Could Much of Edwards Aquifer "Matrix Storage" Actually be Trinity Aquifer Contributions from the Blanco River?

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Most storage within the Barton Springs segment of the Edwards Aquifer is thought to lie within the areas between the major flow conduits (Senger, 1983; Worthington, 1999; Massei, et al., 2007). Worthington (1999) estimated that inside the Edwards Aquifer, 93% of groundwater flow occurred within the main conduits while 99.8% of the storage occurred within the matrix and in fractures between the major conduits. The hydraulic conductivity shows a decline with distance from mapped primary and secondary groundwater flow paths, ranging from more than 100 m/day to 0.1 m/day (Hauwert, 2009). The question remaining is whether the matrix storage areas between the major conduits composed of tiny interconnected pores (less than 1 cm in size) are capable of producing diffuse flow or well-integrated, larger, solution-enhanced voids and fissures.

Karst aquifers such as the Barton Springs Segment of the Edwards Aquifer have frequently been characterized as having diffuse flow matrix as determined by indirect methods, such as interpretations of water-level changes, spring-flow recession, water-quality composition and variation, isotopic age-dating, and core interpretation. Senger (1983) inferred that the Barton Springs Segment had a strong diffuse matrix component based on spring flow and water-level recessions. Hauwert and Vickers (1994) inferred local diffuse flow on the eastern edge of the artesian zone based on slow responses of well 58-50-301 to rainfall events, but Hauwert (2009) subsequently attributed the response to limited-capacity conduit hydrodynamics. It is alternatively possible the slow water level response of this well may be due to partial blockage of the well from collapse of uncased Del Rio Clay into the well (Joe Beery, BSEACD 2009 personal communication). Massei et al. (2007) used specific conductance frequency distributions over a period of four years to estimate that 54% to 69% of Barton Springs-specific conductance frequency distributions originated from the matrix or from poorly connected voids and only about 8% to 15% of Barton Springs discharge was recently recharged. Point dilution tests were used to indicate that Edwards Aquifer groundwater flowed at rates of 2 to 51 ft/day through interstitial pores (Maclay and Rettman, 1972; Ellis, 1985). However, more recent interpretation of core data (Hovorka et al., 1998) suggests that flow is localized in fissures and conduits.

Direct observations generally show the dominance of advective transport through conduits. Groundwater traces show rapid initial arrival flow rates from 5 to 7 miles/day during moderate and high flow conditions with an insignificant diffuse component (Hauwert, 2009). With the exception of common shallow cave ceiling drips that likely reflect diffuse soil moisture drainage or overlying vadose pool drainage, flow can be observed to discharge from springs, into wells, and into caves from solution-enlarged conduits and not seepage faces (Hauwert, 2009). Cave morphology reflecting diffuse-flow sources such as ramiform are completely lacking in the Barton Springs Segment (Palmer, 1991; Hauwert, 2009). Instead, branchwork cave morphology is encountered that reflects discrete recharge sources (Hauwert, 2009).

Groundwater traces conducted during low-flow conditions indicate that the advective to diffusive flow relation diminishes to some, yet unquantified, extent. During low-flow conditions, groundwater velocities decrease considerably to 0.3 to 1 mile per day (Hauwert, 2009). The diminished flow rates during low-flow conditions are much less than could be accounted for by simple lowering of potentiometric gradient. Dye recoveries are lower during low-flow conditions. The uncertainty of arrival times and the need to protect wells and aquatic habitat from excessive dye concentrations increases the complexity of recovering dye pulses in water samples during low-flow conditions in order to quantify the ratio of advective to diffusion and dispersion. Near some of the tracer injection sites, pulses of dye have been measured as much as 10 years after injection, although such pulse behavior may be due to the dye trapped within the unsaturated zone that becomes periodically flushed by larger rain events. Even considering the relatively slower groundwater velocities and lower tracer recoveries during droughts, there is little if any direct evidence that indicates small pores are hydraulically significant within the phreatic zone for either flow or storage in the Edwards Aquifer.

