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Observed trends in air temperature, precipitation, and water quality for Texas reservoirs: 1960-2010

Rodica Gelca[1], Katharine Hayhoe[2], and Ian Scott-Fleming[3]

Abstract: Changes in climate, environmental management, and land use can affect water quality in lakes and reservoirs. Here, we quantify observed trends in water temperature and water quality in the 57 Texas reservoirs that have sufficient data for the period 1960 to 2010. We also quantify trends in air temperature and precipitation at 120 long-term weather stations adjacent to those reservoirs. Annual average temperature, seasonal average temperature, and cold temperature extremes are all becoming warmer near many Texas reservoirs. These air temperature trends are highly correlated with observed increases in water temperature across the state. Slight statewide increases in annual and winter, spring, and summer precipitation have contributed to greater increases in precipitation intensity, which are moderated by increases in the average number of dry days per year. Changes in precipitation can affect runoff and evaporation rates, which may alter levels of salts and minerals in the lakes. In addition, local human activities could be an important contributor to the observed increases in pH and phosphorus across the state and changes in specific conductance, sulfate, and chloride throughout Texas.

Key Words: water quality, trends, reservoirs, climate change

[1] Department of Environmental Toxicology, Texas Tech University, 1207 Gilbert Drive, Lubbock Texas
[2] Climate Science Center, Texas Tech University, 72 Holden Hall, Boston and Akron Streets, Lubbock Texas 79409
[3] Department of Political Science, Texas Tech University, 113 Holden Hall, Boston and Akron Streets, Lubbock Texas 79409

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Terms used in paper

Short name or acronym	Descriptive name
DO	dissolved oxygen
NCDC	National Climatic Data Center
NPS	nonpoint source
USGS	U.S. Geological Survey

INTRODUCTION

The quantity and quality of water stored in surface reservoirs across Texas and the South-Central United States is an important concern. Reservoirs serve as water sources for many municipalities; they provide irrigation water for farmers and ranchers; and some are used to generate hydropower. Reservoirs support a wide variety of aquatic ecosystems and wildlife. Many reservoirs support the economies of local communities as well as contribute significantly to local, county, and state government income. For example in 2006, 1.7 million fresh water anglers spent $2 billion in Texas (USFWS 2006).

Population growth and large-scale depletion of West Texas aquifers have put stress on Texas surface water availability and water quality. Surface water quality has improved largely since the passage of the Clean Water Act, which regulates the discharge of pollutants from point sources (USDA 1997). However, challenges to water quality improvement remain due to unregulated nonpoint source (NPS) pollution, pollution associated with runoff from urban and agricultural lands (USEPA 2000). For example, in the 1980s large amounts of phosphorus (260,000 metric tons) entered the environment from fertilizer and manure application and from wastewater-treatment plant discharges (Litke 1999). Likewise, evaporative dissolution, proximity to ditches for oil-field brine discharge, and anomalously saline salt water wells contributed to an increase in chloride and sulfate in West Texas and Texas Gulf Coastal Plain surface waters (Nance 2006).

Surface water in Texas can also be affected by temperature, precipitation, and other climate conditions, including both short-term extreme events and long-term shifts in mean conditions. Changes in climate can directly affect water quality, water quantity, biogeochemical cycles, and the aquatic biological communities in lakes and rivers (Soh et al. 2008; Paull and Johnson 2011; Delpla et al. 2009). In general, decreases in precipitation and increases in temperature can increase evaporation and reduce inflow, which causes the increase in concentration of salts, minerals, and contaminants (Roelke et al. 2011, 2012). Heavy rains following long dry periods can cause runoff events with elevated episodic inputs of herbicides, pollutants, animal waste, and other contaminants into rivers and lakes (CCSP 2008). Warmer temperatures and shifts in the timing and amounts of precipitation can affect fish community structure, life history traits, feeding modes, behavior, and survival (Jeppesen et al. 2010; Morrongiello et al. 2011; Baez et al. 2011; Roelke et al. 2011).

Climate trends across the broader Great Plains region over the past 50 years include increases in average annual and seasonal temperatures, precipitation intensity, and the amount of rain falling during the most intense 1% of storms (USGCRP 2009). At the other end of the spectrum, the year 2011 was the driest year on record for the state of Texas, and ongoing dry conditions (as of 2014) continue to affect reservoir water quantity and quality. Impacts on communities and ecosystems across the state range from demographic changes, as young adults preferentially move to urban areas (USCB 2009), to loss of wildlife habitat, as increased temperature and evaporation rates can cause playa lakes to dry out more frequently and affect the ability of waterfowl to migrate, mate, and nurture their offspring (Haukos and Smith 1992). Recent fish kills by golden algae (*Prymnesium parvum*) have been linked to low inflows and elevated salinity, which were affected by precipitation and evaporation rates (Roelke et al. 2011, 2012).

Average temperature is also increasing on a global scale. Severe cold is becoming less frequent, and heat waves more frequent. Precipitation patterns are shifting, with dry areas (in general) becoming drier and wet areas becoming wetter. Precipitation intensity is increasing over mid-latitudes, including much of the United States. The upcoming 2014 Third National Climate Assessment documents the potential impacts of these recent trends (Walsh et al. 2014) and highlights the need to quantify ongoing changes in climate and water quality at the local to regional scale.

Here, we quantify observed trends over time in 2 different datasets. The first set of data consists of 31 indicators of seasonal means and extremes, derived from air temperature and precipitation at 120 long-term weather stations. These stations are located nearby or upstream of 59 Texas reservoirs for which long-term water quality data is available from 1960 to 2010 (Figure 1). The second set of data consists of deseasonalized water temperature and 24 other indicators of water quality at 57 of the 59 reservoirs that have sufficient data to assess trends.

The Data section describes the 2 datasets, as well as the quality control and processing methods applied to the data prior to conducting the trend analysis. The Results section summarizes the trend analyses for atmospheric and water variables. Finally, in the Discussion and Conclusions section, we summarize the primary results of this analysis and discuss the implications of observed trends in air temperature and precipitation for water quality, past and future.

DATA

The 2 datasets used in this study consist of: (1) daily maximum and minimum air temperature at 2 meters above land surface and daily 24-hour cumulative precipitation measured continuously at 120 long-term weather stations and (2) daily (but far more sparse) measurements of water temperature and water quality parameters measured sporadically at 59 reservoirs across Texas. The locations of the weather stations and the reservoirs are shown in Figure 1.

Air temperature, precipitation, and secondary climate indicators

To identify which weather stations to use, we first plotted the locations of all long-term weather stations in or near Texas with daily data archived by the National Climatic Data Center (NCDC).[1] We then superimposed rivers, river basins, and reservoirs on this map to identify up to 3 "closest" and up to 7 "upstream" stations for each reservoir. Upstream locations were included because we hypothesized that stations upstream might better capture spatially inhomogeneous precipitation events affecting the reservoirs compared to locations that, while closer, may be located downstream, or in a different watershed. Weather stations were further filtered by removing any data records that had less than 80% coverage of the period between 1960 and 2010 (to be consistent with the same period as the reservoir observations). Daily maximum and minimum temperatures and 24-hour cumulative precipitation observations were then obtained from the NCDC database for each of these stations.

Preliminary evaluation of NCDC raw data had previously revealed the presence of obvious errors such as days with minimum temperature values greater than maximum temperature or outliers beyond the value of plausible observations in the continental United States. Although a few individual outliers would not have a strong influence on the trend analyses conducted here, we still processed the daily air temperature and precipitation observations using a quality control algorithm before conducting the trend analysis (see Appendix A for more details). After quality control, we used the daily time series of temperature and precipitation to calculate a set of secondary climate indicators, 19 for temperature and 12 for precipitation (Table 1). Secondary indicators capture aspects of climate related to annual and seasonal means, as well as to extremes (hot/cold and wet/dry). Each indicator was calculated on an annual basis (i.e., 1 value per weather station for each year in the historical record).

