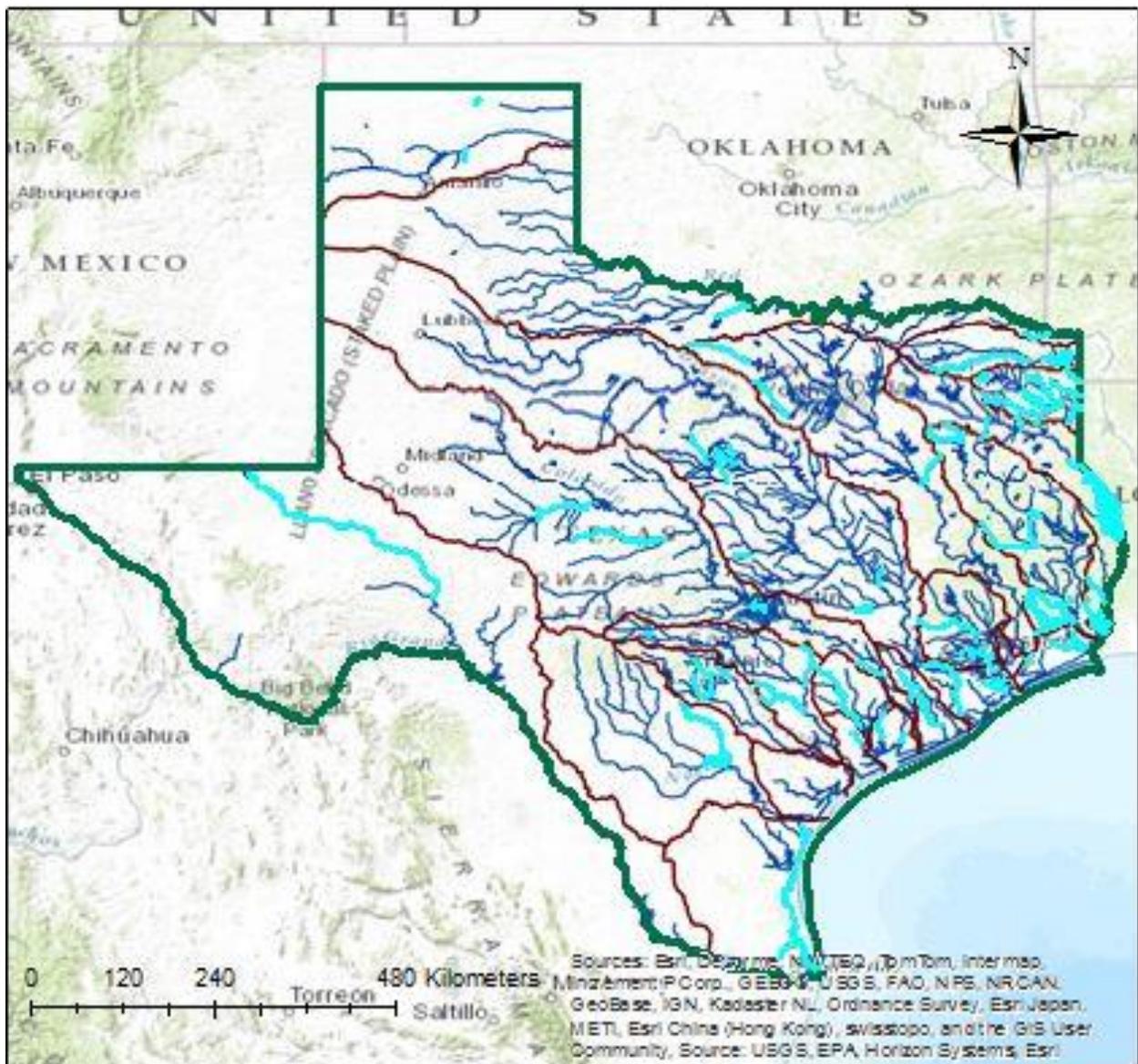


Using GIS to Visualize Impaired Dissolved Oxygen Conditions in Texas and Hypothesize Potential Contributing Factors



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I. Background

A. Texas Surface Water Quality Regulation

According to §307 of the Texas Administrative Code (TAC), which was developed in accordance with the Clean Water Act to regulate standards for surface water quality, dissolved oxygen levels in streams must be maintained to support aquatic life, meaning that they must be sufficient to support existing, designated, presumed, and attainable aquatic life uses.¹ Within 12-24 hours, sustained concentrations of dissolved oxygen falling below 5.0 ppm or 5.0 mg/L yield stressful conditions for fish populations, which cannot survive at concentrations below 3.0 mg/L (Figure 1).

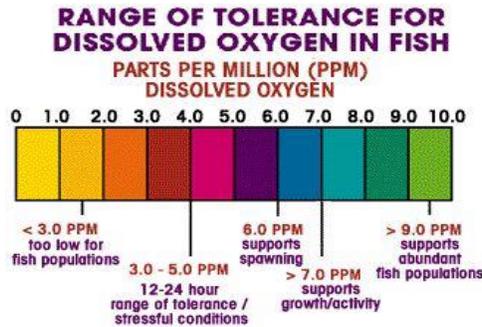


Figure 1: Fish Tolerance for Dissolved Oxygen, Source: Water Research Net

Each stream segment in Texas has been classified as to whether it supports exceptional, high, moderate, or limited aquatic life, with the minimum allowable dissolved oxygen level becoming more stringent with increased aquatic life use.² Appendix A³ in §307 of the TAC lists all minimum 24-hr average allowable concentrations for each classified stream segment in Texas, the average of which lies around 4.0-5.0 mg/L. For the purposes of this project, the minimum allowable daily average concentration will be designated at 5.0 mg/L, the level at which aquatic populations begin to experience stress.

According to the Texas 303d list, or the Texas Integrated Report of Surface Water Quality, there are 95 streams that are classified as having impaired dissolved oxygen levels (see Figure 2).

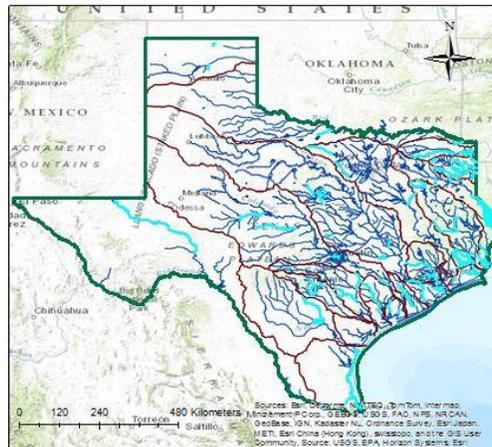


Figure 2: Dissolved Oxygen Impaired Streams in Texas (2010)

B. Causes of Dissolved Oxygen Fluctuations

The solubility of dissolved oxygen in water decreases as temperature increases, as shown in Figure 3). Therefore, it is normal for dissolved oxygen to fluctuate both seasonally and diurnally as surface water temperatures fluctuate. When water temperatures are coldest in the winter, dissolved oxygen levels are expected to be greatest; and when water temperatures are warmest in the summer, dissolved oxygen levels are expected to be lowest.

