly recognizes and protects surface water-groundwater interaction in one hydrologic system—spring flow from the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer. This recognition and protection exists because of a federal lawsuit to protect endangered species in Comal and San Marcos springs (Votteler, 2000). The Texas Legislature responded by creating the Edwards Aquifer Authority, which is required to develop a plan to protect spring flows.

The state also allows groundwater conservation districts to choose to manage their groundwater resources in such a way as to protect spring flow and baseflow to streams. The introduction of joint planning among groundwater conservation districts in groundwater management areas through House Bill 1763 of the 79th Texas Legislature requires groundwater conservation districts to define the desired future conditions of the groundwater resources in their area (Mace and others, 2006). Texas Water Development Board rules define desired future conditions 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…*" (31 Tex. Admin. Code §356.2(8)).

C. Surface water and groundwater interaction in the availability models

The state has developed or obtained surface water and groundwater availability models for many of the water resources of the state. Surface water availability models are developed by the Texas Commission on Environmental Quality and based on the Water Rights Analysis Package, also known as WRAP (Wurbs, 2001). Often referred to in acronym form as WAMs the models simulate the amount of water in a stream under specified conditions. Groundwater availability models—developed or obtained by the Texas Water Development Board, based on Modflow (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh and others, 2000), and often referred to in acronym form as GAMs—simulate the flow of groundwater. These models consider surface water-groundwater interaction with varying degrees of complexity and success.

1. <u>Surface Water and Groundwater Interaction in the Water Availability Models</u>

In 1997, the Texas Legislature directed the Texas Commission on Environmental Quality to develop water availability models for all river basins of the state except the Rio Grande. As a result of subsequent legislation, the Commission developed a special application for the Rio Grande. By 2003, 21 models had been developed, covering the 23 river basins of the state.

The water availability models consist of a set of data on all existing surface water rights, recent water use, wastewater return flows, physical attributes of reservoirs, and other pertinent information. Naturalized flow—the estimated flow in a watercourse with all manmade impacts in the watershed removed—forms the backbone of the water availability analyses, and the models each contain at least 50 years of historical data. The Water Rights Analysis Package is used to run the water availability models. This package performs monthly water volume calculations at each and every point of interest, also known as control points, in a basin, using the predetermined naturalized flow and all known impacts to that flow, to determine how much water is left. In simple terms, the model figures out how much water Mother Nature has provided and how much is legally available throughout the basin. The regulatory and planning agencies can thus determine whether there is any remaining unappropriated flow in the basin, which helps the state plan to meet its future water supply needs and make decisions regarding water right permit applications.

The water availability models consist of input files and calculations at control points within a river basin. For each month of the simulation, and at each and every control point, the water availability model calculates the amount of water in the river by considering all flow-altering actions occurring in the basin. In addition, the model estimates how much water might be available at that point given environmental considerations and obligations to senior water right holders in the basin.

As mentioned previously, the water availability models use predetermined naturalized flows as the basis for all water availability calculations. A number of factors can impact the amount of water lost from one point in the basin to the next, such as reservoir evaporation or a diversion. How the water availability models take into account losses to groundwater varies from model to model. For example, a flow adjustment file can be used to simply add to or remove flow from the monthly naturalized flow time series. This adjustment takes into account known (and varying) groundwater pumping and spring discharge, using measurements determined outside of the water availability model environment.

Channel losses from evaporation or aquifer recharge can also be modeled using a percentage applied between control points. For example, a river may lose 5 percent of its flow between two control points—that factor is simply inserted into the model, and flows are adjusted accordingly. This approach has the potential to overestimate losses during periods of high flow and does not consider the condition of the underlying aquifer. Great care must be taken with both methods to ensure that one does not double-count flow in the river.

2. <u>Surface Water and Groundwater Interaction in the Groundwater Availability Models</u>

In 2001, the Texas Legislature directed the Texas Water Development Board to develop groundwater availability models for all of the major and minor aquifers of the state. By October 2004, 17 models covering the 9 major aquifers had been developed. Board staff expects the models for the minor aquifers to be completed by the end of 2010.