Quinlan et al., (1995) and Davies and Quinlan (1993) argued that in mature karst aquifers, conduits become sufficiently integrated to the point that diffuse flow components are not significant except on small local scales. Also, with further examination there are frequently other explanations to account for the indirect evidence presented for diffuse flow. It was later discovered that many springs on which the Shuster and White (1971) characterized aquifers using variation in specific conductance were influenced by an aliasing bias, where too few samples were collected to adequately describe the variation (White, 2007). Massei et al (2007) noted that karst springs such as Barton Springs have different water-quality sources that complicate characterization using specific conductance alone. One problem in using indirect methods alone to characterize aquifer systems is that the interpretation may not be unique. In addition to recharge from the major creeks and intervening outcrop area, Barton Springs has other recharge sources that may include:

1. Epikarst flows hypothesized by Atkinson (1977) and Klimchouk (2004) to mimic slower-flowing drainage to springs,
2. Urban leakage from irrigation and utility line leaks (Garcia-Fresca and Sharp, 2005),
3. Groundwater flow across the southern divide (Hill, 1892; Guyton, 1964; Johnson and Schindel, 2008; Land, 2010),
4. Leakage from the Saline-Water Zone (Senger, 1983; Hauwert et al., 2004),
5. Trinity Aquifer sources including:
    a. Cross-formational leakage from the Trinity Aquifer (Senger, 1983; Slade et al., 1986), and
    b. Recharge of Trinity Aquifer spring-fed baseflow.

While all of the sources listed above should be further quantified and investigated to determine to what extent, if any, they provide recharge to Barton Springs, this paper suggests only that Trinity Aquifer baseflow from the Blanco River (5b) may account for some indirect observations attributed to “diffuse matrix flow” within the Edwards Aquifer.

From 2008 to 2009, a series of dye traces were conducted in the Blanco River and its major tributary, Halifax Creek, using eosine and sodium fluorescein (uranine) dye (Edwards Aquifer Authority, in preparation). This study was the result of a cooperative effort involving the Edwards Aquifer Authority, Barton Springs/Edwards Aquifer Conservation District, Zara Environmental, and the City of Austin. During the injections, Barton Springs flow varied from 19 to 31 ft^3/s, which is lower than its 53 ft^3/s average flow. Wells in the Ruby Ranch and Mountain City areas previously traced to Barton Springs recovered the eosine dye from multiple injections (**Figure 1**). The dyes initially arrived at Barton Springs within about three months (**Figures 2 and 3**), yielding a flow rate of about 0.3 miles/day. The eosine dye injected in the Blanco River at Halifax Creek also was detected in several wells south of the Blanco River near San Marcos Springs, indicating that a percentage of water moves south as well. The tracing study was definitive in establishing directly, for the first time, that the Blanco River contributes flow to Barton Springs during low-flow conditions and the length of time the process took. However, this tracing has not yet quantified the Blanco River contribution to Barton and San Marcos springs.

Analysis comparing Blanco River recharge to Barton Springs discharge indicates that the Blanco River has a major role in sustaining Barton Springs flow during droughts. The Blanco River has a much larger watershed than the creeks that provide most of the recharge to Barton Springs. The Blanco River is sustained both by stormwater runoff and major springs discharging from the Trinity Aquifer, including Jacob's Well near Wimberley. To estimate the amount of Blanco River flow loss contributing to Barton Springs, Blanco River flow loss was compared to the total Barton Springs discharge for eight low-flow intervals (Hauwert et al., in preparation; **Figures 4 and 5**). For the eight low-flow intervals, Blanco River flow loss compared to 50% to 100% of Barton Springs discharge. Consequently, Blanco River recharge can potentially account for most of Barton Springs discharge during low-flow periods even with a portion of its recharge contributing to San Marcos Springs. While three months are required for recharge from the Blanco River to arrive at Barton Springs, much of the flow path is under artesian conditions such that a pressure pulse can potentially travel nearly instantaneously from recharge to discharge site. Further investigation is needed to determine if low-flow discharge peaks at Barton Springs are associated with corresponding Blanco River flow loss peaks, or if these peaks are not causal but created by other sources, such as stormwater runoff in watersheds closer to Barton Springs (Johns, 2006) or upland recharge.

