EUTROPHICATION ASSESSMENT FOR LYNDON B. JOHNSON LAKE, A SUBTROPICAL RESERVOIR IN CENTRAL TEXAS: IMPACTS FROM URBANIZATION AND UPSTREAM SOURCES

by

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
asl	at sea level
CA	Cluster Analysis
DO	dissolved oxygen
EPA	Environmental Protection Agency
GIS	Geographic Information System
HLWO	Highland Lakes Watershed Ordinance
LBJ	Lyndon B. Johnson
LCRA	Lower Colorado River Authority
N_2	nitrogen gas
NHGIS	National Geographic Information System
NH_4-N	ammonium
NO_{3-}	nitrate
P	phosphorus
SO_4:CL	sulfate:chloride
SPSS	Statistical Package for Social Sciences
SWI	Sediment-water interface
TDT	Texas Department of Transportation
TP	total phosphorus
TN	total nitrogen

TWDB Texas Water Development Board

ABSTRACT

Preliminary observations have suggested that Lyndon B. Johnson (LBJ) reservoir has become significantly more eutrophic in recent years. The reservoir receives water from the upper Colorado River drainage and from its two main tributaries, the Llano River and Sandy Creek. There has been a significant increase in urbanization directly near the reservoir which has the potential to increase nutrients from surface runoff. The goal of this study was to determine the cause(s) of the eutrophication through analysis of a long-term data base of Lake LBJ, between the years 1982-2016. Statistical techniques were applied to data from six stations over the length of the reservoir, to evaluate spatial and temporal variations in nutrient transport and symptoms of eutrophication. Early analysis confirmed that eutrophication has increased over time, and found high concentrations of ammonium and phosphorus coming from the upstream reservoir. A cluster analysis broke the reservoir down into distinct zones based on a stations water column stability. The water column stability at the dam was protected from disruption during summer stratification, allowing for seasonal anoxia and low redox conditions nearly every year in the hypolimnion. These conditions resulted in internal loading of nitrogen and phosphorus. At the other stations, the seasonal development of water column stability was weakened or completely inhibited during periods of heavy spring or summer flooding. There was an increase in developed land and population around the reservoir, which indicated another contributing factor of nutrients from surface runoff. The results suggest that eutrophication has increased over time due to localized

urbanization and increased nutrients from the upstream reservoirs as well. The eutrophication has led to an increase in severe anoxia, severity of redox conditions, and internal loading of both phosphorus and nitrogen.

1. INTRODUCTION

Reservoirs are complex systems that serve as habitat for aquatic plants and animals, sources for drinking water, flood management, energy production, and aesthetic value (Padedda et al., 2017). Unfortunately, eutrophication is an environmental issue that is responsible for the degradation of these systems (Padedda et al., 2017). An abundance of nutrients leads to excessive growth of phytoplankton, which result in algal blooms that are harmful to the ecosystem (Yang, Wu, Hao, & He, 2008). Eutrophication can be caused by surface runoff from precipitation that carry nutrients (external loading) into a reservoir (Yang, Wu, Hao, & He, 2008). Surface runoff is a seasonal process, greatly affected by the local climate, and human activity within the watershed. Human activities are responsible for increasing nutrients through the use of agricultural chemicals, land use change which increases impervious cover, and results in increased runoff (Phung et al., 2015). A more challenging concept of eutrophication comes from nutrients being introduced to a reservoir through internal loading. Internal loading is a process that occurs when nutrients, which have been transported to the bottom sediments associated with organic or inorganic particulates, are released back into the water column under a variety of conditions (Nikolai & Dzailowski., 2014). Reservoirs function as traps for sediment and essentially reflect the activities in the watershed (James, 2016).

Reservoirs, formed when rivers are dammed, change the characteristics of the river ecosystem in chemical, thermal, physical, and biological features (Chapman, 1996). Water released from the bottom of a deep reservoir will be cooler when the reservoir is stratified for the summer and warmer during the rest of the year (McCully, 2001). The density of the inflow usually differs from the density of the reservoir’s water and that dictates whether density currents will enter the epilimnion, metalimnion, or hypolimnion (Ford, & Johnson, 1983). The inflows displace the water ahead of it and cause instability in the water column which impacts water quality (Ford, & Johnson, 1983).

Seasonal variations in precipitation, surface runoff, inflows and outflows, all have a significant effect on a reservoir's eutrophication status (Singh, Malik, Mohan, & Sinha, 2004). Therefore, a regular monitoring program is essential for assessing water quality and providing information about the health and structure of aquatic systems. Multiple sampling stations within a reservoir assist in distinguishing where nutrients are more pronounced and long-term data can serve as a reliable source for identifying seasonal changes and trends over time (Singh, Malik, Mohan, & Sinha, 2004). The evaluation of data determines whether environmental control efforts are working or whether alterations in management practices are needed.

The Highland Lakes in central Texas, are monitored by the Lower Colorado River Authority (LCRA). LCRA monitors six reservoirs along the Colorado River, which includes Lake Lyndon B. Johnson (LBJ). The goal of this study is to determine the cause of eutrophication through analysis of a long-term data base of Lake LBJ, between the years 1982-2016. Preliminary examination of the data, as well as periodic Basin Summary Reports from LCRA, suggests that the LBJ reservoir has become significantly more eutrophic. Statistical techniques will be applied to data from six stations over the length of the reservoir, to evaluate spatial and temporal variations in nutrient transport and symptoms of eutrophication. Geographic Information System (GIS) will be used to determine land use change and population change in the immediate watershed. An assessment of the reservoir will detect chemical, biological, and physical factors that are be driving the eutrophication. The results should improve the current understanding of what is affecting water quality and contribute to ongoing efforts by regulatory and resource managers to guard and maintain the quality of the water in the Colorado River system.

2. METHODS

Study reservoir

LBJ is a subtropical reservoir, part of the Colorado River basin, in Texas (Fig. 1). The Colorado River is approximately 1,387 km in length and begins in Lamesa, Texas. The basin, which covers eight different level 3 EPA ecoregions (Mix, et al., 2016) moves in a southeasterly direction, and roughly mid-reach, forms the Highland Lakes series of reservoirs, that includes Lake LBJ. After passing through the Texas Hill Country, the Colorado River continues flowing southeast, until emptying into Matagorda Bay on the Gulf of Mexico. LBJ reservoir is 33 km long and has a surface area of 25.4 km^2. It begins where water is released from Inks Dam (headwaters) and ends at Alvin Wirtz Dam. The main outlet at the dam is at a bottom elevation of 241.91 m asl, leaving an area of 2.43×10^7 m below the outlet. The reservoir can be as narrow as 50 m near the headwaters, and gradually widens up to 1 km near Wirtz Dam (LCRA, 2011). LBJ is a pass-through lake and consequently remains at a nearly constant level (251.48 – 251.67 m asl).

LBJ reservoir receives most of its water from the two reservoirs directly upstream, Lake Buchanan and Inks Lake (Fig. 1). The reservoir has two major tributaries, the Llano River and Sandy Creek, which enter from the west. The Llano River comprises most of the local LBJ watershed (Fig. 2) and is significant because it provides spring-fed water from the Edwards-Trinity Aquifer, which helps dilute sediments when it merges with the main channel of LBJ (CRPP, 2012). The LBJ watershed is in a semi-arid environment with annual precipitation between 55 to 81 cm (LCRA, 2011). During the summer, the maximum monthly temperatures can reach 36°C and during winter, as low as 4°C. LBJ reservoir experiences annual increases of inflows during the summer, to provide water for irrigation downstream. The Llano River tributary has an unregulated inflow that increases during heavy rain events and decreases during droughts.

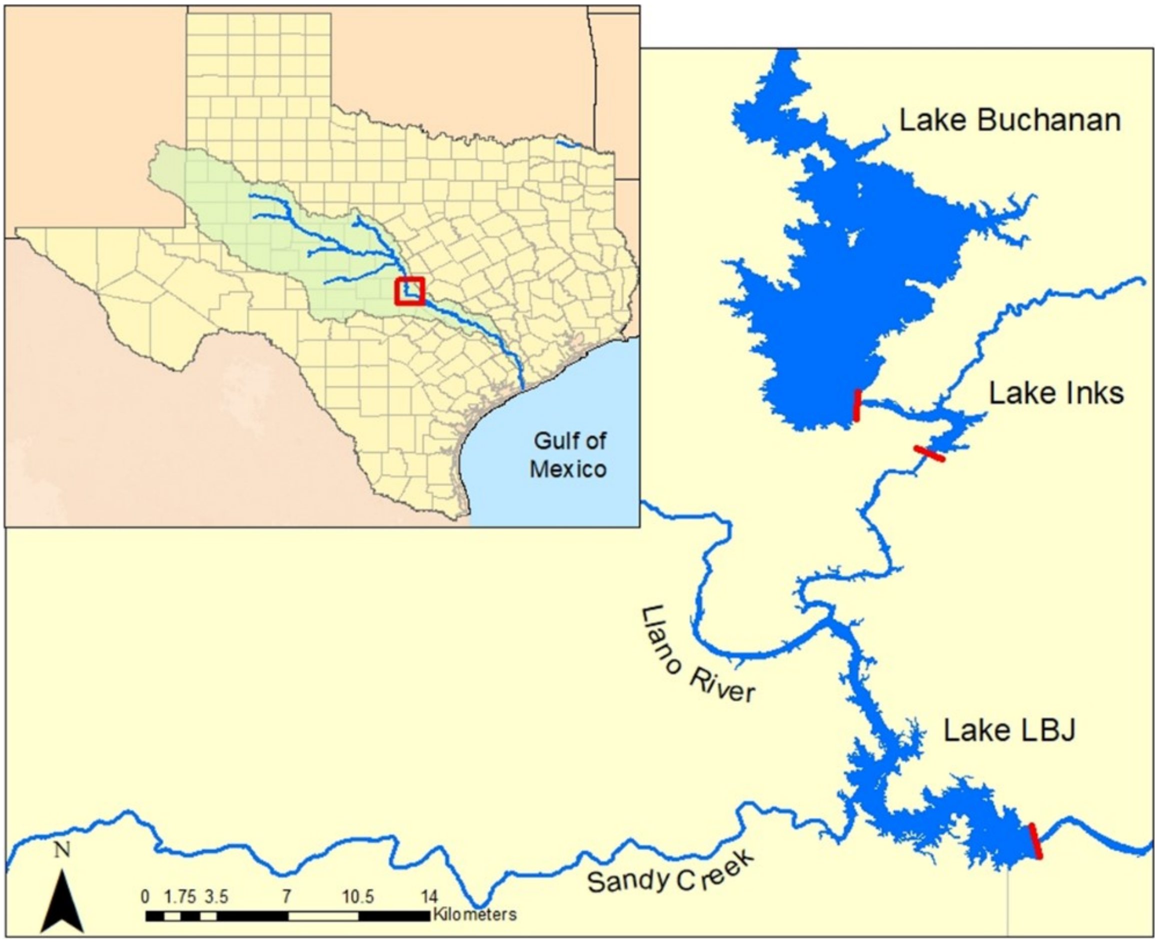

Figure 1. LBJ reservoir located within the Colorado River Basin, in the Hill Country, Central Texas.