Groundwater availability models are driven by a finite-difference code that calculates the movement of water in the aquifer and at the aquifer's boundaries according to measured and calibrated physical hydraulic parameters. The models are generally calibrated to predevelopment (before there was pumping) conditions and to at least 20 years of historical data (generally

1980 to 2000). Calibration targets include water levels and may include spring flow and baseflow.

Because of the importance of surface water-groundwater interaction, this interaction is simulated by the groundwater availability models. How well these interactions are simulated in the models depends on several factors, including (1) the available information on the interactions, (2) how the interactions are represented in the model, (3) how much emphasis the modeler placed on calibrating to known surface water-groundwater interactions, (4) how successful the modeler was in matching known interactions, and (5) the vertical resolution of the model.

To have any hope of accurately simulating surface water-groundwater interaction, there have to have been studies on quantifying that interaction. Springs need to be monitored over a long period of time to capture how they respond to climate and, if applicable, pumping. In the case of streams, there needs to have been a study to identify where streams are gaining and losing due to interactions with the aquifer, how much they are gaining and losing and, if possible, how that gaining and losing has changed over time.

How surface water-groundwater interactions are represented in the model can also affect how accurately the model can simulate them, especially when the model is used to make predictions. Modflow, the modeling code that is the engine for the Texas groundwater availability models, allows surface water-groundwater interaction to be simulated in a number of ways, with varying complexity. Some of the choices include the drain package, the river package, and the streamflow routing package. The drain package allows water to flow from the aquifer to the stream but not from the stream to the aquifer. The river package allows water to flow from the aquifer to the stream and from the stream to the aquifer; however, when water flows from the stream to the aquifer, it does not allow the stream to go dry if the stream loses all of its water. The streamflow routing package allows water to flow from the aquifer to the stream and from the stream to the aquifer and allows the stream to go dry. Most of the groundwater availability models use the streamflow routing package, which offers the most sophisticated and realistic representation of streams. This does not mean that the other packages incorrectly simulate surface water-groundwater interaction for a particular hydrologic system. Whether the packages chosen are correct or incorrect depends on how the hydrologic system behaves and what future scenarios people want to investigate. Modflow also offers several choices for surface water-groundwater interaction between lakes and aquifers, such as the constant head package, the general-head package, and the reservoir package.

When calibrating a groundwater availability model, the modeler tries to match as closely as possible measured values of aquifer water levels and flows between the aquifer and surface water, generally in the form of spring flow and/or baseflow to streams. The quality of this match depends on available information, the importance of surface water-groundwater flow to the overall groundwater flow system, and the ability of the model, as designed, to represent surface water-groundwater interaction. In some hydrologic systems, spring flow is paramount to developing an accurate groundwater flow model, such as the Edwards (Balcones Fault Zone) Aquifer. In the case of the Hill Country part of the Trinity Aquifer, the flow of water to Hill Country streams was extremely important to represent regional groundwater flow and calibrate the model. In aquifers with a great deal of their area and production zones much farther underground, an accurate and detailed representation of surface water-groundwater flow becomes less important.

The success or reasonableness of each model in accurately simulating surface water-groundwater interaction can vary and has to be evaluated on a model-by-model, spring-by-spring, and stream-by-stream basis, depending on the management issue or question. Because the groundwater availability models are regional in nature, most of the models are not able to simulate surface water-groundwater interaction in detail. To use a groundwater availability model for evaluating a surface water-groundwater interaction issue, it is important to first observe how well the model represents the interaction, if at all, and then determine whether or not the accuracy of the interaction is sufficient for evaluating the issue.

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. Modeling work funded by the Lower Colorado River Authority-San Antonio Water System Water Supply Project places a thin layer of the aquifer under the land surface to better simulate surface water-groundwater interaction, and early results of this approach appear promising (Budge and others, 2007).