Water data

Data on water temperature and 24 other water quality parameters had been previously compiled from the U.S. Geological Survey (USGS) National Water Information website, hard-copy USGS Texas Water Data Reports, databases maintained by the Texas Commission on Environmental Quality, and other secondary sources, including the Texas

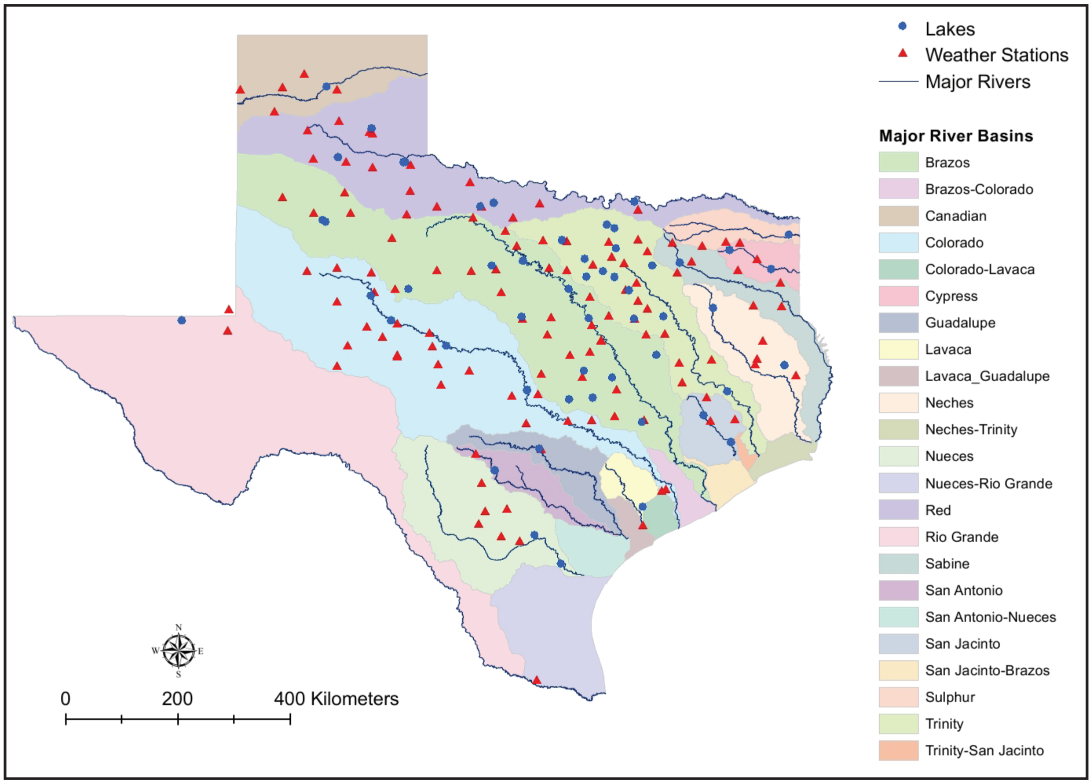

Figure 1. Locations of the 120 weather stations used to quantify surface temperature and precipitation for each of 59 reservoirs. Weather stations were selected to be near to or upstream from each reservoir.

[1] Climate Data v2.0 Summary of the Day, available online at: http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=SOD

Water Development Board and independent river authorities data (as described in Burley et al. 2011). Reservoir data was reviewed to identify anomalous points that could be indicative of observational error: water temperature readings of 55 °C or 131 °F, for example, or hardness readings > 8000 milligrams/liter (all others <500 milligrams/liter). For some of these points, there may be a legitimate reason for the anomalous observation; accidental discharge of chemicals into the watershed could temporarily raise levels of certain water quality parameters beyond observed ranges. However, as the water data is a smaller dataset than the daily air temperature and precipitation data, these outliers have a greater potential to affect the trend analysis than anomalies in weather station data. For this reason, we removed outliers from the water temperature and water quality data using hard limits (listed in Table 2) based on inspection of the data. These hard limits were usually an order of magnitude or more beyond the typical range. Observation depths varied within and between reservoirs, such that we standardized the water data to 2 sets of mean depths, 1 above and 1 below 10 feet (see Appendix B for more details).

Finally, certain water parameters showed a strong seasonal cycle while others did not (Table 2). Seasonal variation, for most reservoirs, occurred in water temperature, dissolved oxygen (DO), pH, nitrate and nitrite, and potassium (unfiltered). While this would not pose a problem for the trend analysis if the observations were evenly distributed throughout the year (as they are for air temperature and precipitation), water data for many reservoirs is sparse and is often unevenly distributed in time. Thus, the water data for reservoirs fails to account for a seasonal cycle in water quality characteristics that may compromise our ability to detect a trend or lack thereof.

For that reason, annual cycles were determined by fitting the data series to the first 2 terms of a Fourier series (the mean value and a cosine term), which is a function commonly used to describe data as a set of oscillating or periodic waves. A least-squares fit was performed on the sin(theta) and cos(theta) to determine the magnitude and phase of the annual cycle. The resulting sinusoid was subtracted from the overall signal,

Table 1. Secondary climate indicators used in trend analysis, including descriptions and abbreviations.

Secondary indicator	Abbreviation
TEMPERATURE (19 indicators)	
Annual mean temperature	T(ann)
Seasonal mean temperature (Winter: Dec-Jan-Feb; Spring: Mar-Apr-May; Summer: Jun-Jul-Aug; Autumn: Sept-Oct-Nov)	T(DJF), T(MAM), T(JJA), T(SON)
Cold days (days per year with minimum temperature below 0 °C or 32 °F)	Tn<32 °F
Average temperature of the coldest consecutive 1, 3, 5, and 10 days of the year	T-cold(1d) to T-cold(10d)
Hot days (days per year with maximum temperature above 32 °C or 90 °F)	Tx>90 °F
Average temperature of the warmest consecutive 1, 3, 5, and 10 days of the year	T-hot(1d) to T-hot(10d)
Duration of summer, defined as the number of days between the first and last day of the year with maximum temperature > 32 °C or 90 °F	Summer(begin/end)
Duration of the growing season, defined as the number of days between the last day in spring and the first day in fall with minimum temperature <0 °C or 32 °F	Growing(begin/end)
PRECIPITATION (12 indicators)	
Annual total precipitation	Pr(ann)
Seasonal total precipitation (Winter: Dec-Jan-Feb; Spring: Mar-Apr-May; Summer: Jun-Jul-Aug; Autumn: Sept-Oct-Nov)	Pr(DJF), Pr(MAM), Pr(JJA), Pr(SON)
Dry days per year, defined as 24h cumulative precipitation <0.01 inches, according to the U.S. National Weather Service definition of "trace"	DryDays
Days per year with more than 1 or 2 inches of precipitation in 24 hours	Pr>1(1d), Pr>2(1d)
Number of 5-day periods per year with more than 3 inches of accumulated precipitation	Pr>3(5d)
Annual precipitation intensity, defined as total precipitation divided by the number of wet days per year	Pr(int)
Hydroperiod – day of the year (in Julian Date) by which 25% and 50% of annual precipitation has accumulated	Pr(25%), Pr(50%)

with the residual signal representing the contribution from all non-annual cycle effects. The magnitude and phase of the annual cycle from all lakes in the region combined were also calculated, and these values were used as a proxy for the annual cycle at any lake where there were insufficient points (<25) to estimate the local annual cycle. For records with more than 25 data points per variable per reservoir, the annual cycle was fit to the data from that reservoir. For variables with less than 25 data points, the regional mean was used to remove the annual cycle. Annual cycles were not removed from reservoirs with more than 25 data points that did not show an annual cycle, even if an annual cycle was evident at the aggregated level.

Statistical trend analysis methodology

Statistical trend analysis was conducted individually for each weather station on the 31 secondary climate indicators listed in Table 1 and for each reservoir on all water variables with sufficient data. As indicated in column 2 of Table 2, variables with sufficient data included water temperature, DO, specific

Table 2. Water temperature and water quality variables collected and analyzed in this study for (a) shallow depths (between the surface and 10 feet) and (b) deeper water (between 10 feet of depth and the bottom of the reservoir). The number of reservoirs for which sufficient data was available for trend analysis is listed in column 3. The water quality variables that displayed seasonal cycles are indicated in column 4 (Yes or Uncertain; no entry implies No). "F" indicates filtered and "U" unfiltered. (Table 2 continued on next page.)

(a) SHALLOW (surface to 10 feet)

Water variable	Reservoirs	Hard limits	Annual cycle?
Calcium-F	48	0-1000	
Chloride	59	0-10000	
Dissolved oxygen	58	0-25	Y
Fluoride-F	46	0-5	
Fluoride-U	50	0-5	
Hardness (as $CaCO_3$)	51	0-2500	
Magnesium-F	37	0-300	
Magnesium-U	48	0-300	
Nitrate-Nitrite	55	0-12	Y
Nitrogen-F	16	0-10	
Nitrogen-U	8	0-5	
Non carbonate hardness-F	10	0-12000	
Non carbonate hardness-U	15	0-12000	
pH	59	0-12	Y
Phosphorus-F	21	0-2	
Phosphorus-U	58	0-10	
Potassium-F	42	0-100	
Potassium-U	34	0-50	U
Salinity	25	0-3	
Sodium-F	42	0-2000	
Sodium-U	36	0-1500	
Specific conductance	52	0-25000	
Sulfate	59	0-2500	
Temperature	59	-5-40	Y

conductance, pH, phosphorus, chloride, and sulfate. Trends were only calculated for climate indicators and water parameters with data points that were distributed over at least 10 years.

