REMOTE SENSING OF THE SURFACE AREA OF WEST TEXAS PLAYA LAKES FROM THE SENTINEL-2A/B SATELLITES

by

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ABSTRACT

The numerous playa lakes found across the Southern High Plains, USA are valued for both their ecological importance and as potential sources of aquifer recharge. The surface water area of these small ephemeral lakes varies significantly due to the highly variable rainfall patterns observed. While a few aircraft and satellite studies have previously studied the larger playa lakes in the region, no known study has utilized the high-resolution capabilities of the European Space Agency's Sentinel-2A/B twin satellites to study thousands of smaller playa lakes. In this study, we analyze variations in playa lake area across Western Texas, USA using data from the Sentinel-2A/B satellites. Playa lake surfaces are identified using the Semi-Automatic Classification Plugin for QGIS. This study demonstrates the feasibility of utilizing Sentinel-2A/B satellite data to both operationally monitor the state of playa lakes across the region for ecological and hydrological applications, as well as potentially identify which playa lakes contribute the most to groundwater recharge.

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CHAPTER 1

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INTRODUCTION

A distinguishing characteristic of the Southern High Plains of North America is the presence of over 50,000 spatially isolated (e.g., disconnected) playa lakes, with over 19,000 playa lakes in West Texas alone (Sublette and Sublette 1967; Smith 2003). Playa lakes are an important hydrological feature in the region and are known ‘biodiversity hotspots’ and a potential source of aquifer recharge (Bartuszevige et al. 2012). Playa lakes are generally defined as ephemeral, depressional lakes within an arid or semiarid region that evaporate during dry periods. While playa lakes exist in both topographically open and closed basins (Rosen 1994), most playa lakes in the Southern High Plains are closed basins, or basins with no surface water outflow. Within closed basins, evaporation and restricted groundwater infiltration are the only escape mechanisms for water within the hydrological cycle.

The geological formation processes for playa lakes in the Southern High Plains are poorly understood (Osterkamp and Wood 1987). Over much of the region, the bottoms of playas are lined with clay that can both dry out and crack or seal with time (Parker et al. 2001). Playas can contribute to recharge through both annular (along the playa edge) or focused (along the playa bottom) infiltration. The extent to which playas contribute to aquifer recharge is an area of ongoing research (Osterkamp and Wood 1987; Scanlon and Goldsmith 1997; Gurdak and Roe 2010). Annular recharge can only occur when the water level in a playa higher is than the clay lining on the playa floor. This allows water to seep down through the more permeable soils found along the playa rim. Recharge may also occur directly through the floor of the playa, although how much water is able to percolate through the clay-lined floors found in many playas is debated (Scanlon and Goldsmith 1997; Wood 1999; Scanlon 1999; Gurdak and Roe 2010). As discussed by Moorhead et al. (1998), "Seepage (in playa lakes) can be minimized by a nearly impermeable lining of montmorillonitic clay soil." In the far Southern High Plains and the adjacent areas of the Rolling Plains (especially south of Midland/Odessa), some playa lakes are located in and near areas underlain by limestone and appear to lack clay-lined floors. The playas in these so-called 'Karst' areas may respond differently to rainfall events and may contribute more rapidly to aquifer recharge through limestone fractures below the playa bottom (Stein and Ozouna 1996).

The Southern High Plains playa lakes are typically very shallow (less than 1m in depth), range in width from tens of meters to several hundred meters, and have typical surface areas of 0.1–1.0km^2 (closed basin drainage areas of 1 to 4km^2) (Sissom 1976; Thurman et al. 2000). As discussed by Howell et al. (2019), the water quality and hydrodynamic cycle in playa lakes are controlled by many factors, including the size of the playa drainage area. Playa runoff may originate from both rainfall and surface irrigation.

Playa lakes are observed to go through regular cycles of inundation and desiccation, but little research has been done on how these ecosystems may respond to climate change (Starr and McIntyre 2020). The inundation and spatial extent of playa lakes has high variability due to irregular precipitation patterns that occur across the region. The mean annual precipitation for Amarillo, Texas between 1947-2020 was 19.70 inches, with a maximum of 36.67 inches recorded in 1960 and a minimum of 7.02 inches recorded in 2011 (Figure 1). Typically, most of the precipitation falls between April and September, with the winter months being drier, although this too is highly variable. Most of the precipitation in spring and summer originates from thunderstorms, which may deliver large amounts of rain to relatively small areas over short periods of time.

As discussed by Bolen et al. (1989), the "shallow, circular basins" of playa lakes provide "localized sites of ecological diversity." These playa wetlands provide critical habitat for many species of mammals, birds, amphibians, and invertebrates (Smith 2003). Migratory shorebirds also depend heavily on playa lakes for habitat and feeding (Davis and Smith 1998; Andrei et al. 2009). Many species of waterfowl use playa lakes as either breeding sites, stopover sites during migration, or as wintering habitat. Large numbers of sandhill cranes (*Antigone canadensis*) overwinter in the Southern High Plains and use playas as roosting sites. Playas wetlands are also important breeding habitat for amphibians such as the spadefoot toads (*Spea* sp.) and tiger salamanders (*Ambystoma* sp.) (Ghioca-Robrecht et al. 2008; Bagwell 2012).

Playa lakes are also important for aquifer recharge to the Ogallala Aquifer (Fernandez-Canel et al. 2019). However, the magnitude and importance of this recharge remains uncertain and an active area of research (Osterkamp and Wood 1987; Gurdak and Roe 2010; Scanlon et al. 2010; Johnson et al. 2019). The Southern High Plains region depends heavily on groundwater from the Ogallala Aquifer to sustain the local economy. The Ogallala Aquifer is an unconfined aquifer, stretching from southern South Dakota, through Nebraska, parts of Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and the Texas Panhandle. The Ogallala Formation primarily consists of unconsolidated sand and gravel. Most of these sediments are between 2-6 million years old, and originated in upland areas to the west.

Analysis of Southern High Plains playa lakes from satellite for both ecological and hydrological applications has been the subject of dozens of research papers and reports over the past few decades. Because water has a distinct reflectance signature that contrasts sharply with most land surfaces, it is relatively easy to characterize water versus land surface areas from satellite. Starr and McIntyre (2020) analyzed several decades of Landsat imagery over a region of West Texas, and found significant decreases in the average playa lake water spatial coverage between 1980 and 2008, as warmer and drier conditions overtook the region and irrigation practices changed. A study by the Texas Water Development Board (TWDB) in 2003 analyzed 300 Landsat satellite scenes between 1985 and 2000 across thousands of playa lakes across West Texas to classify playa lake water holding times and determine their suitability for aquifer recharge. The TWDB study found that "58.6 percent, or 11,275 playas…hold water more than 75 percent of the time." It concluded that these playas would not support significant infiltration to the aquifer (TWDB, 2003). In contrast, some of the playas were dry most of the time, and likely more supportive of aquifer recharge or groundwater infiltration. However, the TWDB study used Landsat imagery. Landsat imagery has a spatial resolution of 30m, which would not capture the numerous smaller playa lakes less than

100 m in diameter. The TWDB study also made no attempt to look at sequential changes in playa lake level over time (TDWB 2003).