Although the Blanco River is the predominant source of recharge to Barton Springs during low-flow conditions, overall its average contribution may be small. During high-flow conditions, it is known that Onion Creek becomes the southern groundwater divide as shown by a groundwater trace injection in 2005 that traveled from Onion Creek to both Barton Springs and San Marcos Springs (Hunt et al., 2006). Peaks in Barton Springs discharge do not generally correspond with Blanco River recharge peaks for Barton Springs flows above 40 ft^3/s. Assuming the Blanco River stops contributing to Barton Springs above 40 ft^3/s, a four-year water balance from 2004 to 2007 suggests that the Blanco River recharge constitutes up to 6% of mean total discharge of Barton Springs plus well pumpage, but it may be less depending on the contribution to San Marcos Springs.

Quantification of the Blanco River and other Trinity Aquifer sources to Barton Springs can be further examined chemically. For 102 measurements reported by the USGS from the Blanco River at Wimberley between 1962 and 2008, the specific conductance ranged from 366 to 532 uS/cm, with an arithmetic mean of 461 uS/cm. These conductivity readings are much lower than the predominant "P1" specific conductance frequency distribution peak of Main Barton Springs identified by Massei et al (2007), which shifted from ranges of about 600 uS/cm in wet years to more than 700 uS/cm during dryer years. However, a specific conductance measurement reflects combined sources present at the time and interpretation of specific conductance frequency distributions assume that there are times when one source is geochemically dominant and other sources are not. During droughts, when the Blanco River contribution is expected to be highest, a higher contribution of highly mineralized Saline-Water Zone leakage is simultaneously occurring; thus there is considerable overlap of the two specific conductance sources, and a small volume contribution of highly mineralized Saline-Water Zone groundwater can easily dominate the geochemistry to varying extents (Senger, 1983; Hauwert et al., 2004). Of the four Barton Springs outlets, the Saline-Water Zone leakage has strongest geochemical influence on Old Mill Springs of the Barton Springs and no geochemical influence on Upper Barton Springs because the Sunset Valley groundwater basin is hydraulically separated (Hauwert et al., 2004; Hauwert, 2009). For springs such as Main Barton Springs, Eliza and particularly Old Mill Springs, it may be impossible to clearly distinguish sources based on specific conductance alone. Senger (1983) observed that Saline-Water Zone, Trinity and Edwards Aquifer sources could be distinguished using chloride and sulfate relationships in water samples (**Figure 6**). Based on sulfate and chloride concentrations, the water quality of Onion Creek (which is the largest recharge source to Barton Springs overall) and the Blanco River are similar to other Trinity Springs sources, but appear to be indistinguishable from each other using sulfate and chloride concentrations alone. As Figure 6 shows, there is considerable overlap between Barton Springs water quality and Trinity Aquifer sources such as the Blanco River, which is consistent with the concept that Barton Springs has a strong geochemical influence from undistinguished Trinity Aquifer sources (including major spring-fed creeks draining the contributing area). Note that wells in the Manchaca groundwater basin, which are largely not expected to receive contributions from the Saline-Water Zone but are likely to be downgradient of Blanco River recharge sources and other Trinity Aquifer sources, have chloride and sulfate relation ranges identical to these Trinity Aquifer sources. While this water quality analysis is preliminary and further investigation should be conducted, the water quality results are consistent with a strong influence of the Blanco River and other Trinity Aquifer sources.

Results from recent studies on the Blanco River recharge contribution to Barton Springs, tested using direct groundwater tracing methods, suggest that this recharge source may account for sustained spring flow and, considering the simultaneous addition of Saline-Water Zone leakage, the water-quality characteristics that have been previously attributed to diffuse matrix flow within the Barton Springs segment of the Edwards Aquifer. When examined solely through indirect methods, the Trinity Aquifer recharge to the Barton Springs Segment resembles storage within the Edwards Aquifer.

