QUANTIFYING WATER EXCHANGE BETWEEN THE BRAZOS RIVER AND THE BRAZOS RIVER ALLUVIAL AQUIFER USING HIGH TEMPORAL RESOLUTION MEASUREMENTS

TWRI Mills Scholarship Final Report

by

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Thanks to the TWRI Mills Scholarship I had funding to perform a detailed study of the connections between the Brazos River and the underlying Brazos River Alluvial Aquifer (BRAA). For this study we installed three pressure transducers (gages) in the river that created two distinct reaches of the Brazos River for us to study: a reach from Bryan to College Station (between the SH21 and SH60 gages), and a reach from College Station to Navasota (between the SH60 and Navasota gages) (Fig. 1).

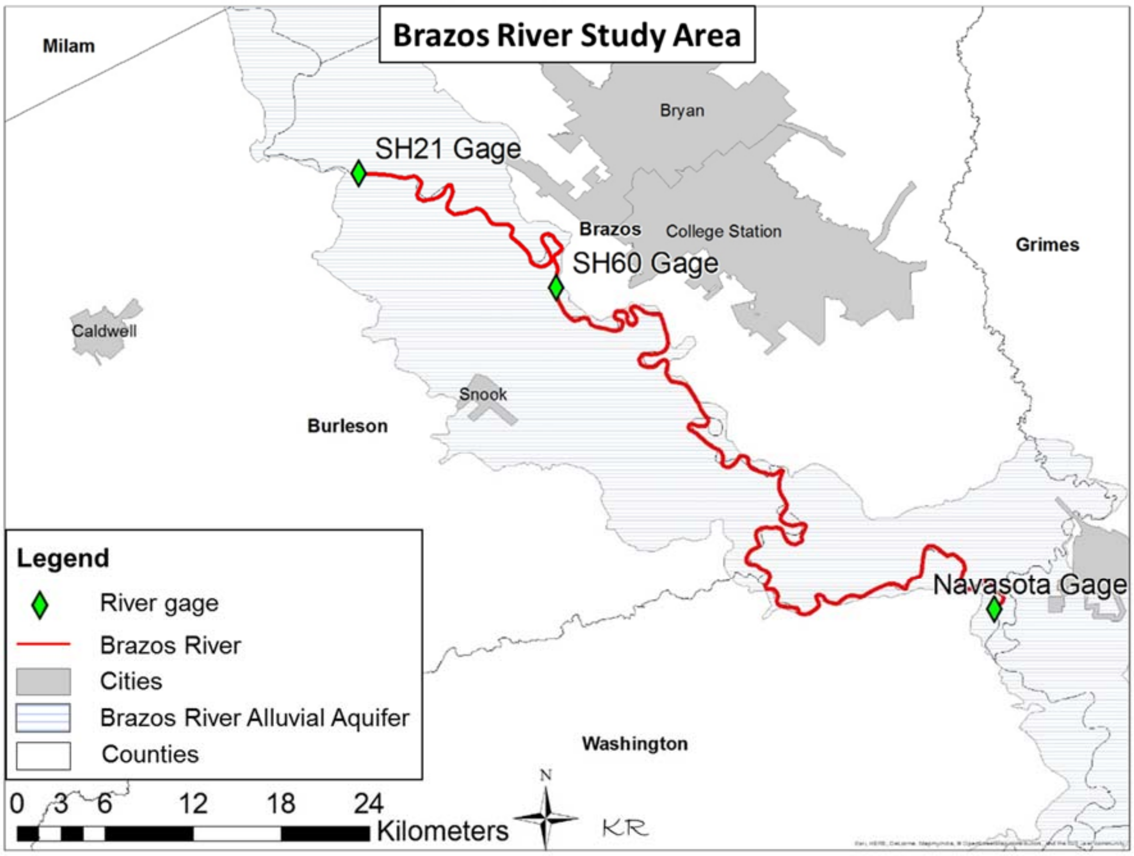

Figure 1: Map of the study area with political boundaries. The area starts at the Brazos River's intersection with SH21 by Bryan, TX, and continues to its intersection with SH105 by Navasota. The reach of Brazos River studied is shown in red. Data provided by TNRIS (2015).