We applied 3 different statistical methods (Pearson product-moment correlation, Spearman's rank correlation, and Kendall rank correlation, also referred to as Mann-Kendall tau) to calculate:

- the total number of weather stations with significant ($p<0.1$) trends in each variable,
- the magnitude of the trend for each climate indicator at each station,
- the number of reservoirs with significant trends in each variable,
- the magnitude of the trend for water temperature and water quality indicators.

For some atmospheric indicators, such as annual and summer average temperature, the number of dry days, and precipitation intensity, the number of significant trends was slightly greater using Pearson, which detects for linear trends. For other atmospheric indicators, such as winter average temperature or average temperature on the coldest days of the year, the nonparametric tests (Kendall and Spearman methods)

Table 2. Water temperature and water quality variables collected and analyzed in this study for (a) shallow depths (between the surface and 10 feet) and (b) deeper water (between 10 feet of depth and the bottom of the reservoir). The number of reservoirs for which sufficient data was available for trend analysis is listed in column 3. The water quality variables that displayed seasonal cycles are indicated in column 4 (Yes or Uncertain; no entry implies No). "F" indicates filtered and "U" unfiltered. (Table 2 continued from previous page.)

(b) DEEP (10 feet to bottom)

Water variable	Reservoirs	Hard limits	Annual cycle?
Calcium-F	25	0-1000	
Chloride	44	0-10000	
Dissolved oxygen	57	0-25	Y
Fluoride-F	24	0-5	
Fluoride-U	2	0-5	
Hardness (as $CaCO_3$)	21	0-2500	
Magnesium-F	25	0-300	
Magnesium-U	9	0-300	
Nitrate-Nitrite	33	0-12	Y
Nitrogen-F	8	0-10	
Nitrogen-U	13	0-5	
Non carbonate hardness-F	10	0-12000	
Non carbonate hardness-U	8	0-12000	
pH	57	0-12	Y
Phosphorus-F	21	0-2	
Phosphorus-U	34	0-10	
Potassium-F	24	0-100	
Potassium-U	8	0-50	Y
Salinity	19	0-3	
Sodium-F	24	0-2000	
Sodium-U	8	0-1500	
Specific conductance	21	0-25000	
Sulfate	43	0-2500	
Temperature	57		Y

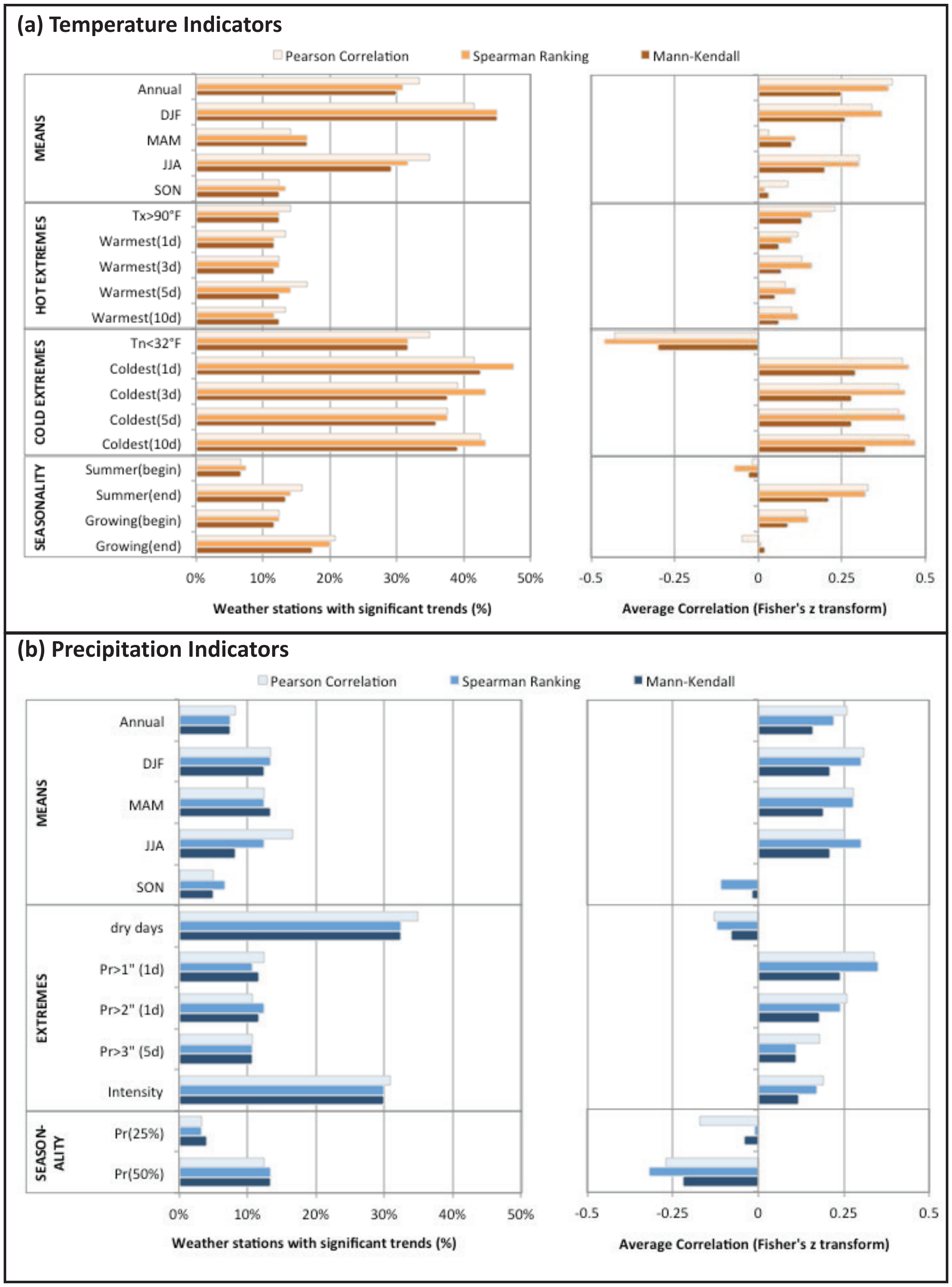

Figure 2(a) (top); 2(b)(bottom). Percentage of weather stations with significant trends according to Pearson, Spearman, and Mann-Kendall tests (left). Fisher's z transform of the correlation coefficient between time and each indicator, averaged across all stations (right).

found more significant trends. To compare the direction and magnitude of trends, we used the average of Fisher's Z transform correlation coefficients (Figure 2, right). An average of coefficients of correlation themselves is statistically unsound because the sampling distribution of coefficients of correlation is not normally distributed (Thomas et al. 2011), that is why we used the Fisher's Z transform of the correlation coefficients to calculate the average. Fisher Z transformation is a method of approximating normality of a sampling distribution of linear relationships.

For water temperature and water quality indicators, with the exception of DO, nonparametric methods also yielded a greater number of significant trends in water parameters than the parametric test for a linear trend using Pearson (Figure 3, left). In terms of the magnitude and direction of the trend, estimates were consistent across all 3 methods (Figure 3, right).

