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PLAYA DYNAMICS AND SALINITY:
A STUDY OF YELLOW LAKE ON THE HIGH PLAINS OF TEXAS

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Abstract.—Saline playas on the Southern High Plains are almost always located on large cattle ranches but they are of limited value to the herds of cattle grazing around their outer margins. Saline playas are often without water for extended periods and, after inundation, they experience considerable evaporative loss leading to hypersaline conditions. The primary goal of this study was to develop a quantitative method that combines the transitory nature of playa lakes and the variability of salinity into a set of parameters that can be used to compare playas or other surface water sources. Regarding water quality, a variable was developed that describes the fraction of observations with salinity levels below the salt tolerance threshold for cattle. With regard to water availability, water depth measurements were used to compute the fraction of time that a playa contains water. These two variables are combined to form a new variable that represents the fraction of time that water is both available and of acceptable quality. To demonstrate the utility of this method, data was collected at Yellow Lake, a large saline playa located on the Yellow House Ranch northwest of Lubbock, Texas. Results suggest that the playa contained water 50.8% of the time over a five-year period but the fraction of water samples with acceptable salinity was only 6.5%. The resulting fraction of time that water was both available and of acceptable quality was only 3.3%. This technique could be used to compare other ephemeral surface water sources in the region.

Keywords: salt lakes, saline playas, water quality, Llano Estacado

The Southern High Plains is a vast region located at the southern end of the Great Plains of North America. This immense stretch of elevated plains is sufficiently distinct from surrounding areas to justify identification as a separate physiographic region (Cummins 1892; Fenneman 1931). The key distinguishing feature is its exceptionally level surface; a surface that generally lacks flowing streams or other forms of organized drainage (Germond 1940). One consequence of this lack of drainage is that rain tends to pool in numerous shallow basins

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called playas, forming ephemeral ponds called playa lakes (Russell 1895; Heintzman et al. 2017).

There are two types of playas on the Southern High Plains – the more numerous and relatively small freshwater playas and the often larger and less vegetated saline playas (Reeves & Parry 1969). Though both playa types share many common features, there are key differences, especially with regard to hydrology (Sabin & Holliday 1995). Freshwater playas lie well above the water table of the underlying Ogallala Aquifer (Wood et al. 1992). Runoff that collects in a freshwater playa is lost through a combined process of downward infiltration and evaporation (Evans & Meade 1945; Holliday 1997). As playa waters percolate downward through the upper sediments, salts are effectively transported away from the freshwater playa system (Wood et al. 1992). As a freshwater playa dries, plants take root and cover the playa surface (Haukos & Smith 1997; Gitz et al. 2013). The waters of a saline playa, on the other hand, cannot seep downward because of the presence of groundwater just beneath the playa surface (Baker 1915; Meigs et al. 1922). Exposed to sun and wind, the ponded waters of a saline playa dry solely by evaporation (Evans & Meade 1945), which leads to high salinity and a lack of vegetative cover on the dry playa surface.

On the Southern High Plains, most saline playas are located within rangeland, often occupying a significant amount of space near the center of large cattle ranches. These ranches support large herds of cattle and collectively contribute to the production of beef cattle, which is an important agricultural product in Texas (USDA-NASS 2019). However, these large saline playas are of little value to ranch managers since they are not a reliable source of water for cattle and dry playas typically provide little or no vegetation for grazing.

There is a limited amount of specific information regarding the physical and chemical characteristics of the ponded waters of saline playas on the Southern High Plains. There have been few long-term or systematic studies of these large saline playas from which to draw conclusions. However, some past measurements suggest that the salinity of playa lake waters can be highly variable (Irelan 1956; USGS 1967; Horne 1974). Following periods of heavy rainfall, playas can receive a considerable volume of water from rain that falls directly on the playa surface and from runoff from the surrounding rainfed catchment. A recently flooded playa can initially contain a significant volume of water with low levels of dissolved salts. As these waters evaporate, however, salinity levels can increase significantly and eventually the playa lake can become hypersaline.

Past research has focused primarily on the flora and fauna of saline playas of the Southern High Plains. The shallow waters of saline playas provide critical habitat for migrating and wintering waterfowl, including many shorebirds and sandhill cranes (*Grus canadensis*) and there has been a significant amount of research on these and other species (Johnson & Stewart 1973; Lovvorn & Kirkpatrick 1981; Melvin & Temple 1982; Haley 1983; Iverson et al. 1987; Littlefield 2010). In addition, there have been studies of phyllopod fauna in the saline waters of playa lakes, such as fairy shrimp (*Artemia salina*) (Sublette & Sublette 1967; Horne 1974). There have also been surveys of salt-tolerant aquatic plants, such as *Ruppia maritima*, which can be found growing in saline playa lakes when conditions are favorable (Kantrud 1991; Rosen et al. 2013). However, despite considerable effort, I have not found any publications that report direct measurements of playa lake depth for any of the saline playas on the Southern High Plains and I have found only a few publications that report specific information regarding the salinity of some saline playa lakes in this region.

The earliest known water samples were obtained in 1952 and 1966 when the Texas Water Development Board (TWDB), in cooperation with the U.S. Geological Survey (USGS), collected surface water samples from two saline playas named Bull Lake and Soda Lake (Irelan 1954; USGS 1967). The chemical analyses of these samples were published in reports titled “Chemical composition of Texas surface waters, 1952” and “Water resources data for Texas, 1967.” These annual publications are typically focused on flowing streams and reservoirs in Texas so it is quite rare to find information regarding saline playa lakes.