We measured groundwater discharge to the Brazos River over each reach using five distinct methods: 1) differential gaging, 2) Endmember Mixing Analysis (EMMA), 3) specific conductance mass balance, 4) the Dupuit equation, and 5) hydrograph separation.

In differential gaging, discharge is measured at two different locations in a river, then the difference between those values is found. If there are no tributary or runoff inflows to the river between the two measurement points, then the difference in discharge can be attributed to groundwater inputs (McCallum et al., 2012; Unland et al., 2013). We measured river discharge at each of our three gage locations every 20 minutes and subtracted the upstream discharge from the downstream discharge during dry periods to estimate groundwater discharge with high frequency. The results of these calculations are shown in green on Fig. 3 for Q_{gw} between SH21 and SH60, and on Fig. 4 for Q_{gw} between SH60 and Navasota.

To perform EMMA, the researcher assumes that the studied body of water receives water from at least three other water bodies, called endmembers. Endmember mixing analysis uses the concentrations of natural tracers found in these endmembers and the water body of interest, and an "unmixing model" to determine the contribution of water from each endmember to the water body being studied. In this study the Brazos River was the water body of interest, and the BRAA, Lake Whitney, bank storage, and water from the Yegua aquifer on the eastern side of the river were identified as four endmembers. Chemistry from Lake Whitney was provided by another study (van Plantinga et al., in press). Water samples were taken from the four other water bodies and analyzed for major ion chemistry on an ion chromatograph. The unmixing model used, from Christophersen et al. (1990), was

$$x = (C^T C)^{-1} C^T s \qquad (1)$$

where x is a matrix of the proportion of each endmember in a given water sample, C is a matrix of the concentrations of conservative chemical tracers in the endmembers, and s is a matrix of the concentration of conservative chemical tracers in the water samples. The ions used were sodium, magnesium, calcium, chloride, sulfate, and bicarbonate.

The difference in the amount of BRAA, Yegua, and bank storage water (all considered groundwater endmembers) found at an upstream and a downstream gage on a given day provided a Q_{gw} estimate for that day. These estimates are shown as pink dots on Fig. 3 for Q_{gw} between SH21 and SH60, and on Fig. 4 for Q_{gw} between SH60 and Navasota.

To perform specific conductance mass balance, specific conductance measurements were taken occasionally at SH21, and continuously every 20 minutes at SH60 and Navasota. These values were converted to total dissolved solids (TDS) by multiplying them by 0.65 (Pai et al., 2015), then input into the following equation from Pai et al. (2015):

$$Q_{gw}C_g = Q_dC_d - Q_uC_u \qquad (2)$$

where Q_{gw} is groundwater discharge to the river (m^3/s), C_g is the total dissolved solids of the groundwater (mg TDS/L), Q_d and Q_u are, respectively, the downstream and upstream discharges of the river (m^3/s) as derived from the river gages, and C_d and C_u are the downstream and upstream total dissolved solids of the river water, respectively (mg TDS/L). The results from these calculations are shown as four black asterisks on Fig. 3 for Q_{gw} between SH21 and SH60, and as a dark blue line on Fig. 4 for Q_{gw} between SH60 and Navasota.

To estimate Q_{gw} using the Dupuit equation we collected hydraulic head data at a point in the Brazos River Alluvial Aquifer just downstream of the SH60 gage (Fig. 2). We used this data and concurrent river stage data from our SH60 gage to estimate Q_{gw} using the Dupuit equation:

$$q' = \frac{1}{2}K\left(\frac{h_1^2 - h_2^2}{L}\right) \qquad (3)$$

where q’ is groundwater flow per unit width, K is hydraulic conductivity, h_1 is the head at the origin where L = 0, h_2 is the head at L, and L is flow length (Dupuit, 1863). We chose this equation because it is appropriate for unconfined aquifers like the BRAA, and it accounts for a non-linearly sloping water table. Well water levels were entered into the Dupuit equation as h_1, and SH60 river levels were input as h_2. Length (L) was given a value of 280 m, the perpendicular distance from the gaged well to the Brazos River. A value of $5.13x10^{-4}$ m/s, as previously calculated by slug tests at the well site by Shuai et al. (2014), was assigned to K. Once q' was found, it was multiplied by the straight distance from SH21 to SH60, and the straight distance from SH60 to Navasota, respectively, to obtain Q_{gw} in m^3/s for each reach. Results from these calculations are shown in dark blue on Fig. 3 for Q_{gw} between SH21 and SH60, and in light blue on Fig. 4 for Q_{gw} between SH60 and Navasota.