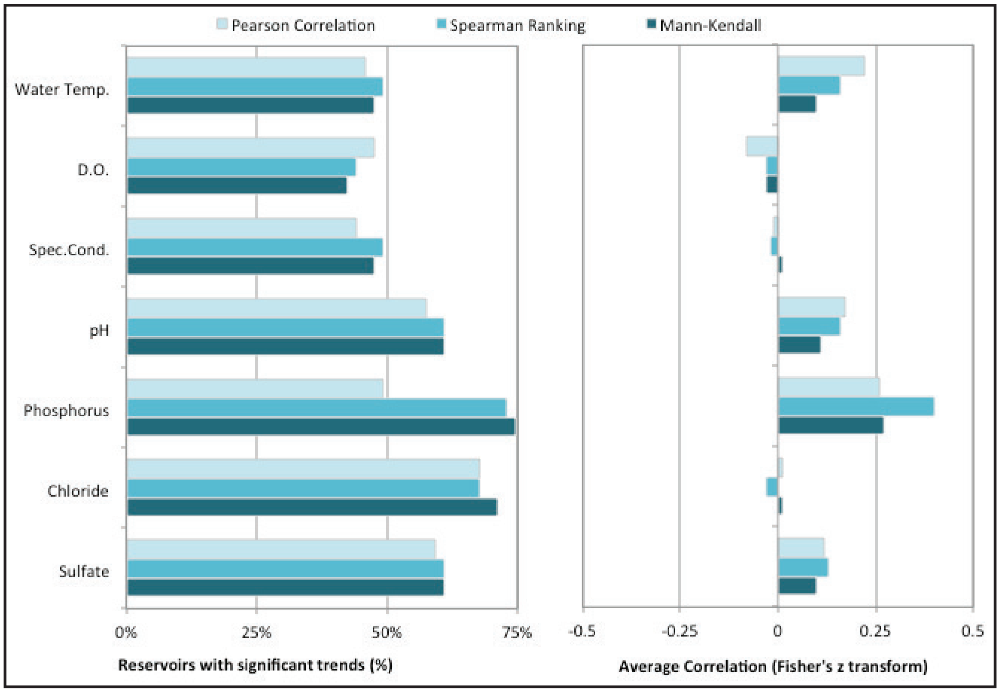

Figure 3. Water trend analysis showing: the percentage of reservoirs out of 59 with a significant ($p<0.1$) trend in water temperature and water quality according to the Pearson, Spearman, and Mann-Kendall trend tests (left); and Fisher's z transform of the correlation coefficient between time and each water quality indicator, averaged across all reservoirs (right).

The only exception was a slightly greater average trend of phosphorus using Spearman's rank.

Overall, all 3 methods of trend analysis show fairly consistent results in terms of the direction of trend and the approximate number of weather stations or reservoirs with a significant trend. However, trends estimated using the Spearman approach are more consistent than those estimated using either Kendall or Pearson, both in the number of stations or reservoirs showing a significant trend and the trend magnitude. For that reason, the data plotted in Figures 4, 5, and 6 are based on Spearman's rank correlation only.

RESULTS

Air temperature trends

Analyses of the mean and extreme indicators of air temperature listed in Table 1 reveal historical trends that, despite some variations from one location to the next, are relatively consistent in the direction of warming temperatures. All trends for temperature are positive, except for days per year below freezing, where a negative trend signifies warming.

Significant ($p<0.1$) increasing trends for temperature-related indicators were identified at many stations (Figure 2a). The variables with the greatest percentage of stations (out of 120) with significant correlations and the largest trends (out of 1.0) were

- annual mean temperature: 31% of stations with a correlation coefficient of 0.39,
- winter (Dec-Jan-Feb) mean temperature: 45% of stations with a correlation coefficient of 0.37,
- summer (Jun-Jul-Aug) mean temperature: 32% of stations with a correlation coefficient of 0.3,
- average temperatures on the coldest 1 to 10 days of the year: between 38% to 48% of stations with correlation coefficients between 0.44 and 0.47, depending on the number of consecutive days,
- days per year below freezing: 32% of stations with a correlation coefficient of -0.46.

Spring and fall average temperatures show largely positive trends at only 17% and 13% of stations, respectively. Trends in warm temperature extremes are also consistent with warming but are much weaker than those in cold temperature extremes, with significant trends observed at only around 15% of all stations and correlation coefficients between 0.1 and 0.16. In terms of seasonality, between 7% to 20% of stations show significant trends in the date of the beginning or end of summer or the growing season, with the greatest correlations and most stations for trends showing an earlier beginning to the growing season and a later end to summer.

Mapping indicators with significant trends in at least 25%

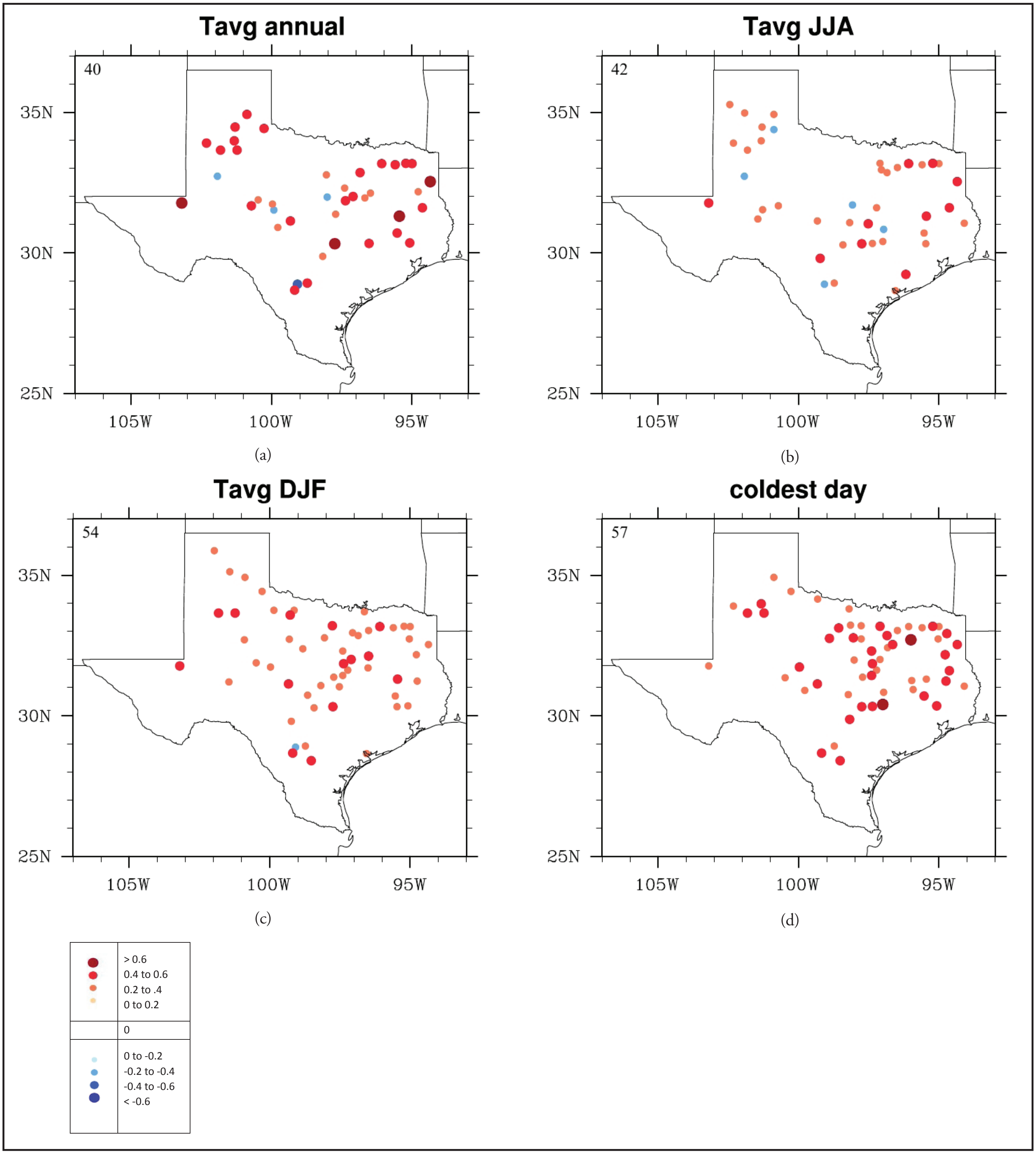

Figure 4 (a-d). Observed temperature trends in weather stations near reservoirs as determined by Spearman ranking. The number of points on each map varies, as only weather stations with a significant ($p<0.1$) trend for that variable are shown. Color indicates a positive (red) or negative (blue) trend, while size indicates the relative strength of the trend. Indicators with more than 25% of stations showing a significant trend consist of: (a) mean annual temperature, (b) summer (Jun-Jul-Aug) temperature, (c) winter (Dec-Jan-Feb) temperature, (d-g) coldest 1, 3, 5, and 10 days of the year, and (h) days per year with minimum temperature <32 °F or 0 °C. (Figure 4(e-h) continued on next page.)