A number of recent studies have investigated variations in lake and wetland surface area from the novel, high-resolution Sentinel-2A (launched in 2015) and Sentinel-2B (launched in 2017) satellites (e.g., Yang et al. 2017, 2020; Xing et al. 2018; Soomets, et al. 2019; Zhang et al. 2020). To the author's knowledge, no study has yet utilized Sentinel-2 mission data to analyze ephemeral playa lakes from space. Sentinel-2 satellite data has approximately three times the spatial and temporal resolution of the previously used Landsat imagery.

In this study, 10-meter resolution reflectance imagery from the European Space Agency Sentinel-2 mission is used to analyze the spatial and temporal changes in water surface area (comprised mainly of playa lakes) over two case study regions in West Texas, USA (shown in Figure 2). Region 1 is selected to represent a classic playa lake environment in the center of the Ogallala Aquifer beneath mainly clay lined soils and hypothetically in a region with lower infiltration rates, while Region 2 is on the southeastern edge of the Ogallala Aquifer in a region with Karst geology, where higher infiltration rates would be expected (Figure 2).

The purpose of this study is to investigate the suitability of using Sentinel-2 satellite retrievals to study the spatial and temporal changes in playa lakes in Western Texas. Specifically, this study seeks to answer the following four questions:

1) *To what extent can time series of Sentinel-2 mission satellite imagery be used to improve understanding of the spatial and temporal variability in West Texas playa lake inundation?*

2) *Do the rates of change in playa lake surface water area vary as a function of time, lake size, and region?*
3) *What new insights do high spatial (~10 m) and temporal (~5 days) resolution satellite imagery from the Sentinel-2A/B satellites provide into the hydrodynamics West Texas playa lakes not available from legacy satellite imagery (e.g., Landsat)?*
4) *Can time series of Sentinel-2A/B satellite imagery be utilized in concert with surface meteorological data to estimate the relative magnitudes of evaporation and ground water infiltration from thousands of playa lakes across the Southern High Plains?*

Ultimately, this study aims to provide a 'feasibility study' on the utility of using high-resolution satellite imagery to monitor the current state of playa lakes on the Southern Great Plains for ecological and hydrological applications and to estimate potential groundwater infiltration rates from playa lakes. While previous studies have used satellite data to examine playa lakes, they primarily used Landsat satellite data (e.g., Howard et al. 2003; Gitz and Brauer 2016). Landsat has a spatial horizontal resolution of about 30 m, which is too coarse to resolve the smallest playas located across the region. Using images from the Sentinel-2A/B satellites, with their 10m spatial horizontal resolution, this study is able for the first time to evaluate smaller playas that have not been previously studied. Each Sentinel-2 satellite also has a 10-day return frequency, such that the combined return frequency of the two satellites (every 5 days) is far improved compared to the 16-day return interval of Landsat.

This study is organized as follows: Chapter 2 elaborates on the Sentinel-2 mission data used and the classification methods and calculations employed to calculate playa lake water surface area. The study results for several case studies are given in Chapter 3. A summary of the key findings of this research and a discussion of the implication for ecological and hydrological applications associated with playa lakes, as well as recommendations for future research are given in Chapter 4.

CHAPTER 2

METHODS

In this chapter, the data and methods used in this study are described. First, the study region and case study periods chosen for analysis are discussed. Next, details on the Sentinel-2A/B satellite data are provided, followed by information on supporting precipitation and evaporation data sets. Finally, the GIS classification and raster algebra processing techniques are described.

Study Region and Case Study Periods

In this study**,** the changes in playa lake surface area over the two regions shown in Figure 2 were analyzed. The first region (hereafter referred to as Region 1) is selected to represent a classic clay-lined playa lake environment in the center of the Ogallala Aquifer that is hypothetically in a region with potentially lower infiltration rates. In contrast, the second region (hereafter referred to as Region 2) is on the eastern edge of the Ogallala Aquifer in a Karst geological zone, where higher infiltration rates would be expected (Figure 2). Within Region 1, two small 5x5 kilometer regions were selected to quantify differences in the temporal evolution playa lake surface area for a region dominated by larger or smaller playa lakes (Figure 3).

Sentinel-2A and 2B satellite imagery with supporting ancillary data sets were analyzed for each of the two study regions of interest (Region 1 and Region 2, shown in Figure 2) for two time periods: September 2019 – February 2020 and April – July 2021

Sentinel-2A/B Satellite Data

Changes in playa lake surface area over the two regions shown in Figure 2 were analyzed by evaluating sequences of satellite images from the Sentinel-2A and Sentinel-2B satellites. The Sentinel-2 mission is comprised of two polar-orbiting satellites in a sun-synchronous orbit, phased at 180° to each other. The goal of the mission is to monitor land and ocean surface variability (Drusch et al. 2012). Sentinel-2A was launched by the European Space Agency (ESA) on June 23, 2015 and has a return frequency of approximately 10 days, assuming no clouds. Sentinel-2B was launched March 7, 2017, in the same orbit but phased at 180° from Sentinel-2A, and also with a return frequency of approximately 10 days. Utilizing imagery from both Sentinel-2A and Sentinel-2B giving a return frequency of data over any given area of earth approximately every 5 days.

The Multi-Spectral Imager (MSI) on the Sentinel-2 satellite contains 13 spectral bands. These bands are shown in Table 2, and vary in wavelength from 442.7 nm to 2202.4 nm and include both visible and infrared bands. The visible reflectance band images from these satellites (channels 2, 3, 4, 8) have a resolution of approximately 10m, which is 3 times the resolution of previously widely utilized Landsat satellite.

