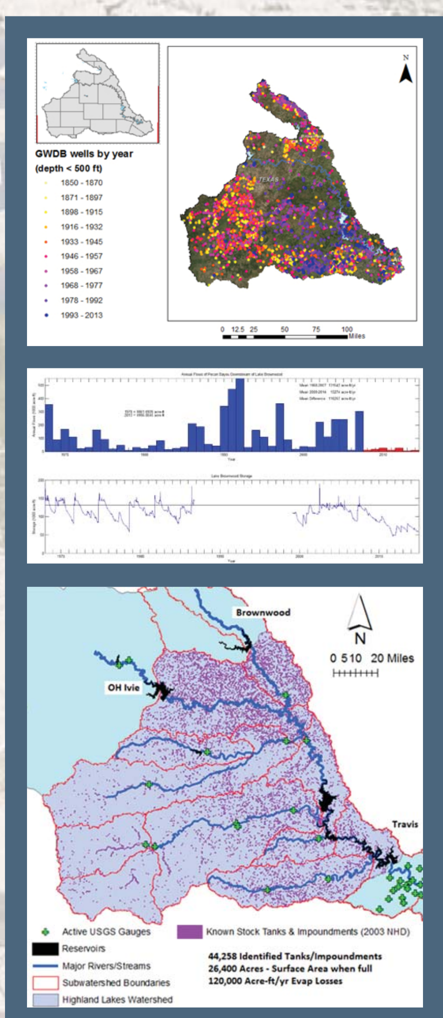
Hydrologic Studies of the Highland Lakes Watershed

Part I

Why are the recent inflows so low?



Prepared For:

CENTRAL TEXAS WATER COALITION

Prepared By:

INTERA
GEOSCIENCE & ENGINEERING SOLUTIONS

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January 21, 2015

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EXECUTIVE SUMMARY

The objective of this work was to perform preliminary assessments as to why inflows to the Highland Lakes have decreased in recent years (2008-Present) compared to those which occurred between 1940 and 2007. The report summarizes investigations undertaken and how results may be combined to suggest both a cause for the low observed flows as well as possible solutions for flow mitigation. INTERA initiated high-level analyses into the following areas: 1) base flow analyses of Highland Lakes inflows, 2) watershed precipitation analyses, 3) watershed land use/land cover analyses, 4) surface water diversion quantification, 5) groundwater well drilling analyses, and 6) soil moisture analyses.

As documented herein, this preliminary analysis suggests that recent rainfall over the Highland Lakes watershed has been, with the exception of 2011, average or nearly so. Therefore, persistent low flows cannot be solely attributed to low amounts of watershed precipitation. Surface water diversions also do not appear sufficient to yield recent low flows. The recent low flows may be attributed to the apparent increase in time between rainfall events of significant magnitude.

During a given rainfall event, previously dry soils readily soak up available precipitation, leaving little to run off overland into the local drainage system. What water does run off is captured within small impoundments scattered throughout the watershed, with water moving downstream only when the impoundments are full. During the dry period between rain events, water stored within the impoundments is lost both to groundwater recharge and evapotranspiration, thus lowering water levels such that inflows from the next rain event may not be sufficient to fill the impoundments and allow further downstream runoff. Had rainfall events occurred more frequently, soil moisture contents would be higher, greater quantities of water would enter creeks as runoff, and there would be a greater likelihood that water would spill over from small impoundments and become inflow to the Highland Lakes.

This hypothesis explains observed inflow reductions, yet further research is needed to solidify the analysis. INTERA proposes a detailed analysis of the timing and magnitude of rainfall events, utilizing multiple rain gauges within the Highland Lakes watershed. Also recommended is a detailed quantification of the increase in watershed area upstream of small impoundments, and a quantification of changes to the Highland Lakes firm yield resulting from the existence of these impoundments.

1.0 STREAMFLOW ASSESSMENT USING A BASE FLOW ANALYSIS

We have previously shown that annual Highland Lakes inflows have decreased significantly (Furnans, 2013). In this analysis, we attempted to determine whether the decrease is due to a reduction in flood-induced inflows, or whether base flows from the streams/tributaries have decreased. Through this analysis, we applied a base-flow separation to the gauged inflows (Colorado, Llano, Sandy, and Pedernales). The separation identifies periods of time when the streamflow consists of both a base flow and a larger flow induced by short-term flow events. The base flow represents the steady watershed/groundwater contribution to the streamflow. By comparing base flows over time, we attempted to determine temporal trends. The base-flow separation program (BFI415) was developed by the US Bureau of Reclamation, downloaded from:

http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/.

Streamflows for the target locations were downloaded from the US Geological Survey National Water Information System (USGS NWIS) internet site:

http://waterdata.usgs.gov/tx/nwis/current/?type=flow&group_key=basin_cd

Streamflows for the Colorado River at San Saba were augmented for the period from 9/21/1991 to the present in order to account for the storage of inflows in OH Ivie Reservoir. Specifically flows were augmented using the following formula:

$$Q_{\text{san saba, augmented}} = Q_{\text{san saba, gauged}} + \left(Q_{\text{Paint Rock}} + Q_{\text{Ballinger}}\right) - Q_{\text{Stacy}}$$

Where “Q” is the streamflow, “san saba” refers to the Colorado River near San Saba, “Paint Rock” refers to the Concho River near Paint Rock, “Ballinger” refers to the Colorado River near Ballinger, and “Stacy” refers to the Colorado River near Stacy, downstream of OH Ivie Reservoir.

Base flow inflows to the Highland Lakes were calculated using the BFI program as applied to the gauges on the Colorado River at San Saba, the Llano River at Llano, and the Pedernales River near Johnson City while applying the drainage area ratios used by the LCRA. Data from these gauges were analyzed because LCRA uses these data to determine Highland Lakes inflows. Data from Sandy Creek was not used as it was not available for the period between 1940 and 1967. Results indicate that current base flow inflows are comparable to those that occurred during the 1950’s drought (Figure 1). The lowest base flow occurred in 2013, yet out of the top 10 lowest-base flow years, 4 occured since the year 2000 and 5 occurred in the 1950’s Drought of Record.

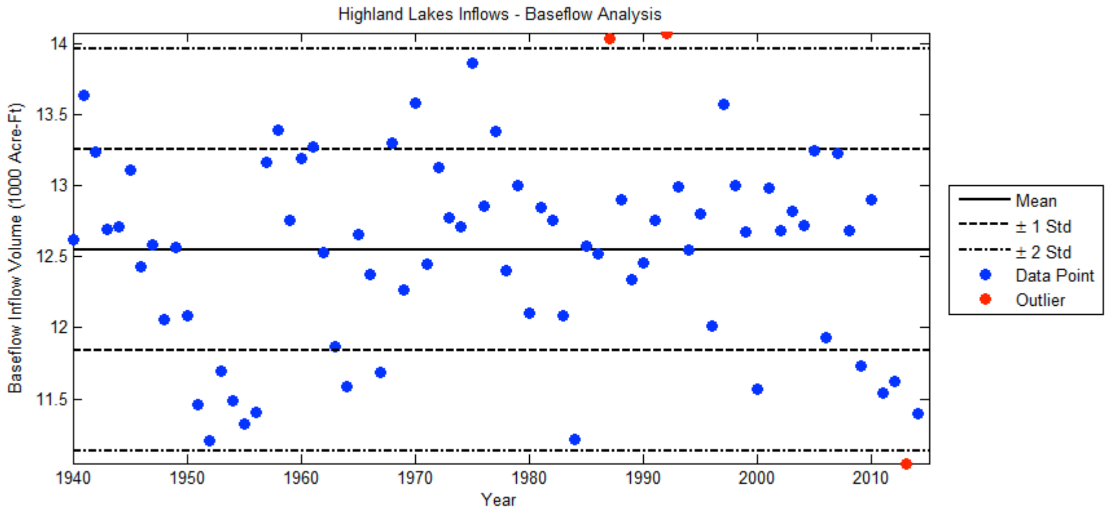

Figure 1 – Base flow Inflows to the Highland Lakes – 1940-2014.

When looking at base flow trends by individual river systems contributing flows to the Highland Lakes, it becomes apparent that the river systems do not show identical trends. For example, the lowest base flows in the Llano River occurred during the 1950s, with recent base flows remaining low, yet less than -2 standard deviations from the mean. Base flows in the Pedernales River were also lowest in the 1950s. In contrast base flows in the Colorado River are lower now than they were in the 1950s.