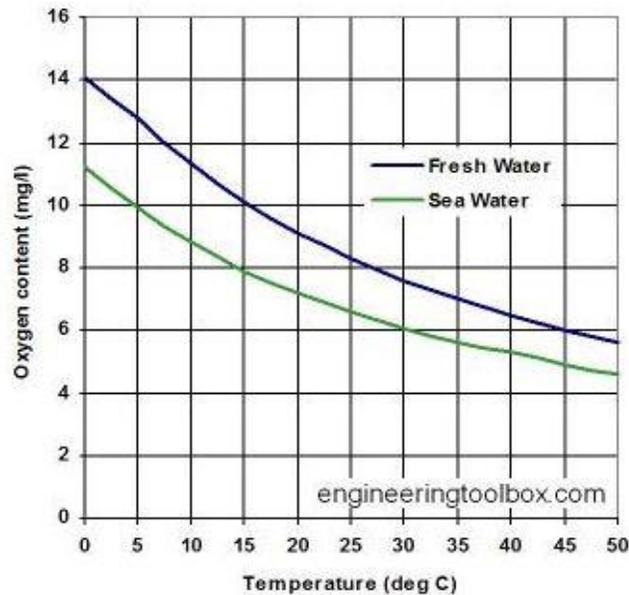


Figure 3: Solubility of Oxygen in Water as a Function of Temperature

Figure 3 also shows that dissolved oxygen solubility is lower in waters with higher salinity, so seawater oxygen levels are lower than that of freshwater. However, even in the most saline water conditions (seawater) and highest water temperature levels (40°C) observed in the Texas stream data, dissolved oxygen levels would not be expected to fall below 5 mg/L without the influence of additional factors.

Since the 95 DO impaired streams in Texas are measuring [DO] levels below 5 mg/L, there are other contributions to these fluctuations. Anthropogenic factors such as wastewater effluent outflows, agricultural runoff, and increase salinity in freshwater can further exacerbate dissolved oxygen levels when paired with natural solubility conditions. When high-level nutrients such as Nitrogen and Phosphorus attributed to wastewater effluent and agricultural runoff are outflowed into water bodies, they over-fertilize the water and create prime conditions for the excessive growth of certain algal plant species, known as algal blooms or eutrophication (Figure 4).



Figure 4: Eutrophication (Source: Environment

The problem with eutrophication is that when these plants die, they become a food source for microorganisms, and these microbial populations expand to consume and break down the huge volume of dead algae. Because microorganisms require high levels of biological oxygen demand (BOD) in order to survive and decompose decaying matter, their expanding populations cause a reduction in dissolved oxygen concentrations.⁵ Eutrophication is considered the most widespread water quality problem in the nation, not only for dissolved oxygen issues, but also for turbidity. Of all listed impaired river segments in the US, 60% are attributed to eutrophication.⁶

II. Project Goals

The purpose of this project was to create a preliminary set of tools for which to assess dissolved oxygen conditions in impaired streams, as well as observe the potential causes of impaired conditions.

GIS can be used to observe how well dissolved oxygen levels follow expected seasonal patterns. If, for example, DO levels are unusually low in the winter months when oxygen solubility in water should be highest, anthropogenic impact may be influencing these atypical patterns. GIS allows for that visualization using the time-series temporal display function. Stream gages representing the sampling conducted at each impaired stream will change color gradients to show temporal fluctuations in water temperature and dissolved oxygen levels across some extended time frame dependent on data availability for the given site. The stream gage color patterns show the extent and duration of stream impairment, as well as whether those impairments occur at atypical temperature gradients. Graphic displays also show the percentage of time when the streams fall below their minimum allowable 24-hr DO concentrations of 5 mg/L.

Wastewater treatment plant locations that outflow to relevant streams will be plotted to determine segments in which anthropogenic effluent outflow might have potential impact on DO levels. SSURGO soil water data will also be used to assess how the ecoregions of Texas could possibly affect dissolved oxygen levels. Land use and population density maps are also utilized to corroborate the extent of urban vs. agricultural impact on existing impairments.

This project will be a pilot assessment of two impaired stream segments: one that follows seasonal dissolved oxygen variations and one that seems to deviate from seasonal trends. Both streams experience significant impairment dips (at least 20% of days/year) but exhibit differing trends.

III. Methodology

Of the 95 impaired stream segments, daily mean dissolved oxygen concentration and surface temperature monitoring data was only available for 6 streams from the Texas Commission of Environmental Quality (TCEQ) Surface Water Quality Monitoring (SWQM) Continuous Water Quality Monitoring (CWQM) program. Figure 5 shows the six stream segments and gages with available data, and Figure 6 shows the extent of the CWQM data limitations.

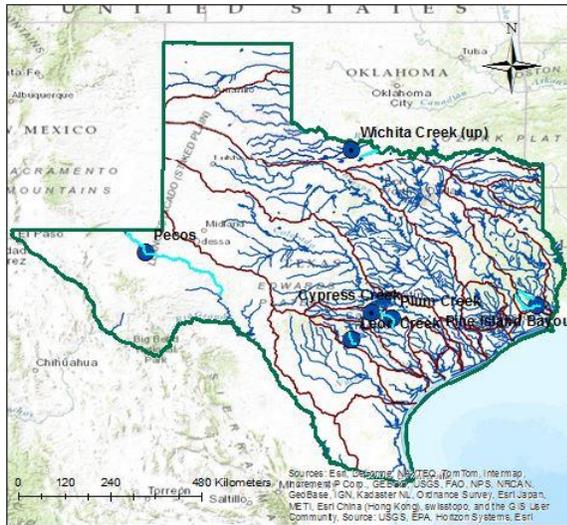


Figure 5: Impaired Streams with Available CWQM Data

Table 1: CWQM Data Limitations

	TOTAL	IMPAIRED	% IMPAIRED
River Basins	23	19	83%
Stream Segments	919	95	13%
Stream Length	550 km	70.7 km	10%
	IMPAIRED	AVAILABLE	% AVAILABLE
River Basins	19	5	26%
Stream Segments	95	6	6.3%
Stream Length	70.7 km	8.7 km	12%

The time frames available for each impaired segment varied extensively as well, limiting the ability to compare streams concurrently. For example, Leon Creek data was available from 2005-2007, Pine Island Bayou data was available for 2013, Plum Creek and Pecos River data were available for 2011, Cypress Creek data was available for 2012, and Wichita Creek data was available from 2009-2010. While Plum Creek and Pecos River data were both available for 2011, both streams were non-impaired (DO > 5mg/L) that calendar year.

Of the six impaired streams with available daily averages, the two impaired streams chosen for the pilot assessment were Pine Island Bayou and Leon Creek, which had the most consistent dataset available (i.e. least missing data) across at least a one year time frame.

Notable differences in dissolved oxygen patterns are shown in Figure 6. Leon Creek has data available for a three year time frame from 2005-2007 whereas Pine Island data only exists in 2013. The second graph normalizes the Leon Creek dataset to one year of data for direct trend comparison with Pine Island. Leon Creek appears to follow seasonal variations of dissolved oxygen, even when impairments occur. On the other hand, Pine Island Bayou experiences some atypical rises in dissolved oxygen during the summer months when DO is expected to be lower.