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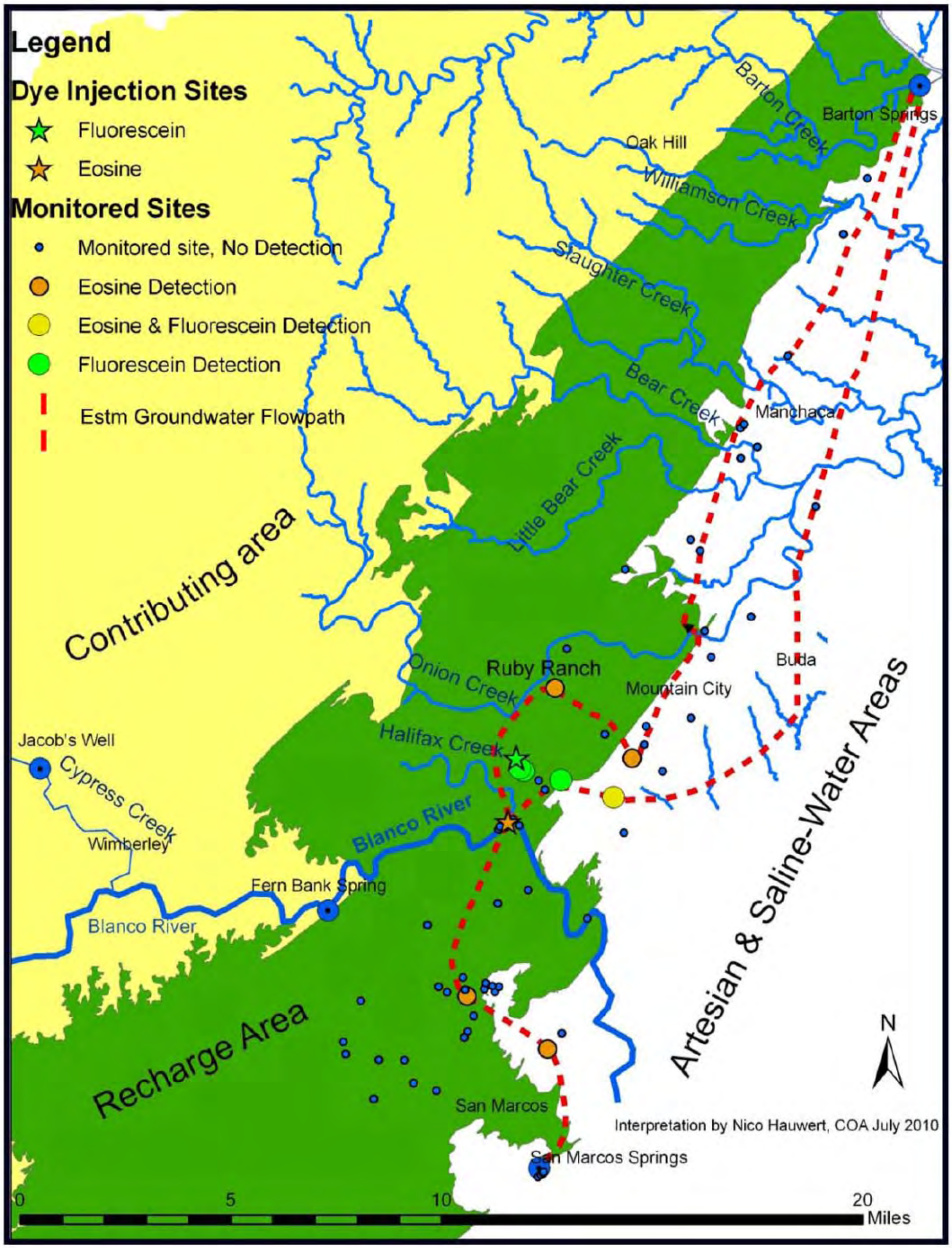

Figure 1. Groundwater-flow paths interpretation of Blanco River injections of 2008-2009. Eosine dye was injected at the mouth of Halifax Creek on four separate pulses. Two groundwater flow paths to Barton Springs and one to San Marcos Springs were interpreted based on dye recoveries in wells and delayed arrival of the dyes to Old Mill Springs.