The LBJ local watershed is mostly rural, with shrubs, grassland, and forest making up most of the land cover (LCRA, 2011). Less than 1% of the watershed is developed (Table 1) however, there has been a lot of development directly around the reservoir (LCRA, 2011). Kingsland (population about 6,030), Granite Shoals (population about 4,910), and Horseshoe Bay (population about 3,418) are the three major communities surrounding LBJ (Fig. 3). The reservoir is used to generate hydroelectric power, manage floods, provide water for irrigation, industrial and domestic use, and recreation. Growing communities around the reservoir represent a potential risk for delivering urban pollution during runoff and impact water quality with little mitigation through the watershed (LCRA, 2011). To maintain the water quality of the Highland Lakes, a regulation was implemented in 1986 to help prevent new point-source pollution. The new regulation prohibited the discharge of wastewater from treatment plants into the Highland Lakes or their tributaries (LCRA, 2011). There are however, eight permitted point sources in the watershed. Two of those are wastewater facilities located along the reservoir, in Kingsland and Granite Shoals. The two facilities have a permitted flow (Table 2) and the effluent can be a contributing factor of eutrophication. LCRA also established the On-Site Sewage Ordinance, to regulate the installation and operation of septic systems. Many houses around the reservoir still use septic systems that could have been installed many years ago. A septic system can fail and cause untreated sewage to be released and flow into the reservoir. To protect the lakes from non-point sources, the Highland Lake Watershed Ordinance (HLWO) went into effect in 2006 (LCRA, 2011). The ordinance manages stormwater runoff by requiring developers to stabilize land and minimize sediment migration (CRPP, 2012). Even with regulations, the reservoir has been impacted by urbanization around the lake. What were once small vacation homes along LBJ Lake, have grown to small cities with infrastructures for people living there year-round.

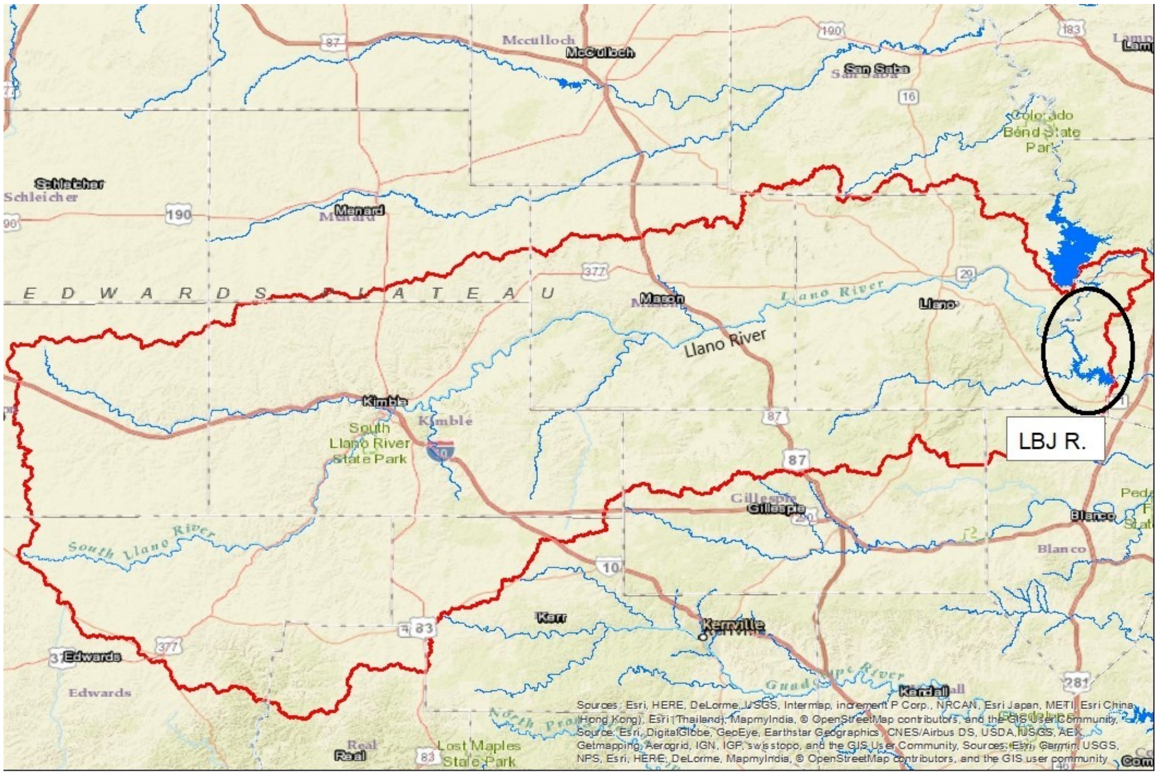

Figure 2. Local watershed of LBJ reservoir.

Table 1. Local watershed land cover for LBJ reservoir

Name	Total Watershed Area (%)
Open Water	0.30
Developed	0.86
Barren land	0.01
Deciduous forest	5.53
Evergreen forest	12.83
Mixed forest	0.01
Scrub/Shrub	70.96
Grassland	8.94
Pasture/hay	0.28
Cultivated crops	0.27
Woody wetlands	0.01

Table 2. Permitted discharge flow and concentrations in LBJ reservoir.

Permittee	Permitted flow (MGD)	Avg. flow (MGD)	TSS (mg/L)	TP (mg/L)	NH_3 (mg/L)
Lake LBJ MUD	1.5	0.0[a]	10	3.2	2
AquaSource Utilities	0.03	0.02	1.9[b]	1.0[b]	2
Kingsland MUD	0.75	0.31	3.5[c]	1.1[c]	2

Notes:

[a] Land application- no direct discharge

[b] Average of self-reported monthly average concentrations for Aquasource Utilities for the period April 2000 to December 2008

[c] Average of self-reported monthly average concentrations for Kingsland MUD for the period February 1998 to December 2008

Table information obtained from LCRA CREMS report, 2011.

Sampling and analysis

Water quality data of the reservoir, during the period of this study, was obtained from the LCRA monitoring program data base. Chemical and biological data at each station were collected at the surface and near-bottom (1 m from the bottom) as well as vertical profiles with a multiprobe sonde system, and analyzed according to the guidelines of the Quality Assurance Project Plan (QAPP, 2013). The data set for this study is comprised of nineteen water quality variables (Table 4), from six different stations (Fig. 3) along the thalweg, or river channel. The location of the stations were in key areas, to account for determinants that alter water quality, such as tributary inputs. Station S1 is located near the dam, which is also the deepest part of the reservoir and close to the city of Horseshoe Bay. Station S4 is in the Llano River tributary and is also found near a major city. Downstream of where the Llano River merges with the LBJ main channel, is another monitoring station. Each station varies in depth (Table 3) and location, as a result, may experience differences in hydrodynamics.

Table 3. Stations throughout the LBJ reservoir with descriptors, depth, and distance from Wirtz Dam.

LBJ Station	**River km up from dam**	**Depth (m)**	**Descriptor**
S1	0.1	21.9	Dam
S2	6.1	12.2	Confluence Sandy Ck
S3	20.6	8.8	Confluence Llano R.
S4[a]	19.8	3.7	Llano arm
S5	23.8	10.1	Kingsland Cove
S6[b]	35.1	3.7	Headwaters

[a] - the Llano River arm enters LBJ 19.8 km from the dam, site 4 is 2.1 km upstream from the Colorado River thalweg