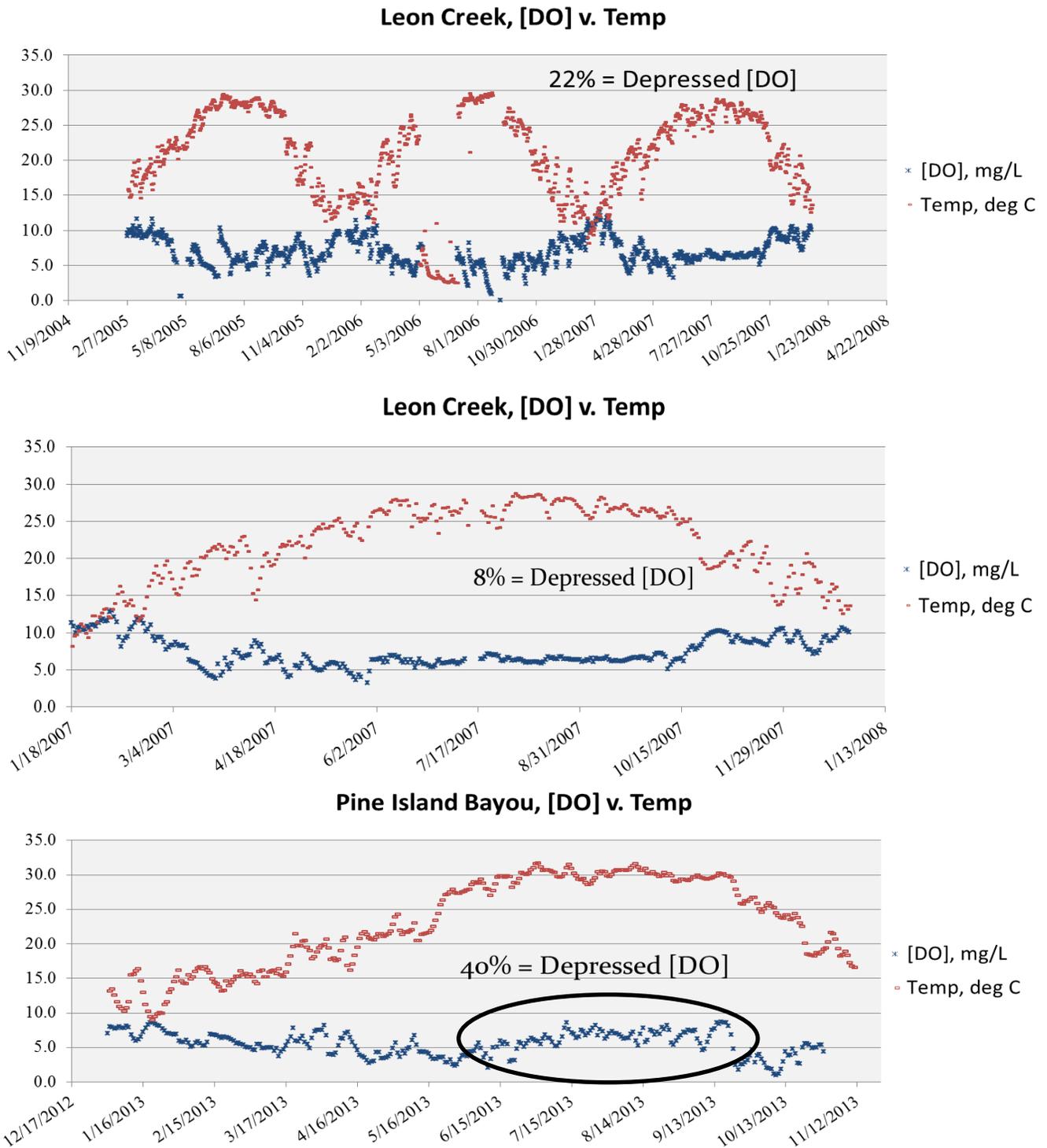


Figure 6: DO Concentration vs. Temp for Leon Creek and Pine Island Bayou. a) Leon Creek – 3, year time frame 2005-2007 b) Leon Creek, normalized to 1 year time frame, 2007, for comparison purposes c) Pine Island Bayou, 1 year frame, 2013

All available daily dissolved oxygen concentrations and temperature data were joined to each stream gage representing the impaired stream segment. The time function was then enabled for the gage of interest, and the daily levels were visualized using color gradients designated for the physical gage.

To explore potential explanations of impairment for the stream segments, GIS was used to map population density, contributing streamflow rates corroborated by USGS data, wastewater outfalls associated with each stream segment, as well as cropland distribution and available soil water storage to serve as an indicator of the extent of vegetation around the impaired stream and the possibility of agricultural runoff adding high-level nutrients from vegetation to the stream segment.

IV. GIS Analysis

A. Visualizing Dissolved Oxygen as a function of Surface Water Temperature

Two stream gages are layered at the impaired site to represent changes in dissolved oxygen concentration and surface water temperature. To make the visualization more useful, daily mean dissolved oxygen is displayed by the larger diameter gage for just two categories: either red for impaired (below 5 mg/L) or blue for permissible (above 5 mg/L). Temperature is displayed by the small diameter gage in a designated gradient. Figures 7 and 8 display several examples of daily averages for Pine Island Bayou and Leon Creek, respectively.

Video graphics of both case studies are publically available on youtube. The Pine Island Bayou Visualization is available at <http://www.youtube.com/watch?v=pLz0OjWyH-U> for 4/16/2013-8/14/2013 using the temperature and DO concentration legend provided in Figure 7. The Leon Creek Visualization is available at <http://www.youtube.com/watch?v=XQY8PRLTTs8> for 1/12/2006-1/2/2007 using the temperature and DO concentration legend provided in Figure 8.

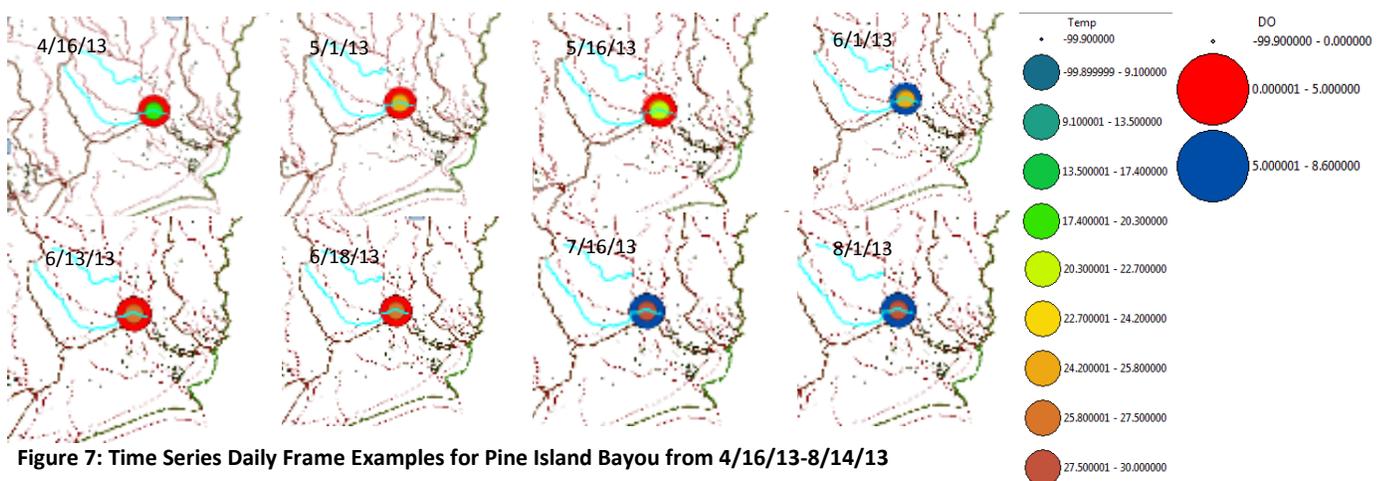


Figure 7: Time Series Daily Frame Examples for Pine Island Bayou from 4/16/13-8/14/13