3. Interaction Between the Water Availability Models and the Groundwater Availability Models

Although surface water and groundwater interact, there has been little interaction between the surface water and groundwater availability models. A primary reason these models have not been directly connected is because the two models are very different. The water availability models are accounting tools created to evaluate permits, whereas the groundwater availability models numerically simulate groundwater flow to evaluate changes in water levels and, in some cases, spring flow and baseflow.

There has been one exception—the interaction between the groundwater availability model of the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer and the water availability model for the Guadalupe River. Part of the naturalized flow in the Guadalupe River is sourced from Comal, Hueco, and San Marcos springs, which issue from the Edwards Aquifer. Pumping in the aquifer, as well as climate, affect spring flows, which then affect flow in the river.

Because managing the Edwards Aquifer continues to be a topic of debate, there have been some recent cases where the Texas Water Development Board and the Texas Commission on Environmental Quality have used the groundwater and surface water availability models to assess the effects of different management scenarios. In one case, the South Central Texas Water Advisory Committee requested the Commission to evaluate the possible effects of a junior-senior permitting plan proposed by the Edwards Aquifer Authority on spring flow and downstream surface water rights (Mace and Wade, 2005; Densmore, 2005). The Board first ran the groundwater availability model to assess what spring flow would be, and then the Commission adjusted naturalized flows in the water availability model based on the groundwater modeling results to evaluate surface water rights. In a similar analysis but for a different management scenario, the Commission and the Board ran the models at the request of a representative of the Texas Legislature (Mace and others, 2007; TCEQ, 2007).

IV. WHAT NEXT?

There have been two state-funded studies concerning surface water-groundwater interaction and the connection between the surface water and groundwater availability models. One of the studies is by Scanlon and others (2005), funded by the Texas Commission on Environmental Quality, and the other study is by HDR (2007), funded by the Texas Water Development Board. Each study made recommendations on what additional research needed to be done, how to improve the water and groundwater availability models, and how best to proceed with getting the two models to interact with each other.

Scanlon and others (2005) investigated surface water-groundwater interaction issues in Texas. In one of their tasks, Scanlon and others (2005) investigated connecting the groundwater availability model for the central part of the Carrizo-Wilcox Aquifer to the water availability models for the Guadalupe, Colorado, Brazos, and Trinity aquifers. To improve simulations of surface water-groundwater interactions, they suggested that future studies (1) test the validity of simulated baseflow response to increased pumpage using more detailed site-specific simulations and field-based measurements, (2) standardize how surface water-groundwater interactions are simulated in the groundwater availability models, (3) standardize the resolution of representing stream networks in the groundwater availability models, (4) conduct field studies to estimate baseflow and groundwater evapotranspiration (the consumption of groundwater by plants or by evaporation), and (5) modify the water availability models to distinguish between baseflow and runoff.

Scanlon and others (2005) also recommended future studies to better understand surface water-groundwater interaction in Texas, including (1) co-locating groundwater monitoring wells with streamgages, (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.

HDR (2007) evaluated linking the surface water and groundwater availability models. They concluded that a linked model should not be pursued at this time because (1) the models are developed and operated with different paradigms, spatial scales, and temporal scales; (2) there is limited information to describe surface water-groundwater interaction; and (3) actively linking the models at this time would provide little additional information that the models do not already provide separately. HDR (2007) recommended that the water availability models be improved by updating the period of record to increase the reliability and consistently representing streamflow gains and losses. They recommended that groundwater availability models be improved by consistently representing streams, springs, wetlands, and reservoirs; groundwater evapotranspiration; and recharge. They also recommended (1) systematic baseflow surveys, (2) localized measurements of groundwater levels and stream stages, (3) spring flow and baseflow measurements in small tributaries, and (4) improved estimates of groundwater evapotranspiration parameters.

HDR (2007) noted there are two ways to connect the surface water and groundwater availability models:

actively and passively. When people talk about wanting to connect surface water and groundwater availability models, they are generally talking about an active connection where the surface water availability model and the groundwater availability model work as one. However, there is another, perhaps more appropriate, approach given the differences between the state's availability models: a passive connection as described between the groundwater availability model for the Edwards Aquifer and the water availability model for the Guadalupe River in the previous section.