[b] - station 6 is also 0.57 km downstream of the Inks Dam

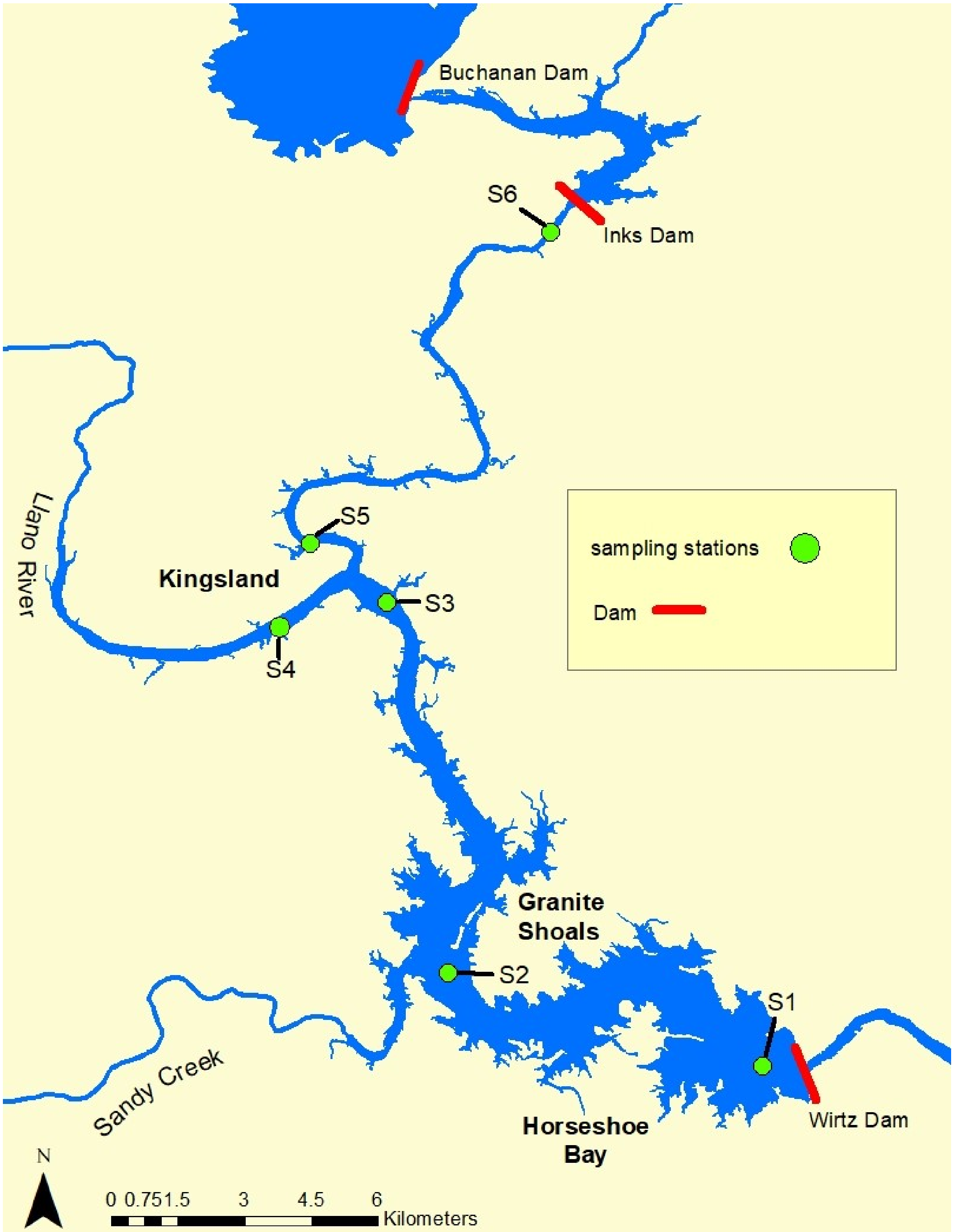

Figure 3. LBJ reservoir water quality sampling stations and dams.

Table 4. Analyzed water quality variables and the corresponding units.

Variables	**Abbreviations**	**Unit**
Specific conductance	Sp. Cond.	ms/cm
Temperature	Temp	°C
Dissolved oxygen	DO	mg/L
Dissolved oxygen saturation	Do sat	%
pH	pH	
Alkalinity	Alk	meq/L
Chloride	Cl	meq/L
Sulfate	SO_4	meq/L
Sulfate: chloride	SO_4:Chl	
Total suspended solids	TSS	mg/L
Total organic carbon	TOC	mg/L
Nitrate+nitrite nitrogen	NO_3N	mg/L
Ammonium- nitrogen	NH_4	mg/L
Total kjeldahl nitrogen	TKN	mg/L
Soluble reactive phosphorus	SRP	mg/L
Total phosphorus	TP	mg/L
Chlorophyll a	Chl α	ug/L
Total nitrogen	TN	mg/L
Total nitrogen: total phosphorus	TNTP	

Statistical analysis methods

The water quality data for this study was obtained from LCRA and had to be reorganized in Excel for this study. Each monitoring station was split into different files that had varying starting dates for the monitoring period. The first sample date that all stations had in 1982 was used as the starting date and the last date in 2016 that all stations shared, was used as the ending date. Each station was then broken down into surface and bottom water quality data. Surface data for each station was created by combining the variables in the shallowest depth for each sampling date. The bottom data for each station was created by combining the variables in the deepest depth for each sampling date.

Sampling was done on a monthly basis, then switched to bi-monthly around 1986, making a complete set during even months (Feb, Apr, Jun, Aug, Oct, and Dec) for the 34-year record. In analyses where data might be skewed, as a result from this sampling change, only used even months were used. Not all stations were sampled for all variables, for examples, stations S4 and S5 did not have data for alkalinity. If no data were available for a particular variable, statistical techniques were not performed on that variable. In addition, some variables had data missing for some dates due to bad weather or samples for the specific variable stopped being collected. If a variable had less than one-third of the total samples missing, it was not used for analysis.

Analysis of the water quality data set was performed using Pearson correlation, cluster analysis (CA), and trend analysis through graphs (boxplots and line graphs). All statistical computations were performed using IBM SPSS statistical software. GIS ArcMap and remote sensing applications where used to find the extent of changes in population, as well as land use change in the watershed.

CA is a multivariate statistical technique used for finding groups of cases based on similarities. Hierarchical clustering combines clusters chronologically, reducing the number of clusters until only one is left (Roy, Kar, & Das, 2015). The clusters are connected at increasing levels of dissimilarities (Roy, Kar, & Das, 2015), revealing patterns that may not previously been known. The groups are illustrated by a dendrogram (tree diagram), which provides a visual summary of clusters and their proximity (Bhat, Meraj, Yaseen, & Pandit, 2013). Hierarchical CA was applied on the standardized data set (mean of variables over the whole period) for surface and bottom stations, using the Ward's method with squared Euclidean distances (Singh, Malik, Mohan, & Sinha, 2004). This technique was applied in an effort to group similar sampling sites (spatial variability) spaced longitudinally over the reservoir. If stations were grouped together, that would mean that they share chemical or physical characteristics. Stations S4-S6 had limited variables available. In an effort to maximize the amount of stations used for the analysis, only five variables were used (temperature, specific conductance, dissolved oxygen, dissolved oxygen saturation, and pH).

Pearson correlation coefficient (r) is used for detecting the linear relationship between two variables and quantifies the strength of the relationship. The product will provide an r value to convey the strength of the relationship. The r value lies between -1, which indicates a strong negative linear relationship, and +1, which indicates a strong positive linear relationship (Bewick, Cheek, & Ball, 2003). A value close to 0 indicates no relationship or a nonlinear relationship may exist (Bewick, Cheek, & Ball, 2003). Pearson correlation coefficient at a 0.05% level of significance ($P<0.05$), was applied to variables at the surface and bottom data, as a preliminary assessment to identify any unknown relationships.

Remote sensing with GIS, is used to classify and map changes in land cover and land use changes, through multiple techniques (Butt, Shabbir, Ahmed, & Aziz, 2015). Landsat images are used for classification of different landscapes at large scales (Butt, Shabbir, Ahmed, & Aziz, 2015). In order to study the land use change in the immediate watershed, satellite images were acquired for 1984, 1998, and 2016 from United States Geological Survey (USGS). The year 1984 was selected instead of 1994 because there were no satellite images available earlier than 1983. Each image was classified using the unsupervised classification method, to give each pixel a unique value, representing a desired land cover type (water, grass/shrubs, developed, and forest). The pixels were then tabulated with the corresponding cover type for each year used.

GIS in conjunction with census data, was used to calculate population change in the immediate LBJ watershed. Shapefiles for the state and counties of Texas were obtained from the Texas Water Development Board (TWDB) and Texas Department of Transportation (TDT). Census data tables and mapping files were acquired for 1990, 2000, and 2016, from the National Historical Geographic Information System (NHGIS). Llano and Burnett county census data was used for this study because the reservoir is found between the two counties. The census data for each year was mapped and cropped to only include the area surrounding the reservoir.

3. RESULTS AND DISCUSSION

Water quality evaluation

The inflows from Inks reservoir, which accounted for most of the total inflows, show a seasonal variation (Fig. 4), with higher inflows between May and September, due to historical patterns of summer release below Austin for downstream rice cultivation. The Llano River inflow (Fig. 5) is generally lower in the summer except when there are heavy rain events, indicated by outliers. When the upstream reservoir is stratified and water is released from the bottom, the water being released is cold and that can modify the thermal structure and chemical gradients downstream (Chapman, 1996). Inflows not only effect the stability of the water column, but they carry solids, nutrients, bacteria and other pollutants that may alter the water quality (Ford, & Johnson, 1983).

The mean and standard deviations were calculated for the water quality variables at all six stations (surface and bottom) of the reservoir for the years 1982-2016 (Table 5 and 6). The mean concentration of dissolved oxygen (DO) at S1 was very low at the bottom (2.96 mg/L), due to the seasonal anoxia associated with stratification. The water released at Wirtz Dam is not discharged from the very bottom, which leaves a large volume of dead space when the reservoir is stratified (Fig. 6). It is important to note that the bottom of Station S1 also had high concentrations of ammonium (NH_4-N), total phosphorus (TP), and total nitrogen (TN) late in the stratified period.

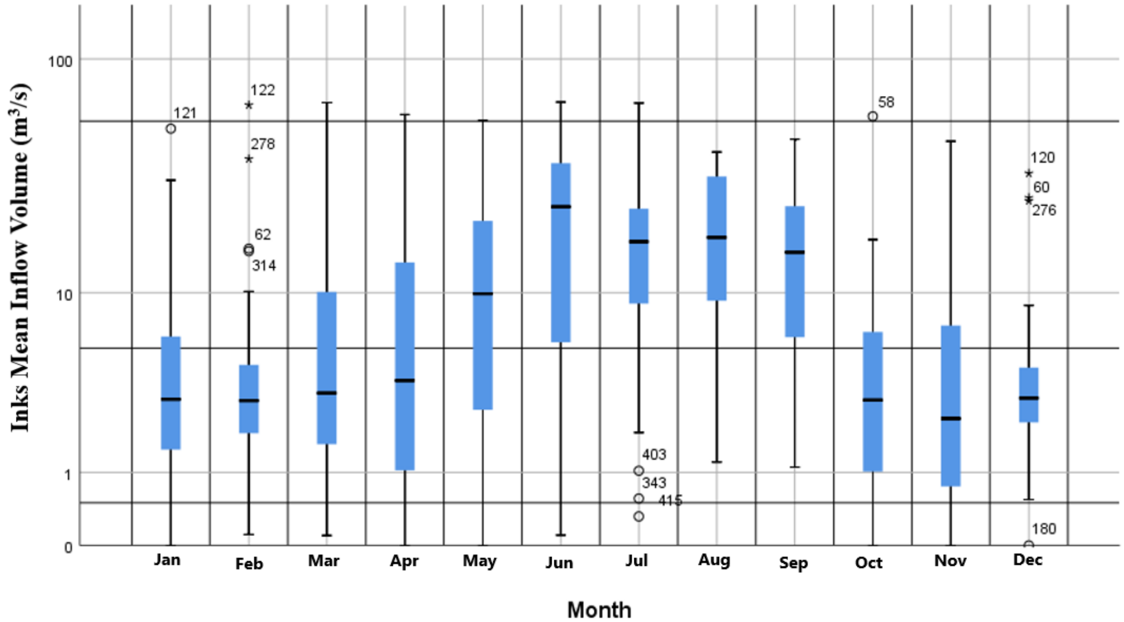

Figure 4. Mean inflow from Inks Dam (turbine).