The most significant reconnaissance of saline playas on the Southern High Plains was conducted by Horne (1974), who studied the phyllopods of saline playas and managed to collect a number of water samples of some of the more well-known playas located south of Lubbock, such as Cedar Lake, Double Lakes, Guthrie Lake, McKenzie Lake, Mound Lake, Rich Lake, and a small, previously unnamed, playa called Snow Drop. No specific information regarding the depth of water in these playas was provided but Horne (1974) clearly recognized that "from the time of initial filling to complete drying, significant increases in salinity occur ..." The limited number of samples collected by Horne (1974) clearly show that the salinity of playa waters on the Southern High Plains can vary widely from one playa to another and, more importantly, salinity can vary significantly over time.

These early observations are valuable, however, they are of limited value when attempting to determine the dynamic relationship between playa ponding and salinity. None of the observations provide information regarding the depth of water at the time of sampling. In addition, specific conductance values are either single observations or there are multiple observations often spaced many months, years, or decades apart. An important goal of this field campaign was to obtain more frequent and more continuous observations of both salinity and depth of standing water during multiple ponding events over a period of many years.

This paper represents an attempt to develop a quantitative method that combines the ephemeral nature of playa lakes and the variability of salinity into a set of parameters that can be used to compare the water quality and water availability of playas or other surface water sources. Regarding water quality, a variable was developed that describes the fraction of samples with salinity levels below the salt tolerance threshold for cattle. With regard to water availability, a continuous series of water depth measurements were collected to compute the fraction of time that a playa contains water. Since a water sample can only be obtained when water is available, these two variables can be combined to form a new variable that represents the fraction of time that water is both available and of acceptable water quality. To demonstrate the utility of this method, data was collected at Yellow Lake, a large saline playa located on the Yellow House Ranch northwest of Lubbock, Texas.

MATERIALS & METHODS

For a water source to be of any value it must satisfy two criteria – water must be available and the water that is available must be of sufficient quality. It is possible to quantify both of these criteria for the waters of any lake or pond.

With regard to water availability, it is possible to use measurements of water depth to compute the fraction of time that a playa contains detectable standing water (depth greater than zero). For each observation one can define a binary variable β that is assigned a value of 0 when the lake bed is dry or assigned a value of 1 when playa lake depth is greater than 0. This may be written as:

$$\beta = \begin{cases} 0, \text{if depth} = 0 \\ 1, \text{if depth} > 0 \end{cases} \tag{1}$$

Note that when the playa contains water, the value of β is assigned a value of 1 regardless of the actual depth, as long as the depth is greater than zero. If we have N observations of playa lake depth then we can compute P, the "ponding time fraction" or the fraction of time that the playa contains standing water as:

$$P = \frac{1}{N}\sum_{i=1}^{N} \beta_i \ , \tag{2}$$

where *P* is a dimensionless fractional value that can vary from 0 to 1. Small values are associated with highly intermittent lakes that are often dry or simply have no standing water whereas large values, approaching 1, would indicate playa lakes that are often wet.

Regarding water quality, one can define a dimensionless variable, *S*, that describes the fraction of samples with acceptable water quality. For each water sample one can define a binary variable λ that is assigned a value of 0 when the concentration of dissolved salts is greater than or equal to a threshold value, *T*, or assigned a value of 1 when the concentration of dissolved salts is less than *T*.

$$\lambda = \begin{cases} 0, \text{ if salinity} \geq T \\ 1, \text{ if salinity} < T \end{cases} \tag{3}$$

If we have M water samples then one can compute the fraction of samples with acceptable water quality as:

$$S = \frac{1}{M}\sum_{i=1}^{M} \lambda_i \ , \tag{4}$$

where *S* is a dimensionless fractional value that can vary from 0 to 1. Small values of the salinity fraction are associated with water that is often too salty whereas large values, approaching 1, indicate ponded waters that almost always contain water that is safe to use.

Since a water sample can only be obtained when the playa contains water, the value of *P* defines the fraction of time when water is available and, therefore, water samples can be obtained. Thus, values of *P*, can be multiplied by the salinity fraction, *S*, to form a fractional value *R* that represents the fraction of time that water is both available and of sufficient quality, which may be expressed as:

$$R = P \cdot S \, . \tag{5}$$

The value of *R* can be demonstrated with a few simple examples. For example, suppose there is a perennial lake of hypersaline water with salinity values always well above the threshold value *T*. In this case,

$P = 1.0$ and $S = 0$ so that $R = 0$. This result suggests that livestock or wildlife will never find water of sufficient quality despite the fact that water is always available.

Now suppose there is a permanent lake with highly variable salinity. Again, the ponding time fraction $P = 1.0$ while the salinity fraction $0 < S < 1$. For example, if 50% of the water samples taken from the playa lake have salinity values less than T then $S = 0.5$ and combined with a P value of 1.0 results in an R number equal to 0.5. This suggests that livestock or wildlife will find water of sufficient quality half the time despite the fact that water is always available.

Now suppose we have an ephemeral lake with consistently low salinity. In this case, the ponding time fraction $0 < P < 1$ whereas the salinity fraction $S = 1.0$. If the playa contains standing water half of the time then $P = 0.5$ and combined with a salinity fraction $S = 1.0$ results in an R number of 0.5. Thus, the playa provides water of sufficient quality half the time despite the fact that low salinity water is always available when the playa is not dry.

Note that R numbers for the last two examples were both equal to 0.5 for very different reasons. In the first example, ponding was continuous while salinity values were variable whereas in the second example, ponding was intermittent while salinity values were consistently below T. In either case, both playas provide water of sufficient quality only half the time.