The Sentinel-2A/B satellite data were downloaded through the Copernicus Open Access Hub maintained by the European Space Agency. A free account allowed easy downloading and retrieval of the satellite images. In total, 87 satellite scenes (each occurred on a different day) from the Sentinel-2A and 2B satellites were downloaded and 21 of these satellite scenes were fully analyzed. A 2TB external hard drive provided adequate storage for storing the satellite images, which were 96 GB total in size (~1.1 GB per file). Each downloaded Sentinel-2A/B satellite data zip file (which contains 13 files for each of the 13 bands described below) was 10980 pixels by 10980 pixels at 10m resolution. A smaller 3000 by 3000 pixel subsection was selected for analysis (either Region 1 or Region 2, Figure 2) from the larger parent image. The water surface area within each 3000 by 3000 pixel region of the Sentinel-2A or 2B satellite imagery was then identified using the Semi-Automatic Classification Plugin (Congedo 2016) in QGIS (QGIS 2021). The QGIS software and Semi-Automatic Classification Plugin was run on a Windows 10 OS laptop with an Intel i7-9750H processor.

Precipitation and Evaporation Data Sets

Several precipitation and evaporation estimate data sets were used in this study. Daily precipitation data was obtained from the National Climate Data Center (NCDC) for Plainview, Texas (for Region 1), as well as radar precipitation estimates from the Advanced Hydrologic Prediction Service (AHPS) website: https://water.weather.gov/precip/. Monthly evaporation estimates from the Texas Water Development Board (TWDB) were obtained from the online download portal at: https://waterdatafortexas.org/lake-evaporation-rainfall. TWDB provides evaporation estimates on gridded one-degree latitude by one degree longitude quadrangles for the entire state of Texas. The 'gross lake evaporation' rate, which is defined as the 'water loss caused by evaporation' was derived from Class A pan evaporation data.

Classifying Playa Lake Water Surfaces and Playa Lake Area Calculations

The QGIS Semi-Automated Classification Plugin (Congedo 2016), available from: https://plugins.qgis.org/plugins/SemiAutomaticClassificationPlugin, was used to classify the type of land cover and identify playa lakes using spectral signature analysis in the QGIS Geographic Information System software, available from: https://www.qgis.org/en/site. A wide variety of techniques exist in the scientific literature for identifying water surfaces from satellite, using threshold values for different spectral bands (as discussed earlier, 13 spectral bands are available from Sentinel-2A/B satellite). The most common approach to estimate water surfaces is using the Normalized Difference Water Index (NDWI) or related algorithms (Gao 1996; McFeeters 1996; Xu 2006), which uses the differences between visible and near infrared channels to distinguish between water and non-water surfaces. In this study, the spectral signatures of band data from bands 2, 3, 4, 5, 6, 7, 8, 8A, 11, and 12 (Table 1) were utilized to identify water surfaces. The Semi-Automatic Classification Plugin utilizes the unique spectral signatures from these various bands to classify all water-covered regions within each image.

The entire workflow from within the Semi-Automatic Classification Plugin is briefly described here. First, the satellite data is downloaded from the ESA Copernicus Open Access Hub: https://scihub.copernicus.eu/. Second, the Sentinel-2 images are converted to reflectance values and an atmospheric correction is applied. Third, the Sentinel-2 reflectance band data is then clipped for the regions of interest to minimize storage and computational time requirements. Fourth, the Semi-Automatic Classification Plugin is used to create a database of spectral signatures using the various band data, which is then used to identify or 'classify' the water surfaces in the Sentinel-2 imagery. Several regions of interest (ROI) for each of the major landcover types are manually selected using the Semi-Automatic Classification Plugin graphical user interface (GUI), such as cropland, urban land, and water. The Semi-Automatic Classification Plugin then separates the spectral signatures of the different types of surfaces. The spectral signatures of the different selected land use types are subsequently used to classify every pixel of each satellite scene. An example of the result of the output from applying the classification process to a small region in West Texas is shown in Figure 4, where various lakes and various cropland can be classified and distinguished by the Semi-Automatic Classification Plugin based on their reflectance signatures. In this study, all lake surfaces within a range of spectral signatures were grouped together in creating the final maps, since the purpose of the classification was to identify water surfaces, but not to categorize different types of water types (e.g., silty versus clear water).

The total number of pixels and resulting surface area of playa lakes within each satellite image were then calculated using the raster layer unique values report tool in QGIS. The number of pixels and surface area were then calculated for each sequential image to calculate the changes in playa lake surface area in the case studies for the analysis in Regions 1 and 2.

CHAPTER 3

RESULTS

In this study, temporal variations in playa lake surface area were analyzed using Sentinel-2A and 2B satellite data obtained over Region 1 and 2 (Figure 2). For Region 1, results from two case study periods (September 2018 – February 2019 and March – July 2021) are presented.

Playa Lake Variations: September 2018 - February 2019

Several rainfall events occurred across West Texas between September 20 and October 20, 2018, bringing between 3 and 10 inches of rainfall to West Texas (Figures 5 and 6). In Region 1, only a few of the larger playa lakes had retained water prior to this rainfall event (Figures 7). The playa lake surface water area estimated from classified Sentinel-2A/B satellite imagery for Region 1 from September 25, 2018 to February 17, 2019 is listed in Table 2 and are shown graphically in Figure 9 and spatially in Figure 7. The corresponding "true color" image, which shows different land use, such as vegetation and other land surfaces for the corresponding time periods is shown in Figure 8. Between September 25 and October 3, the total playa lake area across Region 1 increased from 1.1 to 8.2 square kilometers (Table 2). Additional increases in total playa lake surface area from 8.2 to 14.5 square kilometers was noted between October 3 and October 10, 2018. These two increases in playa lake surface area can be directly attributed to two main rainfall events – one in late September and another around October 9 (Figure 5). Several additional smaller rainfall events between October 10 and October 28 were sufficient to maintain the total playa lake surface area in Region 1 to 14.6 square kilometers on October 25, increasing slightly to a peak Region 1 playa lake surface area of 15.2 square kilometers on October 18, 2018 (Table 2).

The wet period noted from late September through October 2018 shifted to a dry weather pattern for all of November and the first half of December 2018, followed by several light precipitation events from late December 2018 – February 2019 (not shown). The absence of significant precipitation during the November through February period implies that the observed rates of change in playa lake surface area across Region 1 should be primarily due to evaporation or groundwater infiltration and not runoff within these closed basins. Between October 25, 2018 and February 17, 2019, a steady decrease in the total playa lake surface area across Region 1 was noted (Figure 9). While clouds blocked the satellite retrievals on 36 of the 54 available Sentinel-2 images between September 25, 2018 and February 17, 2019, the available retrievals indicate temporal variations in the rate of decrease in playa lake surface area during the study period. In-between October 28 and November 19, the playa lake surface areas average rate of change in Region 1 was a decrease of ~0.33 square kilometers per day. In the following 3 months between November 19 and February 17, the rate of decrease was about a quarter that of the earlier period, averaging about 0.08 square kilometers per day (Table 2 and Figure 9).