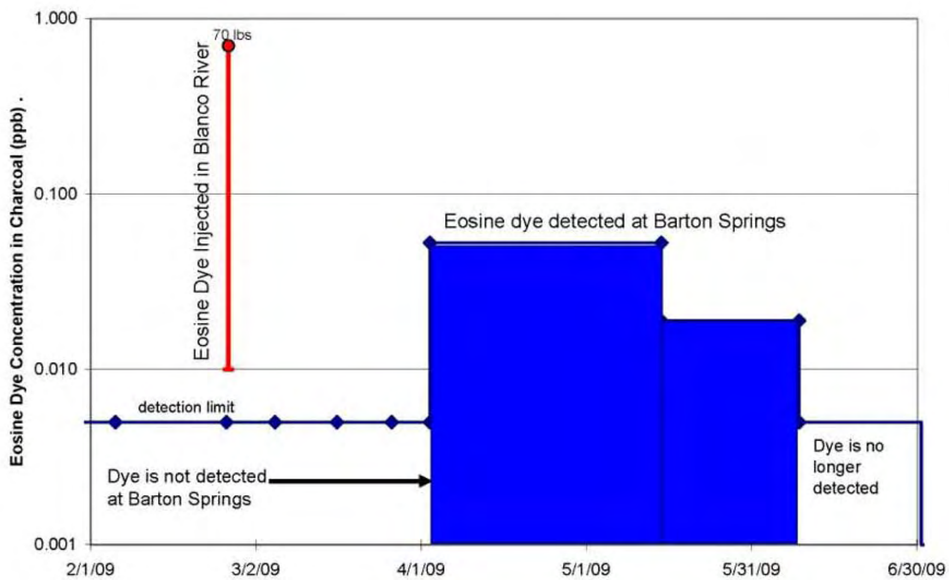

Figure 2. Breakthrough of one of four eosine injections at Barton Springs.

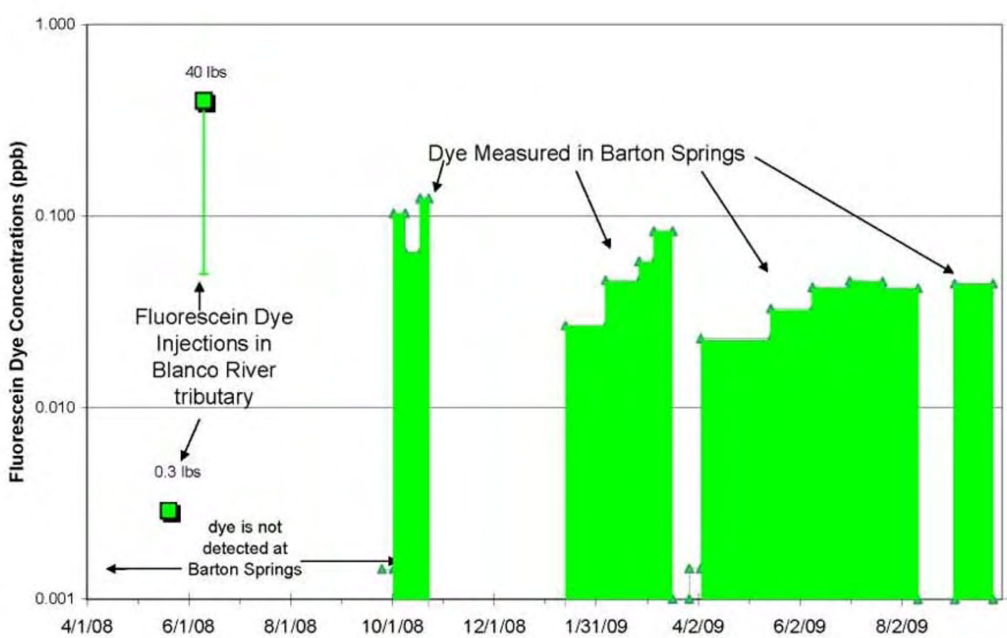

Figure 3. Arrival of fluorescein dye from a sinkhole in a Halifax Creek Tributary north of the Blanco River.