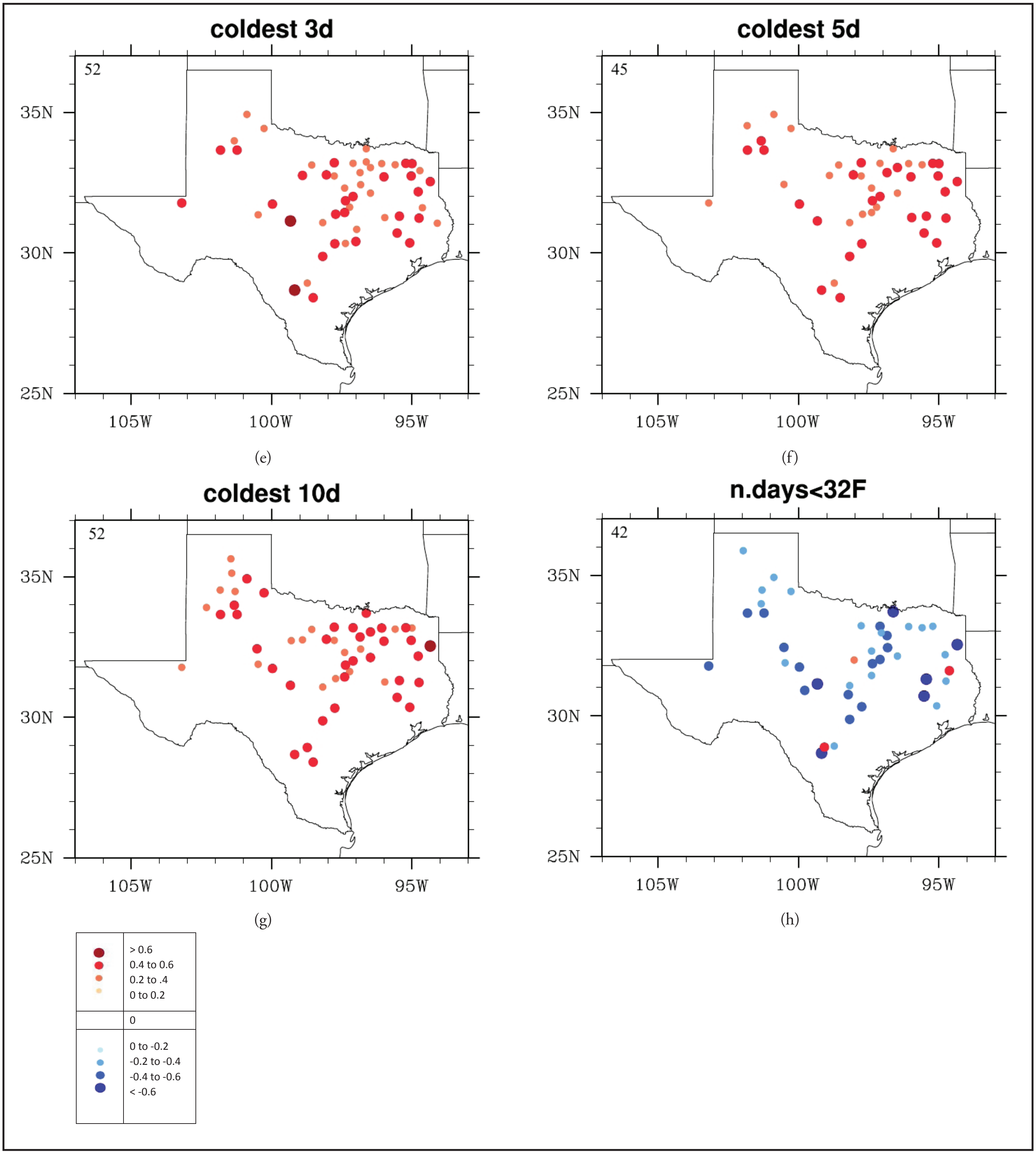

Figure 4(e-h). Observed temperature trends in weather stations near reservoirs as determined by Spearman ranking. The number of points on each map varies, as only weather stations with a significant ($p<0.1$) trend for that variable are shown. Color indicates a positive (red) or negative (blue) trend, while size indicates the relative strength of the trend. Indicators with more than 25% of stations showing a significant trend consist of: (a) mean annual temperature, (b) summer (Jun-Jul-Aug) temperature, (c) winter (Dec-Jan-Feb) temperature, (d-g) coldest 1, 3, 5, and 10 days of the year, and (h) days per year with minimum temperature <32 °F or 0 °C. (Figure 4(a-d) on previous page.)

of weather stations shows that, across the state, annual average temperature shows the strongest trends among all climate indicators, while increases in winter temperature tend to be more geographically consistent than increases in summer temperature (Figure 4(a-c)). These results do not indicate a specific region or set of watersheds that are warming more than others; instead, trends seem to be distributed consistently across the state. A few stations exhibited a negative or cooling trend, as indicated by blue dots. Most of these trends were relatively small and may be associated with local factors, such as irrigation or land use change that can alter humidity levels and temperature. Kueppers et al. (2007) found that climate effects of irrigation can be relatively large on a regional scale and hypothesized that expansion of irrigation may have masked regional increases in temperature due to increases in greenhouse gases. Changes in temperature trends were observed also with rural to urban land use/land cover changes (e.g. Gallo et al. 1999; Hale et al. 2006). It is likely that the rapid increase in population in South Central Texas and extensive irrigation in the North West region have an impact on temperature variability across the state. Alternatively, given the large sample of 120 stations, these could also be statistical anomalies.[2]

These trends signify the strong positive trends in cold temperatures, specifically the temperature of the coldest 1, 3, 5, and 10 days of the year (Figure 4(d-g)). A greater number of stronger trends are seen in the eastern as compared to the western half of the state, but every station with a significant trend in these variables shows a warming. Trends in the number of days per year below freezing (Figure 4(h)) show a similar geographic distribution to trends in cold temperature extremes, but the results are less consistent due to the comparison to an artificial threshold (0 °C or 32 °F), e.g., days below freezing might be quite common in the northwest part of the state, but relatively rare in the southeast.

Precipitation trends

Trends in annual and seasonal total precipitation from 1960 to 2010 are generally positive in all seasons except fall, with correlation coefficients ranging from 0.22 to 0.3 (Figure 2b, right). Seasonal precipitation trends are generally significant at 13% of stations (Figure 2b, left). This small number could be the result of 2 factors: (1) weaker trends as compared to temperature, and/or (2) greater inter-annual variability in precipitation than for temperature, both of which would make detection of significant trends more challenging. About 13% of stations showed that the date of the year at which 50% of precipitation has occurred is moving to an earlier date, consistent with increases in winter and spring precipitation, with an average correlation coefficient of -0.32. Due to the relatively small number of stations with significant trends in mean precipitation and the seasonality of precipitation, we do not plot the geographic distribution of these trends.

For precipitation extremes, 30% of stations have significant trends in precipitation intensity (defined as average annual precipitation divided by the number of wet days per year) and 33% have significant trends in the average number of dry days per year (defined as days with less than 0.01 inches of cumulative precipitation in 24 hours; Figure 5a-b). For these 2 variables, however, there is significant spatial inhomogeneity in the magnitude and the direction of observed trends. For precipitation intensity, approximately two-thirds of stations with significant trends show increases, and one-third show decreases. For the average number of dry days per year, it is the opposite: approximately one-third of all stations show an increase and two-thirds, a decrease.

Changes in precipitation intensity are related to either annual precipitation and/or the number of dry days per year. With some evidence for increasing seasonal and annual precipitation, locations with increases in precipitation intensity are likely driven by a general increase in average precipitation, combined with either little change or an increase in the number of dry days per year. In contrast, locations with decreasing precipitation intensity likely also have decreases in dry day frequencies, combined with decreases or no change in average precipitation. We explore these relationships in Figure 5c, which shows the combined direction of trends in mean precipitation, precipitation intensity, and dry day frequency. As expected, stations with an increase in precipitation intensity also show an increase in the number of dry days per year (14 stations; red/pink colors). Similarly, stations with a decrease in precipitation intensity show a decrease in the average number of dry days per year (11 stations; dark blue/green colors). Only 8 stations show trends in intensity but not in dry days and 12 stations show trends in dry days but not in intensity. The mean of Fisher's Z transformed correlation coefficient over all stations with significant trends shows an overall positive trend in precipitation intensity and average annual precipitation and a decrease in dry day frequency (Figure 2b, right). This can be explained by the predominance of strong negative trends in dry days and strong positive trends in precipitation intensity.

Trends in water variables

Almost 50% of reservoirs show significant ($p<0.1$) trends in water temperature and 43% show significant trends in DO, a related indicator (Figure 3, left). Trends in water temperature from 1960 to 2010 across the state are largely positive, reflecting the increase in water temperature likely because of increase in air temperature shown in Figure 6a. A few reservoirs show negative trends in water temperature; these have no significant

[2] A p-value of 0.1 implies a 10% chance of a false trend being identified at a given station.