Figure 2 presents the amount of Highland Lakes inflow coming from base flow by year. As shown, there is a definite increasing trend, which is statistically significant based on the standard Mann-Kendall test (significance > 1, positive S). Figure 2 suggests that the Highland Lakes are getting a greater percentage of their inflows now due to base flow, and thus a lesser percentage based on runoff from storm events. This suggests that runoff-generating storm events are possibly less frequent, less able to generate runoff, or a combination of both of these characteristics.

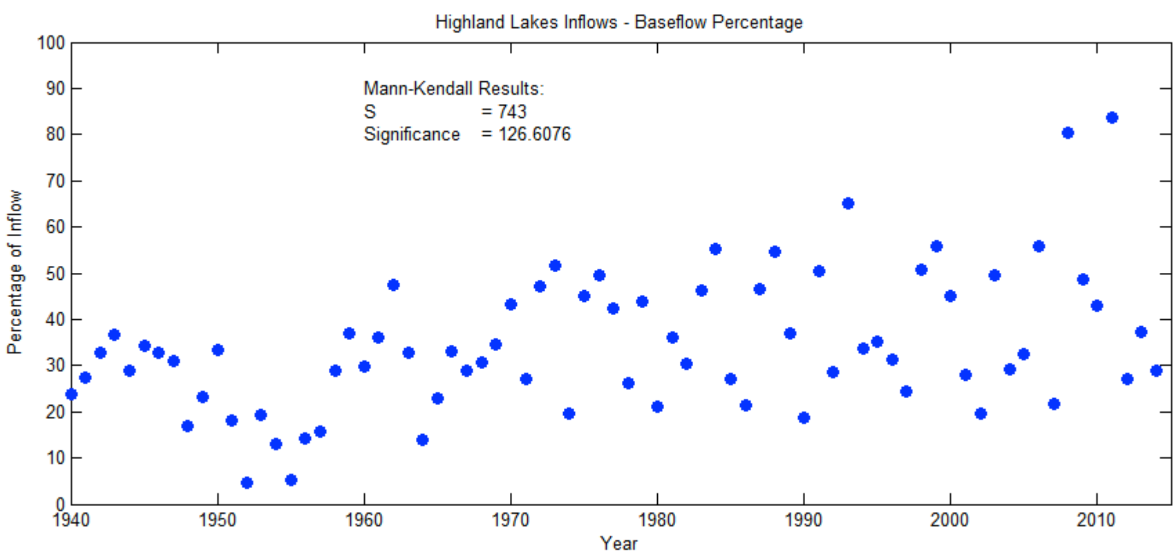

Figure 2- Percentage of Highland Lakes inflow derived from base flows.

2.0 PRECIPITATION ANALYSIS

In this analysis, INTERA attempted to determine if the volume of precipitation within the Highland Lakes watershed has changed appreciably over time. INTERA also attempted to determine if the watershed response to precipitation has changed appreciably. For this analysis, INTERA defined the Highland Lakes watershed as the land area upstream of the outlet of Lake Travis yet downstream of OH Ivie Reservoir. INTERA also excluded the watershed contributing flow into Lake Brownwood through Jim Ned Creek, yet included the area contributing to Lake Brownwood through Pecan Bayou. To compute precipitation over the watershed, INTERA used the monthly precipitation totals provided by the TWDB as an aerial average by quadrangle (http://www.twdb.texas.gov/surfacewater/conditions/evaporation/index.asp). INTERA multiplied the TWDB-provided precipitation depths by the area of the Highland Lakes watershed within each TWDB-specified quadrangle, and then summed the total volumes for the all quadrangles. The results are provided in Figure 3.

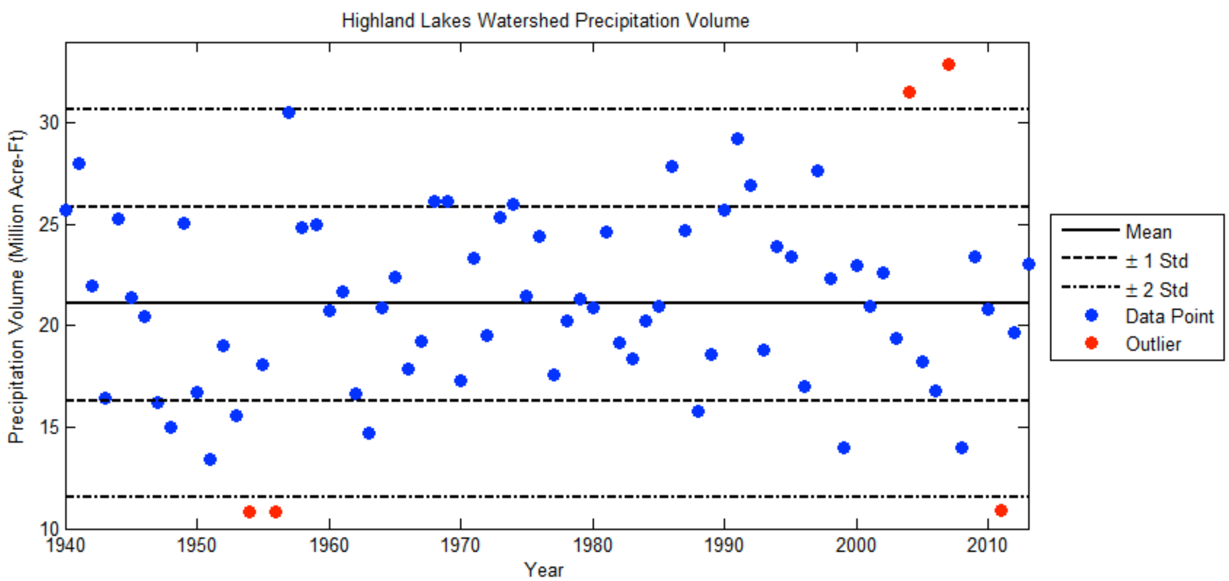

Figure 3 – Annual Precipitation Volumes for the Highland Lakes Watershed, 1940-2013

As shown in Figure 3, recent annual precipitation volumes for the Highland Lakes watershed do not suggest any anomalous trends with the historical record. Volumes were low in 2011 yet back to normal in 2012 and 2013. The volume for 2011 was also comparable to that from two years during the 1950's drought of record. Figure 4 presents the same precipitation volume data as in Figure 3, yet limited only to the portion of the Highland Lakes watershed immediately downstream of OH Ivie Reservoir. As shown, recent precipitation in this region has been at or above average, with the exception of 2011.

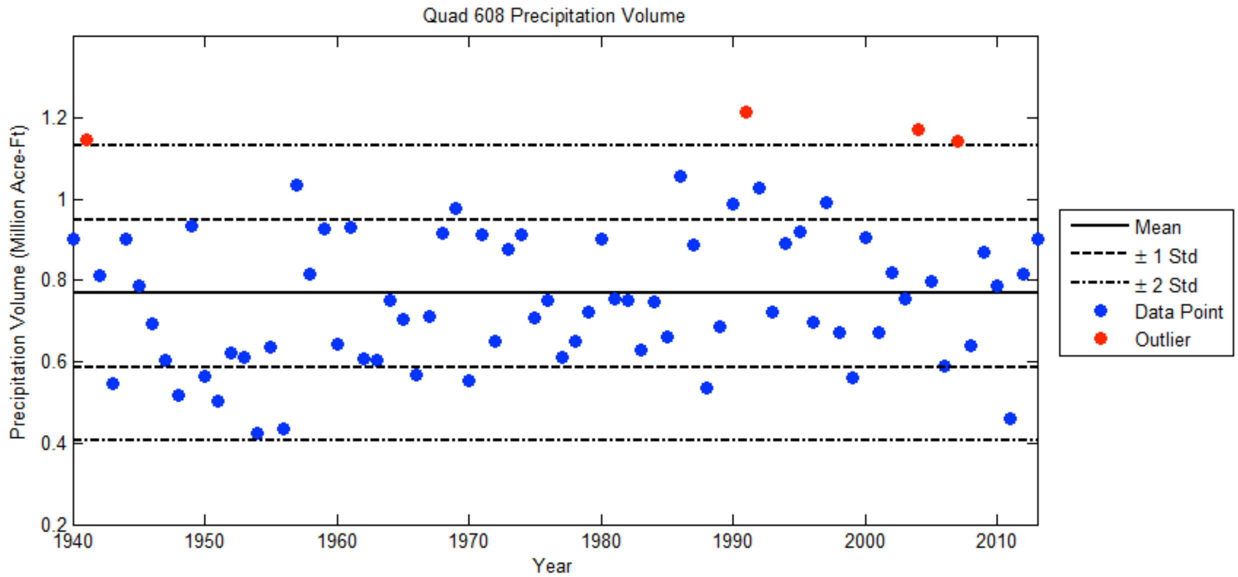

Figure 4 – Annual Precipitation Volumes for the "Quad 608" located downstream of OH Ivie Reservoir within the Highland Lakes watershed, 1940-2013