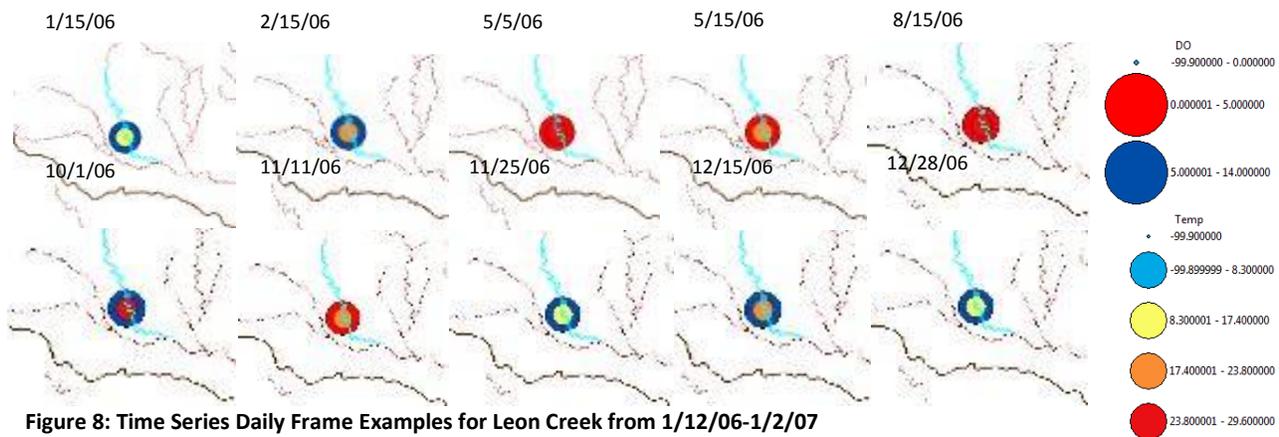


Figure 8: Time Series Daily Frame Examples for Leon Creek from 1/12/06-1/2/07

Notable conditions to identify for each daily average event are whether observed trends cannot be explained by natural patterns, i.e. a) during a series of low DO impairment events, temperatures tend to be uncharacteristically low (e.g. red outer gage paired with blue, green, or yellow inner gage), or b) during a series of healthy, permissible DO levels, temperatures tend to be uncharacteristically high (e.g. blue outer gage paired with red or orange inner gage). From the GIS time series visualization, Pine Island Bayou exhibits more of both the atypical cases whereas Leon Creek trends align with temperature and dissolved oxygen (e.g. high dissolved oxygen, lower temperature and low dissolved oxygen, higher temperature).

Monitoring the impairment cases may give a sense for the times of year where anthropogenic activities are most influential, and from there, possibly which sources could be targeted by regulatory programs to improve DO conditions. On the other hand, monitoring the case b) conditions is also useful because this scenario represents the most optimal condition where dissolved oxygen levels remain healthy even with high temperature conditions.

Neglecting urban/agricultural runoff and wastewater discharge impacts, the saturated dissolved oxygen level should not drop below 8 mg/L at a max temperature of 30°C, as presented in Figure 3. However, both streams exhibit impairment conditions, Pine Island 40% of the available data time frame and Leon Creek 20% of the available data time frame (Figure 6). The goal in the following section is to assess potential anthropogenic factors that could affect dissolved oxygen levels throughout Texas overall as well as in the specific subwatersheds of concern.

B. Assessing Potential Anthropogenic Factors on Dissolved Oxygen Levels

1. Population Density and Wastewater Outflows Hypothesis

Permitted wastewater outfall locations were downloaded from TCEQ and layered on a map with population density, downloaded from ESRI ArcGIS Online. Impaired stream segments were added to the map by downloading all streams with available surface water quality data from TCEQ, selecting the attributes of all streams with DO impairments, and creating a new feature class of

impaired streams. The overall trend shows that impaired streams tend to be clustered around areas of highest population and wastewater outfall density.

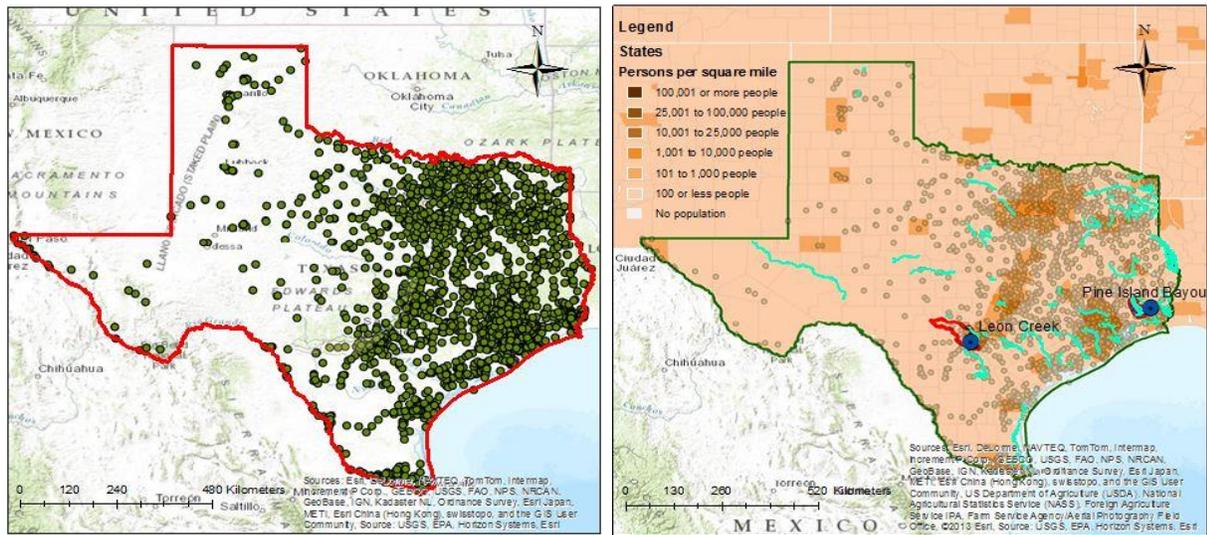


Figure 9: a) Texas Wastewater Outfalls b) Texas Wastewater Outfalls layered with Population Density

Zooming in on the Leon Creek and Pine Island Subwatersheds

Using HUC watershed reach codes, the subwatersheds associated with Leon Creek and Pine Island Bayou were delineated. These gages do not encompass flow from all of the streams within each subwatershed; rather, the gages are surface water quality monitoring stations set up at specific locations to observe impaired stream segments. To clarify this, the main contributing upstream lengths that *do* flow into the impaired segment at the gage were delineated in bolded dark blue as a separate feature class from the NHDPlusV2 flowlines using the “Extract Landscape Source Data” geoprocessing tool and visually selecting for the upstream segments. Figure 10 shows these contributing reaches layered with wastewater outfalls and population density for the two subwatersheds.

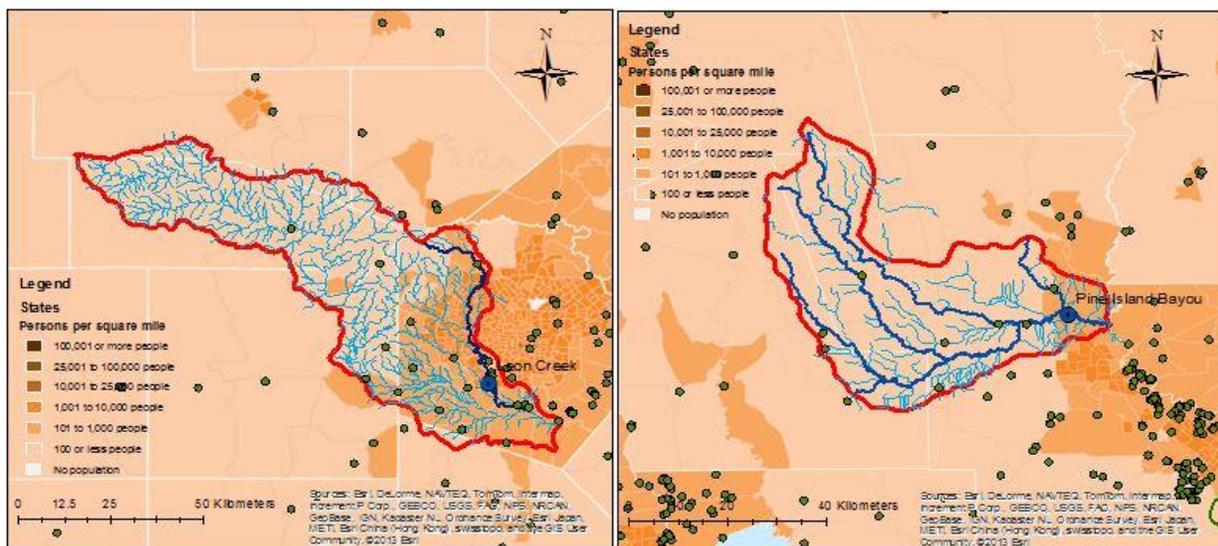


Figure 10: Wastewater Outfalls, Contributing Reach/Channel, and Population Density for a) Leon Creek in Medina Subwatershed b) Pine Island Bayou in Pine Island Bayou Subwatershed