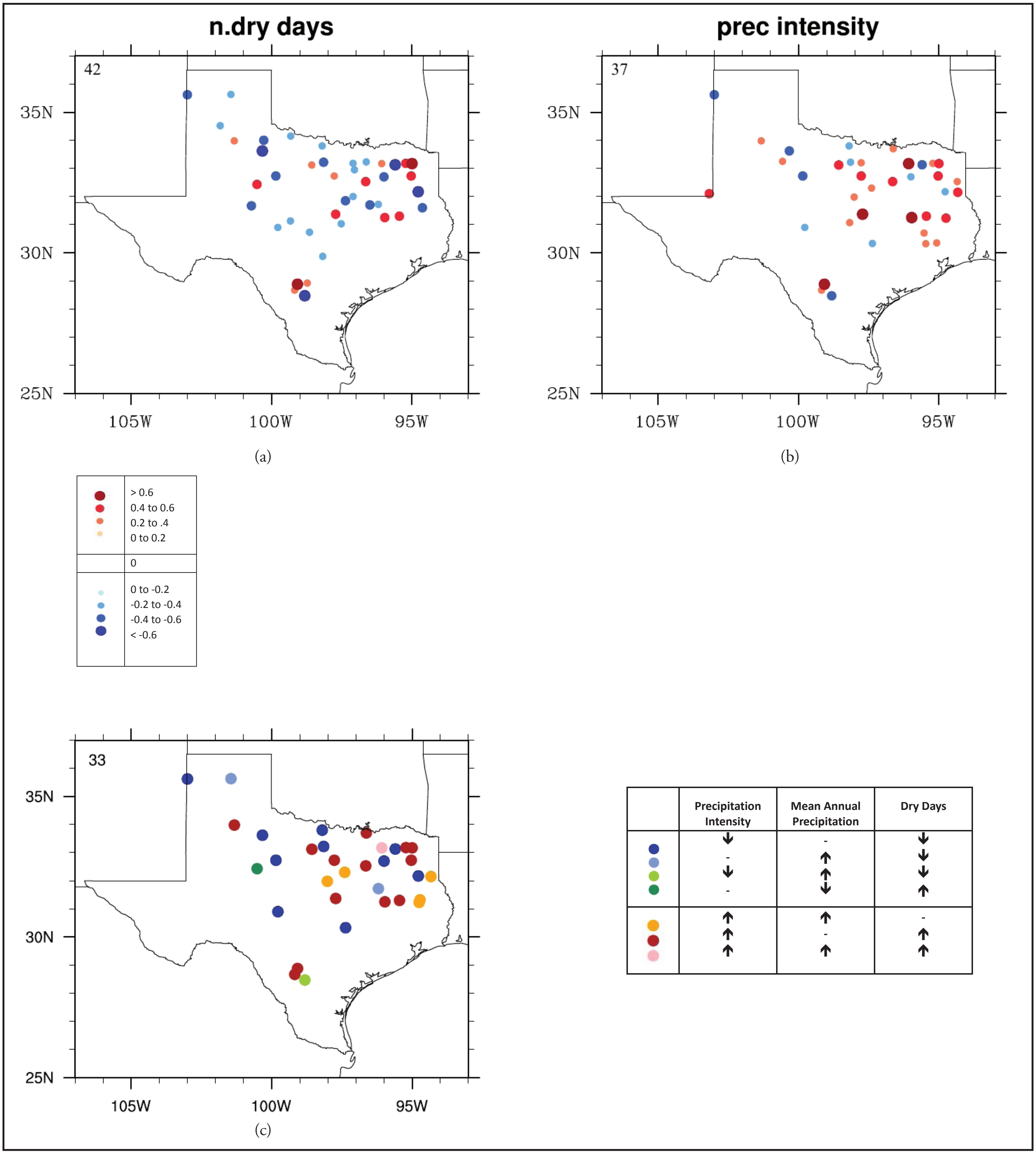

Figure 5(a-c). Observed precipitation trends in weather stations near reservoirs as determined by Spearman's rank. The number of points on each map varies, as only weather stations with a significant ($p<0.1$) trend for that variable are shown. Color indicates a positive (red) or negative (blue) trend, while size indicates the relative strength of the trend. Indicators with more than 25% of stations showing a significant trend consist of: (a) total number of dry days per year, and (b) mean annual precipitation intensity. Also shown is (c) a combined analysis highlighting the relationship between observed trends in precipitation intensity, mean annual precipitation, and the number of dry days per year.

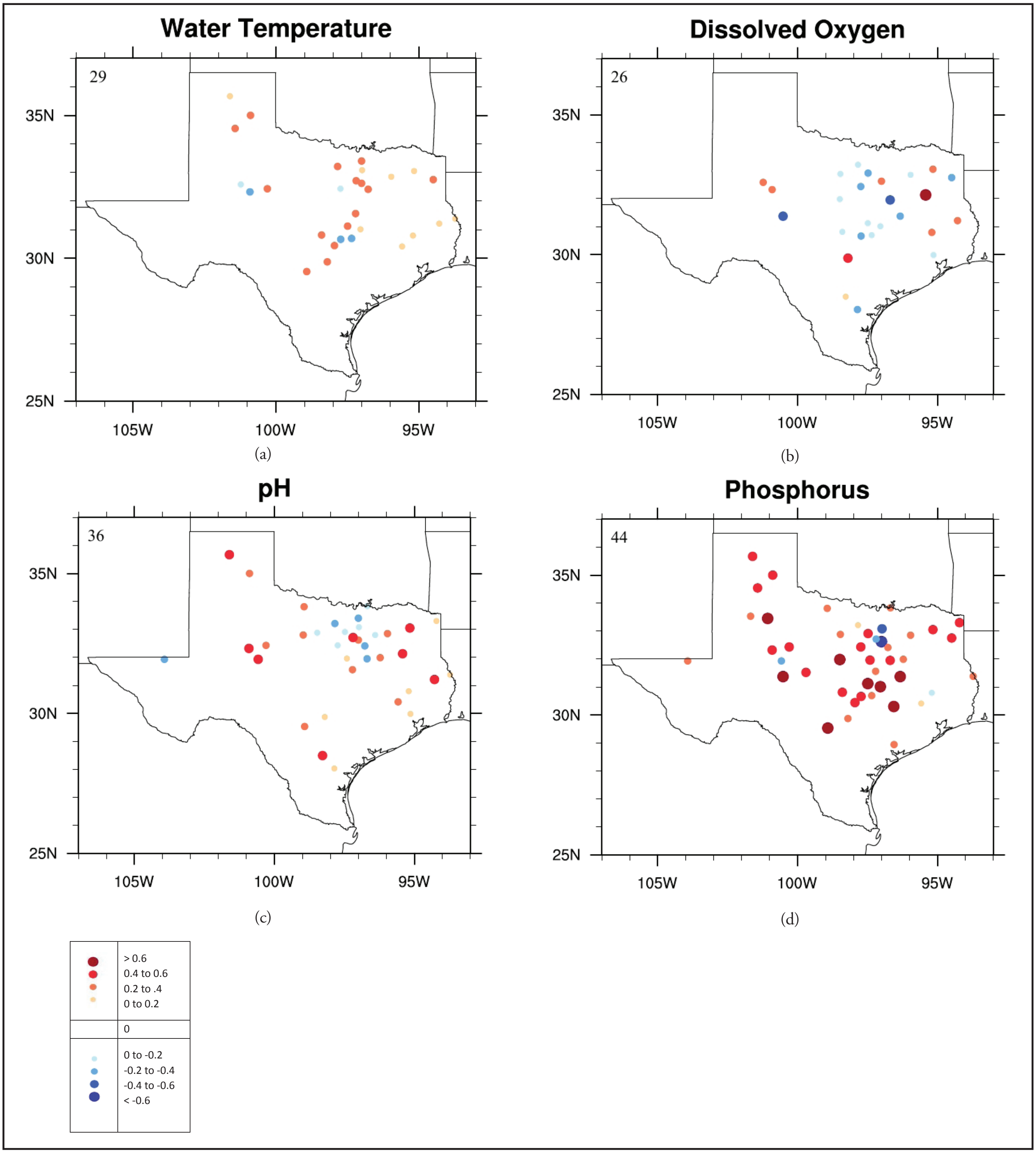

Figure 6(a-d). Observed trends in Texas reservoirs as determined by Spearman's rank. The number of points on each map varies, as only reservoirs with a significant ($p<0.1$) trend for each variable are shown. Color indicates a positive (red) or negative (blue) trend, while size indicates the relative strength of the trend. Indicators consist of: (a) reservoir water temperature, (b) dissolved oxygen, (c) pH, (d) specific conductance, (e) phosphorus, (f) chloride, and (g) sulfate at depths above 10 feet. No significant trends for variables at depths below 10 feet were detected, at least in part due to data sparseness.(Figure 6(e-h) continued on next page.)