To assess if there are distinguishable changes in streamflow response to precipitation events, INTERA utilized a precipitation gauge within 25 miles of the USGS gauge on the Colorado River near Winchell, TX. This USGS gauge is located within the portion of the Colorado River watershed upstream from Lake Buchanan yet downstream from OH Ivie Reservoir. The gauge went out of service in 2011. Shown in Figure 5 is a comparison of streamflow response to a 0.7 inches rainfall event measured at the Winchell gauge on April 14, 1958 and April 12, 2009. In 1958, the rainfall event occurred when there was flow within the stream channel, and stream flows increased to a peak in the early morning of April 17th. In 2009, the rainfall event occurred when the Colorado River was completely dry, and no response in streamflow was recorded. For this analysis, INTERA could not find a set of times with similar rainfall events, antecedent rainfall conditions, and antecedent streamflows. The reduced streamflow in 2009 is likely due to the existence of OH Ivie Reservoir upstream on the Colorado River, which began impounding water in 1991.

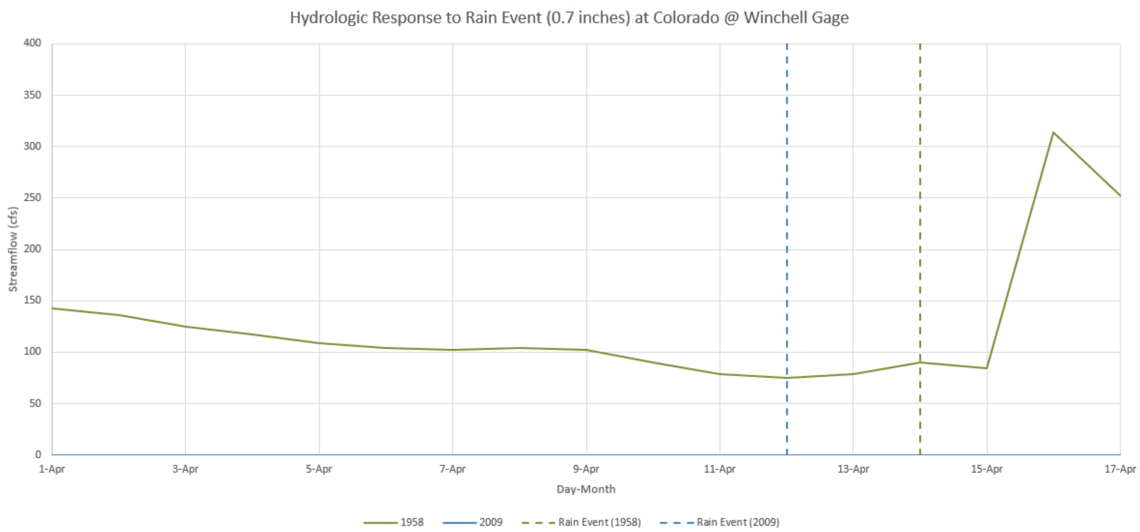

Figure 5 – Streamflow responses to a 0.7 inch storm event in 1958 and 2009 near Winchell, TX.

Data from the same rain gauge near Winchell, TX used in creating Figure 5 was plotted in Figure 6, showing the timing of when rainfall events occurred for the periods from 1948-1965 and 2008-2011. INTERA has yet to statistically analyse the data, yet through visual inspect it appears that longer dry periods occurred during recent years, compared to periods during the drought of record.

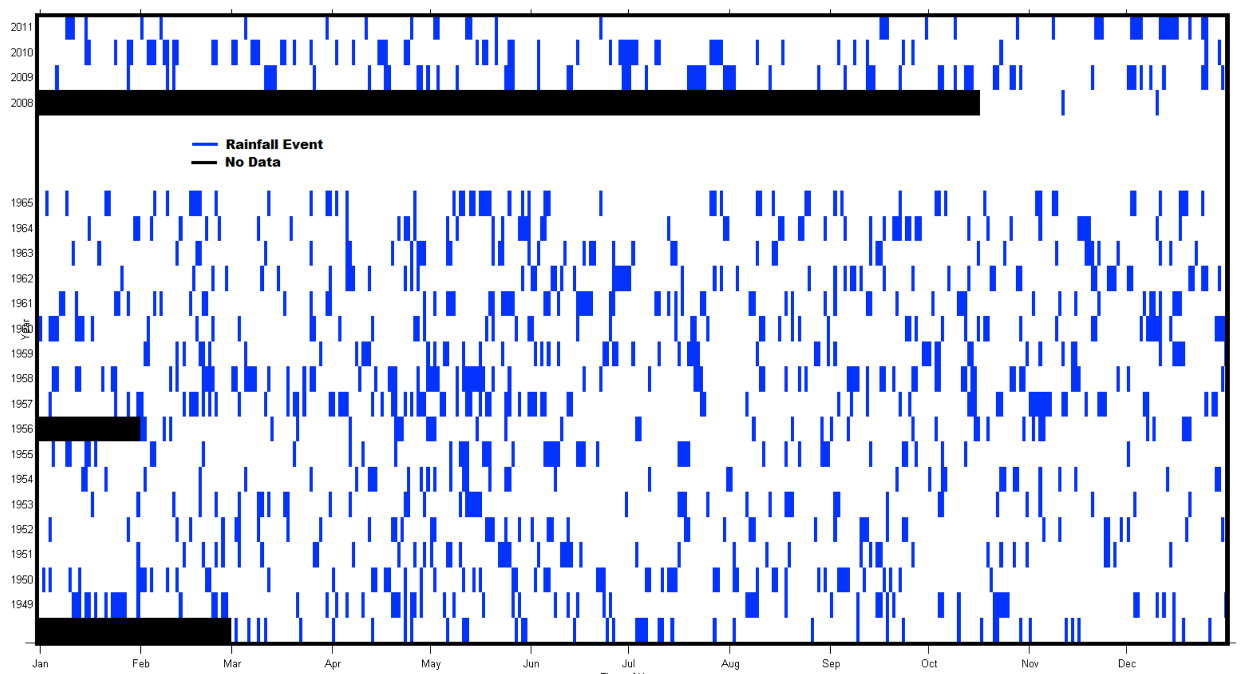

Figure 6 – Rainfall Calendar for the area near Winchell, TX (1948-1965, 2008-2011).

At the request of CTWC, INTERA performed an additional analysis of water levels in Lake Brownwood, as well as the gauged flows downstream of Lake Brownwood in Pecan Bayou. As shown in Figure 7, Pecan

Bayou flows have been significantly reduced during the current drought (2008-present), with a mean difference in flow of over 116,000 acre-ft/yr. The lowest flow on record at this gauge was 4,995 acre-ft in 2011. Data is unavailable from the drought of record in the 1950s. Figure 7 also demonstrates that water levels have dropped during the drought period, with little recovery events occurring in 2012-2013. In each event, the water levels rose rapidly, and then declined less rapidly, nearly back to the previous low-levels. Water level data for Lake Brownwood was not available from 1987 through 1998, and the current conservation pool capacity of the lake is approximately 135,000 acre-ft. Lake Brownwood has a priority date senior to the Highland Lakes, and is therefore able to impound inflows rather than having to pass inflows downstream to the Highland Lakes.