Both gages designating the impaired segment exist in higher density population areas, although the majority of contributing reach for Pine Island lies in lower density areas. Higher density population areas may be attributed with increased municipal outflow if the wastewater outfalls are located on the contributing stream. Although Leon Creek is surrounded by denser populations, only 3 wastewater outfall discharges flow directly into the contributing stream; of those, 1 is municipal waste, 1 is military waste, and 1 is industrial utility waste. On the other hand, 8 wastewater outfall discharges flow into Pine Island's contributing channel, of which 7 are municipal waste and 1 is lumber waste. Figure 11 shows the variable nature of wastewater types along each contributing channel. Outfalls closest to the gage may have the greatest impact on water quality by being the least diluted. However, without knowing the waste volumes and nutrient concentrations of the discharges, which are unavailable to the public, conclusions cannot be drawn comparing the relative extent of anthropogenic effect on either stream. It can definitively be concluded though that anthropogenic effect exists for both streams, and GIS can help regulators attempting to propose non-point source laws decide which wastewater outfall sources to investigate more extensively for waste volumes and nutrient concentration based on proximity to the gage, or impairment location.

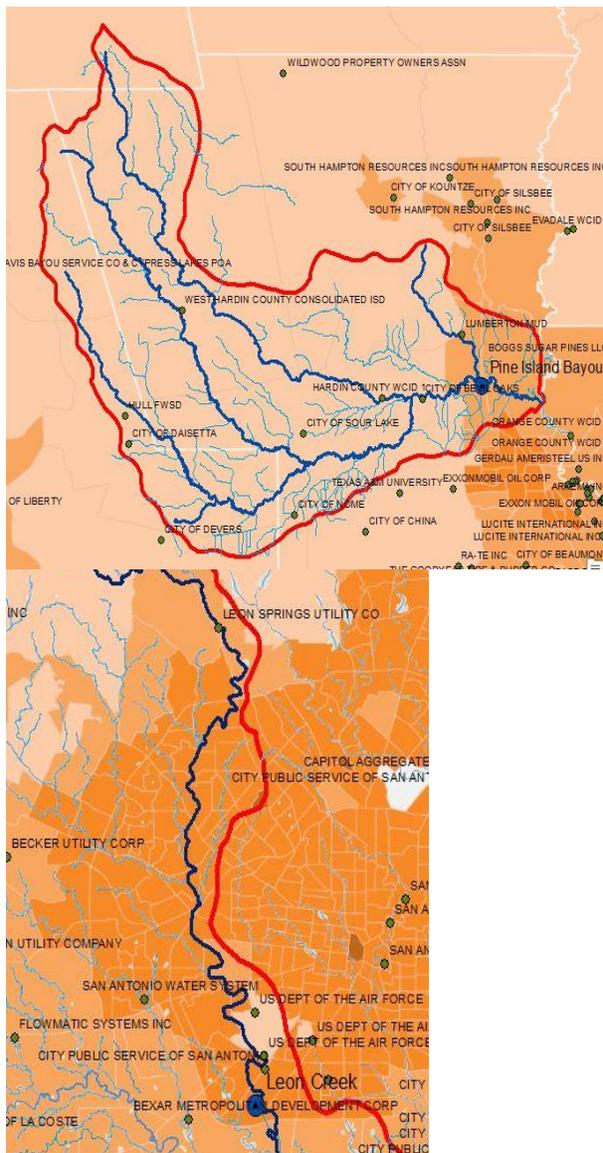


Figure 11: Wastewater Outflow Types along the Contributing Streams for a) Pine Island Bayou b) Leon Creek

2. Mean Annual Flow Hypothesis

Using summary statistics on the delineated contributing stream lengths, a total of 89.6 km of measured stream length flows into the Leon Creek gage at a mean annual flow rate of 27 cfs, and a total of 323.2 km of measured stream length flows into the Pine Island Bayou gage at a mean annual flow rate of 323 cfs. These GIS-calculated statistics are corroborated by the NWIS streamflow data downloaded from USGS, as shown in Figure 12, which depict similar scale averages across the available time frame of data.

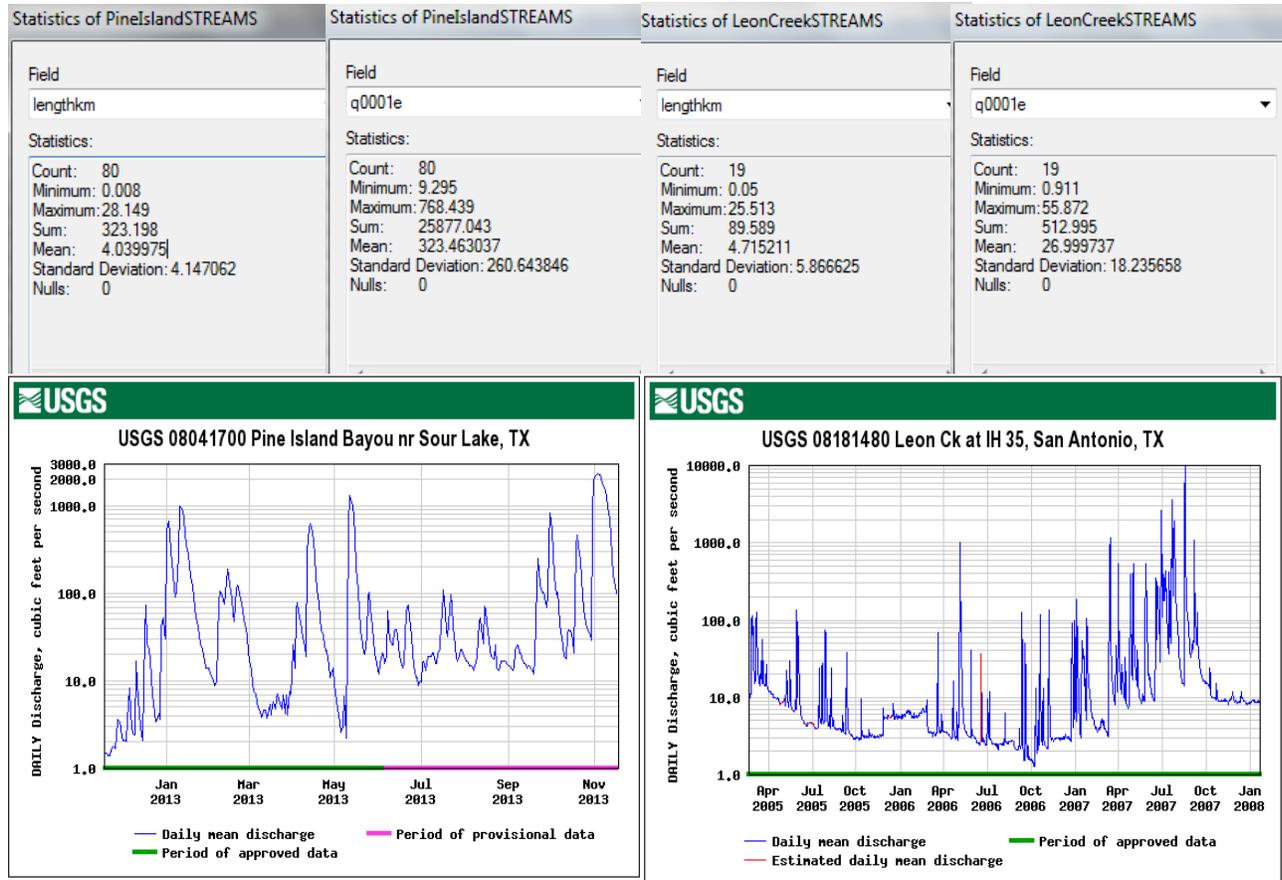


Figure 12: Stream length and flow rates for Pine Island and Leon Creek, matching the available dataset time frames