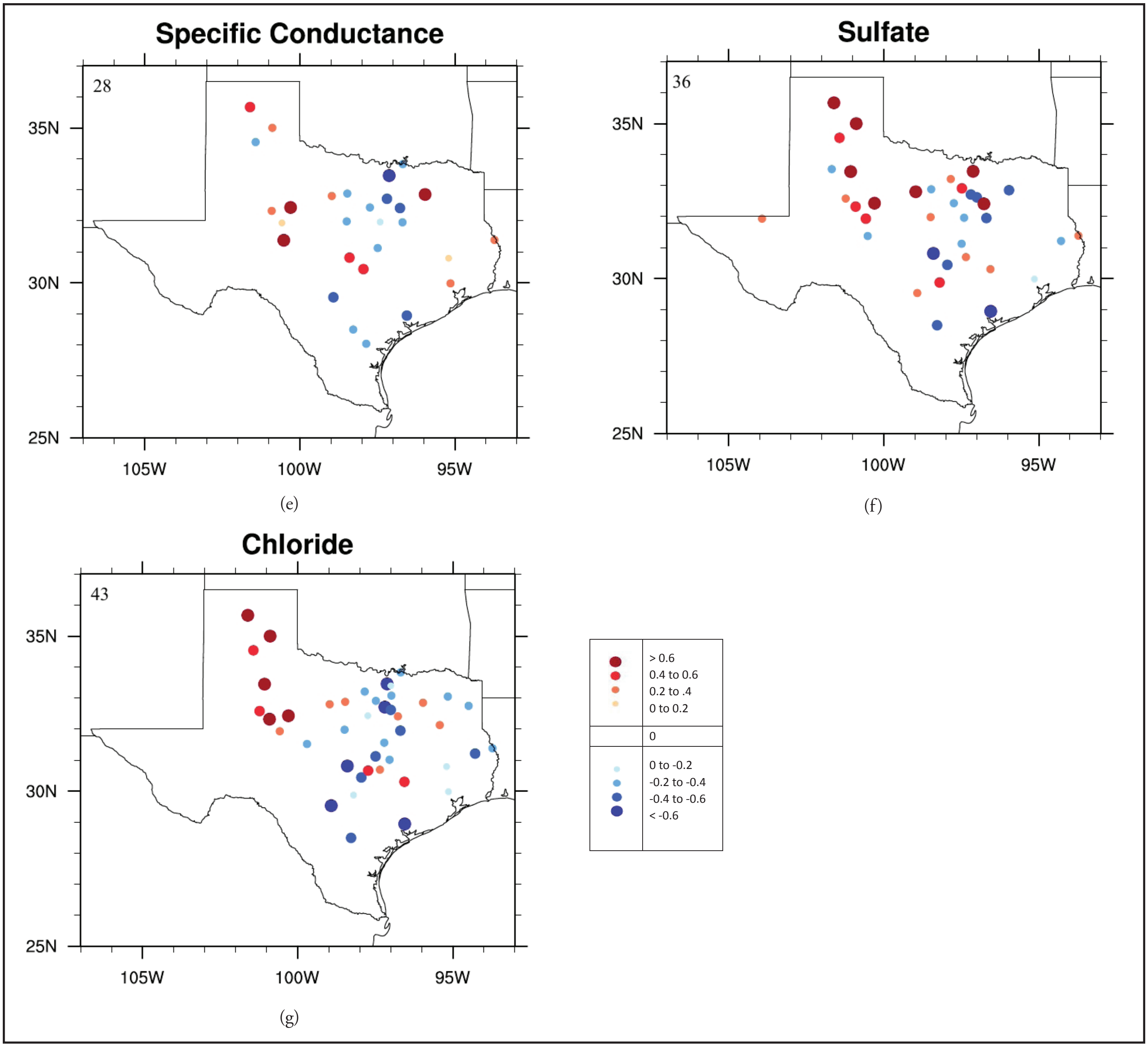

Figure 6(e-g). Observed trends in Texas reservoirs as determined by Spearman's rank. The number of points on each map varies, as only reservoirs with a significant ($p<0.1$) trend for each variable are shown. Color indicates a positive (red) or negative (blue) trend, while size indicates the relative strength of the trend. Indicators consist of: (a) reservoir water temperature, (b) dissolved oxygen, (c) pH, (d) specific conductance, (e) phosphorus, (f) chloride, and (g) sulfate at depths above 10 feet. No significant trends for variables at depths below 10 feet were detected, at least in part due to data sparseness. (Figure 6(a-d) on previous page.)

trend in air temperature at nearby weather stations.

As water temperature increases, DO would be expected to decrease, since warmer water holds less oxygen. This general trend is illustrated in Figure 3 (left). However, Figure 6b shows that out of the 16 reservoirs that have significant trends in both water temperature and DO, only half of those show the expected inverse relationship between temperature and DO (i.e., that one is increasing while the other is decreasing or vice versa). This highlights the importance of other variables besides mean temperature, such as precipitation events, natural and human-induced loading of organic materials and associated bacteria-mediated decay, and biological processes (photosynthesis and respiration), in determining the amount of DO in the water.

In terms of water quality, specific conductance, pH, phosphorus, chloride, and sulfate show significant trends in 49% to 73% of Texas reservoirs (Figure 3, left). The most consistently positive trends across the entire state are seen in pH, sulfate, and phosphorus, respectively (Figure 3, right and Figure 6c,d,f). Specific conductance and chloride also show a large number of significant trends (Figure 6e,g), but the Fisher's Z transform of the correlation coefficients across the state averages out to near zero (Figure 3, right) because of large increases in West Texas contrasted with large decreases in East Texas.

In Figure 7, we summarize statewide trends in the primary air and water variables that have consistent trends across the state. We compare the direction and magnitude of trends in water quality parameters with those in atmospheric variables. We exclude DO, sulfate, and chloride, as they show both positive and negative trends and the Fisher's Z average is close to zero. This figure illustrates the complex nature of the interactions between trends in atmospheric variables such as temperature and precipitation and trends in water temperature and quality. Comparing Texas-wide average trends in air temperature (red symbols) with trends in water temperature (diamond shapes) shows that both are increasing but with proportionally greater changes in air temperature. The observed increase in average annual precipitation (blue symbols) is correlated with an increase in water temperature, phosphorus, pH, and specific conductance (upper right). Large increasing trends in phosphorus (circles) appear correlated with temperature and cold days (red and purple symbols).

Although our trend analysis was applied to all the water quality variables listed in Table 2, we do not discuss the results for variables where fewer than 20 reservoirs recorded significant trends over the period of record. However, it is important to note that lack of a significant trend with $p<0.1$ does not necessarily mean there is no trend; instead, lack of significance could be due to data sparseness. For that reason, this analysis should not be taken as definitive proof of absence of trend, but rather absence of information available to quantify a trend at this time.

DISCUSSION AND CONCLUSIONS

Using long-term water quality data collected at 59 Texas reservoirs, we identified 120 weather stations adjacent to or upstream of the reservoirs and analyzed trends in air temperature, precipitation, water temperature, and water quality parameters at the 57 reservoirs with sufficient data from 1960 to 2010. This period was defined by the length of available water data. Our purpose was to quantify recent trends in atmospheric and water conditions for Texas reservoirs, which are important sources of surface water for human consumption, recreation, agriculture, and aquatic ecosystems.