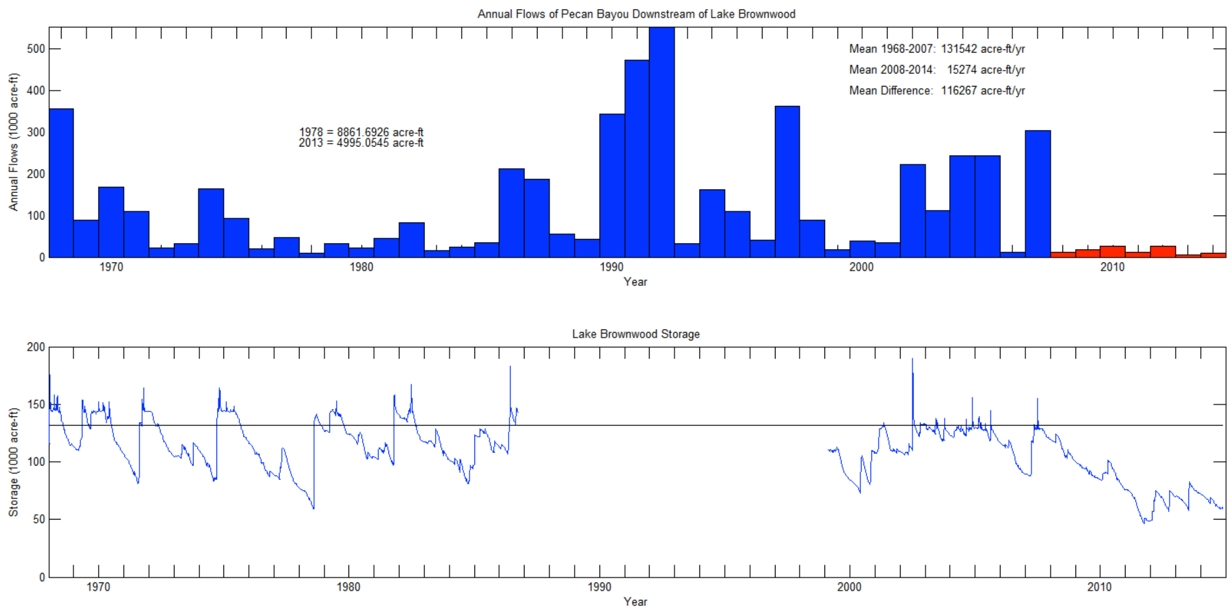

Figure 7 – Water levels in Lake Brownwood, and Flows in Pecan Bayou.

3.0 WATERSHED LAND USE/LAND COVER ANALYSIS

INTERA utilized the National Land Cover Database (USGS-NLCD) maps of 1992 and 2011, the recent National Cropland Data Layer (USDA-NCDL) crop maps between 2008 and 2013, and LANDSAT imagery to track the extent of standing water visible by satellite imagery at 30 by 30 meters pixel resolution. USGS-NLCD results indicate that within the Highland Lakes watershed, the areal extent of standing water ranges from 20,000 surface acres to 42,000 surface acres during dry (2011) and wet periods (1992). These results do not include water stored in the Highland Lakes, OH Ivie Reservoir, or Lake Brownwood. Annual USGS-NLCD total area for open water show an increasing relationship between total annual precipitation and total open area water with the lowest value in 2011. LANDSAT imagery has been analyzed to evaluate seasonal variations at the county level but still needs to be aggregated at the watershed scale.

INTERA found 44,258 small impoundments within the Highland Lakes watershed National Hydrography Dataset (NHD). These combined for a surface area of 26,400 acres (Figure 8), which is comparable to the area of Lakes Buchanan and LBJ combined when full. Evaporation from 26,400 acres amounts to an average loss of approximately 120,000 acre-ft/yr. The density of small impoundments included within the NHD dataset is greatest for the watersheds immediately downstream of OH Ivie Reservoir and Lake Brownwood. Upstream of the USGS gauge on Pecan Bayou, there exist 3,969 ponds covering 2,954 surface acres.

The NHD data shown in Figure 8 was created in 2003, and therefore reflects conditions known to exist at that time. Other sources of available land surface data include Google Earth images (dates from 2010-2014), aerial photos (latest from 2012) and USGS digital raster-graphic topographic maps (with revised dates from the 1960's to the 1980's). Figure 9 presents a comparison of the various datasets. As shown, in the 2008 aerial photo, a third downstream pond is visible. This pond is not included in the USGS map dated from 1967, thereby indicating that this third pond was created sometime after 1967 and before 2008. The three ponds are visible in Google Earth images from 2014.

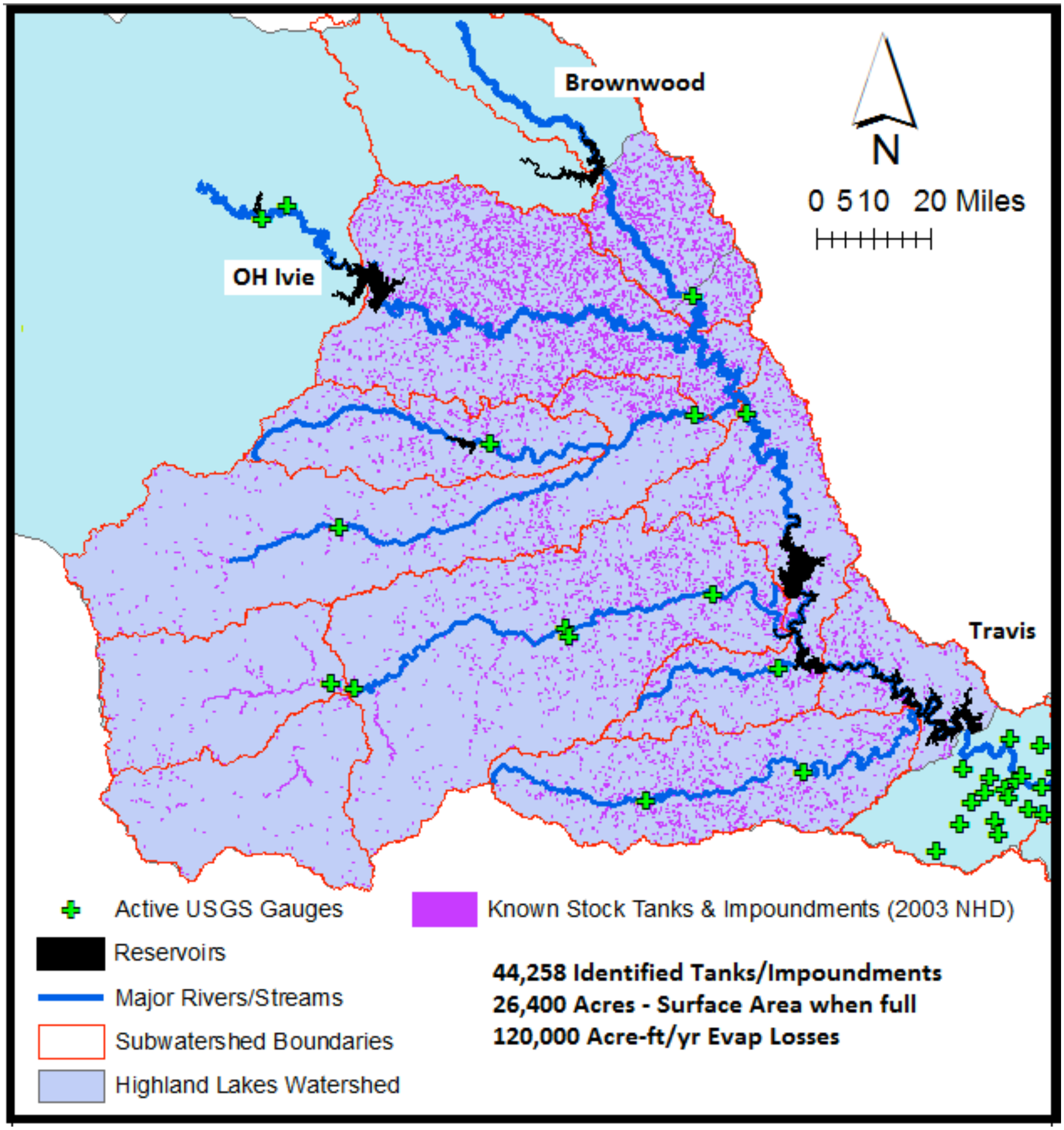

Figure 8 – Highland Lakes watershed showing small waterbodies/impoundments in 2003 NHD data.