Of course, these are simple examples that provide insight into the value of computing R numbers. One can apply these same techniques to compute R numbers for any playa site as long as there is sufficient ponding and salinity data to fully characterize ponding continuity and water chemistry. Clearly, one would prefer data taken for more than a few years and samples obtained at different times during each year to better define seasonal patterns. The resulting R values computed for each playa site can then be used to compare playas with regard to their value as sources of water for livestock or wildlife.

Field Study.–There are fifty saline playas scattered across the Southern High Plains with a wide range of playa surface areas. The largest saline playa is Cedar Lake in Gaines County, Texas, with a playa surface area of 22.9 km^2. Salt Lake (also known as Arch Lake) in Roosevelt County, New Mexico, is the second largest with a playa surface area of 10.5 km^2. Other large saline playas include Shafter Lake (5.7 km^2), Mound Lake (5.1 km^2), Coyote Lake (3.7 km^2) and Illusion Lake (3.2 km^2). Yellow Lake, the focus of this study, ranks seventh with a playa surface area of 3.1 km^2.

Most saline playas are clustered within much larger closed basins that may have once held much larger playas. The Yellow House Basin (Figure 1), which contains both Yellow Lake and Illusion Lake, is the third largest closed basin on the Llano Estacado with a depression area of approximately 74 km^2 (Reeves 1966). It is likely that Yellow and Illusion lakes once formed a single continuous playa but today the two are separated by a thin “aeolian dam” formed by wind deflation and subsequent deposition of playa sediments derived from both playas. These two playas occupy the lowest level within Yellow House Basin at an altitude of 1,040 m above sea level, which is roughly 30 to 40 m below the level of the general land surface outside of the basin.

Periods of high rainfall intensity within Yellow House Basin can trigger significant runoff, which is divided unequally between the two playas. Yellow Lake tends to be the drier of the two playas, which suggests that Illusion Lake receives more runoff than Yellow Lake. Yellow Lake receives most of its water from intermittent stream channels called “draws” which primarily originate along the western margins of the basin. Runoff collected by Yellow Lake typically forms a broad shallow pool that occupies a limited fraction of the playa surface. Immediately following inundation, the ponded waters are cloudy with fine sediment. Water clarity tends to improve over time as sediments gradually deposit but strong winds can stir the waters and cause fine sediments to become re-suspended.

Figure 1. Aerial image of the Yellow House Basin, which contains two saline playas: Illusion Lake and Yellow Lake.

Anyone who has ever visited Yellow Lake when it is dry will swear that the lakebed is absolutely flat. However, when a playa lake is formed, the pool of water tends to center at a topographic low point on the playa surface, indicating that the surface is not truly flat. Strong winds can cause the shallow pool to slowly move about the lakebed, a phenomenon that has been observed at other locations (Motts &

Carpenter 1969; Torgersen 1984; Dinehart & McPherson 1998). As the shallow pool shifts position, water recedes from the upwind shore and may moisten downwind portions of the lakebed that were formerly dry, thereby increasing the overall surface area of evaporation. As winds abate, gravity will re-center the wandering pool to the topographic low point on the playa surface.

Gradually the pool shrinks both laterally and vertically as pure water is evaporated, leaving a moist clay surface. Desiccation cracks often appear when the surface dries sufficiently and further weathering forms clay aggregates that can be moved by the wind (Sweeney et al. 2016). The finest clay particles often become suspended by turbulent winds, forming dust clouds that may extend great distances downwind of the playa. Larger sand-size clay aggregates skip across the playa surface and deposit along the partially vegetated playa margins where they form clay dunes, known as fringing dunes or lunettes (Coffey 1909; Hills 1940; Bowler 1968). Unlike sand dunes, clay dunes do not migrate downwind from where they are first formed; rather, they tend to remain at playa margins growing with additional accumulations during successive periods of aeolian activity (Bowler 1973; Holliday 1997; Butler 2003). At Yellow Lake, clay dunes are found primarily along the eastern edge of the playa where they extend to as high as 40 m above the playa surface.

In preparation for the field study, a sampling system was constructed to measure the depth of ponded water at what was judged to be the lowest point on the playa surface (Figure 2). Key system components included an ultrasonic water-depth sensor, a tipping-bucket rain gauge, a data logger powered by a 12-volt battery, and a solar panel.

The water-depth sensor was mounted on an arm that extends from a small tower. The sensor has a transducer that emits brief pulses of ultrasonic waves directed toward the playa surface. The ultrasonic pulses either reflect off the playa surface or they bounce off the ponded waters of the playa lake and travel back to the sensor where they are detected by a microphone. The depth of ponded water is determined by

Figure 2. Sampling system resting on a dry and a wet playa at Yellow Lake.

detecting the time from the initial sonic pulse to the detection of the reflected sound wave.

As we began construction of the sampling system, we naturally wondered about the maximum possible water depth. Our system is designed to rest upon the lakebed and is not submersible, so the sensor and associated electronics must remain above the potential high-water mark. On the other hand, we were tempted to mount the sensor as close to the playa surface as possible since the depth sensor is more accurate when it is positioned closer to the target surface. Literature searches for information regarding potential water depth for Yellow Lake, or for any large saline playa on the Llano Estacado, uncovered no useful information. In the end we simply estimated the maximum depth to be less than 1 m and chose a height of 1.5 m for the sensor.

One month prior to deployment, the site was visited in an attempt to determine the best location for the sampling system. During this scouting trip, a small pool of water less than 10 cm deep occupied a portion of the playa surface. We waded into the water and marked the center of the pool. A few weeks later, we returned with the finished sampling system and found that the pool of water had evaporated. We pushed the sampling system across the muddy surface to the point we had marked earlier and secured the tower with stakes. We then powered up the system and made minor adjustments to the offset so that the depth sensor properly read zero when there was no standing water.