For air temperature, approximately one-third to one-half of

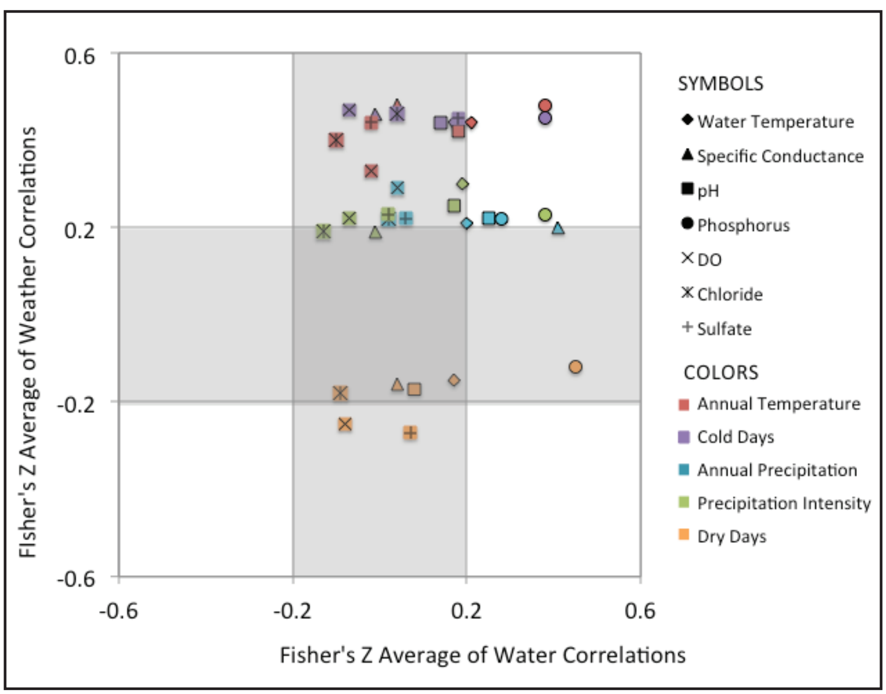

Figure 7. Comparison of the Fisher's Z transform trend magnitude (rho) of each water parameter averaged over all reservoirs showing a significant trend with that of each climate indicator averaged over all stations with significant trend and located nearby each reservoir. Colors represent water parameters and symbols represent the weather indicators.

stations showed significant increases in annual and seasonal temperatures, particularly in winter and summer (Figure 2a). The strongest and most consistent temperature-related warming trends were for cold temperatures; specifically, the average temperature of the 1, 3, 5, and 10 consecutive coldest days of the year and the number of days per year with minimum temperature below freezing.

Weather stations with significant warming trends are distributed across the state (Figure 4), suggesting that a larger-scale warming trend is being superimposed on local-scale variability that can modify the magnitude and even, for a few locations, the sign of the trend. Trends for the near-reservoir weather stations are consistent with Texas-wide trends documented by the NCDC's Climate at a Glance[3] averaging +0.3 °F per decade for annual, +0.5 °F per decade for winter, and +0.2 °F per decade in summer temperatures for the same time period.

For precipitation, a relatively small number of stations (8-13%) show significant increases in annual and seasonal amounts for every season except fall (Figure 2b). A much larger number of stations show significant trends in precipitation intensity (30%) and dry days (33%). In most locations, precipitation intensity is increasing and dry days are decreasing (Figure 5a,b). Increases in average precipitation increase the amount of rain in an event, while a decrease in dry days means that the same amount of precipitation is falling in more wet days. Additional analysis summarized in Figure 5c suggests that an increase/decrease in precipitation intensity is usually accompanied by a matching increase/decrease in the number of dry days. In some locations, an increase in precipitation intensity is also accompanied by an increase in average precipitation. These trends are consistent with an observed increase in the frequency of extreme precipitation events and time of day of DO measurement over the United States as a whole, as well as over the Great Plains region of which Texas is a part (USGCRP 2009).

In terms of changes in reservoir characteristics, nearly half the reservoirs show significant increases in water temperature (Figure 3, left). Given the widespread increases in air temperature observed across the state and the strong correlation between the magnitude of trends in air and water temperature for individual reservoirs (Figure 7), it is likely that water temperatures are responding to increases in air temperatures. Some locations show decreases in DO consistent with increases in water temperature; other locations, however, do not. This suggests that DO may also be moderated by other factors such as precipitation, where an increase in precipitation intensity and number of dry days is decreasing overall precipitation events and increasing DO, natural and human-induced loading of organic materials and associated bacteria-mediated decay, and biological processes (photosynthesis and respiration) (Figure 7).

Significant trends in 5 indicators of water quality were also identified for 49% to 73% of reservoirs (Figure 3). Of these 5 variables, pH, and phosphorus increase consistently across most locations (Figure 6c,d). The remaining 3 variables—sulfate, chloride, and specific conductance—show strong regional diversity. All are more likely to have positive trends in West Texas and negative trends in the central and eastern part of the state (Figure 6e-g).

In terms of the 2 variables that both show increases across the state, phosphorus shows the strongest and most consistently positive increases in 73% of reservoirs across the state. The majority of these increases are likely the consequence of phosphorus-containing fertilizers used in agriculture across the United States since the 1950s[4] and long-term accumulation of phosphorus in reservoir sediments. However, the increases could also be the result of an increase in nutrient runoff from other human sources: urban runoff, discharge of treated domestic waters. However, higher temperature and more intense precipitation events can also contribute by increasing evaporation and fertilizer runoff (Figure 7). With the exception of a small cluster of reservoirs in northeast Texas, pH also shows increasing trends at most reservoirs across the state. Increases in water temperature and nutrients might result in higher productivity in reservoirs; in turn, photosynthetic processes increase pH (Michaud 1994).

Specific conductance, sulfate, and chloride all show patterns of strong increases in the west and slightly weaker decreases in the east. Decreases in the central/eastern parts of Texas could be related to increased dilution of salts from increases in precipitation. Lacking any significant trends in dry days or indications of increased evaporation, which would tend to concentrate salts (other than that implied by increasing seasonal temperatures), the large increases in the western part of the state are more likely primarily from a decrease in reservoir water levels because of human withdrawals and possibly the effects of local activities such as oil and gas extraction (Vance 2006).

These findings have important implications for water quantity and quality in Texas reservoirs. Increasing air temperature may be contributing to increases in water temperature, decreases in DO, and increases in pH, which can affect the survival of aquatic life. Increases in phosphorus concentration could be from runoff from urban and agricultural lands and long-term accumulation of phosphorus in sediments. Increases in sulfate and chloride concentrations in West Texas reservoirs might be caused by proximity to ditches for oil-field discharge and saline water wells, as well as by decreases in water levels from human withdrawal. Increases in precipitation intensity (coupled, at some locations, with increases in the number of dry days) could have consequences on the streamflow rate and runoff events,

[3] http://www.ncdc.noaa.gov/cag/

[4] http://www.tfi.org/statistics/statistics-faqs

with direct impacts on reservoir water quality. Increases in precipitation intensity in areas dominated by agriculture, such as parts of West Texas, will result in increased nutrient runoff. This can contribute to reservoir eutrophication and could potentially create optimal conditions for golden algae blooms (Yates and Rogers 2011). More research is needed to determine how changes in air temperature and precipitation will affect water quality in Texas reservoirs. In our future work, we plan to quantify the influence of atmospheric predictors, flow rate, and water level on inter-annual variability and long-term trends, water temperature, and water quality variables. This will help to evaluate how long-term climate change will affect water quality over the coming century and the impact on aquatic biota, the local economy, water availability and treatment, and recreational activities throughout the state of Texas.

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APPENDIX A. WEATHER STATION DATA QUALITY CONTROL

Our quality control process for daily weather station data checks for and removes the following errors:

- minimum temperature greater than maximum temperature on the same day
- temperature values above the maximum or below the minimum record values in the continental United States
- precipitation values above the maximum record value in the continental United States or less than zero
- any values that are repeated exactly, to within one-tenth of the measurement unit, for 5 or more consecutive days

Through the quality control process, we identified errors in all but 1 of the 120 stations tested. Days where minimum temperature exceeded maximum temperature were identified in 4 out of 120 stations. No range errors were found for temperature or precipitation. The largest source of error came from temperature repeats. Both maximum and minimum temperature repeats occurred in more than 99% of the records, but non-zero repeats in precipitation were found in only 1 of the 120 stations. Despite the number of errors identified, the actual number of data points removed to account for all errors or questionable data points from each file was small (<1% and in most cases <0.1%), so this quality control process is not likely to affect the robustness of the trend analysis.

APPENDIX B. WATER DATA STANDARDIZATION PROCEDURE

The water temperature and quality observations used in this analysis come from a variety of sources. These observations were made at different depths at the same location over time, at different locations within the same reservoir, and different depths in different reservoirs. Before analyzing the data, it had to be standardized. To differentiate between water closer to the surface, which would be more strongly affected by short-term variations in temperature and precipitation over timescales of days to weeks, and deeper water, which would respond more slowly to longer-term changes over timescales of months to years, we standardized the water data to 2 mean depths: 1 above 10 feet (i.e. between the surface and 10 feet of depth) and 1 below 10 feet (i.e. between 10 feet of depth and the bottom of the reservoir).

A weighted mean of each water quality parameter for depths above and below 10 feet was computed for each available day using the concept of a layered model. Available depths in each reservoir determined the width of the layers within each zone (above and below 10 feet). The center of each inner layer was set at half the distance between 2 sampling depths, and the boundary layers were centered at 0, 10 feet or the lowest sampling depth by doubling the distance from the boundary to the center of the nearby layer. The weight for each layer was calculated as the vector sum of the layer width weight and inverse variance weight divided by 2. These weights were then used to calculate the weighted mean of each parameter in each zone (above or below 10 feet).