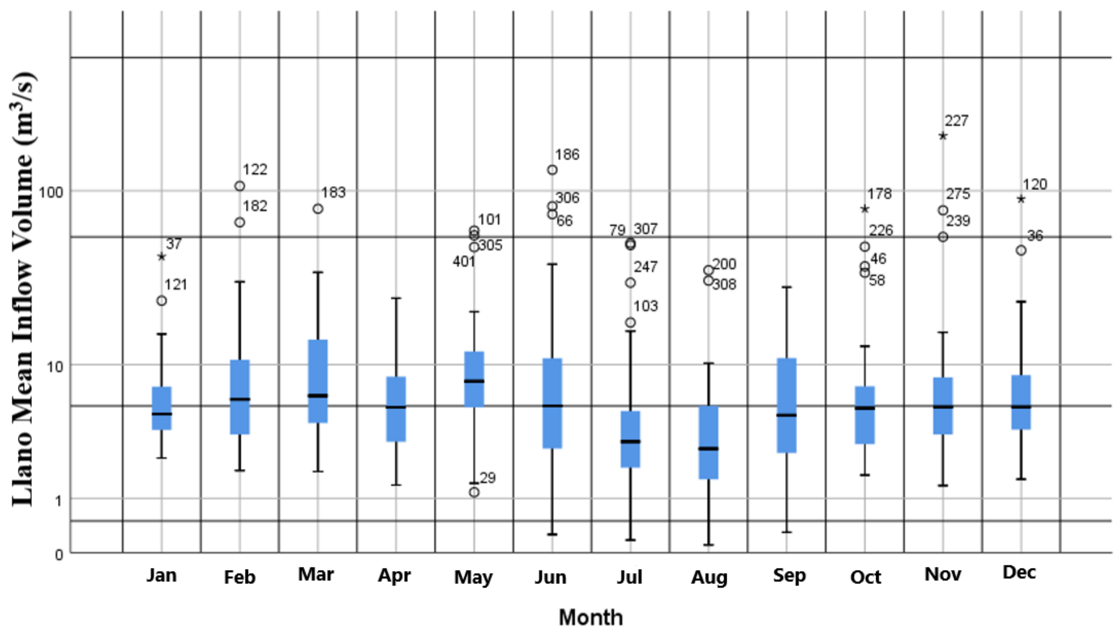

Figure 5. Mean inflow from Llano River.

Table 5. Mean values with (standard deviations) of key water quality variables at the surface of LBJ reservoir during 1982-2016. (*) Indicates variable not collected at the station or depth.

Variable	Station S1	Station S2	Station S3	Station S4	Station S5	Station S6
Sp. Cond. (µS/cm)	550 (172)	544 (164)	523 (138)	423 (64)	571 (176)	691 (277)
Temp. (°C)	21.22 (6.56)	21.41 (6.97)	21.57 (7.01)	21.70 (7.24)	21.78 (6.79)	19.94 (5.97)
DO (mg/L)	8.00 (1.79)	8.35 (1.55)	8.46 (1.44)	8.60 (1.58)	8.68 (1.42)	7.50 (2.56)
DO Sat. (%)	88.77 (14.86)	93.08 (10.88)	94.92 (10.65)	96.22 (9.12)	98.00 (13.56	80.46 (23.08)
pH	8.13 (0.25)	8.20 (0.21)	8.22 (0.19)	8.27 (0.19)	8.25 (0.22)	8.00 (0.32)
Alk (meq/L)	2.93 (0.28)	2.94 (0.27)	3.00 (0.28)	*	*	2.83 (0.23)
Cl (meq/L)	1.75 (1.10)	1.70 (1.05)	1.50 (0.86)	*	*	2.64 (1.71)
SO_4 (meq/L)	0.82 (0.62)	0.79 (0.58)	0.70 (0.48)	*	*	1.27 (1.00)
SO_4:Cl	0.46 (0.10)	0.45 (0.08)	0.70 (0.48)	*	*	0.46 (0.08)
TSS (mg/L)	5.09 (3.40)	7.11 (6.05)	7.97 (5.02)	*	*	5.52 (2.55)
TOC (mg/L)	4.06 (1.87)	3.99 (1.05)	3.80 (1.09)	*	*	4.35 (0.85)
NO3-N (mg/L)	0.10 (0.17)	0.09 (0.15)	0.10 (0.21)	*	*	0.06 (0.10)
NH_4 -N (mg/L)	0.04 (0.06)	0.03 (0.05)	0.03 (0.04)	*	*	0.05 (0.08)
TKN (mg/L)	0.53 (0.36)	0.59 (0.35)	0.55 (0.28)	*	*	0.64 (0.33)
SRP (mg/L)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	*	*	0.01 (0.01)
TP (mg/L)	0.04 (0.12)	0.04 (0.07)	0.03 (0.05)	*	*	0.04 (0.06)
Chl a (ug/L)	8.00 (7.18)	9.26 (7.01)	10.68 (8.15)	*	*	10.36 (13.33)
TN (mg/L)	0.63 (0.39)	0.67 (0.38)	0.65 (0.35)	*	*	0.71 (0.34)
TN:TP	96.75 (96.85)	95.88 (93.37)	87.52 (93.72)	*	*	89.41 (92.10)

Table 6. Mean values with (standard deviations) of key water quality variables at the bottom of LBJ reservoir during 1982-2016. (*) Indicates variable not collected at that station or depth.

Variable	Station S1	Station S2	Station S3	Station S4	Station S5	Station S6
Sp. Cond. (μS/cm)	586 (176)	575 (196)	573 (202)	487 (173)	644 (249)	*
Temp. (°C)	16.11 (4.10)	18.91 (6.06)	20.21 (6.52)	20.24 (6.98)	19.25 (5.87)	*
DO (mg/L)	2.96 (3.38)	4.18 (3.50)	5.73 (3.02)	5.65 (3.62)	4.48 (3.30)	*
DO Sat. (%)	28.01 (31.36)	41.41 (32.54)	60.18 (27.38)	57.89 (32.83)	45.33 (30.70)	*
pH	7.42 (0.42)	7.66 (0.36)	7.89 (0.29)	7.90 (0.37)	7.72 (0.32)	*
Alk (meq/L)	3.16 (0.47)	3.00 (0.26)	3.00 (0.27)	*	*	*
Cl (meq/L)	1.77 (1.13)	1.78 (1.12)	1.63 (1.05)	*	*	*
SO_4 (meq/L)	0.78 (0.66)	0.82 (0.63)	0.77 (0.59)	*	*	*
SO_4:Cl	0.41 (0.14)	0.45 (0.09)	0.46 (0.08)	*	*	*
TSS (mg/L)	8.70 (7.65)	11.71 (7.88)	14.81 (16.53)	*	*	*
TOC (mg/L)	3.97 (0.98)	3.92 (0.87)	3.85 (1.08)	*	*	*
NO3-N (mg/L)	0.13 (0.18)	0.10 (0.15)	0.10 (0.16)	*	*	*
NH_4-N (mg/L)	0.53 (0.98)	0.10 (0.15)	0.05 (0.08)	*	*	*
TKN (mg/L)	1.07 (1.10)	0.64 (0.33)	0.61 (0.45)	*	*	*
SRP (mg/L)	0.05 (0.09)	0.01 (0.01)	0.01 (0.01)	*	*	*
TP (mg/L)	0.12 (0.24)	0.05 (0.11)	0.04 (0.04)	*	*	*
Chl a (ug/L)	3.90 (2.55)	5.96 (3.71)	*	*	*	*
TN (mg/L)	1.20 (1.07)	0.73 (0.35)	0.71 (0.51)	*	*	*
TN:TP	79.79 (97.94)	79.60 (75.63)	78.99 (115.65)	*	*	*

Figure 6. Cross section of LBJ reservoir.

Internal loading is the process where nutrient concentrations increase in the hypolimnion during summer stratification (Nurnberg, 2009). When reservoirs stratify during the summer, it splits the system into an epilimnion and hypolimnion that is divided by a thermocline, which separates nutrients cycling processes spatially and vertically (James, 2016). Patterns of DO at the bottom of S1 showed seasonal anoxia typically every year (Fig. 7). There are also seasonal high concentrations of TP, TN, and NH_4-N (Fig. 8-10), that are not seen at the surface. The release of these nutrients are clearly occurring at the sediment-water interface (SWI), and there is a strong relationship between these increasing nutrients and decreasing redox potential as reflected in the decreasing sulfate:chloride (SO_4:Cl). Sediments have different chemical composition and content such as, aluminum, calcium, and other elements with the capacity to bind and release phosphorus (P) at the SWI (Sondergaard, Jensen, & Jeppesen, 2003). Limestone surrounds the watershed and provides calcium rich water, therefore, the release of P can be associated with the dissolution of calcium-bound P at the onset of anoxia. The amount of sediment released P is influenced by the duration and extent of the anoxia area, which was demonstrated by seasonal patterns of DO and TP.

There was a correlation between total organic carbon (TOC) and TN ($r = 0.498$, $P < 0.01$), suggesting that the TN concentration is strongly influenced by organic sources (Hou et al., 2013). When algae die and decompose, nutrients that had been taken up during growth are released into the water (DePinto, & Verhoff, 1977). Nitrogen cycling is linked to the oxygen status of overlaying water and during oxic conditions, oxygen at the SWI promotes the oxidation of organic matter (Beutel, 2016). When the reservoir is oxygenated, the liberated NH_4-N is oxidized into nitrogen gas (N_2) or nitrate (NO_{3-}). The nitrate-nitrogen (NO_3-N) at the bottom decreases during June-October, the months when NH_4-N increases, indicating a decrease in redox potential. When the reservoir is anoxic at the bottom, these mechanisms cannot take place and NH_4-N from the decay of organic matter diffuses into the water column (Beutel, 2016). This indicates that during summer stratification high concentrations of NH_4-N are being diffused from alga decay under anoxic conditions. Algal decay is also another source for internal loading of P, which is also taken up during algal growth. There was a significant trend over time ($P<0.01$) among TP, TN, NH4, and TOC, at the bottom of S1, indicating that the effects of internal loading are increasing over time.