As with most transducers, it was found that the output from the depth sensor would gradually drift over time. Often, the sensor would falsely indicate a few millimeters of standing water when the playa was actually dry. To avoid this problem a camera system was developed to take one photograph of the playa surface each day. These photos were used to determine if and when there was standing water beneath the sensor. When photos revealed there was no standing water, a small correction was applied to compensate for drift. For those hours without photographic confirmation, the magnitude of the error correction was estimated by linear extrapolation between known values. This post-experiment processing of the final data set improved our ability to more precisely define periods of standing water.

Although depth measurements were collected continuously, water samples were collected intermittently by wading into the playa lake and filling a 250 mL bottle. The time and date of the sample was recorded so that it was possible to match the sample to a measured playa lake depth as recorded by the sampling system. Water samples were taken back to the lab where they were analyzed. Of primary interest was the electrical conductivity of the water sample at a temperature of 25 C, known as specific conductance. We used a calibrated Hach MP-4 conductivity sensor to measure specific conductance of each water sample. First, samples were allowed to “rest” so that fine sediments could settle to the bottom of the bottle and the temperature of the sample was allowed to approach a uniform room temperature of around 20–25° C before a preliminary specific conductance value was measured. The preliminary value was used to determine the best conductivity standard solution to use to calibrate the instrument. Typically, a conductivity standard was chosen that was close to or slightly higher than the preliminary conductance value. After the sensor was carefully calibrated, a final conductance value was measured and recorded.

Specific conductance is a measure of the ability of water to transmit a weak electrical current. The more dissolved solids in the water sample the greater the specific conductance. Thus, specific conductance correlates closely with the concentration of dissolved minerals within a water sample and can provide a convenient and rapid method for estimating the concentration of total dissolved solids (TDS) in water (Durfor & Becker 1964). Although TDS is most accurately measured by a careful chemical analysis, this method usually requires laboratory analysis by a trained chemist. As TDS and electrical conductivity of the water are usually highly correlated, it is more common and practical to measure specific conductance, rather than TDS (Lazarova et al. 2005; Wagner et al. 2006; USGS 2019). Unfortunately, there is no universal relation between specific conductance and total dissolved solids; rather, the relation is dependent on the specific ionic concentrations of dissolved minerals and must be determined empirically for each situation (Wagner et al. 2006).

RESULTS & DISCUSSION

Hourly values of water depth measured at Yellow Lake are plotted as a time series in Figure 3. Black lines indicate the depth of the playa lake in centimeters whereas white dots indicate water samples. Note that the vertical scale for each year is uniformly set at 0 to 50 cm, except for 2019. Overall, the results provide a fairly detailed record of the depth of standing water measured from January 2016 through September 2021.

There are numerous periods of ponded water and many periods with no standing water over the five-year sampling period. Variations in ponding activity generally reflect weather conditions, especially with regard to rainfall. Periods of heavy and frequent rainfall contribute to periods of enhanced ponding and prolonged drought can cause playas to remain dry for extended periods. Of course, water samples could only be collected when standing water was available.