To better understand surface water-groundwater interaction, Texas Water Development Board staff suggests focusing on three areas of study: measuring streamflow gains and losses, identifying better ways to consider surface water-groundwater interaction in the groundwater availability models, and identifying the appropriate ways to connect water availability and groundwater availability models. Given the fundamental differences between the models and their goals, Board staff believes that the goal should be to passively connect surface water-groundwater availability models.

V. CONCLUSIONS

Surface water and groundwater clearly interact in the physical realm, but that interaction is limited in the legal and modeling realms in Texas. The interaction between surface water and groundwater in Texas has affected both water resources, although in different ways at different locations, such as at Comanche Springs, Lake Amistad, and the Rio Grande near El Paso. Although Texas statute does not explicitly recognize the connection between surface water and groundwater, there are exceptions (for example, the Edwards Aquifer Authority) and opportunities (for example, when considering surface water permits and when defining desired future conditions of an aquifer). The surface water and groundwater availability models are not currently actively connected to each other, but there is an opportunity to passively connect the two, something that has already happened between the groundwater availability model for the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer and the water availability model for the Guadalupe River. However, additional information needs to be collected on surface water-groundwater interactions and the surface water and groundwater availability models need to be improved before all models can passively interact with each other.

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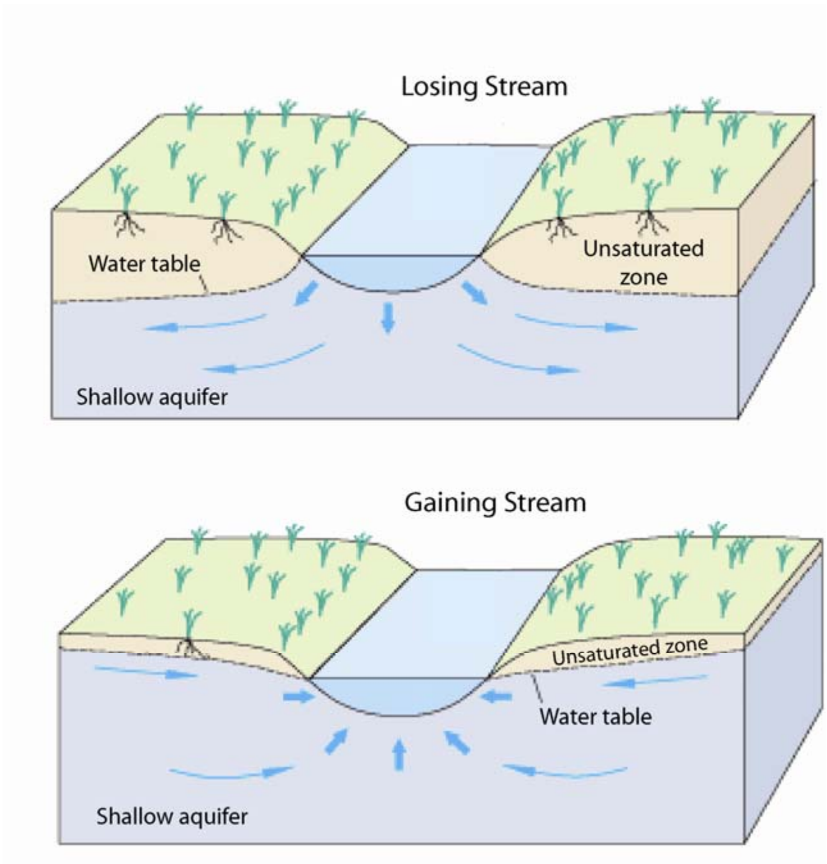

Figure 1: Diagrams of how streams can interact with an aquifer. In the top diagram, the water level in the stream is higher than the water level in the underlying aquifer; therefore, water flows from the stream into the aquifer, and the stream is termed a losing stream. In the lower diagram, water levels in the aquifer are higher than the water level in the stream; therefore, water flows from the aquifer into the stream, and this stream is termed a gaining stream. These examples assume that water can flow between the stream and the aquifer. In some cases, there may be clays on the streambed that prevent the stream and aquifer from interacting (modified from Winter and others, 1998).