Generally, Pine Island experiences an order of magnitude larger streamflow than Leon Creek. While it is difficult to assess what this observation means for dissolved oxygen levels, hypotheses can be made. Faster streamflow at Pine Island could mean that the upstream nutrients outflowed from wastewater outfalls along the four distinct tributaries reach the impaired segment more quickly and concentrate when the individual tributaries merge at the gage confluence. Following that hypothesis, when flow slows down, less nutrients reach and concentrate at the gage, which means less algal metabolism and leads to a rise in dissolved oxygen. This behavioral hypothesis might reflect the seasonally atypical trend at Pine Island Bayou, where flow decreasing an order of magnitude from May to September results in elevated dissolved oxygen levels, which are normally expected to drop during summer when temperatures are highest.

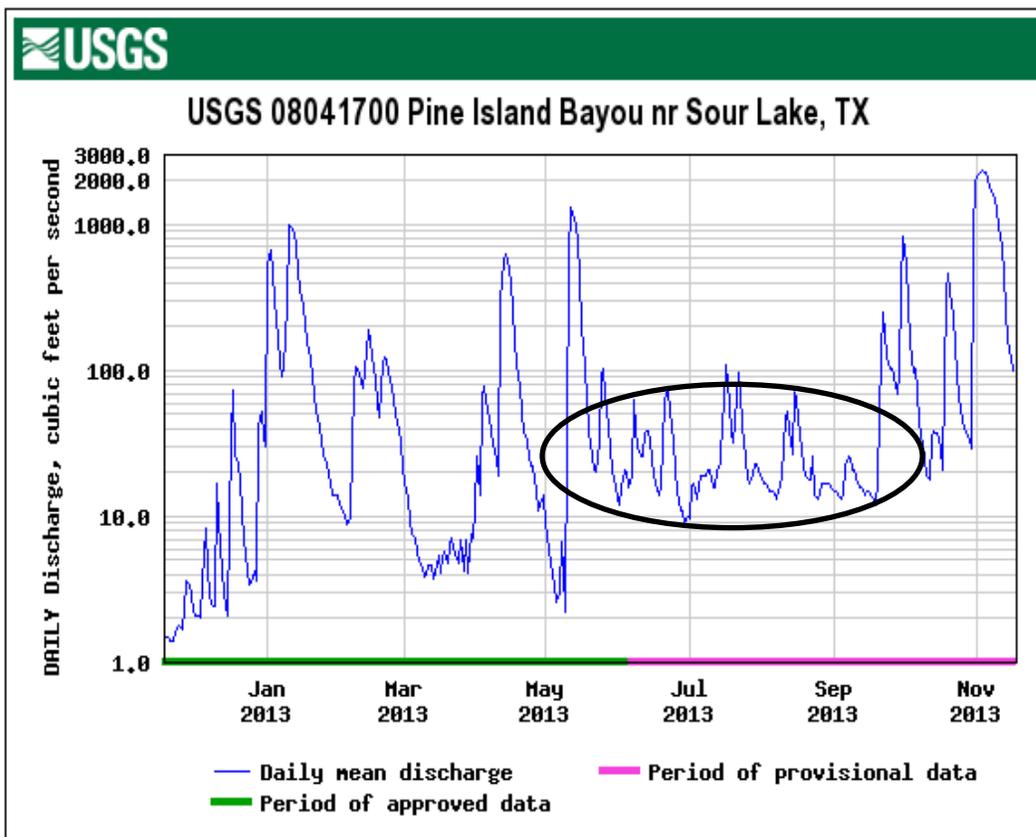
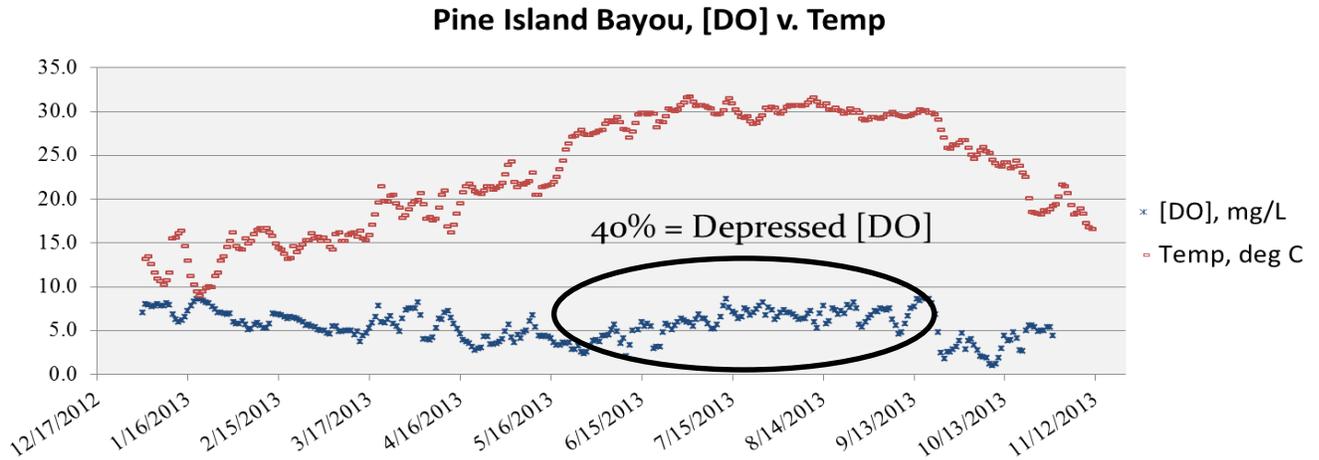


Figure 13: Comparing streamflow fluctuations with dissolved oxygen trends at Pine Island Bayou

Using the same hypothesis for Leon Creek in Figure 14, although the flowrate average for Leon Creek is much slower, there are several consistent high flow flooding events from April 2007 – September 2007, which correspond to lower dissolved oxygen levels, as hypothesized. However, the trend here overlaps with normal seasonal temperature increases and lower oxygen solubility, so it is not possible to tell how much impact can be attributed to the increased streamflow hypothesis.