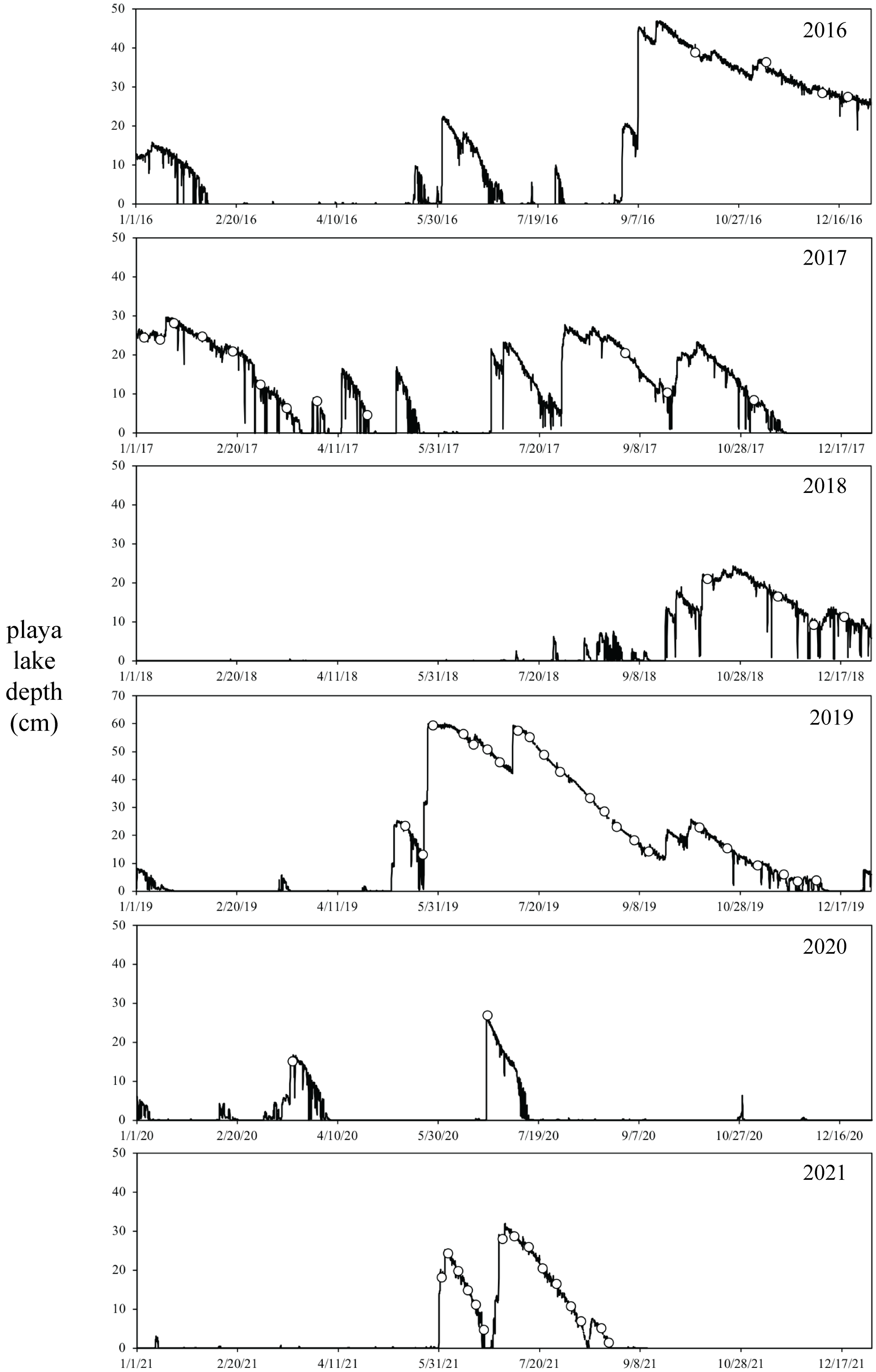

Figure 3. Hourly measurements of water depth at Yellow Lake 2016–2021. White dots mark the time and date of water samples.

Discrete periods of playa lake formation, referred to as "ponding events," appear throughout the record. A typical ponding event begins with an initial steep rise followed by a more gradual decline as the pool of water evaporates. Often, additional rain events will occur while the depth of the shallow lake is on the decline causing the depth to suddenly rise again, producing a complex saw-tooth pattern, and extending the life of a ponding event. In a region with potential evaporation rates as much as four to five times annual rainfall, the ponding event eventually ends as the playa lake is evaporated to dryness.

Throughout the record one can observe occasional instances when playa lake depth suddenly drops followed by a nearly full recovery despite no additional rainfall. Initially, it was assumed that our depth transducer was intermittently malfunctioning but it was later determined that these sudden and dramatic "dropouts" were associated with a wind-induced phenomenon that has been observed at other locations (Torgersen 1984; Drews & Han 2010). Winds blowing across a shallow pool for an extended period can temporarily move the playa lake away from the topographic low point such that there is little or no water beneath the sampling system. Once the winds slacken, the pool gradually returns under the force of gravity to occupy the lowest portion of the basin and the sampling system will once again record the proper depth. It is interesting to note that these wind-induced "dropouts" tend to occur less frequently when the playa lake is full since a deep lake also occupies more horizontal space and therefore has less space to move. In other words, the horizontal movement of a larger playa lake is more restricted as it is wedged against steep banks.

The peak water depth of 60.2 cm was recorded in the early morning of 29 May 2019. This high-water mark followed an exceptionally wet period that produced a single ponding event that persisted for 218 days beginning 7 May 2019 and ending 11 December 2019. Another long ponding event stretched from 25 August 2016 to 23 March 2017, a period of 210 days, reaching a maximum depth of 46.9 cm on 16 September 2016 at noon.

The mean depth of ponded water over the full five-year sampling period was 8.9 cm. Mean depth was obtained by averaging all hourly values measured during the 5-year sampling period, including the many hours of zero depth.

Water samples and salinity.–A total of 62 water samples were collected during this study, as summarized in Table 1 and marked with white dots in Figure 3. A larger number of samples would have been preferable but there are limitations. Perhaps the biggest limitation was that a water sample can be collected only when there is standing water in the playa. Throughout the full record there were long periods in which it was not possible to collect a water sample due to a lack of water. For example, a sample was collected in June of 2020 and after this ponding event ended, it was not possible to collect another sample until June of 2021.

Samples were collected over a wide range of playa lake depths and each water sample can be paired with a measured depth, as presented in Table 1. For example, a water sample was collected 28 May 2019 when the playa lake depth had reached a high point of 59.5 cm and a sample was collected when the playa lake depth was only 1.5 cm on 23 August 2021. All depth values represent the depth of standing water measured at the sampling system during a period of light winds. Samples were not collected when the playa lake was temporarily blown away from the sampling system by strong winds, as discussed earlier.

The relationship between playa lake depth and salinity is not intuitively obvious. A plot of specific conductance as a function of playa lake depth at Yellow Lake yields a scatter plot, as shown in Figure 4. Here we find that specific conductance tends to be relatively low when the playa lake depth approaches 60 cm but similar low conductance values are also found at shallow depths between 15 and 30 cm. Figure 4 also reveals that there is significant scatter at the low end of the scale.