Figure 2: Areas in Texas where streams overlie the recharge zones of the state's major and minor aquifers.

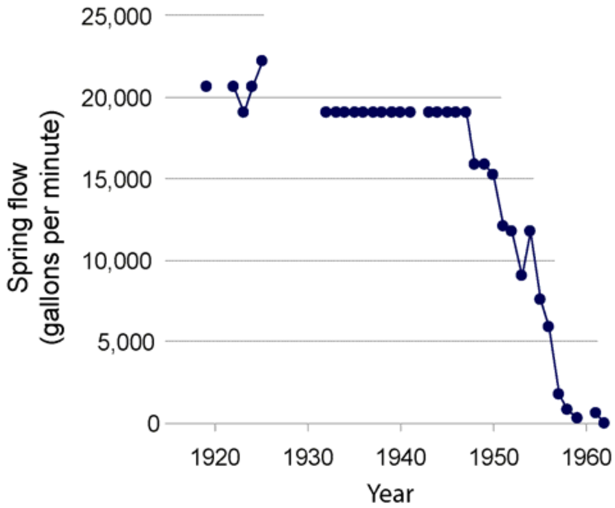

Figure 3: Flow measured at Comanche Springs (data from Brune, 2002; sequential annual data are connected with lines). Since 1962, the springs only flow episodically during the non-irrigation season.