The rates of change in playa lake surface area were also observed to vary between lakes of different sizes. Figure 3 delineates the location of the small and large playa sub-regions within Region 1. Within the sub-region that was analyzed that comprised of mostly smaller playa lakes, a more rapid decrease in water surface area was noted compared to the sub-region that contained primarily larger playa lakes (Figures 10 and 11). This is particularly noticeable during the first month after the heavy rainfall event (late October to late November 2018), when the playa lake surface area decreases by ~75% in the "small lake" sub-region but only by around 30% in the "large lake" sub-region during this period.

Within Region 2, only 2 cloud-free images were available during the September 2018 – February 2019 time period, precluding a detailed analysis in this region. As shown in Figure 12, limited differences in lake area are seen between October and November 2018, except for the flooded Centralia Draw seen on October 10, 2018, which only has water in it after a heavy rainfall (Figure 12).

Playa Lake Variations: April - July 2021

The time period between April and July 2021 was characterized by multiple periods of rainfall that saw the removal of severe drought across West Texas (Figure 13). Widespread heavy rainfall between 3 and 10 inches was noted across the region in June alone (Figure 14). As is often the case with predominantly thunderstorm or convective precipitation, large variations in rainfall over small distances were observed. This was the case in Region 1 during June 2021, with total rainfall in the region between 15 June and 15 July 2021 varying by as much as 4 inches over less than 10 kilometers (Figure 15). All playa lakes in Region 1 were dry with no surface water observed on April 25, 2021 (Table 3 and Figure 16). However, as spring and summer rainfall began in May, some increases in playa lake surface water were noted, with 2.76 square kilometers of playa lake surface area in Region one on June 9, 2021. However, it was not until very heavy rainfall occurred in the northern and western portions of Region 1 in late June and early July 2021 that more significant increases in total playa lake surface area of 15.23 square kilometers were noted (Table 3). However, those areas in the southeastern third of Region 1 where less rainfall was observed saw only minimal increases in playa lake surface area, whereas large increases were noted elsewhere (Figures 15 and 16).

In the Karst region (Region 2 in Figure 2), very few changes were noted between available imagery during the April — July 2021 time period. Most of the shallow depressions in the region noted on Google Earth or from Sentinel-2 mission data showed no water collecting even after periods of rainfall. An example image of one these depressions is shown in Figure 17. Visual analysis of two satellite imagery taken 10 days apart on June 6 and June 16, 2021 indicated a rapid decrease in water surface area in several small playa lakes in the southern portion of Region 2 in the center of the Karst limestone region (Figures 18 and 19).

CHAPTER 4

DISCUSSION

The improved spatial, spectral, and temporal resolution of Sentinel-2 satellite imagery has allowed for many small, variable inland water bodies such as rivers, glacial lakes and rice paddies to be studied globally for the first time from space. This study is the first to the authors' knowledge to demonstrate the feasibility of using Sentinel-2 satellite mission imagery to quantify spatial and temporal changes in playa lakes in the Southern High Plains, USA. The high spatial resolution (10 meters) and frequent satellite overpasses (every 5 days) has revolutionized the ability to analyze the thousands of typically small and variable bodies of water such as the playa lakes of the Southern High Plains.

Key Research Study Findings

The main findings of this research are summarized below in the partial answers to the initial questions posed in the introduction.

- *To what extent can time series of Sentinel-2 mission satellite imagery be used to improve understanding of the spatial and temporal variability in West Texas playa lake inundation?*

This study demonstrated that applying a water surface classification algorithm to Sentinel-2 mission satellite imagery results in spatially and temporally coherent data sets for investigating the surface extent of playa lakes larger than 30m (3 pixels) wide. Cloud cover was found to restrict the available imagery over 50% of the time during the Region

1 case study. Despite this, sufficient satellite retrievals were obtained to demonstrate both temporal and spatial variability in playa lake inundation. Average annual cloud cover over West Texas is less than 50%. Despite the selection of an anomalously cloudy period in this study, the usefulness of Sentinel- 2 mission satellite imagery for studying spatiotemporal variations in playa lakes was still demonstrated. The monitoring of spatiotemporal variations in small, seasonal wetlands has been conducted in other areas (Kordelas et al. 2018; Yang et al. 2020) but not before for playa lakes to the authors' knowledge. Sentinel-2 satellite data has also been used worldwide for a number of recent studies on the seasonal hydrology and wetland dynamics (for example, alpine wetlands (Carlson et al. 2020) and thermokarst and glacial ponds (Watson et al. 2018; Chand and Watanabe 2019).

Significant temporal variability in playa lake inundation was noted, ranging from no observable surface water area during drought conditions of April 2021 to over 15 square kilometers of surface water area following rainfall events in both October 2018 and July 2021. The rate of change in playa lake area also varied over time and from Region 1 and Region 2. Within Region 2, several playa lakes lost their water very quickly, while other depressions never filled with water, indicating the potential for identifying closed basin depressions that may provide enhanced groundwater recharge from satellite. *In situ* analysis and validation of these locations combined with satellite imagery is needed to verify this hypothesis.

- *Do the rates of change in playa lake surface water area vary as a function of time, lake size, and region?*

The case studies analyzing playa lake surface area in Regions 1 and 2 for several time periods demonstrated that the rates of change in playa lake surface water area vary as a function of time, lake size, and region. In Region 1, rainfall variations were directly correlated with variations in playa lake surface area in both the October 2018 – February 2019 and April – July 2021 time periods. Smaller lakes were found to lose water surface area more quickly than larger playa lakes, and both large and small playa lakes were observed to decrease in surface water area more quickly at higher water levels than at lower water levels. One hypothesized reason for this observed difference may be an increase in playa water infiltrating into the ground (potentially through annular recharge) when the playa lakes are fuller, but more detailed analysis of individual playas with *in situ* data is needed to further test this hypothesis. The pan evaporation rates across Region 1 during the October 2018 – February 2019 period (Table 4) were relatively constant, implying that the differences in rates of decrease in surface water area noted between October 2018 and February 2019 are likely not driven by changes in evaporation rates.

- *What new insights do high spatial (~10 meter) and temporal (~5 days) resolution satellite imagery from the Sentinel-2A/B satellites provide into the hydrodynamics West Texas playa lakes not available from legacy satellite imagery (e.g., Landsat)?*

This study has demonstrated that changes in playa lake surface area on times scales on 5 days (time between satellite passes) can be obtained in cloud-free conditions from the Sentinel-2A and 2B satellites. No previous studies to the author's knowledge have ever used satellite data to evaluate temporal changes in playa lakes on time scales less than yearly (conducted with Landsat). In addition, this is the first study to evaluate utilizing satellite imagery to identify water within numerous smaller playas (less than 100 m in diameter). The ability to operationally monitor these playas on a 5-10 day time scale could be of benefit to ecological and hydrological managers across the Southern High Plains.