Hydrograph separation was performed in the USGS Groundwater Toolbox using our gage data. The Q_{gw} results from this method are shown as black lines in Fig. 3 and Fig.4.

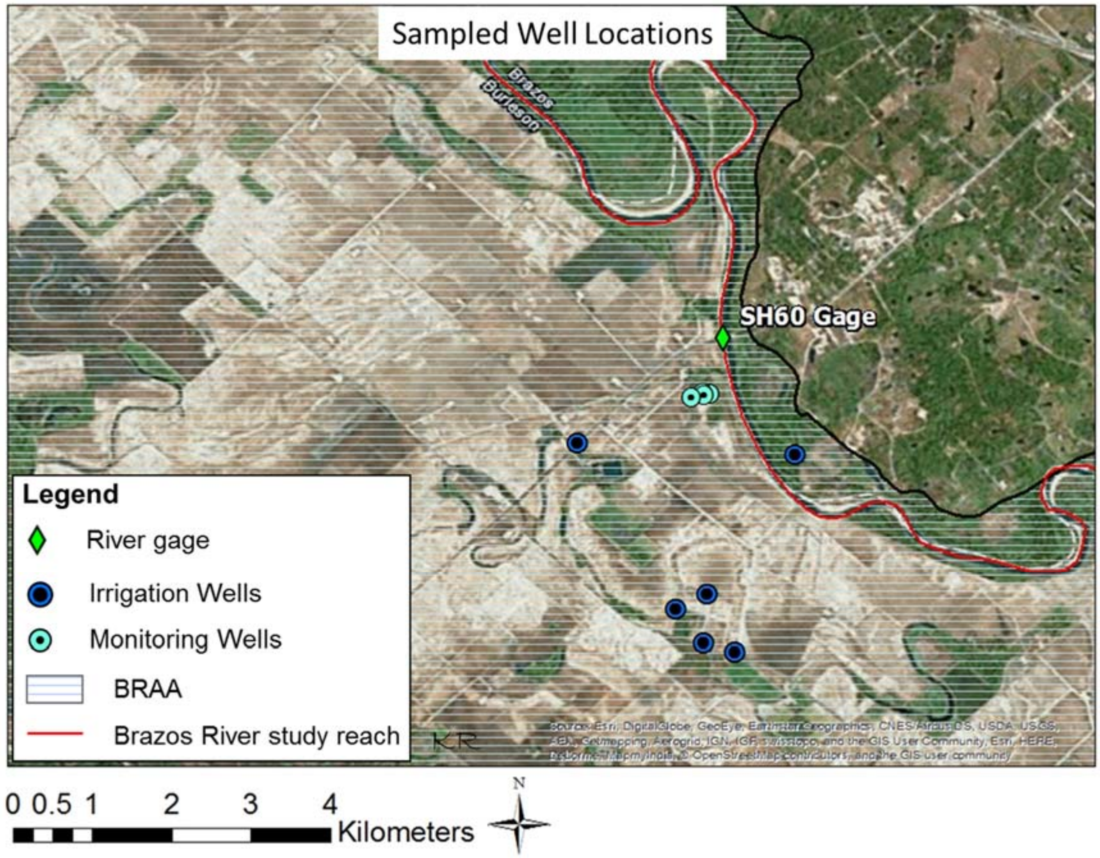

Figure 2: Locations of the 9 sampled wells with respect to the SH60 gage. The well on the eastern side of the river, although it appears to be within the BRAA extent provided by the TNRIS (2015) dataset, has different chemistry from the wells in the west side of the river. This suggests to us that it is in a different aquifer, likely the Yegua. Of the three monitoring wells, water levels used in Dupuit equation estimates were recorded in the center well. Satellite imagery provided by ESRI.