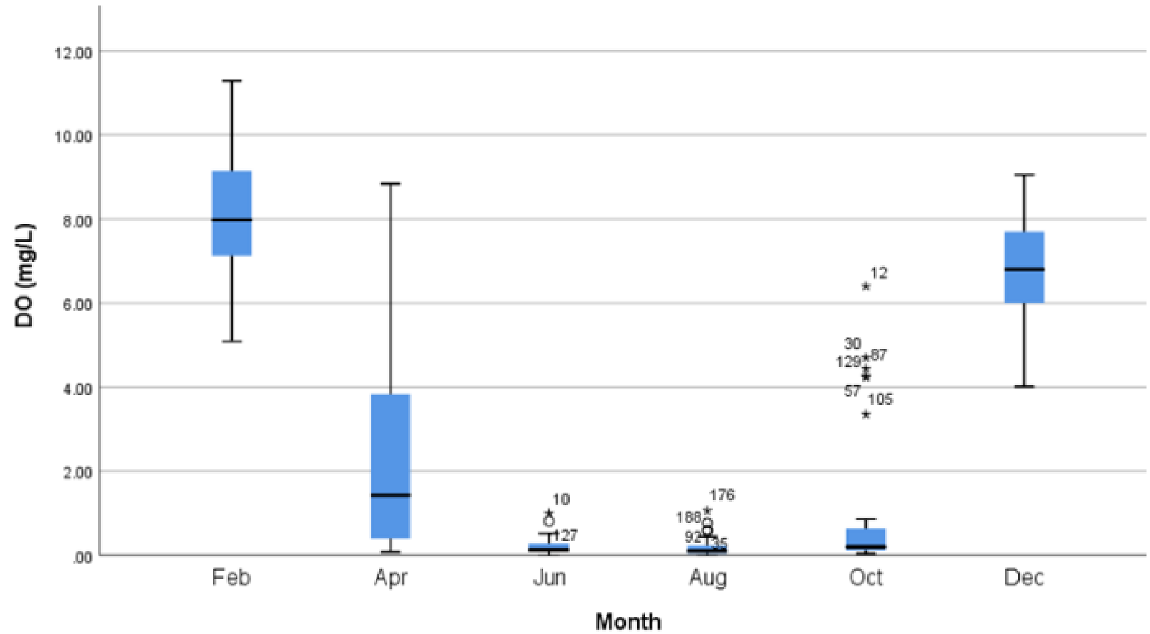

Figure 7. Mean dissolved oxygen concentrations by month at the bottom of station S1.

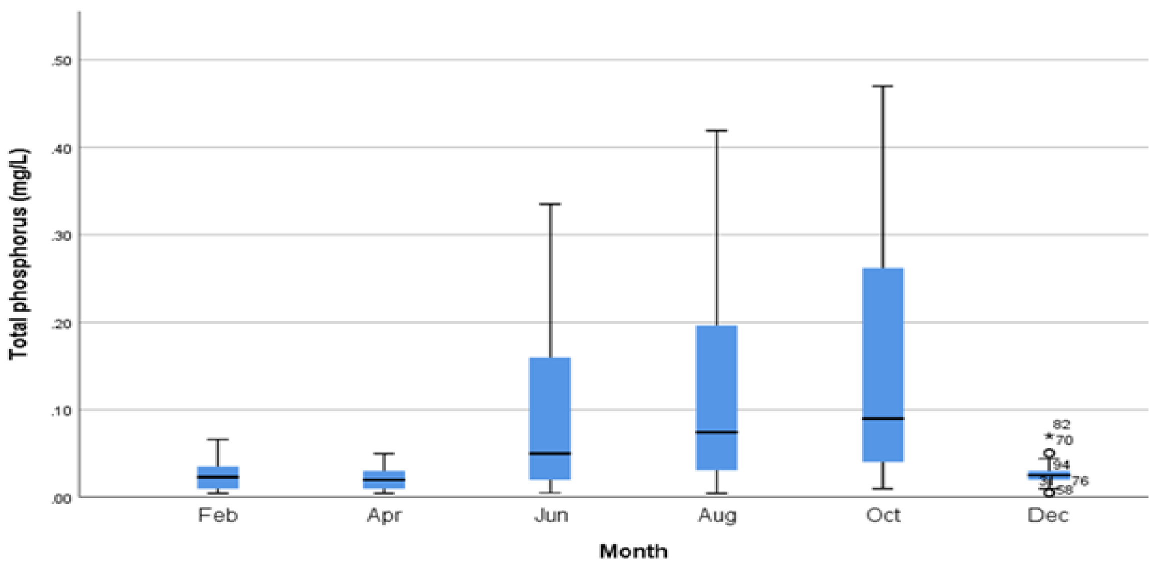

Figure 8. Mean total phosphorus concentrations by month at the bottom of station S1.

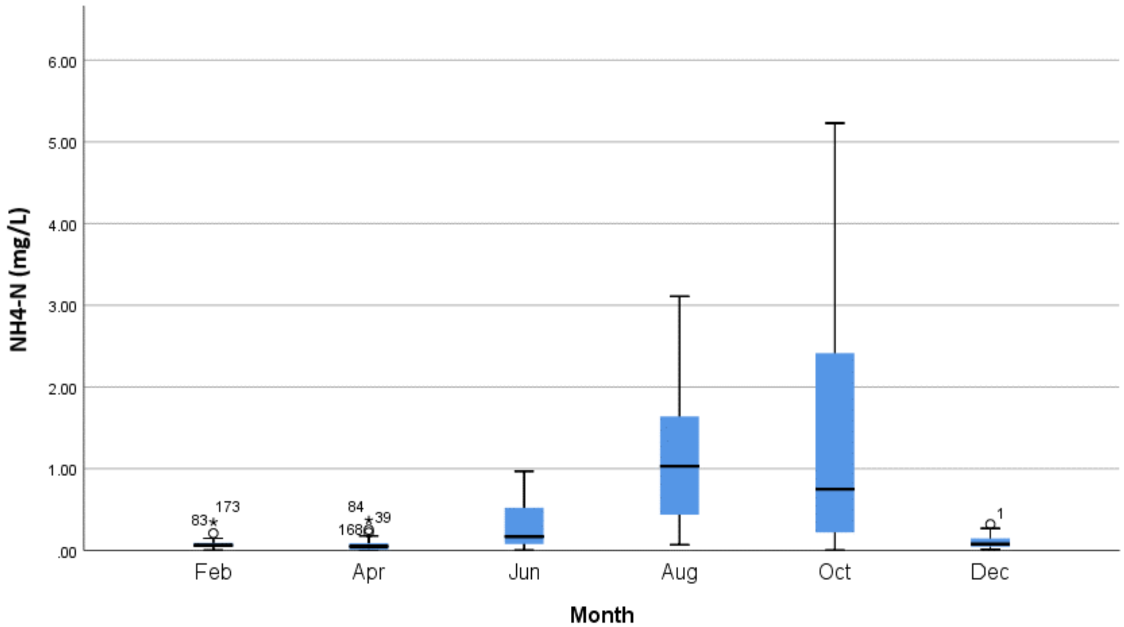

Figure 9. Mean concentration of ammonium at the bottom of station S1.

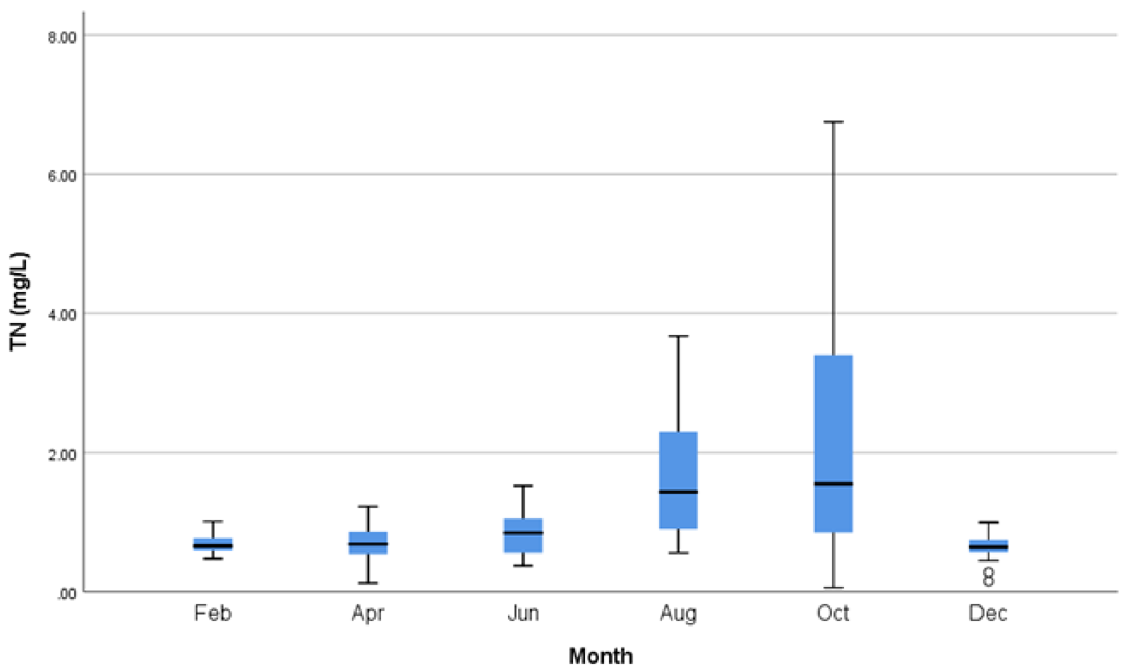

Figure 10. Mean total nitrogen concentration by month at bottom of station S1.