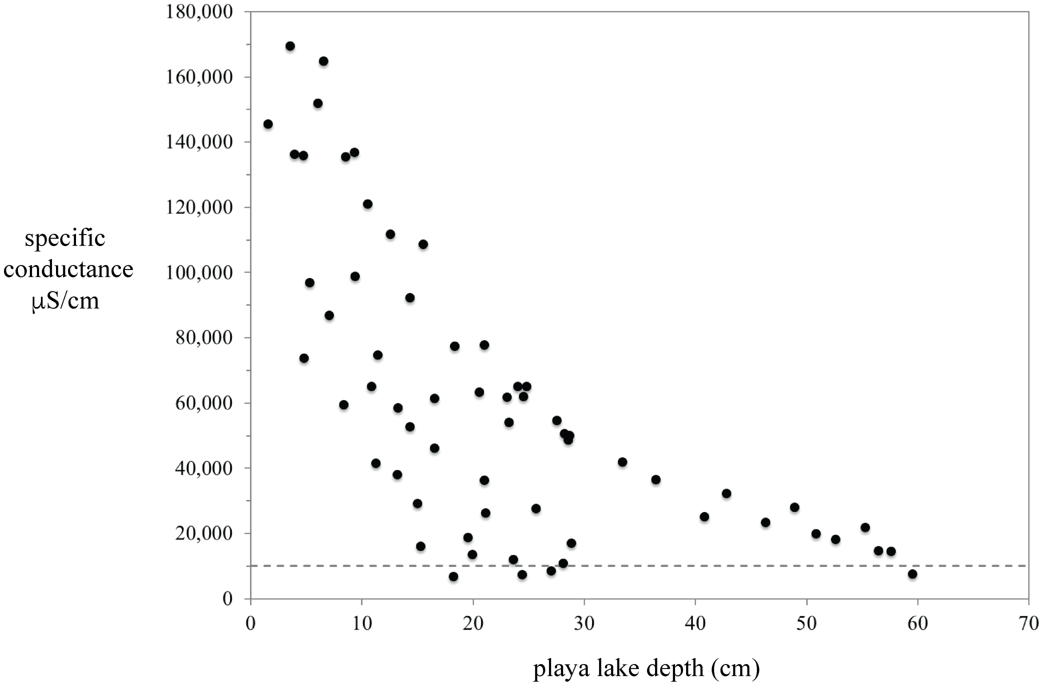

Figure 4. Playa lake salinity vs. depth at Yellow Lake. The dashed line marks the salt tolerance threshold for cattle, a specific conductance of 10,000 µS/cm.

The relationship between specific conductance and playa depth exhibits a form of hysteresis such that the salinity of playa lake waters can be very different when the lake is rising during the flooding phase of the ponding event compared to when the lake is declining during the evaporation phase. During the flooding phase, low-salinity rainfall and surface runoff pour onto the playa surface and, therefore, the initial pool will have relatively low levels of dissolved salts. During the evaporation phase, pure water is evaporated from the playa lake, leaving behind dissolved salts in a playa lake that is gradually shrinking in volume.

For example, suppose a newly formed playa lake reaches a peak depth of 20 cm. One would expect that the concentration of dissolved salts would be relatively low for a newly formed playa lake with a depth of 20 cm. Now suppose that a newly formed playa lake reaches a peak depth of 60 cm and then, after many months have passed, the playa lake is reduced to a depth of 20 cm due to evaporation. In this case, the concentration of dissolved salts would be expected to be relatively high when the playa lake depth reaches 20 cm. Thus, a playa lake can have a low or high concentration of dissolved salts at a given depth, depending on its history.

To complicate matters further, the history of a ponding event can be very complicated. A playa lake can form and then partially evaporate and then rise again due to additional rain events. This process of evaporation and replenishment can occur numerous times and, as a result, it becomes very difficult to estimate the concentration of dissolved salts based solely on the depth of the playa lake.

Overall, specific conductance values measured at Yellow Lake span a wide range of values from a low of 6,833 μS/cm to a peak value of 169,500 μS/cm. Low conductivity values are typically associated with newly formed playa lakes where runoff from rain events have recently flooded the playa whereas large conductivity values are typically associated with remnant pools that have undergone significant evaporation such that much of the pure water has evaporated causing the dissolved minerals to become highly concentrated.

It is interesting to note that the peak value of 169,500 μS/cm is more than three times that of seawater. The salinity and specific conductance of seawater can vary somewhat from one location to another (Forchhammer 1865); but for comparison purposes a "standard seawater" was adopted, which corresponds to the physical properties of seawater at mid-latitudes. Standard seawater has a salinity of 35,000 mg/L or an electrical conductance of 53,088 μS/cm at a temperature of 25° C (Lide 2004). Comparing the specific conductance of standard seawater to water samples collected at Yellow Lake we find that nearly half the samples (46%) have conductance values that exceed that of standard seawater and therefore are by definition "hypersaline."

Salt tolerance threshold.–To calculate the salinity fraction using Equations (3) and (4), one must first define the salt tolerance threshold *T* for the situation of interest. For example, one might consider if the salinity of Yellow Lake is ever low enough for humans. The EPA has established “National Secondary Drinking Water Regulations,” a set of non-mandatory water quality standards for 15 contaminants. The maximum level for total dissolved solids is 500 mg/L, which is approximately equivalent to 725 µS/cm. The lowest value measured at Yellow Lake, 6,833 µS/cm, is nearly an order of magnitude larger than the National Secondary Water Quality Standard for drinking water.

Even if one adopts a less stringent standard and only considers if the water can at times be considered “potable,” the waters of Yellow Lake still come up short. According to the CRC Handbook, the conductivity of potable waters in the United States ranges generally from 50 to 1500 µS/cm (Clean Water Team 2004). The conductivity values of Yellow Lake are nearly 4.6 times larger than the upper limit for potable waters. Clearly, the salinity of playa lake waters at Yellow Lake tend to remain well above levels safe for human consumption.

Livestock, however, can tolerate much higher levels of dissolved salts in their drinking water, although a review of past research reveals some disagreement regarding the salt tolerance of livestock. The lack of consensus suggests a need to consider a number of factors when evaluating a water source for livestock use. Important factors include the type, age, and sex of the animals; whether they are pregnant or lactating; the intensity of animal activity; local climatic conditions; type and amount of minerals in the diet; moisture content of feed; type and level of salts in the water; access to other sources of water; and whether or not animals have been adapted to the salty water (National Research Council 1974). Most of these factors are difficult to control in animal experiments so the relative importance of some factors remains uncertain. Nevertheless, over the past century a consensus has developed with regard to general guidelines for the salt tolerance of various animals under normal environmental conditions.