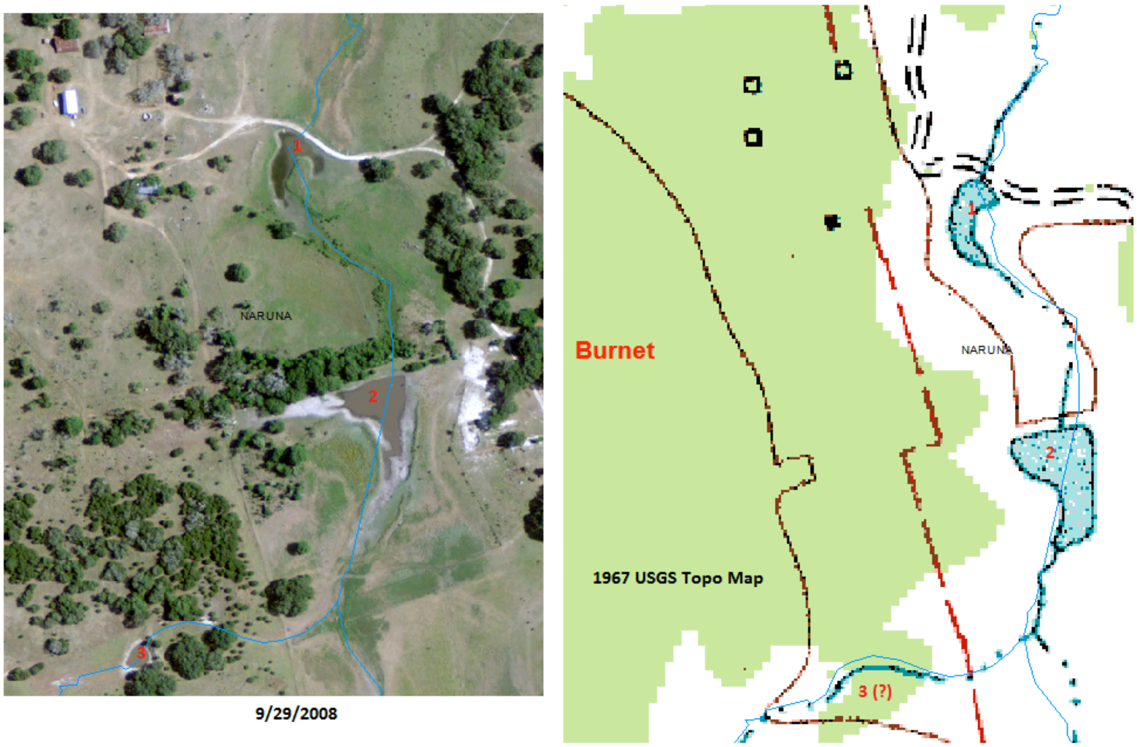

Figure 9 – Comparison of ponds in 2008 (TNRIS aerial photos), and 1967 (USGS Quad Maps). Pond #3 did not exist in 1967. Similar results found throughout the Highland Lakes watershed.

Figure 10 presents a similar comparison of current conditions (2012) versus conditions in 1986 for a portion of the watershed surrounding Onion Creek. The currently existing pond has a surface area of 1 acre and a maximum depth of 12 ft, and impounded water does not flow downstream in Onion Creek as it had before dam construction. This impoundment was created on ranch property for the personal enjoyment of the owner.

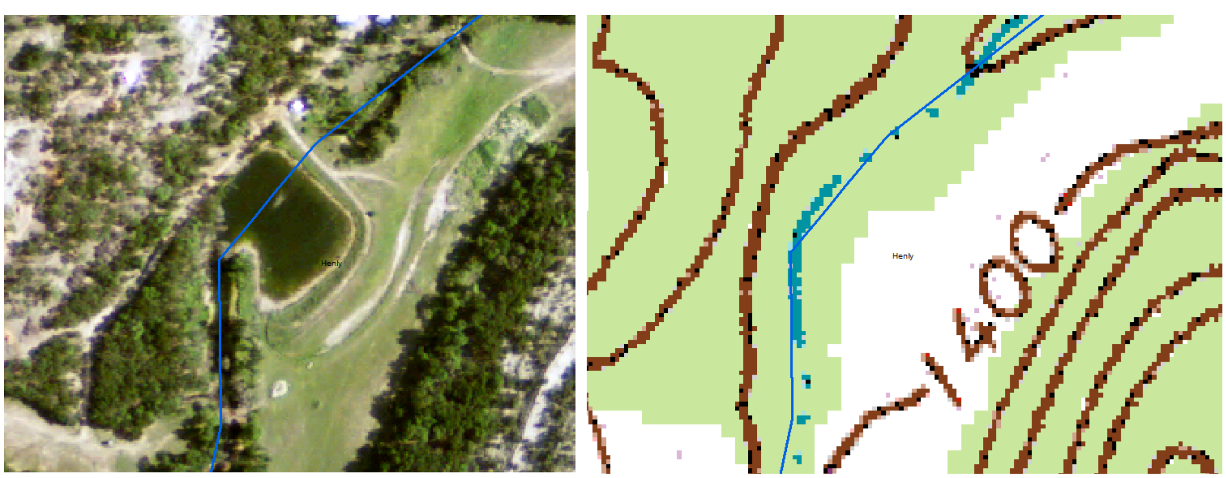

Figure 10 – Pond on Onion Creek that exists after 2012 yet was not retaining water in 1986.

4.0 ANALYSIS OF SURFACE WATER DIVERSION RECORDS

It is possible that Highland Lakes inflows are low simply because available streamflow is being diverted upstream of the Highland Lakes, before the water enters the actual lake bodies. To assess this possibility, INTERA geo-referenced TCEQ water usage records from 2008-2013 and determined the total quantity of water diverted (per the reports, which may be of questionable accuracy). INTERA determined that 715 water rights have been issued by TCEQ allowing diversions within the Highland Lakes watershed, with approximately 300 rights having a priority date SENIOR to the Highland Lakes. Holders of such senior rights would be able to legally divert surface water (subject to permit conditions) without having to let water flow downstream into the Highland Lakes. Per the Texas Water Code, holders of rights JUNIOR to the priority date of the Highland Lakes can be prevented from diverting water from the streams until the needs of downstream senior water right holders are satisfied.

INTERA determined that for the 6-year period from 2008 to 2013, a total of 145,682 acre-ft of streamflow was diverted in the Highland Lakes watershed upstream of the Highland Lakes (Figure 11). Of this total, only 25,754 acre-ft was diverted by water right holders JUNIOR to the Highland Lakes. The average surface water diversion upstream of the Highland Lakes totals 24,280 acre-ft/yr.