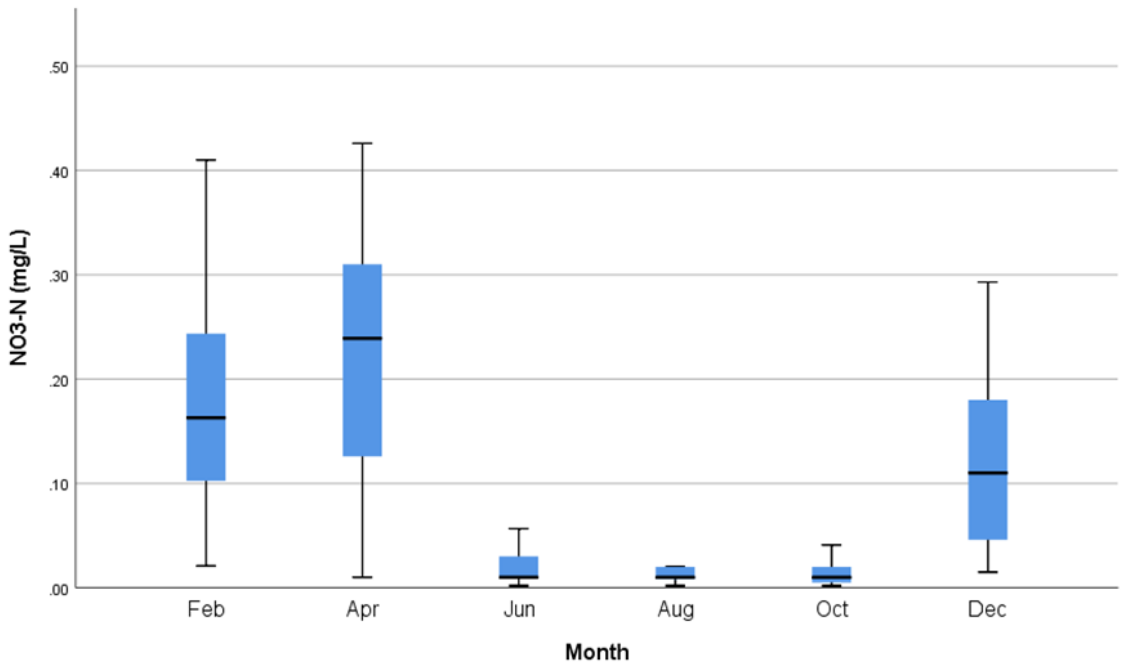

Figure 11. Mean concentration of nitrate-nitrogen at the bottom of station S1.

Table 7. The Pearson correlation coefficients between date, TP, TN, TOC, NH_4-N, and pH for station S1 (bottom). (*) indicates significant at P<0.01

	Date	TP	TN	TOC	NH_4-N	pH
Date	1	0.370*	0.269*	0.381*	0.348*	0.007
TP	0.370*	1	0.0730*	0.730*	0.800*	-0.349*
TN	0.269*	0.730*	1	0.498*	0.914*	-0.463*
TOC	0.381*	0.399*	0.498*	1	0.487*	-0.206*
NH_4-N	0.348*	0.800*	0.914*	0.487*	1	-0.498*
pH	0.007	-0.349*	-0.463*	-0.206*	-0.498*	1

Spatial and temporal analysis

CA analysis rendered a dendrogram with four clusters for the surface (Fig. 12) and three for the bottom stations (Fig. 13). The clusters throughout the reservoir (Fig. 14) were grouped into distinct zones based on the water column stability. Station S6 was the most dissimilar of the stations. This station is close to the water coming in from Inks Lake, a small reservoir with little retention time. The water further upstream comes from the Buchanan reservoir which discharges water from the bottom. During summer stratification the water coming in is cold and low in DO, indicated by the low mean values. Stations S2 and S5 are found in the middle of the reservoir and have similar shallow depths (Table 3). Both of these stations had water columns with characteristics of easily disturbed water columns by enhanced flows. Station S5 is susceptible to mixing when there are high inflows from the upstream reservoirs during the summer. The cold water with low DO comes into LBJ as an underflow, and as a result will have slightly lower temperatures at the bottom. During the rest of the year, the water comes in as overflow with high turbidity and results in high specific conductance. Station S2 is also susceptible to mixing when there are high inflows from Sandy Creek. Station S3 and S4 were clustered together and represented the Llano River influenced zone. The water from the Llano River is in pristine condition, lower in specific conductance, and warmer because the river is shallow. When the river merges with the main channel of LBJ, this decreases specific conductance and increases temperature at the surface and bottom. Station S1 was very different from the other stations at the bottom because it had very low DO values. During summer stratification, anoxia is formed almost every year in the hypolimnion because the water column is protected by high inflows and water is released at a mid-depth. Since warm water inflows did not affect the surface, the temperature was higher than the upstream station.

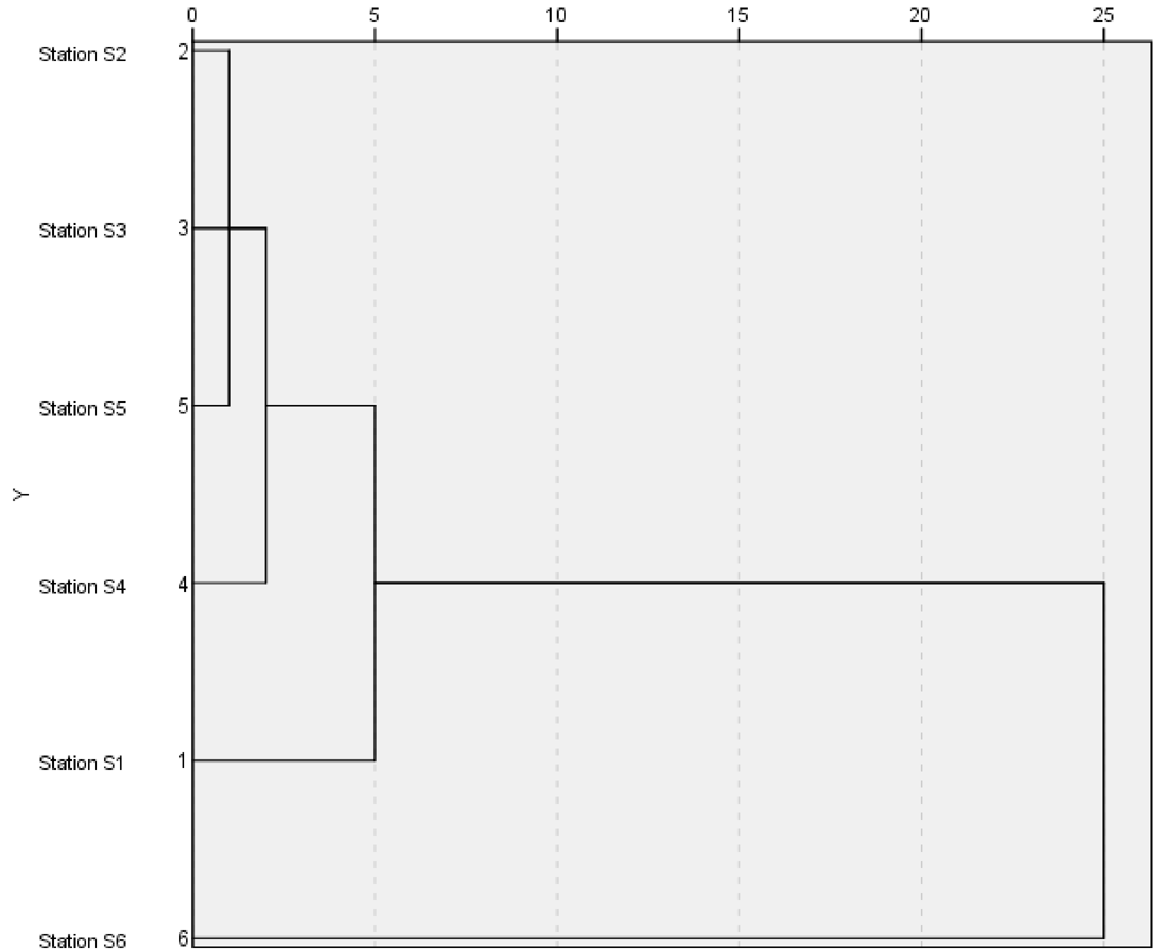

Figure 12. Dendrogram clusters for the surface of LBJ reservoir.

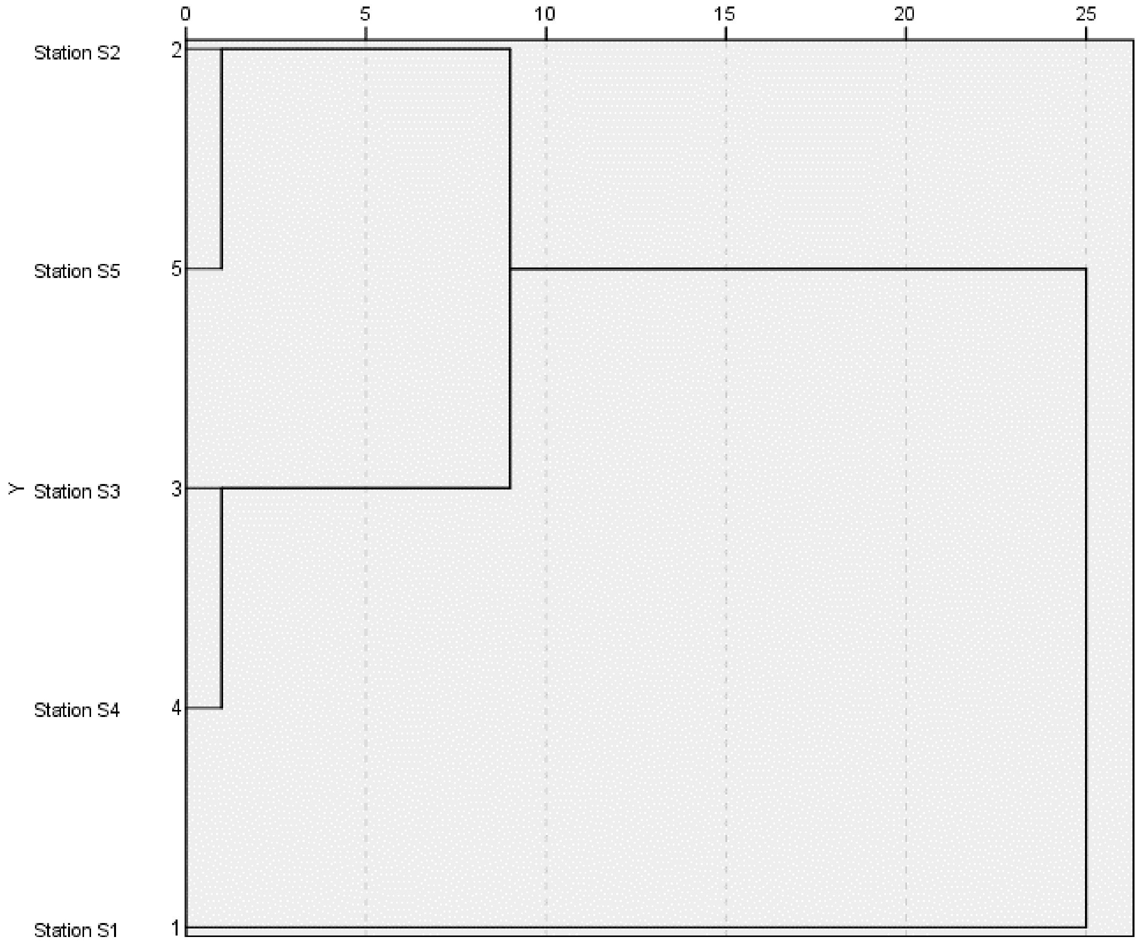

Figure 13. Dendrogram clusters for the Bottom of LBJ reservoir.