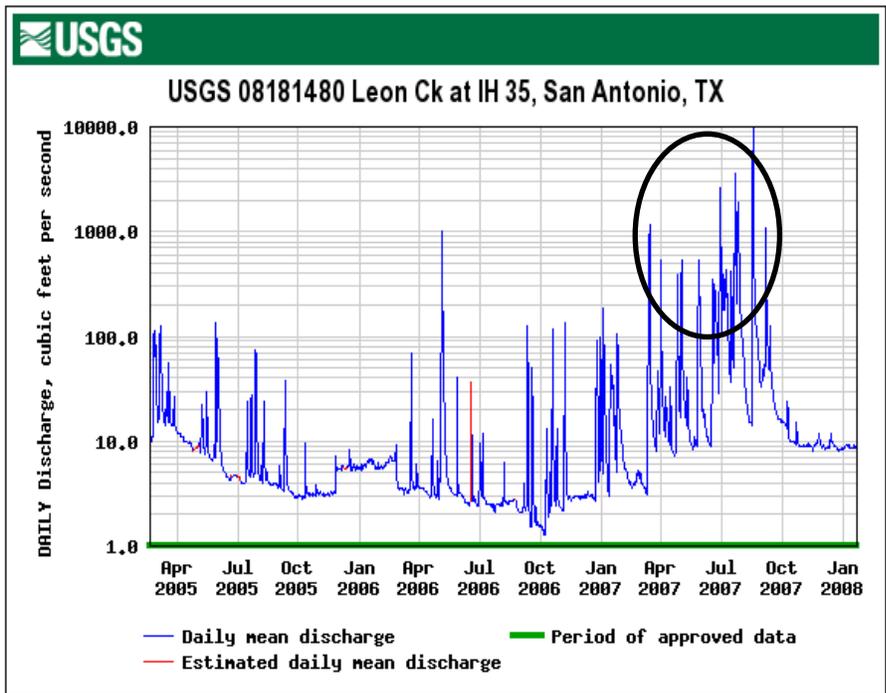
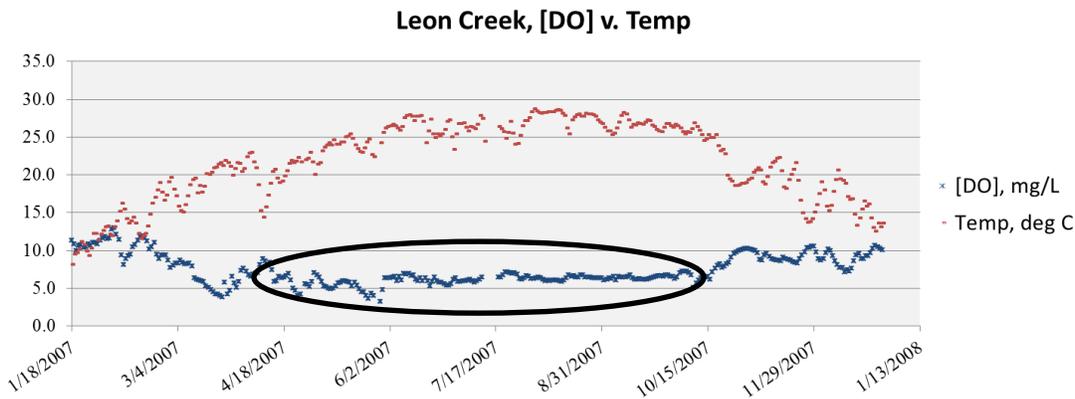


Figure 14: Comparing streamflow fluctuations with dissolved oxygen trends at Leon Creek

3. Urban vs. Agricultural Runoff Hypothesis using Land Use Distribution and SSURGO Soil Water Moisture Availability to Represent Vegetation Density

Given limited data resources for Texas agricultural runoff, soil water moisture and land use distribution maps were used as a surrogate to represent vegetative densities (Figure 15). Regions with high soil water are associated with denser vegetation, which leads to excess nutrients flowing into surface waters with runoff from precipitation, and excess nutrients in surface waters leads to enhanced vegetative algal growth and eutrophication, which in turn depletes dissolved oxygen.

The Pine Island Bayou impaired stream segment is located 125km northeast of Houston in the Pine Island Bayou subwatershed in the Neches Basin. The Leon Creek impaired stream segment is located directly in San Antonio proper, in the Medina subwatershed of the San Antonio Basin.

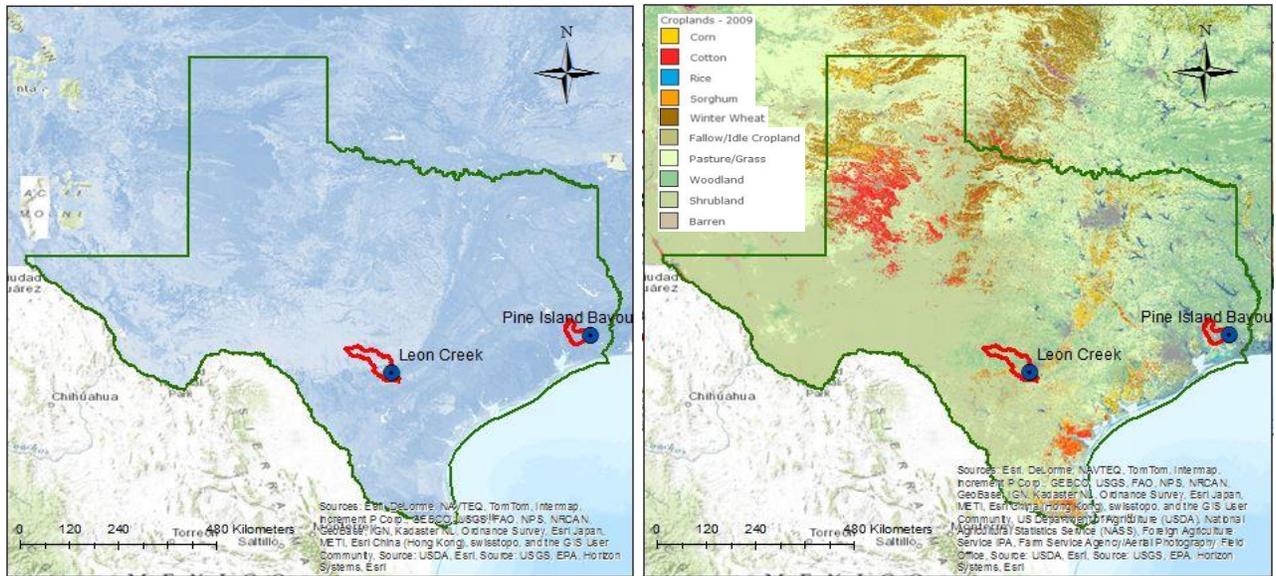


Figure 15: a) Texas SSURGO Soil Water Availability b) Texas Croplands Distribution