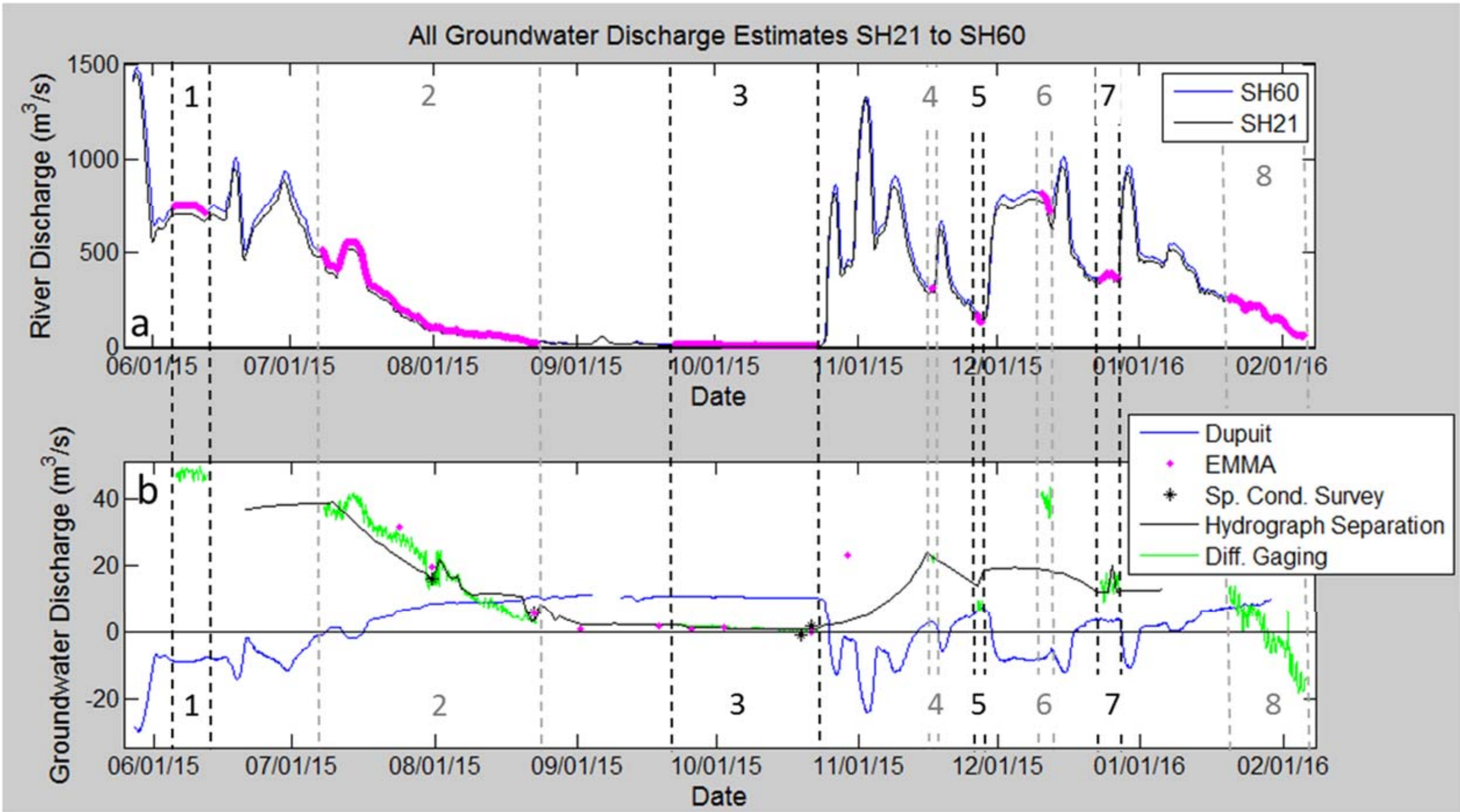

Figure 3: The river discharges at SH21 and SH60 are shown for the entire study period. Dry periods over which differential gaging was performed are shown on the SH60 hydrograph in pink and labeled with numbers 1-8 (a). Estimates from all five methods used to estimate groundwater discharge are shown for the entire study period with each dry period labeled 1-8 (b).