- *Can time series of Sentinel-2A/B satellite imagery be utilized in concert with surface meteorological data to estimate the relative magnitudes of evaporation and ground water infiltration from thousands of playa lakes across the Southern High Plains?*

This study demonstrated that changes in playa lake water surface area over short periods (5 days or less) can be regularly obtained from the Sentinel-2 satellite, although cloud cover limits the availability of data in some situations.

Satellite data are already being used to assist with determining Groundwater Recharge Potential (GWP) (e.g., various biophysical and environmental factors estimated from Google Earth imagery, such as geomorphology, soil, land use land cover, slope, and aspect assisted in assessing the groundwater recharge potential (GWP) by Chaware et al. 2020). As previously noted, evaluating the changes in playa water inundation from satellite may be useful for identifying playas with higher groundwater recharge potential. Gitz and Bauer (2016) found in a study of 3 clay-lined playas surrounding Lubbock, Texas that water loss exceeded potential evapotranspiration by a factor of 1.6-15.7, implying significant ground water infiltration in the playa lakes they surveyed. At the far southern end of the Ogallala Aquifer, a recent study found evidence through isotopic analysis that increases in aquifer levels resulted from playa lake recharge (Davidson et al. 2019). Some playa basins infiltrate water to the aquifer quickly while other playa lakes are nearly perennial with little ground water infiltration (TDWB 2008). Satellite analysis like that which is employed here could potentially quantify those playa lakes where infiltration rates are highest by identifying playa lakes with rapid decreases in surface water area. While case studies have demonstrated that variable infiltration and aquifer recharge occur from playa lakes on the southern Great Plains, *in situ* monitoring of potential water inflow, evaporation, and infiltration rates for the tens of thousands of Southern High Plains playa lakes is simply not feasible due to the large number of small playa lake basins occurring throughout the region. The high-resolution Sentinel-2 mission satellite data in combination with survey data on playa depth and nearby meteorological data (to determine evaporation rates) may be a major step forward in being able to estimate playa lake groundwater recharge relatively cheaply and extensively across the Southern High Plains.

Thus, assuming that accurate information pertaining to playa depth, basin drainage area, and precipitation, wind, and humidity were available, then the relative magnitudes of evaporation and ground water infiltration could be determined from the rates of change in satellite-derived playa lake surface area. One ongoing research question is whether ‘focused recharge’ occurs via the playa floor or the playa edge (annulus). In this study, the decrease in surface playa lake surface water area in Region 1 was found to decrease faster when the playas were more filled immediately following rain events than when they were smaller in size. Thus, it is possible that some of this difference could be attributed to increased annular recharge when the playa lakes are higher in level, but this cannot be proven without supporting *in situ* data or more accurate water budget analyses infiltration rates.

Recommended Future Work

This research has demonstrated the feasibility of utilizing the Sentinel-2 mission satellite imagery to quantify rates of change in playa lakes for several case studies in West Texas, USA. While time and technical constraints limited the scope of this study, this research could be expanded to benefit ecological and surface and groundwater management across the Southern High Plains. There are a number of threats to playas, and usage of high-resolution satellite imagery may help to better understand and respond to these threats. For example, many playas have been modified for agricultural purposes, typically by digging pits or ditches to concentrate and direct water. Roads built through playa basins impact the flow of water. Sedimentation caused by runoff from agricultural areas limits the amount of water playas can hold and can impact the infiltration of water into the surrounding soil. Overgrazing by livestock can destroy playa vegetation that provides food and shelter for wildlife. Increased monitoring of changes in playa lakes from satellite would improve quantification of these multitudinous threats.

Based on the preliminary ‘proof-of-concept’ usage of Sentinel satellite imagery to quantify the current state of playa lakes on the Southern Great Plains presented in this study, the following future work is recommended:

- *Near real-time monitoring of playa lake surface area over broad areas.* This recommended future work could be conducted by any number of state ecological or water resource agencies willing to invest in a robust workstation and a part-time programmer or geographic information system (GIS) analyst. Monitoring could be extended to cover much larger areas than were possible in this study. An automated system could be set up to download the free Sentinel-2 imagery and identify water surface area using a classification system such as the QGIS Semi-Automated Classification Plugin (Congedo 2016). Automated classification algorithms would need to be tested to determine the best method for accurately classifying water area. Two additional Sentinel satellites are planned to be deployed in the next few years, which would double the current temporal resolution and data availability.

- *Identifying fast-draining playas.* Earlier studies (TWDB 2003) showed that some playa lakes drain more quickly than others, but the Landsat data available at that time was insufficient for mapping most of the smaller playas, and was too infrequent to conduct the highly resolved temporal analysis presented in this study. Sentinel-2 imagery combined with datasets delineating playa basins could be analyzed over a wider area and longer time period than in this study to identify fast-draining playas which may be more important to conserve as they could be contributing more focused aquifer recharge.
- *Estimating aquifer recharge rates from Sentinel-2 data.* This would require combining *in situ* depth sensors and elevation surveys or data sets with Sentinel-2 imagery to accurately quantify potential groundwater infiltration and aquifer recharge. Two additional Sentinel-2 satellite are expected to be launched in the next few years, which will double the temporal resolution capabilities for this type of analysis. A robust analysis would also need to include accurate weather station

data (for evaporation estimates) and precipitation data (for inflow estimates) to be able to accurately determine groundwater infiltration rates.

- *Classify playa water quality with Sentinel-2 imagery*. Changes in the turbidity of water results in variations in the satellite reflectance. Coupling the satellite reflectance data with *in situ* water quality sensors for a "training set" of playa lakes could potentially be used to obtain water quality information for many thousands of playas where installing *in situ* sensors is not feasible. Because the satellite reflectance signatures differ between waters of differing turbidity and quality, properties of the water quality or wetland vegetation types can potentially be estimated from satellite reflectance imagery (Toming et al. 2016; Tian et al. 2020). Investigating this topic in greater depth is recommended for future work over the Southern High Plains playa lakes.

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Table 1. Sentinel-2A/B Satellite Bands.