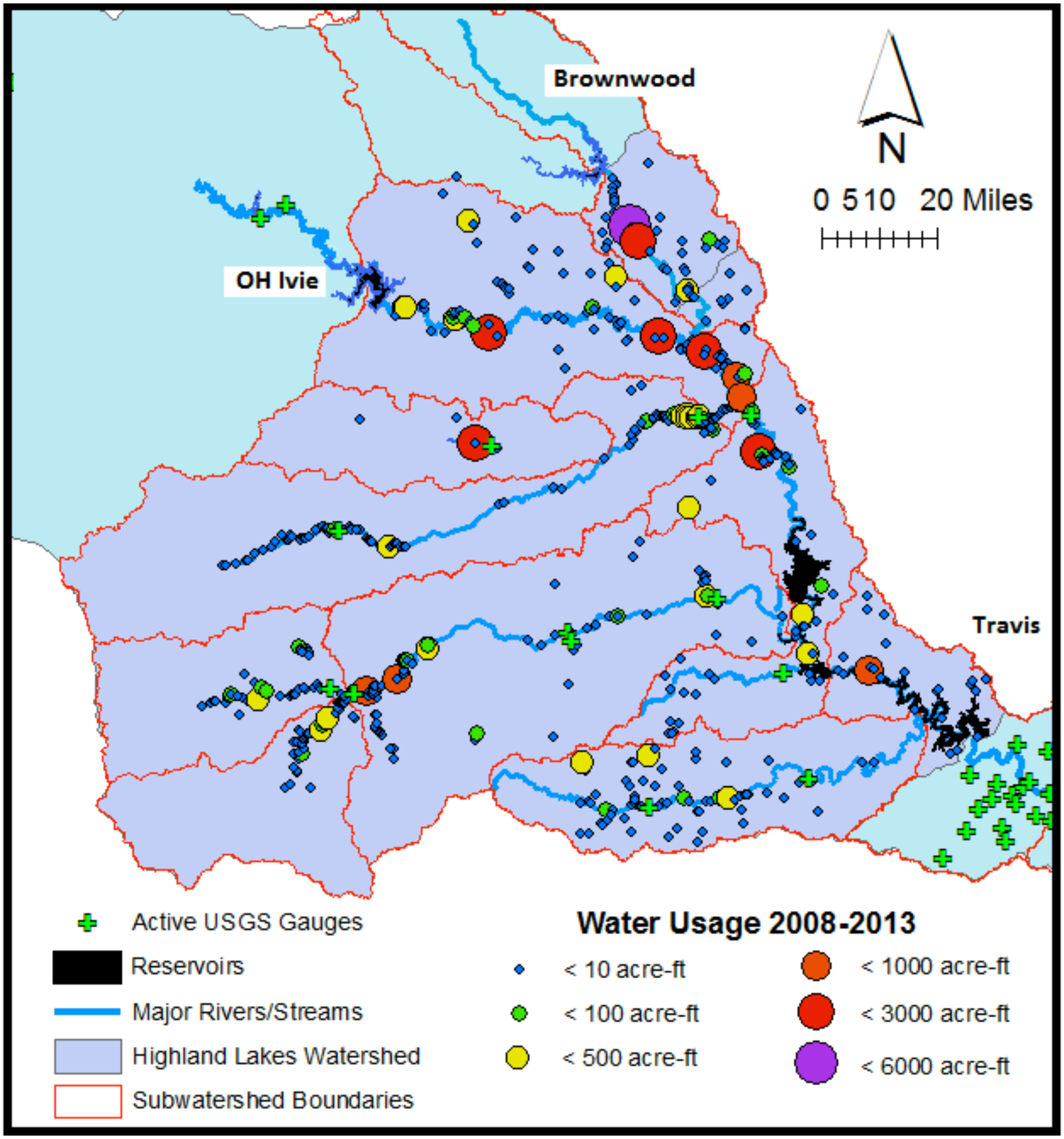

Figure 11 – Surface water diversions in the Highland Lakes watershed during the current drought (2008-2013). Total usage = 145,682 acre-ft (24,280 acre-ft/yr). Of this total, 25,754 acre-ft of usage was by water right holders JUNIOR to the Highland Lakes.

5.0 ANALYSIS OF GROUNDWATER WELL RECORDS

In the Texas Water Code, "groundwater" is defined as "water percolating below the surface of the earth" and is typically thought of as water underlying the ground surface, moving slowly though pores in the soil matrix and being re-charged through infiltration. Near a stream, however, groundwater can directly contribute to streamflow, with groundwater discharges coming as inflows to the stream through the streambed. Conversely the stream can also contribute directly to groundwater recharge, as often occurs when streamflows are high and stream water levels exceed the hydraulic head that maintains local groundwater levels. In essence, it is the relative height difference between the groundwater and surface water sources that drives whether streamflow is being lost to the aquifer, or vice versa.

Groundwater levels are directly affected by local recharge and the rates at which groundwater is withdrawn from any wells pumping in an area. INTERA is arguably the state-wide expert in developing detailed groundwater models used to predict groundwater availability and assess groundwater-streamflow interaction. To apply this expertise to the Highland Lakes watershed on a preliminary basis, INTERA quantified and mapped all known/reported groundwater wells. This was performed using data available from the Texas Water Development Board.

Figure 12 shows the Highland Lakes watershed and the locations off all known groundwater wells. The wells are colored by the date of drilling, with younger wells shown in blue, concentrated around Johnson City and the areas adjacent to Lake Buchanan and Lake LBJ. It must be noted that the date of drilling only indicates the date after which the potential existed for pumping to alter the water table and affect streamflow. Texas does not maintain detailed pumping records for groundwater wells, and does not require reporting in any detailed manner.

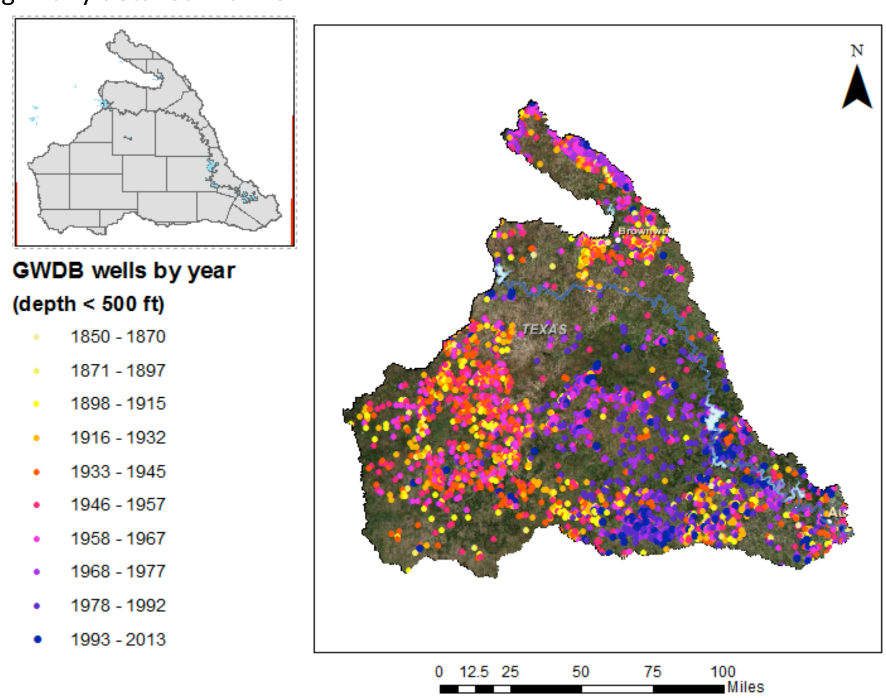

Figure 12- Groundwater wells in the Highland Lakes watershed, color-coded by date of drilling.

Interpreting the groundwater data is extremely difficult without actual pumping records. As an example, consider the situation immediately upstream of the USGS gauge on the Llano River near Llano (Figure 13). As shown in the figure, there exist 7 groundwater wells in the area upstream from the USGS gauge where HW 281 crosses the Llano River. The wells closest to the river were drilled in the early 1980's, with more recent wells drilled further from the stream. Conventional wisdom would suggest that the wells closest to the river would impact the streamflow to a greater degree, yet without more knowledge about well properties, pumping histories, and properties of the aquifer, actual assessments are difficult.