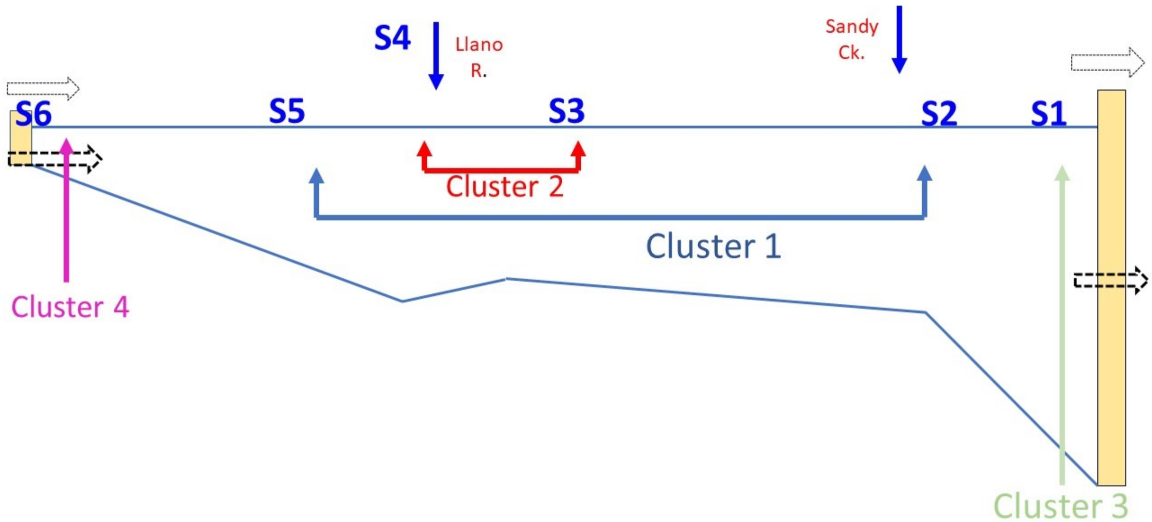

Figure 14. Longitudinal cross section of LBJ reservoir with clusters from CA results.

Land use/ population change

The land use and population change around the LBJ reservoir were analyzed using GIS ArcMap. Four types of cover (developed, forest, grass/shrubs, water) were used for classification of land around the reservoir (Fig. 15). The years for the classification period were 1984, 1998, and 2016. Developed land around the reservoir covered an area of 52.13 km^2 in 1984, 57.76 km^2 in 1998, and 64.16 km^2 in 2016. That is a 1.93% increase between the first two periods. This could be attributed to a construction boom in the early 1990's, that resulted in more houses being built around the lake. Development appears to be pronounced at the north side of the lake, below the Inks Dam and in Kingsland. Between 1998 to 2016, there was a 2.19% increase in developed land, or a total increase of 4.12% between 1984 to 2016.

Census data from 1990, 2000, and 2016, showed a change that coincides with the increase in developed land. The population has increased around the three major cities

(Kingsland, Granite Shoals, Horseshoe Bay) surrounding the reservoir (Fig. 16). Although there was urbanization in the early 1990's, the houses that were built around the lake served mostly as vacation homes (Fig. 17). Throughout the years however, more people have chosen to live there year-round, and communities continue to expand. The present communities, as well as continued development, could have significant effects on runoff. An increase in impervious cover can generate a substantial amount of runoff, even from small rain events (Engel, Ahiablame, & Leroy, 2015). Considering that there are mostly houses around the reservoir, runoff could be a significant source of sediments and nutrients.

There was a significant positive trend over time ($P < 0.01$) for TOC and chlorophyll α at all surface stations (with the exception of S4 and S5 which did not have enough data). These trends confirm that, throughout the longitudinal length of the reservoir, eutrophication has increased over time. Water quality from the Llano River and Sandy Creek is in excellent condition because the watershed is practically undisturbed by human activity. Therefore, nutrients are likely coming from the upstream reservoirs and local communities from surface runoff. Higher nutrients from the upstream reservoirs is indicated by the increase over time in NH4-N and TP, during August months in Inks reservoir (Fig. 18). The nutrients coming from localized urbanization could not be quantified but there are indications that there is a heavy use of fertilizers. In addition, recently in 2020, a leaking pipe was discovered from the wastewater facility in Kingsland. It is unknown how long this pipe had been leaking but it presents another potential source of nutrients. A nutrient budget would be beneficial, to quantify concentration of nutrients coming from the upstream and determine what is coming directly from communities around the reservoir.

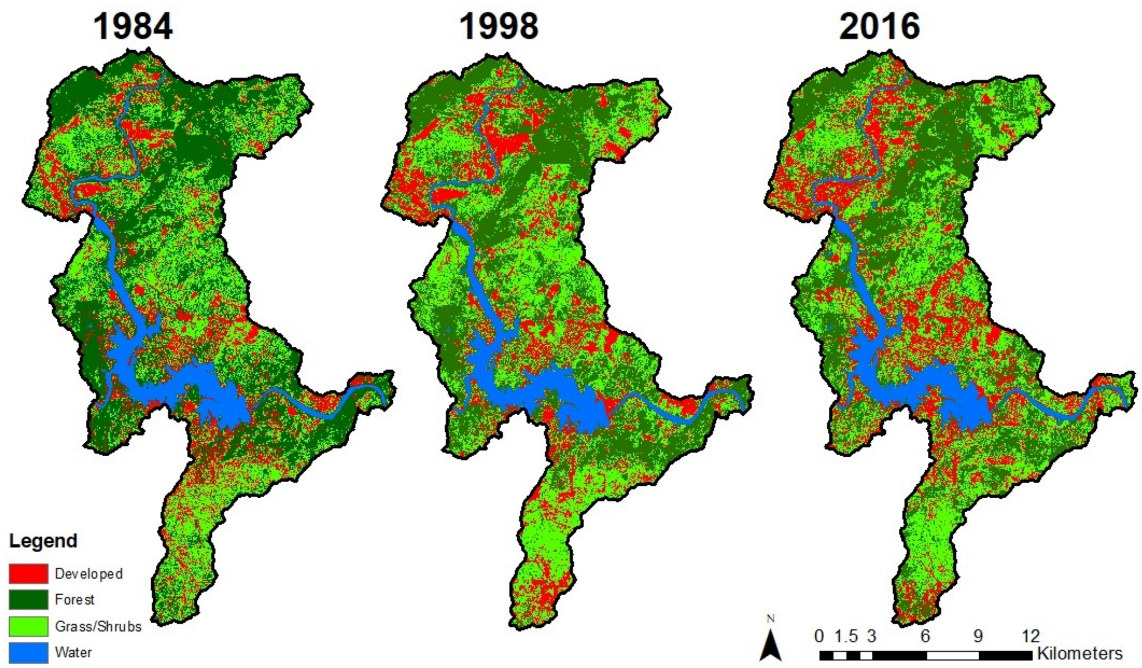

Figure 15. Land use change around LBJ reservoir between 1984, 1998, and 2016.

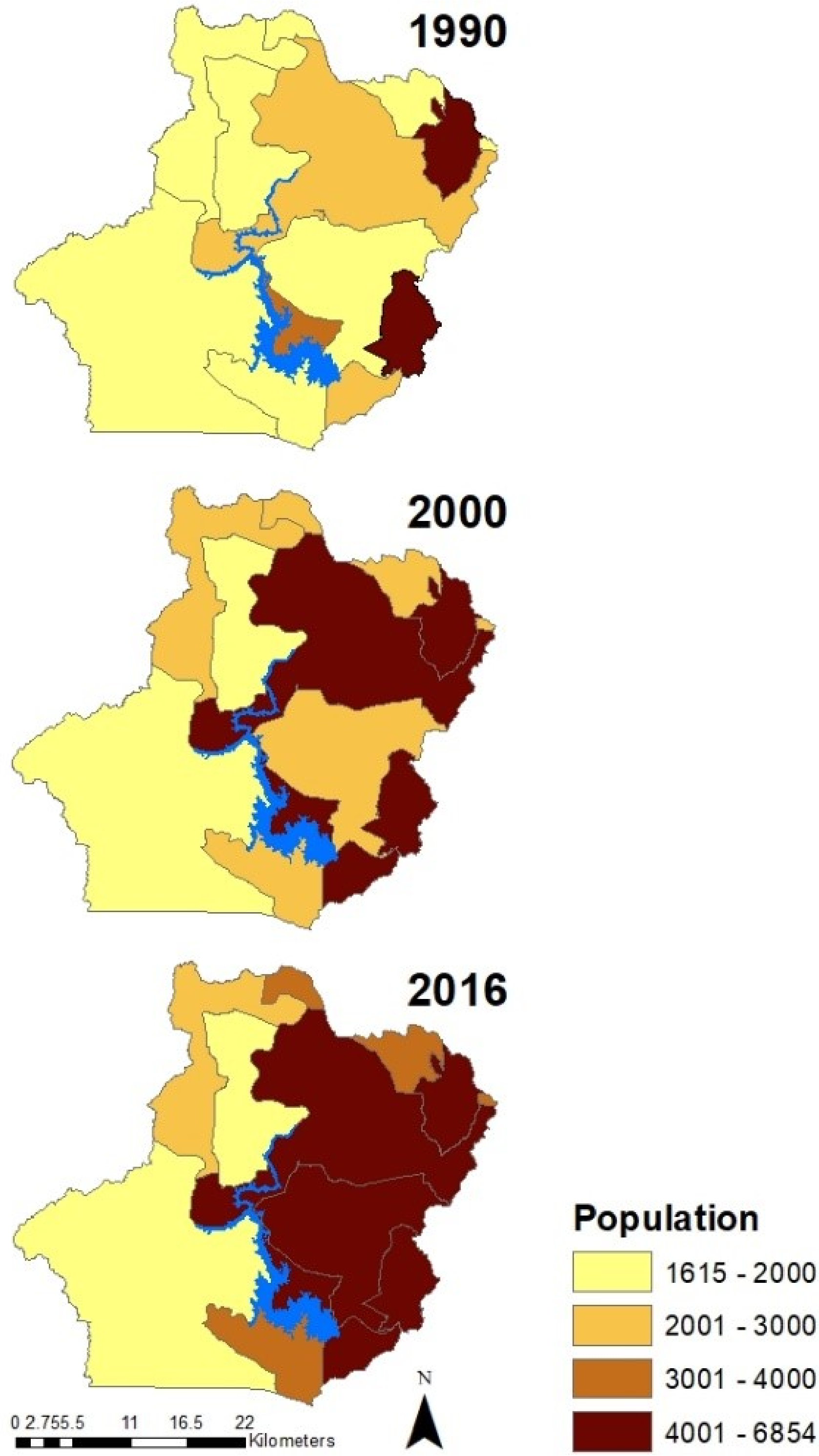

Figure 16. Maps showing population change between 1990, 2000, and 2016, around LBJ reservoir.