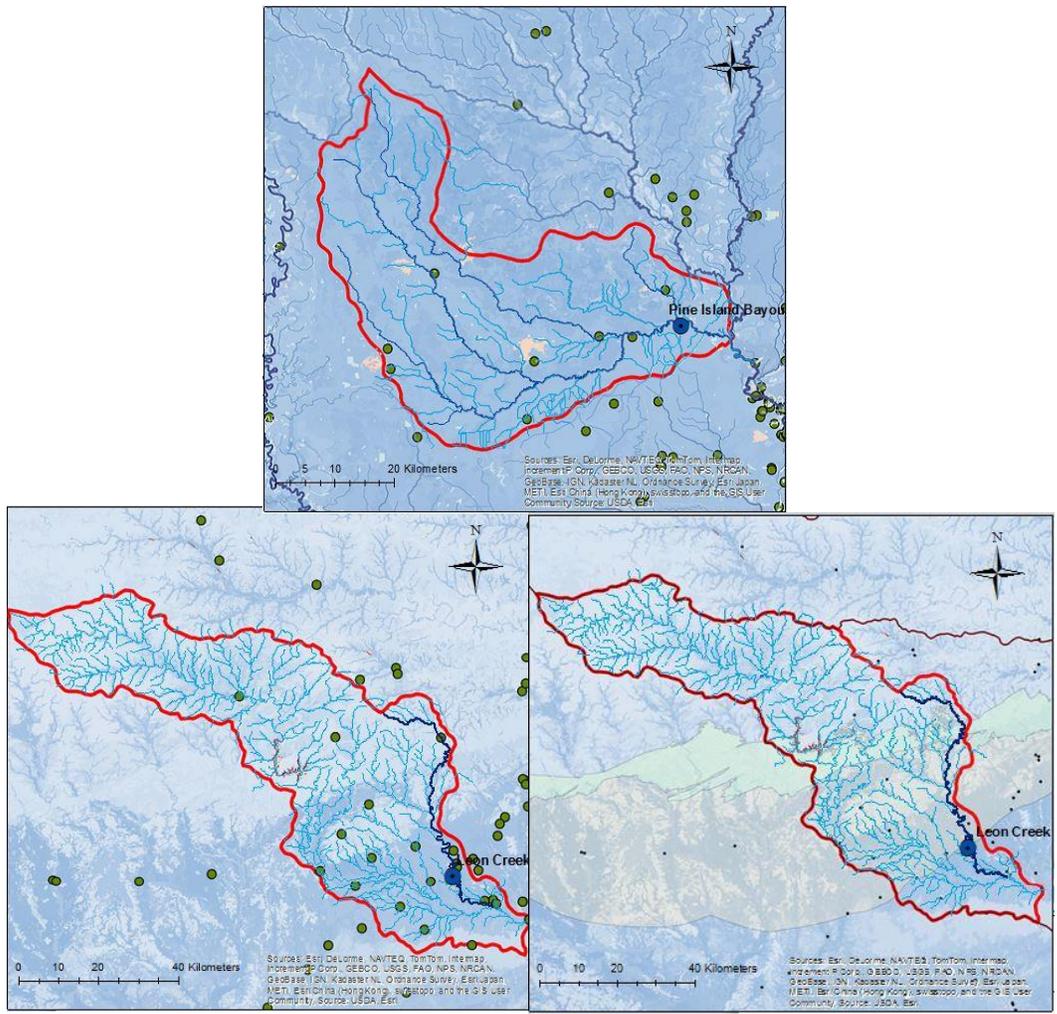


Figure 16: SSURGO Soil Water Moisture Available for a) Pine Island Bayou b) Leon Creek c) Leon Creek with Edwards Aquifer overlay

Figure 16a shows that Pine Island Bayou and its contributing streams exist in a high soil water region with an average of 27cm of available water storage, so vegetative nutrient runoff might be expected to have a large impact on impaired DO conditions.

Figures 16b and 16c show a distinct division in available soil water storage of the Medina subwatershed at Leon Creek occurring at the boundary of the Edwards Aquifer. The soil water storage profile is split in two; the region northwest of the diagonal divide exhibits a majority of ~3-5cm of available water storage, whereas the region southeast of the diagonal divide exhibits a majority of ~20-28cm of available water storage. The region northwest of the Edwards Aquifer is comprised primarily of clays in its upper layer, which have less permeability and are more compact, with less vegetation potential. The younger rock and soils southeast of the divide are more gravelly sand types with more permeable limestone, explaining the greater availability of soil water storage.

The SSURGO data is corroborated by the land use and croplands layer (Figure 17). The Leon Creek region above the Edwards Aquifer consists primarily of woodland oaks⁷, shrubland, and grassy pastures, which only affects the most northern portion of the contributing stream. The gray region surrounding the majority of the contributing stream designates regions with high urban development and roadways. Some agricultural areas for corn and cotton industry exist near the gage, but overall, the main cause for impairment at Leon Creek is likely due to urban runoff.

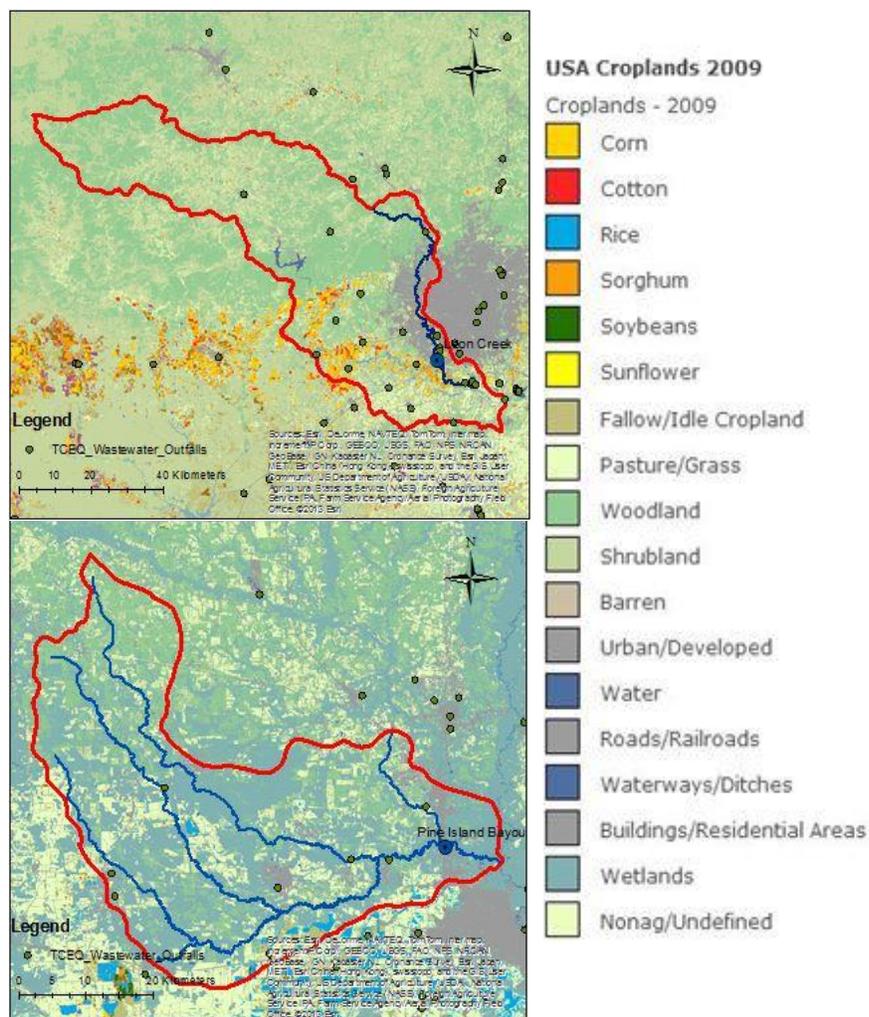


Figure 17: Land Use and Croplands Distribution Map for a) Leon Creek b) Pine Island Bayou

On the other hand, the Pine Island Bayou contributing streams are all located in a region consisting primarily of wetlands, likely with higher nutrient content and vegetative density. Several pockets of urban areas exist near the gage region, but the main cause for impairment in the Pine Islands region is likely runoff from natural high-nutrient wetlands, which also indicates why streamflow fluctuations may directly affect the density of nutrients being carried downstream.

V. Conclusions

This pilot project shows the importance of having available continuous water quality monitoring data, not only with DO and temperature, but also with Nitrogen, Phosphorus, and salinity concentrations. If surface water quality measurements were taken for all streams and automatically populated into a GIS server database similar to the functionality of GRACE for soil moisture, the impairment of streams could be monitored using map visualization to observe pattern changes over time. If wastewater outfall volumes were available, it would also be possible to back-calculate urban and agricultural runoff volumes across a specified area using the precipitation data for that region.

There are many complex factors that contribute to fluctuations in dissolved oxygen levels, and current data limitations preclude our ability to make quantifiable assessments about impairment causes. However, GIS is still a valuable tool in laying out the key predictive factors that might help regulators keep track of consistently problematic streams and design mitigation programs to tackle potential causes. We may legislatively be a long way off from developing effective non-point source pollution regulations, but GIS has undoubtable merits in being a part of that investigation.

VI. References

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VII. Acknowledgements

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