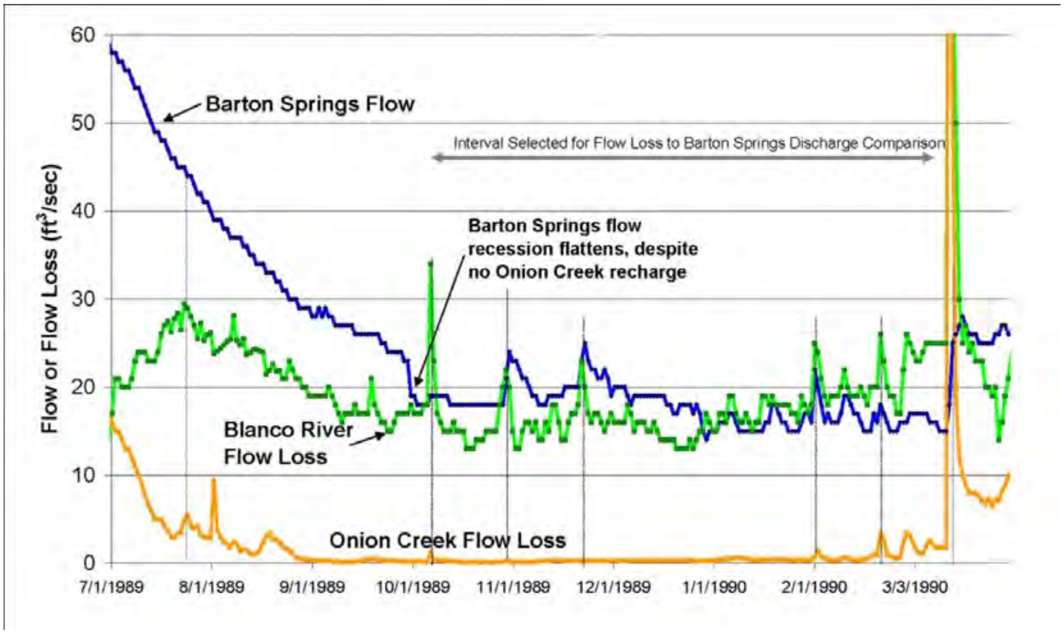

Figure 4. Barton Springs flow mirrors Blanco River flow loss during low-flow conditions in 1989 and early 1990. Eight intervals were selected to compare flow loss with springflow. The three-month travel time was not factored into the flow comparison.

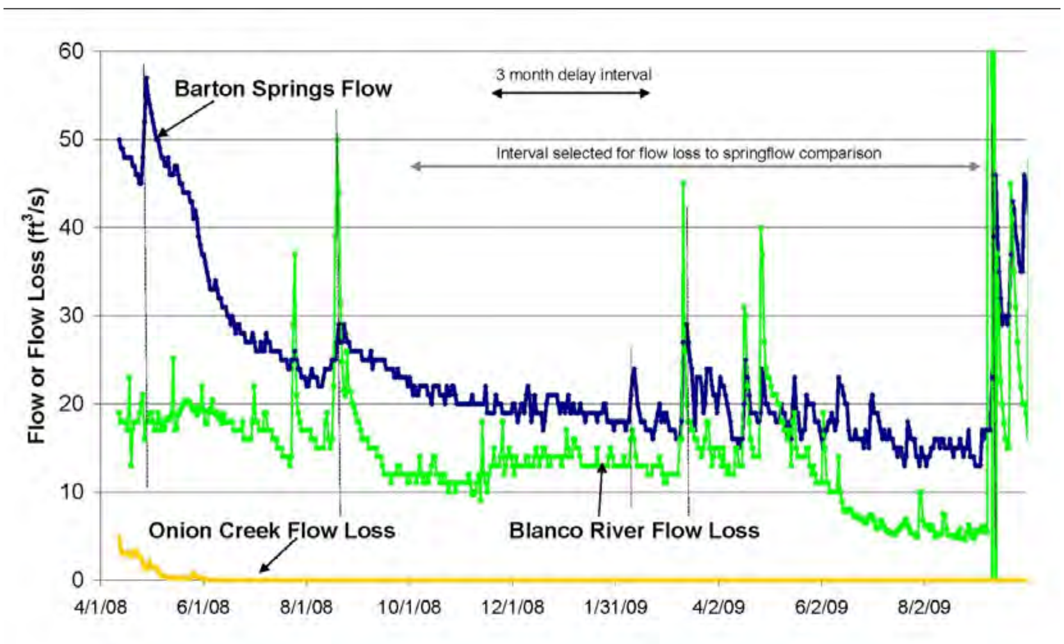

Figure 5. Comparison of Blanco River flow loss to Barton Springs discharge in 2008 and 2009. Note that Onion Creek was dry during most of this period. Peaks in Barton Springs flow does not appear to correspond to Blanco River flow loss above 40 cfs.