Spatial resolution (m)	Band number	Sentinel-2A		Sentinel-2B	
		Central wavelength (nm)	Bandwidth (nm)	Central wavelength (nm)	Bandwidth (nm)
10	2	492.4	66	492.1	66
	3	559.8	36	559.0	36
	4	664.6	31	664.9	31
	8	832.8	106	832.9	106
20	5	704.1	15	703.8	16
	6	740.5	15	739.1	15
	7	782.8	20	779.7	20
	8A	864.7	21	864.0	22
	11	1613.7	91	1610.4	94
	12	2202.4	175	2185.7	185
60	1	442.7	21	442.2	21
	9	945.1	20	943.2	21
	10	1373.5	31	1376.9	30

Table 2. Playa lake surface water area estimated from classified Sentinel-2A and 2B satellite imagery for Region 1 from September 25, 2018 to February 17, 2019.

Date	Water Area (square kilometers)		
	North Study Area	Small Pond Subregion	Large Pond Subregion
9/25/2018	1.0829	0.1313	0.2612
10/3/2018	8.2211	0.8026	0.8546
10/10/2018	14.3083	0.7105	1.806
10/25/2018	14.4102	0.9217	2.2141
10/28/2018	15.1795	1.1664	2.3473
11/2/2018	12.6756	0.6279	2.0141
11/19/2018	9.8409	0.2728	1.7169
12/14/2018	9.0151	0.1463	1.6559
12/27/2018	8.5002	0.1115	1.5123
1/18/2019	7.0222	0.0519	1.29
1/23/2019	6.4821	0.0364	1.2385
1/31/2019	5.228	0.0055	1.003
2/17/2019	3.9383	0	0.7412

Table 3. Playa lake surface water area for Region 1 from April 25, 2021 to July 9, 2021.

Date	Water Area (square km)
4/25/2021	0
6/9/2021	2.7684
6/16/2021	1.3105
7/9/2021	15.2308

Table 4. Estimated evaporation calculated by the Texas Water Development Board from November 2018 – February 2019 for Region 1 in this study.

Month	Monthly Gross Lake Evaporation Estimate (inches)
November 2018	3.41
December 2018	2.85
January 2019	2.53
February 2019	3.67

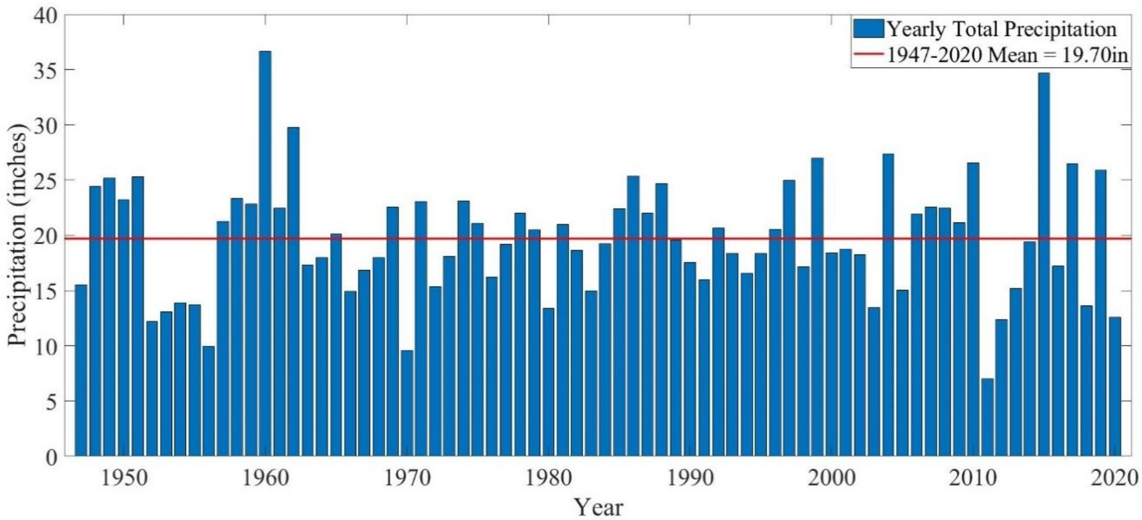

Figure 1. Annual precipitation for Amarillo, Texas from 1947-2020. Data source: National Climate Data Center.