Figure 17. LBJ reservoir with local lake houses.

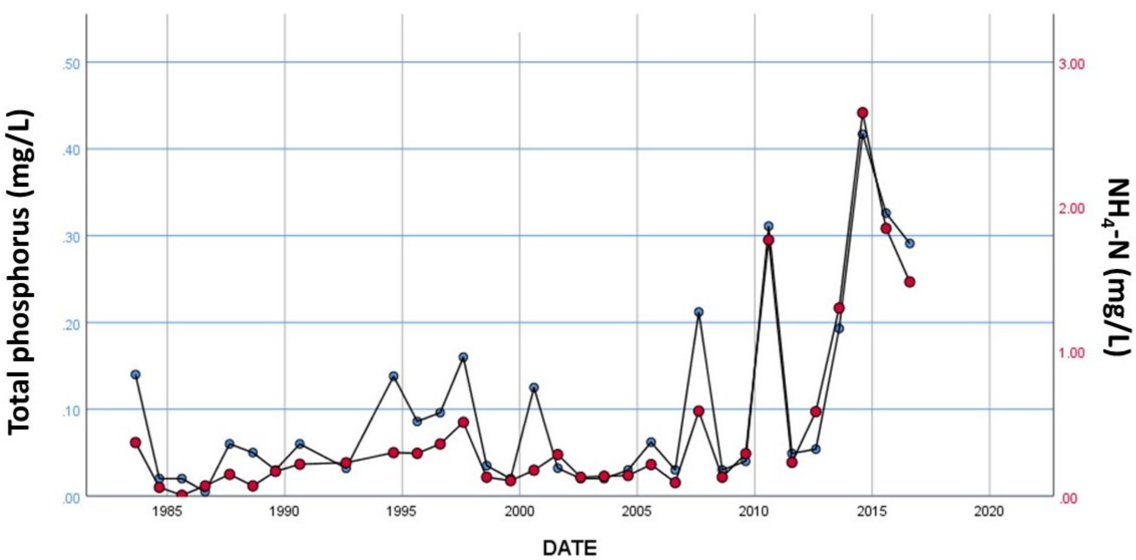

Figure 18. Total phosphorus and ammonium during August months at the bottom of Inks reservoir.

4. CONCLUSIONS

This study examined a long-term data base (1982-2016) with chemical, physical, and biological characteristics, to determine the cause(s) of eutrophication in the LBJ reservoir. Early analysis showed eutrophication has significantly increased over time. There was a significant increase in internal loading of phosphorus and nitrogen near the Wirtz Dam. The hypolimnion at the dam was below the depth of discharge, and this large volume of dead-space water formed a very stable environment where seasonal anoxia and development of low redox conditions developed nearly every year. Cluster analysis found spatial variability and broke the reservoir into distinct zones, including headwaters, mid-reservoir, a Llano river influenced zone, and near-dam. Most of the stations water column stability was weakened or completely mixed during periods of high spring and summer inflows. Land use change indicated that local urbanization has increased as well as population around the reservoir. The results suggest that eutrophication has increased over time due to localized urbanization and increased nutrients from the upstream reservoirs as well.

REFERENCES

Barakat, A., Baghdadi, M. E., Rais, J., Aghezzaf, B., & Slassi, M. (2016). Assessment of spatial and seasonal water quality variation of Oum er rbia River (Morocco) using multivariate statistical techniques, *International Soil and Water Conservation Research, 4* (4), 284-292. doi.org/10.1016/j.iswcr.2016.11.002

Beutel, M. (2016). The other internal loading – A look at nitrogen and mercury. *Lakeline*, 36 (1), 13-16.

Bewick, V., Cheek, L., & Ball, J. (2003). Statistics review 7: Correlation and regression, *Critical Care*, 7 (6), 451-459. doi: 10.1186/cc2401

Bhat, A. S., Meraj, G., Yaseen, S., & Pandit, K. A. (2013). Statistical assessment of water quality parameters for pollution source identification in Sukhnag stream: An inflow stream of Lake Wulhar (Ramsar site), Kashmir Himalaya, *Journal of Ecosystems*, 2014 (2014), 1-18. doi: 10.115/2014/898054

Butt, A., Shabbir, R., Ahmen, S. S., & Aziz, N. (2015) Land use change mapping and analysis using remote sensing and GIS: A case study of Simly watershed, Islambad, Pakistan, *The Egyptian Journal of Remote Sensing and Space Science*, 18 (2), 251-259. doi.org/10.1016/j.ejrs.2015.07.003

Chapman, D. (1996). *Water quality assessments – A guide to use of biota, sediments and water in environmental monitoring*. London, United Kingdom: F & FN Spon.

CRPP (Clean Rivers Program Partners). (2012). Basin summary report, A summary of water quality in the Colorado River basin- 2007-2011.

CRPP (Clean Rivers Program Partners). (2017). Basin summary report, A summary of water quality in the Colorado River basin- 2014-2017.

DePinto, V. J., & Verhoff H. F. (1977). Nutrient regeneration from aerobic decomposition of green alae. *Environmental science & technology*, 11 (4), 371-377.

Engel, B. A., Ahiablame, L, M., & Leroy, J. D. (2015). Modeling the impacts of urbanization on lake water level using L-THIA, *Urban Climate*, 14 (4), 578-585. doi.org/10.1016/j.uclim.2015.10.001

Ford, D, E., & Johnson, M. C. (1993). An assessment of reservoir density currents and inflow processes, technical report E-83-7.

Hou, D., He, J., Lu, C., Sun, Y., Zhang, F., & Otgonbayer, K. (2013). Effects of environmental factors on nutrients release at sediment-water interface and assessment of trophic status for a typical shallow lake, Northwest China, *Scientific World Journal*, 2013. doi.org/10.1155/2013/716342

Hupfer, M., & Lewandowski, J. (2008). Oxygen controls the phosphorus release from lake sediments – A long-lasting paradigm in limnology, *International Review of Hydrobiology*, 93 (4-5), 415-432. doi.org/10.1002/iroh.200711054

James, W. (2016). Internal P loading: A persistent management problem in lake recovery. *Lakeline*, 36 (1), 6-9.

Nikolai, S. J., & Dzialowski, A. R. (2014). Effects of internal phosphorus loading on nutrient limitation in a eutrophic reservoir. *Limnologica, 49*, 33-41.

Nurnberg, G. K., (2009). Assessing internal phosphorus load – problems to be solved, *Lake and Reservoir Management*, 25 (4), 419-432. doi.org/10.1080/00357520903458848

LCRA (Lower Colorado River Authority). (2006). Highland Lakes Watershed Ordinance Regulations Handbook. LCRA, Austin,Texas.

LCRA (Lower Colorado River Authority). (2011). Colorado river environmental models phase 3: Inks Lake, Lake LBJ, Lake Marble Falls.

McCully, P. (2001). Silenced rivers: the ecology and politics of large dams. New Yor, New York: St. Martin's Press.

Mix, K., Groeger, A.W. & Lopes, V.L. (2016). Impacts of dam construction on streamflows during drought periods in the Upper Colorado River Basin, Texas. *Lakes and reservoirs: Research and Management, 21,* 329-337.

Padedda, B. M., Sechi, N., Lai, G. G., Mariani, M. A., Paulina, S., Sarria, M., Satta, C. T., Virdis, T., Buscarinu, P., & Luglie, A. (2017). Consequences of eutrophication in the management of water resources in mediterranean reservoirs: A case study of Lake Cedrino (Sardinia, Italy), *Global Ecology and Conservation, 12*, 21-35. doi.org/10.1016/j.gecco.2017.08.004

Phung, D., Huang, C., Rutherford, S., Dwirahmadi, F., Chu, C., Wang, X., Nguyen, M., Nguyen, N. H., Do, C. M., Nguyen, T. H., & Dinh T. A. D. (2015). Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: A study in Can Tho City, a Mekong Delta area, Vietnam, *Environmental Monitoring and Assessment*, 187, 229. doi.org/10.1007/s10661-015-4474-x

Roy, K., Kat, S., Das, N. R. (2015). Understanding the basics of QSAR for applications in pharmaceutical sciences and risk management. doi.org/10.1016/C2014-0-00286-9

Singh, K. P., Malik, A., Mohan, D., & Sinha, S. (2004). Multivariate statistical techniques for evaluation of spatial and temporal variations in water quality of Gotmi River (India)- A case study, *Water Research*, 38 (18), 3980-3992. doi.org/10.1016/j.watres.2004.06.011

Sondergaard, M., Jensen, P. J., & Jeppesen, E. (2003). Role of sediment and internal loading of phosphorus in shallow lakes, *Hydrobiologia*, 506, 135-145. doi.org/10.1023/B:HYDR.0000008611.12704.dd

Manson, S., Schroeder, J., Riper, V. R., & Ruggles, S. IPUMS National Historical Geographic Information System: Version 14.0 [database]. Minneapolis, MN: IPUMS. 2019. doi.org/10.18128/D050.V14.0

TWDB (Texas Water Development Board). (2007). Volumetric and Sedimentation Survey of Lake Lyndon B. Johnson. Texas Water Development Board. Austin, Texas.

Yang, X., Wu, X., Hao, H., & He, Z. (2008). Mechanisms and assessment of water eutrophication, *J Zheijang Univ Sci B, 9* (3), 197-209. doi:10.1631/jzus.B0710626