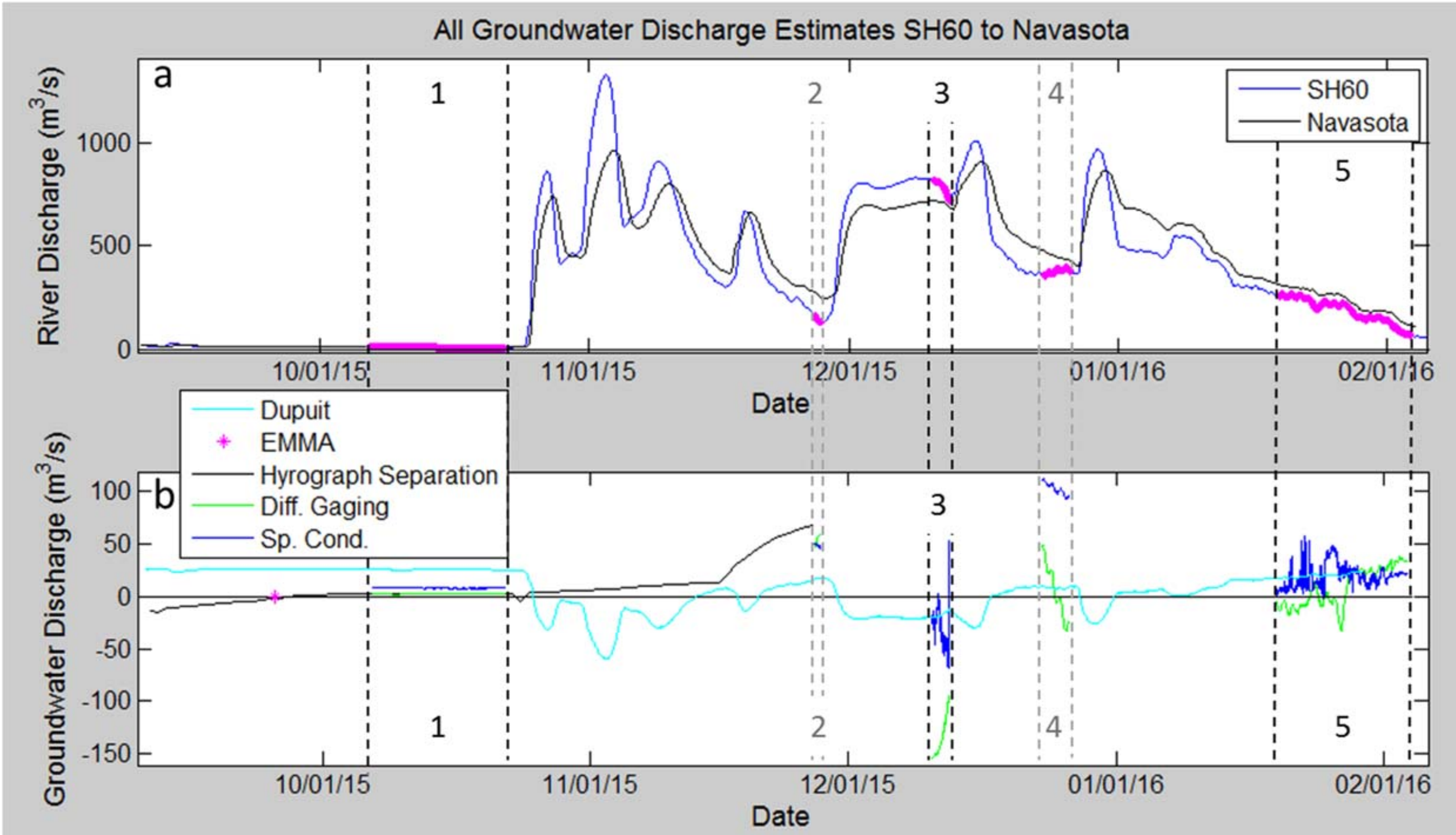

Figure 4: The river discharges at SH60 and Navasota are shown for the entire study period of this reach. Dry periods are shown on the SH60 hydrograph in pink and labeled with numbers 1-5 (a). Estimates from all five methods used to estimate groundwater discharge are shown for the entire study period with each dry period labeled 1-5 (b).