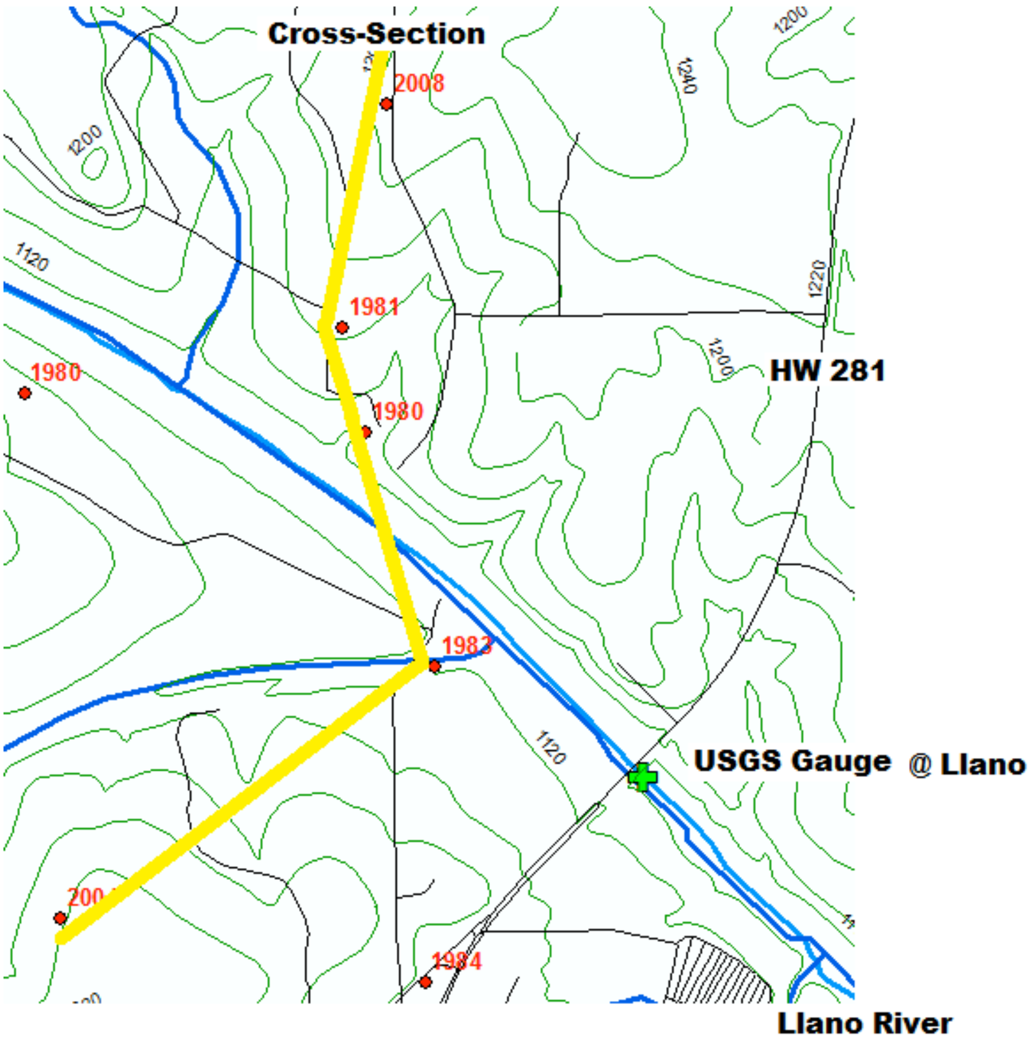

Figure 13 – Topography of the Llano River watershed near Llano, TX, showing well locations and the date of installation. Yellow line indicates cross-section shown in Figure 14, green lines are topographic contours of the land surface.

Typically rivers like the Llano River receive some amount of groundwater influx and are thus considered to be gaining streams. In this situation, the original water table would be at higher elevations than the stream, and groundwater would flow into the river. However, if pumping from local groundwater wells causes sufficient drawdown of the local water table, the Llano River could be made to be a losing stream. This could happen only at times when the wells are producing, or it could happen over time as the cumulative amount of pumped groundwater exceeds the local area recharge.

Figure 14 presents the cross-section view of the yellow line depicted in Figure 13. In this view, the depth of the groundwater wells becomes evident. It is logical to assume that wells are all screened near the bottom, meaning that they draw in groundwater from the deepest point in the well and possibly from the entire well-depth. This is not discernible from available data. The depth of well screening and the pumping rate from each of the wells will determine the elevation of the local water table, and will affect the shape of the local water table. Wells located closer to the river and screened at shallower depths will have greater impacts on streamflow, unless other wells are pumping at higher rates. Without detailed knowledge of well properties and pumping histories, the impact of groundwater withdrawals on streamflow cannot be discerned.

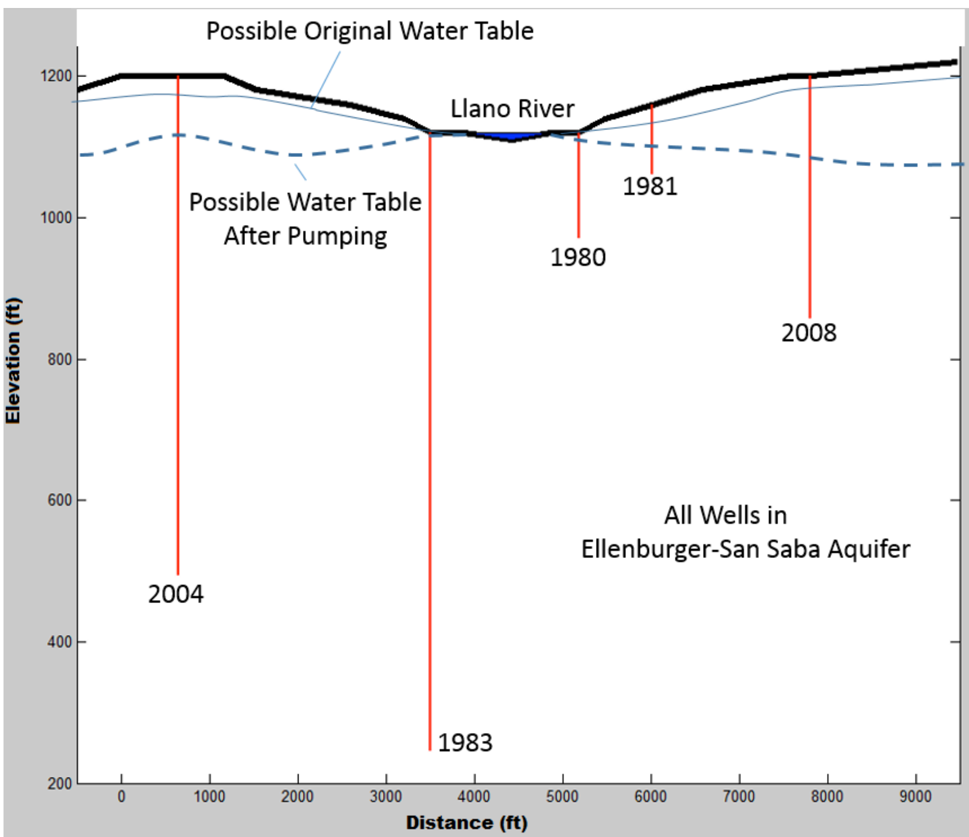

Figure 14 – Topographic Cross-Section through the Llano River near Llano, TX showing local groundwater well depths and the date of well installation. Water tables are examples only and not based on measured data.

6.0 ANALYSIS OF SOIL MOISTURE DATA

The final preliminary analysis undertaken by INTERA in an attempt to understand the causes for low inflows to the Highland Lakes involved investigating soil moisture data within the watershed. This was achieved through review of the GRACE satellite data, available at: http://geoid.colorado.edu/grace/. The GRACE satellites collect ultra-precise readings of the earth's gravitational pull, with local differences attributed to differences in soil moisture content. GRACE data is available for the entire Colorado River basin, and is provided as an average depth of water above or below the mean depth for an area over a period of time. GRACE data therefore indicates RELATIVE changes in soil moisture content. GRACE data for the Colorado River basin is provided in Figure 15.

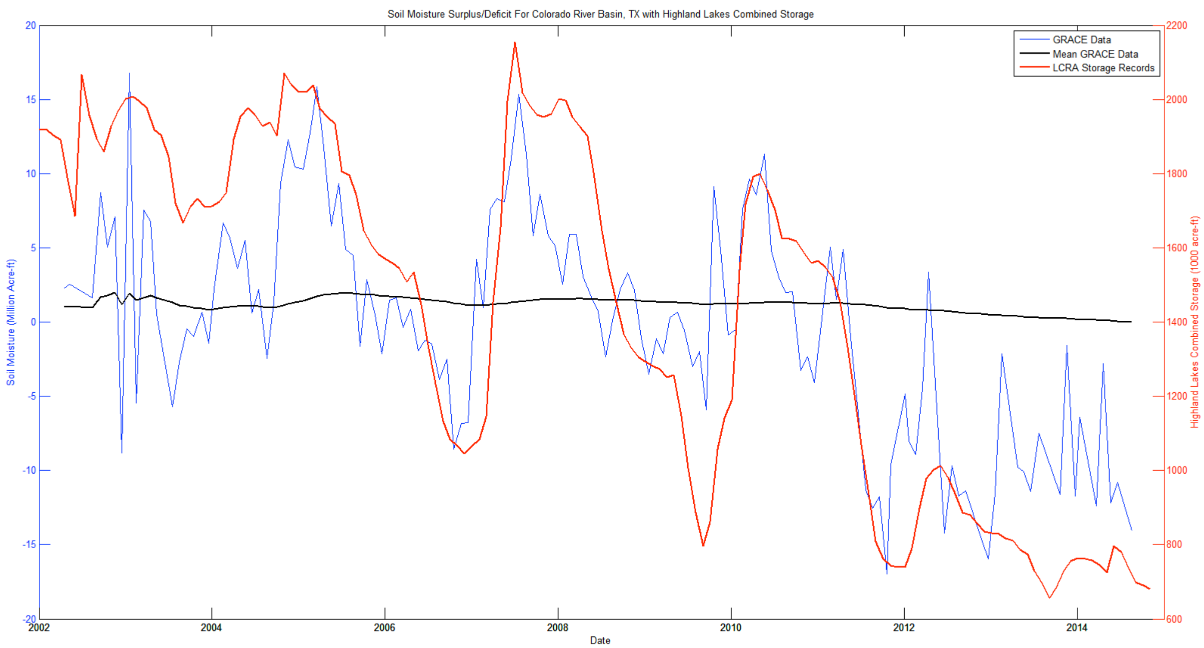

Figure 15 – GRACE Soil Moisture Data from 2002 to the Present for the Colorado River basin, TX (Blue) overlain with changes in combined storage of the Highland Lakes (Red) and a moving average (Black) of the GRACE data.