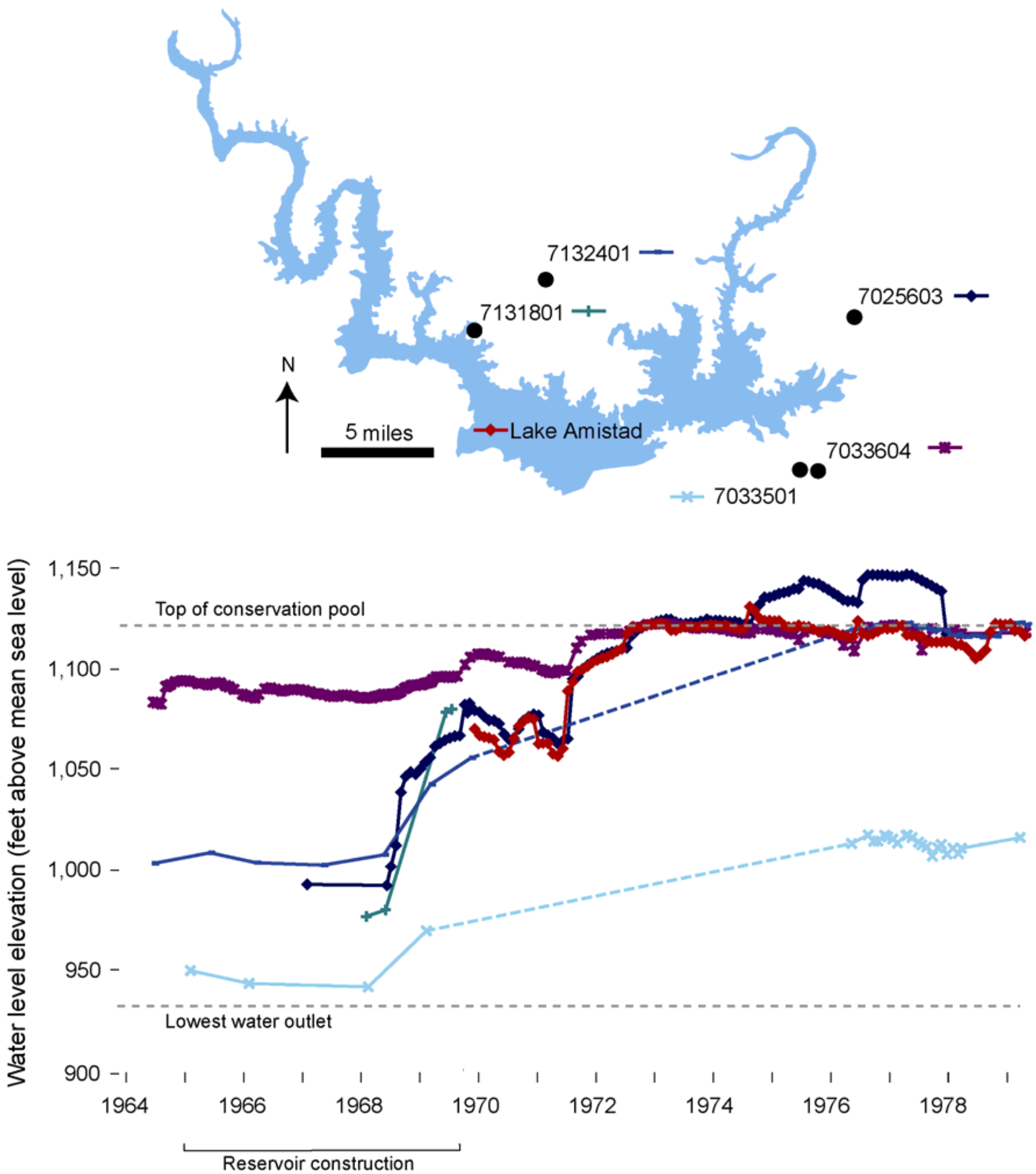

Figure 4: Water level elevations in test wells in the Edwards-Trinity (Plateau) Aquifer and in Lake Amistad during and after construction of the dam. Two of the lines are dashed because of the long intervals (greater than five years) with no data (data for Lake Amistad is from files of the International Boundary and Water Commission).

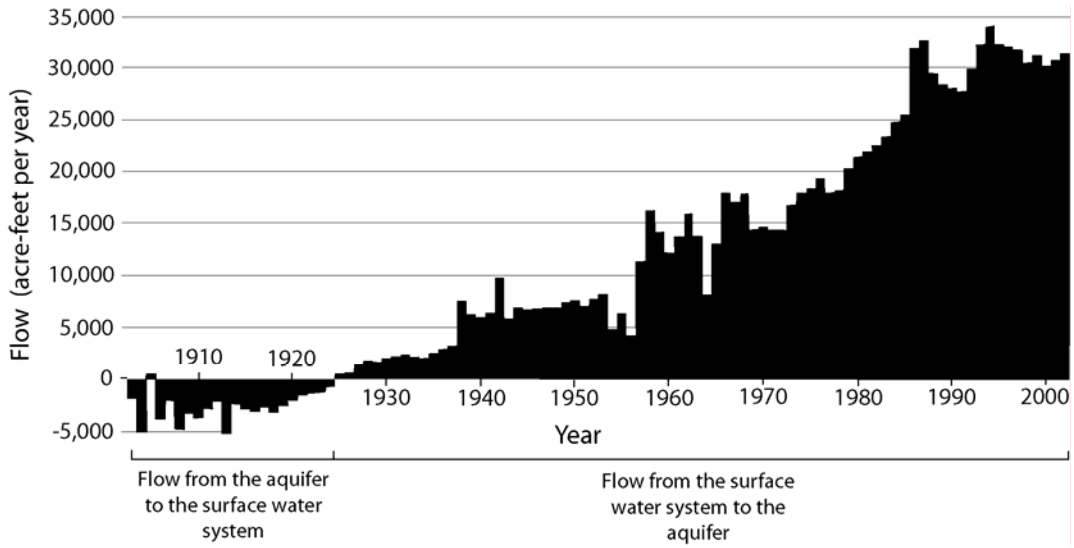

Figure 5: Inflow of surface water to the Hueco Bolson Aquifer in the El Paso area in Texas (modified from Hutchison, 2006, p. 171). Negative values indicate flow from the aquifer to the surface water system and positive values indicate flow from the surface water system to the aquifer.