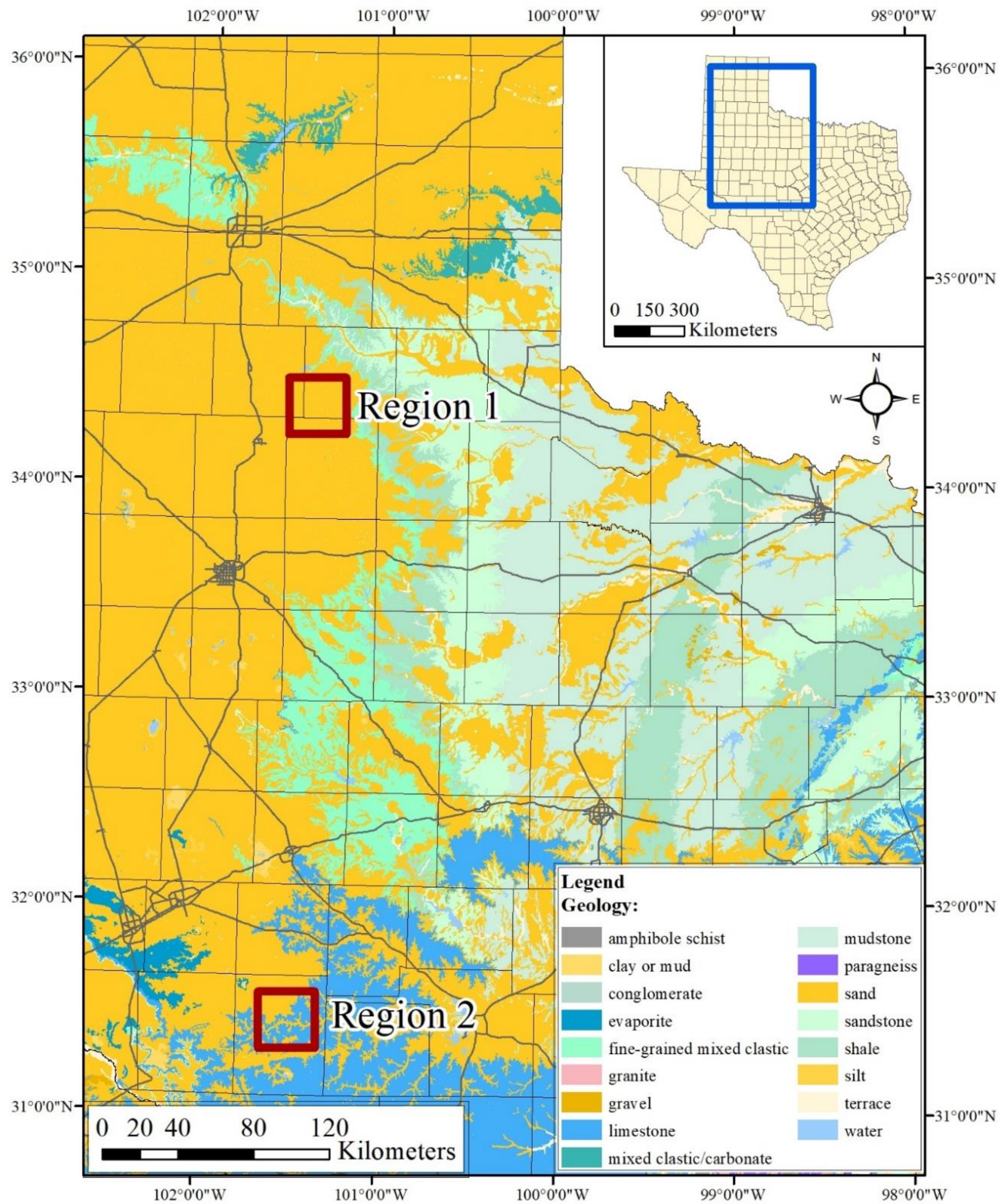

Figure 2. Map showing the geology of Texas and the 2 subregions (Region 1: northern clay-lined playa region and Region 2: southern karst limestone region) where playa lake surface area was analyzed in this study.

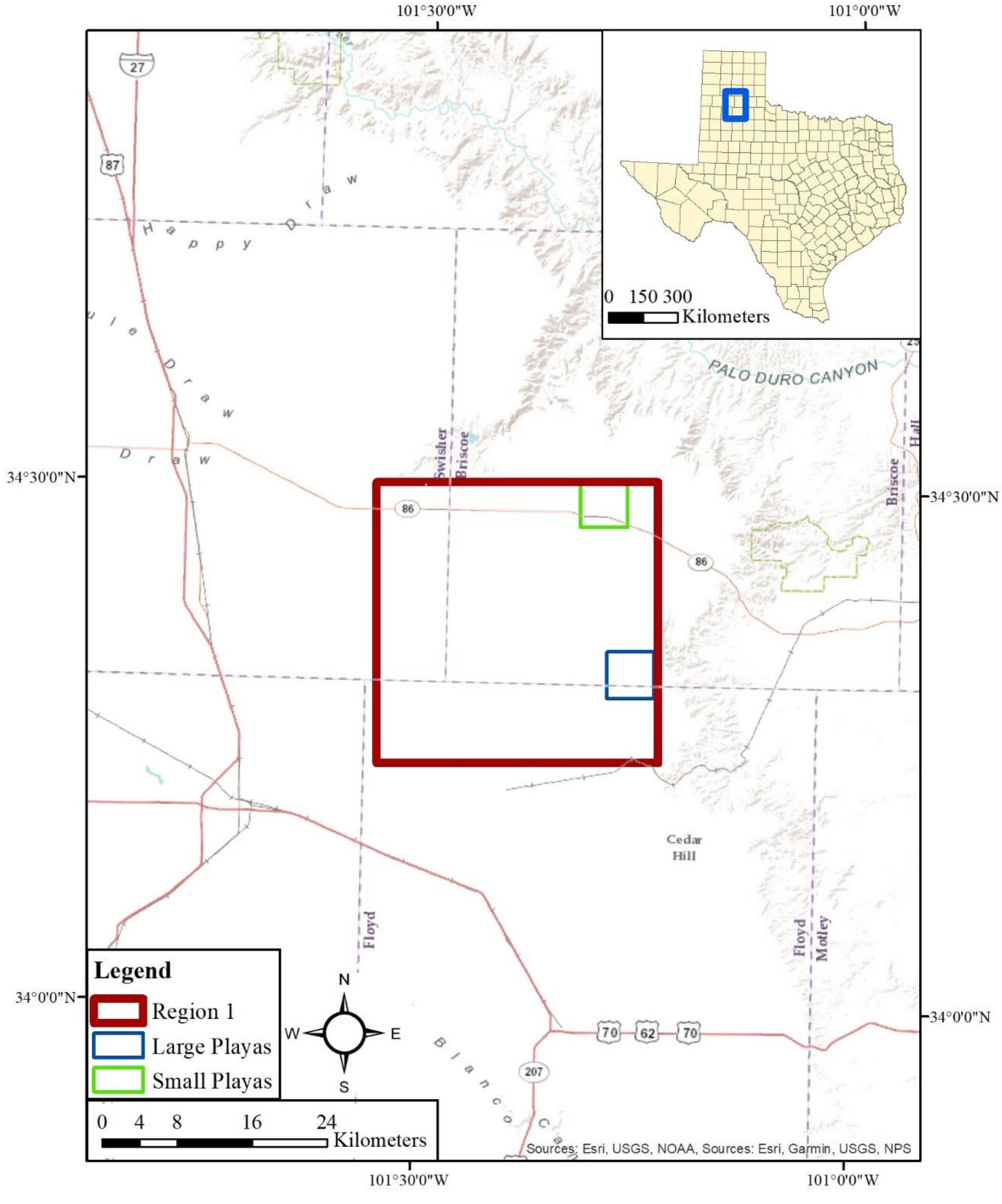

Figure 3. Close-up map of Region 1 (brown box). The small green box delineates the location of the 'small playa lake' zone while the blue box delineates the location of the 'large playa lake' zone.