As shown in Figure 15, basinwide soil moisture has fluctuated since 2012, with fluctuations imperfectly mimicking the timing of large fluctuations in combined storage of Lakes Buchanan and Travis. Since late 2011, soil moisture content has been well below average for the GRACE period of record, indicating that an additional 15 Million acre-ft of soil moisture is needed (basinwide) to return to watershed conditions last seen in 2011.

7.0 CONCLUSIONS & RECOMMENDATIONS

While informative, the preliminary analyses presented in this report do not identify a "smoking gun" which clearly signals why recent Highland Lakes' inflows have been so low. The combination of factors, however, do yield a hypothesis suitable for further study.

INTERA has previously demonstrated that recent Highland Lakes inflows have been the lowest on record and are statistically outside the bounds of what would be expected based on measured historical precedent. LCRA itself has recognized that 2011 had the lowest ever annual inflows, with 2014 being the second lowest. This analysis presented data suggesting that recent rainfall over the Highland Lakes watershed has been, with the exception of 2011, average or nearly so. Therefore, persistent low flows cannot be solely attributed to low amounts of watershed precipitation.

Baseflow analyses on the gauged streamflow records indicate that baseflows have been recently low, yet not historically unprecedented. Further analysis showed that the portion of inflows entering the Highland Lakes as baseflow (as opposed to from flood/storm events) has been increasing with time. This trend is supported by results from a rather cursory analysis of rainfall timing, which indicates that current rainfall events are occurring less frequently. A possible result from the less-frequent rainfall is that the soils would become drier, as evapotranspiration (and possibly groundwater pumping) would diminish soil moisture content between the infrequent rainfall events. Finally, there is evidence that the number of small impoundments within the watershed is increasing; these impoundments only allow passage of inflows when the impoundments are full, which is likely to occur infrequently given the lack of frequent rainfall.

All of these observations combined suggest that the Highland Lakes watershed is drying out due to an increase in the timing between rainfall events. During the rainfall event, dry soils readily soak up available precipitation, leaving little to run off overland into the local drainage system. What water does runoff is captured within small impoundments scattered throughout the watershed, with water moving downstream only when the impoundments are full. During the dry period between rain events, water stored within the impoundments is lost both to groundwater recharge and evapotranspiration, thus lowering water levels such that inflows from the next rain event may not be sufficient to fill the impoundments and allow further downstream runoff.

Had rainfall events occurred more frequently, soil moisture contents would be higher, greater quantities of water would enter creeks as runoff, and there is a greater likelihood that water would spill over from small impoundments and become inflow to the Highland Lakes.

This hypothesis explains observed inflow reductions, yet further research is needed to solidify the analysis. INTERA proposes a detailed analysis of the timing and magnitude of rainfall events, utilizing multiple rain gauges within the Highland Lakes watershed. Also recommended is a detailed quantification of the increase in watershed area upstream of small impoundments, and a quantification of changes to the Highland Lakes firm yield resulting from the existence of these impoundments. Such an analysis was performed for the relatively small watersheds above Lake Coleman and Cedar Creek Reservoir (Brandes, 2011), from which it was demonstrated that yields can be reduced from 24% to 40% for more arid regions with large numbers of small impoundments (like in the Highland Lakes watershed).

If, through further analysis, the hypothesis presented herein is proven correct, there remains the question "Well now what do we do about it?" Ultimately, the watershed (and inflows) will return to normal conditions after a series of rain events without large intermittent dry spells. Yet if hydrologic rainfall patterns have, in fact, changed, then waiting for a "return to normal" may not be a suitable option. Another option is to modify small impoundments to allow for the passage of water under low-inflow conditions. Such an action would be unprecedented in Texas history and would require action by the Texas legislature. It would require altering private property laws and much greater government oversight of water storage practices.

Adjusting water management practices held by the LCRA would be an easier means for reacting to the changed hydrologic conditions. This would likely involve re-calculation of the system firm yield, and then adjusting LCRA's water sales contracts accordingly.

8.0 CITED REFERENCES

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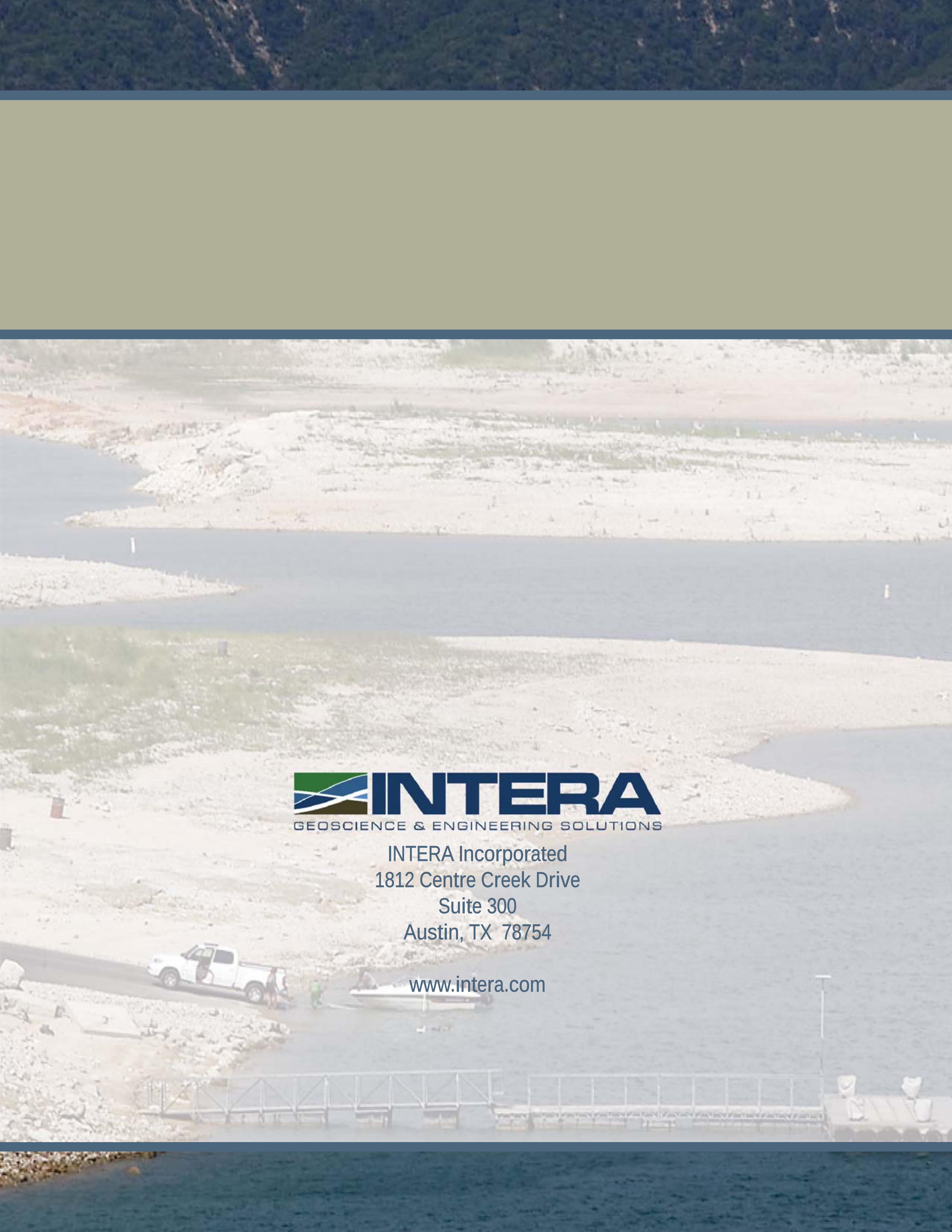
Furnans (2013) "Evidence for the Need to Change the Approach to Water Planning in the Lower Colorado Basin" Prepared for the Central Texas Water Coalition. May 8, 2013.



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