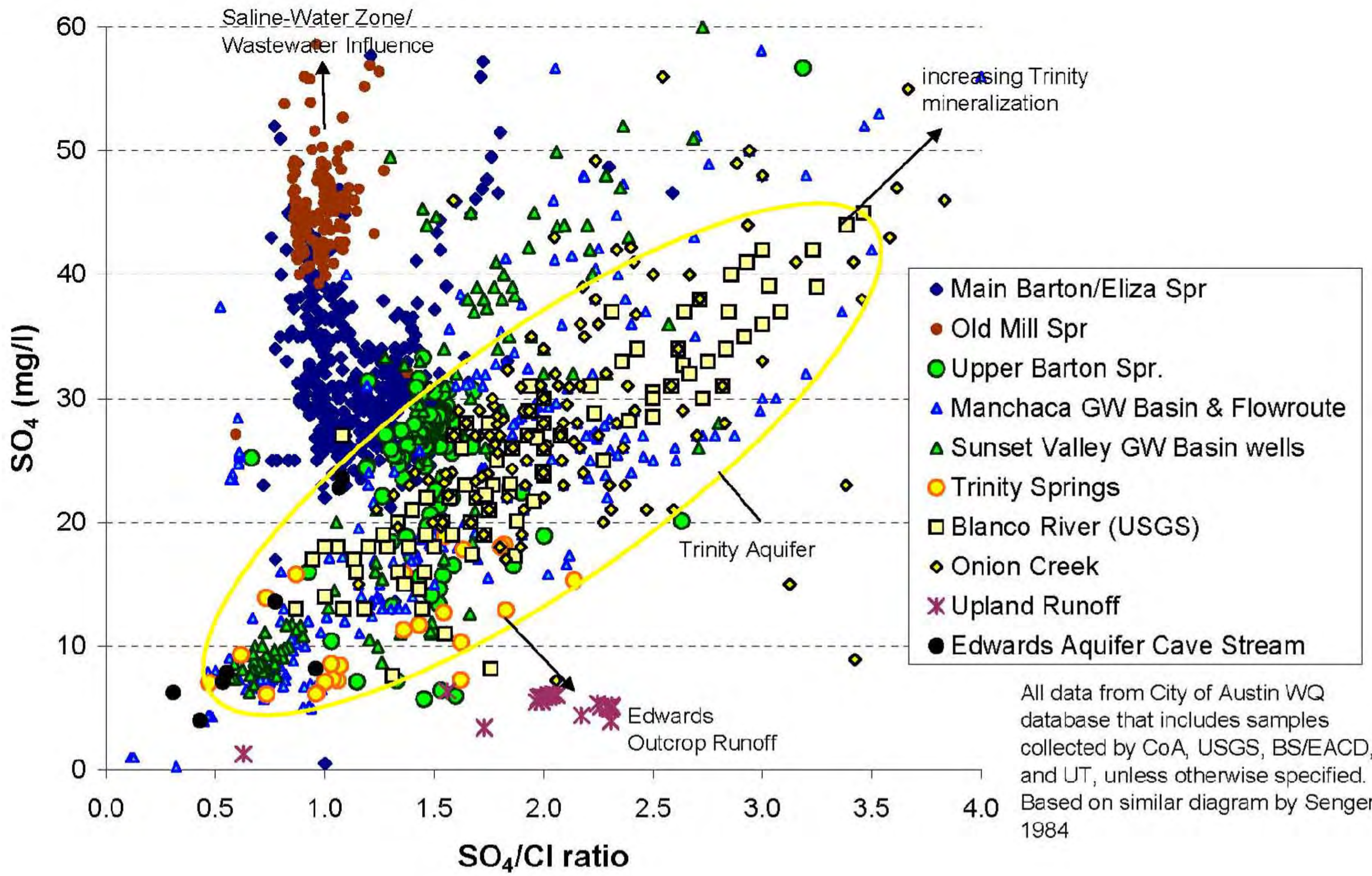

Figure 6. Sulfate and chloride relationships in type waters. During low-flow conditions Main, Eliza, and Old Mill Springs trend toward Saline-Water Zone water type. Wells in the Sunset Valley Groundwater Basin that discharge from Upper Barton Springs do not receive contributions from either the Saline-Water Zone or Blanco River, but overlap considerably with Trinity Aquifer water types (indicated by yellow oval). Most water wells within the Manchaca groundwater basin do not receive Saline-Water Zone contributions but follow trends of undistinguished Trinity Aquifer sources such as subsurface leakage from the Trinity Aquifer or Trinity Aquifer spring-fed flow to the major recharge creeks and the Blanco River.