It is generally agreed that goats and sheep are more salt tolerant than cattle and cattle are more tolerant than swine, poultry or horses (Ramsay 1924). The focus of this paper is on cattle since, on the

Southern High Plains, most saline playas are located on cattle ranches. It is important to point out that cattle need salt in their diet. Substances such as nitrates and sulfates may be beneficial at low concentrations but are harmful at high levels (National Research Council 1974). The consumption of highly mineralized waters can cause physiological disturbances of varying degrees of severity (McKee 1952).

An early study of saline water on dairy cows conducted in South Dakota by Larsen & Bailey (1913) compared the performance of cattle that drank rainwater collected from the roof of a barn and saline water collected from a nearby well drilled into saline groundwater. Of course, rain water is mostly free of dissolved salts and the brackish groundwater had as much as 7,369 mg/l of dissolved solids. They found that dairy cows would initially refuse to drink if they were suddenly switched from freshwater to saline water but would eventually drink the water if the salinity level was gradually increased or if the cows became very thirsty. They concluded that dairy cows receiving saline water for a period of about two years suffered only minor problems and analyses of their vital organs revealed nothing abnormal.

Another early study by Embry et al. (1959) concluded that waters with 7,000 ppm or more of soluble salts caused little, if any, real damage to livestock, but because of taste qualities and laxative effects from certain salts these waters could not be considered satisfactory for livestock. Incorporating a reasonable margin of safety to provide for exceptional conditions, Embry et al. (1959) concluded that water with over 7,000 ppm of soluble salts should be considered unsatisfactory for livestock.

Perhaps the most cited review of the literature on salt tolerance of animals was performed by the U.S. National Research Council Subcommittee on Nutrient and Toxic Elements in Water (National Research Council 1974). This report, published by the National Academy of Sciences, summarized existing data on the effects of saline waters on livestock and set forth general guidelines. They concluded that waters within a range of 5,000–7,000 mg/l “can be used with reasonable safety for dairy and beef cattle…" The range of 7,000–10,000 mg/l may present considerable risk for pregnant or lactating cows and water with concentrations greater than 10,000 mg/l was not recommended for use under any conditions.

More recent guidelines, mostly published as "fact sheets," tend to be more cautious. For example, Faries et al. (1998) and Looper & Waldner (2002) suggested that the 5,000–7,000 mg/l range should be avoided for pregnant animals and baby calves. Higgins et al. (2008) and Gadberry (2016) cautioned that the 5,000–7,000 mg/l range may lead to reduced performance in cattle. Sallenave (2016) suggested that the 5,000–7,000 mg/l range is marginal for beef cattle and waters of the 7,000–10,000 mg/l range should be avoided for all animals if possible. In conclusion, it appears that the concentration of total soluble salts of around 7,000 mg/l is a threshold value above which more serious adverse health effects begin to appear.

If we define the salt tolerance threshold T for cattle to be 7,000 mg/l, then it is possible to compare this value to water samples collected at Yellow Lake (Table 1). However, values of specific conductance and the salt tolerance threshold have different units and therefore are not directly comparable. To compare the measured values of specific conductance to the 7,000 mg/l threshold one could convert all 62 measured values of specific conductance to TDS units of mg/l; however, this conversion could introduce errors since the exact relationship between specific conductance and TDS is uncertain over a wide range of concentrations. One alternative is to convert the 7,000 mg/l salt tolerance threshold to a value of specific conductance for comparison to the 62 water samples. Thus, only the salt tolerance threshold value of 7,000 mg/l needs to be converted to units of μS/cm and no conversion would be necessary for the 62 water samples.

It has been found that total dissolved solids (TDS) can be estimated from measurements of specific conductance (SC) assuming a linear relationship between these two parameters as $\mathrm{TDS} = A \cdot \mathrm{SC}$, where A is a scaling factor with appropriate units that depend on the units of

Table 1. Playa lake depth and specific conductance of water samples collected at Yellow Lake, Hockley County, Texas.

sample date	playa depth (cm)	specific cond. (μS/cm)	sample date	playa depth (cm)	specific cond. (μS/cm)
08/22/2012 09:25	19.5	18870	07/15/2019 09:50	55.2	21940
09/20/2012 10:05	13.2	58550	07/22/2019 08:30	48.9	28090
08/23/2013 10:00	14.3	52848	07/30/2019 08:01	42.8	32300
10/05/2016 09:00	40.8	25150	08/14/2019 08:00	33.4	42050
11/09/2016 14:00	36.4	36690	08/21/2019 08:00	28.6	50180
12/07/2016 12:30	28.5	48840	08/27/2019 09:05	23.2	54190
12/20/2016 11:00	27.5	54760	09/05/2019 08:00	18.3	77428
01/04/2017 12:30	24.5	62080	09/12/2019 12:21	14.3	92400
01/12/2017 10:28	24.0	65157	10/07/2019 13:15	23.0	61900
01/19/2017 10:08	28.2	50780	10/21/2019 09:18	15.5	108700
02/02/2017 12:00	24.8	65077	11/05/2019 10:51	9.3	136900
02/17/2017 11:40	21.0	77878	11/18/2019 15:00	6.0	152000
03/03/2017 11:00	12.5	111900	11/25/2019 10:38	3.5	169500
03/16/2017 09:30	6.5	164900	12/04/2019 13:10	3.9	136300
03/31/2017 09:45	8.3	59610	03/18/2020 12:05	15.3	16100
04/25/2017 08:45	4.7	135900	06/23/2020 12:30	27.0	8621
08/31/2017 09:00	20.5	63490	06/01/2021 08:20	18.2	6833
09/21/2017 09:30	10.5	121100	06/04/2021 09:40	24.4	7383
11/03/2017 09:11	8.5	135500	06/09/2021 07:50	19.9	13730
10/11/2018 15:35	21.1	26330	06/14/2021 07:40	15.0	29300
11/15/2018 15:07	16.5	61510	06/18/2021 07:33	11.2	41710
12/03/2018 11:20	9.3	98900	06/22/2021 06:58	4.8	73940
12/18/2018 09:43	11.4	74850	07/01/2021 09:09	28.1	10860
05/14/2019 09:15	23.6	12050	07/07/2021 07:36	28.8	17170
05/23/2019 08:40	13.1	38070	07/14/2021 08:50	25.6	27820
05/28/2019 09:20	59.5	7567	07/21/2021 08:25	21.0	36360
06/12/2019 09:46	56.4	14860	07/28/2021 07:30	16.5	46240
06/17/2019 10:04	52.6	18188	08/04/2021 10:13	10.8	65110
06/24/2019 10:20	50.9	19960	08/09/2021 08:05	7.0	87000
06/30/2019 11:20	46.3	23560	08/19/2021 11:05	5.2	97000
07/09/2019 08:50	57.6	14550	08/23/2021 07:30	1.5	145700