CONCLUSIONS AND SUMMARY OF RESULTS

The reach from SH21 to SH60 was found to be gaining for most of the year, with higher groundwater discharges at high river flows and lower groundwater discharges at low river flows. As river discharge slowly decreases, groundwater discharge also decreases in this reach (Fig. 3, periods 2, 6, and 8, all methods except Dupuit). The EMMA method indicated that bank storage made up a large proportion of river discharge (71 to 99%) soon after rain events, with the highest proportions of bank storage observed in the river at flows above 80 m^3/s before and after the dry summer (August to late October). This finding of bank storage discharge after rain events and the finding by Chakkah and Munster (1997) and Chowdhury et al. (2010) that there is little correlation between rainfall and aquifer levels in the BRAA have implications for the Brazos River-BRAA system. These findings suggest that a bank storage component is recharged by the river during rain events, then the recharge slowly returns to the river starting soon after the rain event ends. The inability of the Dupuit equation to predict Q_{gw} patterns similar to those observed by our other methods suggests that the Brazos River is not as well connected to its alluvial aquifer as has often been suggested in the past. The river is instead more connected to a near-river part of the alluvium, and separated from its wider alluvial aquifer by past flood-plain deposits that have low hydraulic conductivities.

Compared to the reach from SH21 to SH60, we observed different groundwater-surface water interaction dynamics in the southern reach from SH60 to Navasota. This reach was not consistently gaining water from the aquifer, but often was losing water (Fig. 4, periods 3, 4, and 5). In the northern reach from SH21 to SH60 groundwater discharge was observed to start immediately following rain events. The southern reach, in contrast, was observed to lose water at high flows and only gain water below certain threshold river discharges. In late December

(Fig. 4, period 4) the southern reach only gained water while river discharge was below 386 m^3/s, and in late January it started gaining after river discharge dropped below 212 m^3/s (Fig. 4, period 5) (according to differential gaging-based estimates).

We suspect the reason for this difference between reaches, with the northern reach primarily gaining and the southern reach switching between gaining and losing, is related to the location of the Brazos River within the BRAA and its floodplain. In nearly the entire northern study reach, the Brazos River flows diagonally across the alluvium (Fig. 1). The river does not abut the elevated Eocene formations that bound the BRAA except for over a very short segment near the end of the reach. In the southern study reach, the Brazos River abuts the sides of the BRAA for nearly its entire length (Fig. 1). This location along the side of the floodplain brings the river into contact with the elevated Eocene formations beyond the BRAA, allowing interactions to occur. These interactions include possible losses of water from the river to the deposits. The threshold value at which the river switches from losing to gaining water must therefore be dependent on antecedent aquifer conditions in both the BRAA and the other formations bordering the alluvium.

We learned from EMMA that the Brazos River recharges bank storage in the BRAA during high flow events, then regains the water lost starting immediately after the high flow event ends. If much of the water sent into the banks of the river during high flow events goes into formations outside of the BRAA in the southern reach, it may not be returned to the river the way it is from the BRAA. As much as half of the water that flows into the banks could be lost because one side of the river flows up against formations external to the BRAA, allowing interaction with and loss of water to peripheral formations, while the other side of the river sends bank storage into the alluvium that likely returns to the river eventually. If this is the case, hydraulic gradients in the formations bordering the BRAA must slope away from the river at high flows, and may or may not slope towards it during low flows. It is possible that there is little interaction between the Brazos River and the Eocene formations beyond the BRAA during low flows when the river is not losing water to its banks. The observed groundwater discharge may be from bank storage in the BRAA and not these external formations.

A past study by Turco et al. (2007) suggested that the section of Brazos River overlying the Yegua-Jackson (Yegua) aquifer should be gaining due to contributions from that aquifer. Both of our study reaches, however, overlie the Yegua-Jackson outcrop (Fig. 5), and only the northern reach is primarily gaining. Our EMMA results indicated that water likely from the Yegua formation can be found in the river at all three of our gage sites, confirming the suggestion that the Yegua aquifer contributes flow to the Brazos River in this area. Both of our studied reaches are located above the outcrop of the Yegua-Jackson aquifer, however, and the southern reach was often losing water. These water losses above a major aquifer outcrop mean that the river position over aquifer outcrops is not the only driving factor behind water gains and losses in the Brazos River. We have found that the location of the river in the alluvium, either in the middle of the alluvium or abutting the side of it, is even more important.

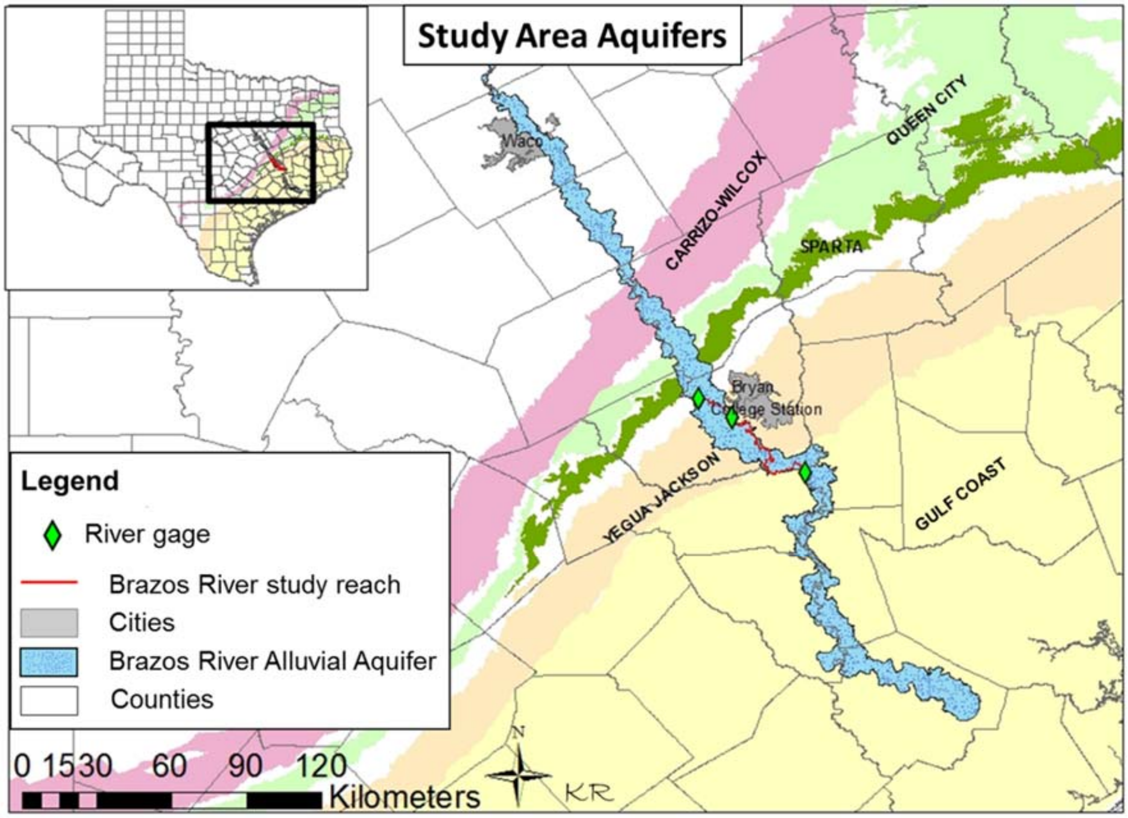

Figure 5: Map showing the extent of the Brazos River Alluvial Aquifer, outcrops of other aquifers, and our study area. Our gage sites are demarcated by green diamonds, and the studied reaches of the Brazos River are shown in red. Data provided by TNRIS (2015).

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