TDS and SC (Hem 1985). In most natural waters at a temperature of 25°C, it has been found that the scaling factor, *A*, typically lies within a range from 0.55 to 0.7 when TDS is expressed in mg/l and SC is expressed in μS/cm (American Public Health Association 1955). For example, the Australian Laboratory Handbook of Soil and Water Chemical Methods recommends a scaling factor, *A*, of 0.67 (Rayment & Higginson 1992) whereas Curran (2014) recommends a value of 0.64 and Durfor & Becker (1964) recommend a value of 0.65.

For a salt tolerance value *T* of 7,000 mg/l (expressed as total dissolved solids) and assuming the scaling factor *A* can vary from 0.55 to 0.7, the range of SC values can vary from 10,000 to 12,727 µS/cm. The value of the salt tolerance threshold for cattle, *T*, is not meant to be a precise value but rather it is more of an order of magnitude. Typically, values of SC for each water sample will either be well above or well below the value of the salt tolerance threshold *T*. Here we chose the lower end of the range or *T* = 10,000 µS/cm as the salt tolerance threshold for cattle.

Water quality and water availability.–Over the entire five-year sampling period, 62 water samples were collected and only 4 of these water samples had specific conductance values less than a *T* value of 10,000 µS/cm. Thus, the computed salinity fraction *S* for Yellow Lake is 0.065, which suggests that salinity was less than *T* for 6.5% of all the samples collected over the five-year sampling period.

With regard to water depth, a total of 43,354 hourly depth observations were collected from October 2016 through September 2021 and a total of 22,103 values were greater than zero. Thus, the computed ponding time fraction *P* was 0.508, which suggests that a pool of water was available for 50.8% or roughly half of the time.

Since the fraction of samples with acceptable salinity levels for cattle *S* is 0.065 and the ponding time fraction *T* is 0.508, the resulting *R* number is 0.033, which suggests that water is both available and of acceptable quality for only 3.3% of the time at Yellow Lake.

CONCLUSIONS

The issue of water quality and freshwater availability is of great concern across the Southern High Plains region. Water continues to play a critical role in the success or failure of West Texas farms, cattle ranches, and the rural communities they support. As groundwater resources are gradually depleted, it may become necessary to consider water sources that were once considered to be of little value.

For a source of water to be of value to livestock or wildlife it must not be highly ephemeral and it must be of adequate water quality. Saline playa lakes on the Southern High Plains, such as Yellow Lake, fall short with regard to both of these criteria. Saline playas are often dry and the salinity of these shallow lakes can vary from brackish to hypersaline. But not all playas are alike. At the outset of this project, however, it was not clear how to quantify these characteristics so that one could compare one playa lake to another. The primary goal of this study was to develop a quantitative method that could combine the transitory nature of playa lakes and the variability of salinity into a set of parameters that could be used to compare playas.

Regarding water quality, a dimensionless variable S was developed that describes the fraction of samples with acceptable water quality. With regard to water availability, a continuous series of water depth measurements was used to compute the fraction of time that a playa contains water, called the ponding time fraction P. Since a water sample can only be obtained when the playa contains water, it is possible to combine these two variables to form a new variable R that represents the fraction of time that water is both available and of acceptable water quality.

For the case of Yellow Lake, the ponding time fraction P was equal to 0.508, which suggests that cattle will find water slightly more than half the time. During those periods when the playa contains water it was found that the salinity fraction S was equal to 0.065 or, in other words, 6.5% of all of the water samples have a salinity level that is below the salt tolerance threshold T of 10,000 μS/cm. It is important to point out that this does not mean that cattle might be able to drink playa lake waters 6.5% of the time, it simply means that 6.5% of the water samples were below the salt tolerance threshold. To determine the fraction of time that water is both available and of acceptable water quality the two factors P and S must be multiplied together to form another dimensionless fraction R. In the case of Yellow Lake, the R number is 0.033, which suggests that water was both available and of acceptable water quality only 3.3% of the time over the five-year sampling period.

It is not surprising that the value of *R* for Yellow Lake is a very small number. It is well known that the waters of any saline playa lake are of little value to cattle and cattle raisers. The results of this study demonstrate that the magnitude of an *R* number generally reflects the value of a surface water source for watering cattle. If we were to use this same technique for a freshwater playa or for man-made cattle tanks, the *P* and *S* values and the resulting *R* number would likely be much higher, suggesting that these water sources are potentially more valuable. Unfortunately, data regarding the water depth and water quality of freshwater playas and cattle tanks have not been collected and so it is not yet possible to compute *R* numbers for these surface water sources.

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