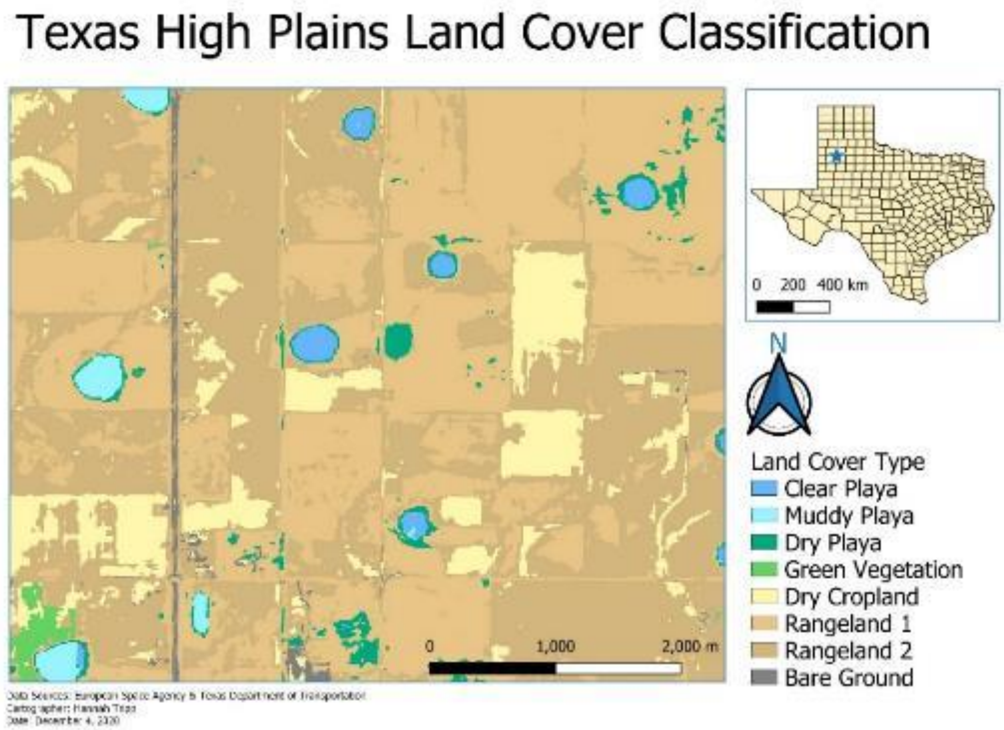

Figure 4. Example of Sentinel-2A Satellite Imagery from October 13, 2019 over West Texas, USA illustrating the 'spectral classification' of various land and water surfaces using the QGIS Semi-Automatic Classification tool (Congedo 2016).

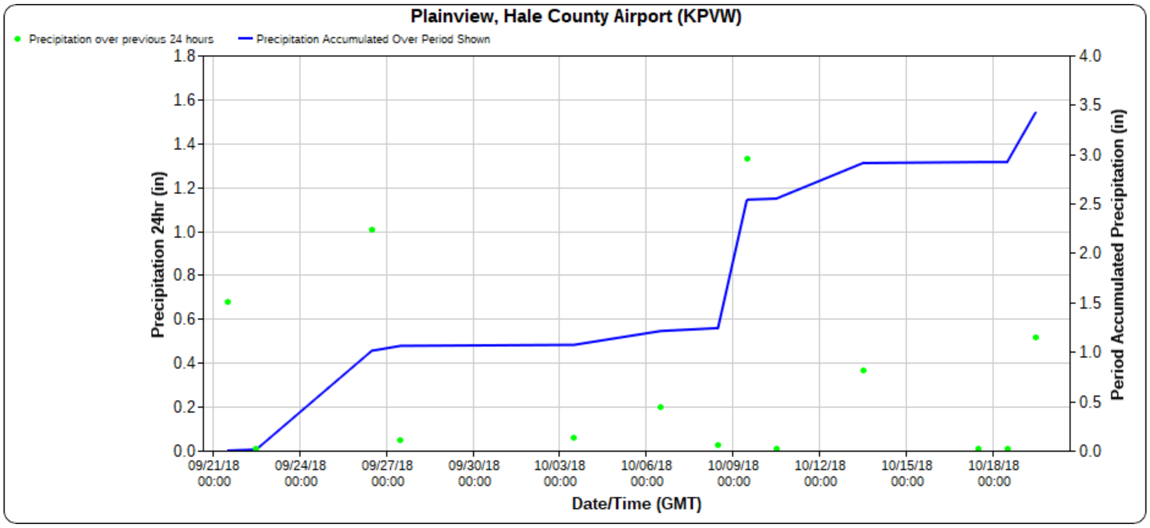

Figure 5. Precipitation (both individual events shown by green dots and cumulative rainfall shown by the blue line) at the Plainview National Weather Service weather station between September 21, 2018 and October 21, 2018.

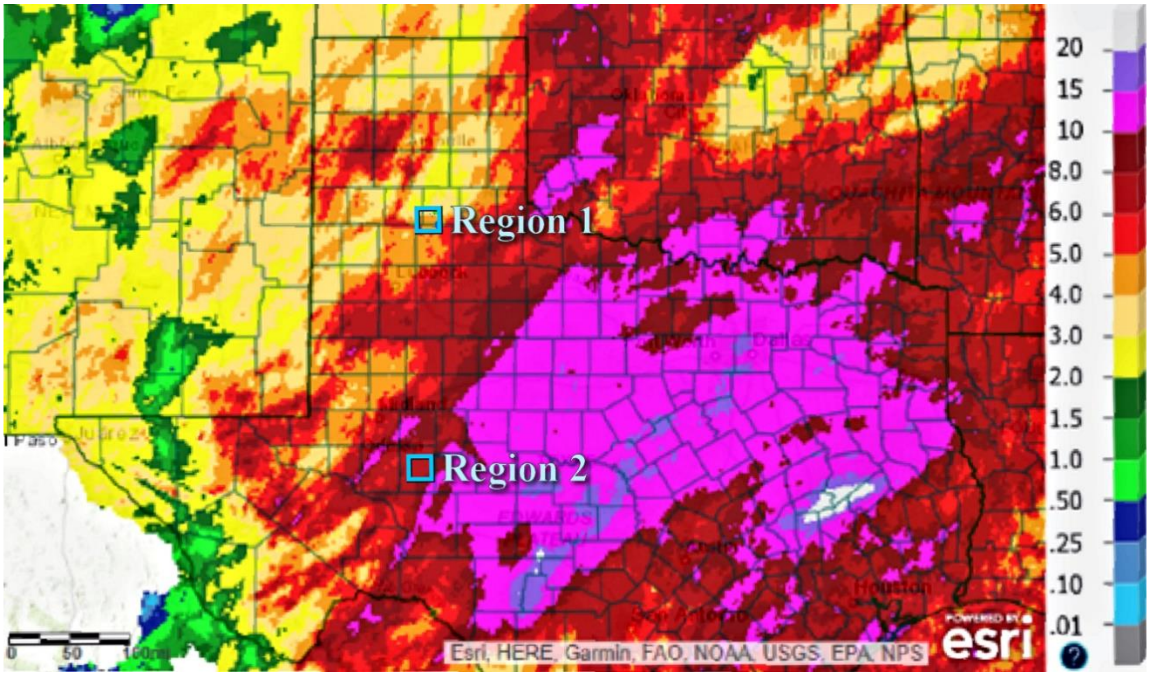

Figure 6. Radar estimated precipitation in Texas and surrounding states for October 2018. Map courtesy of the National Weather Service Advanced Hydrological Prediction Service https://water.weather.gov/precip/).

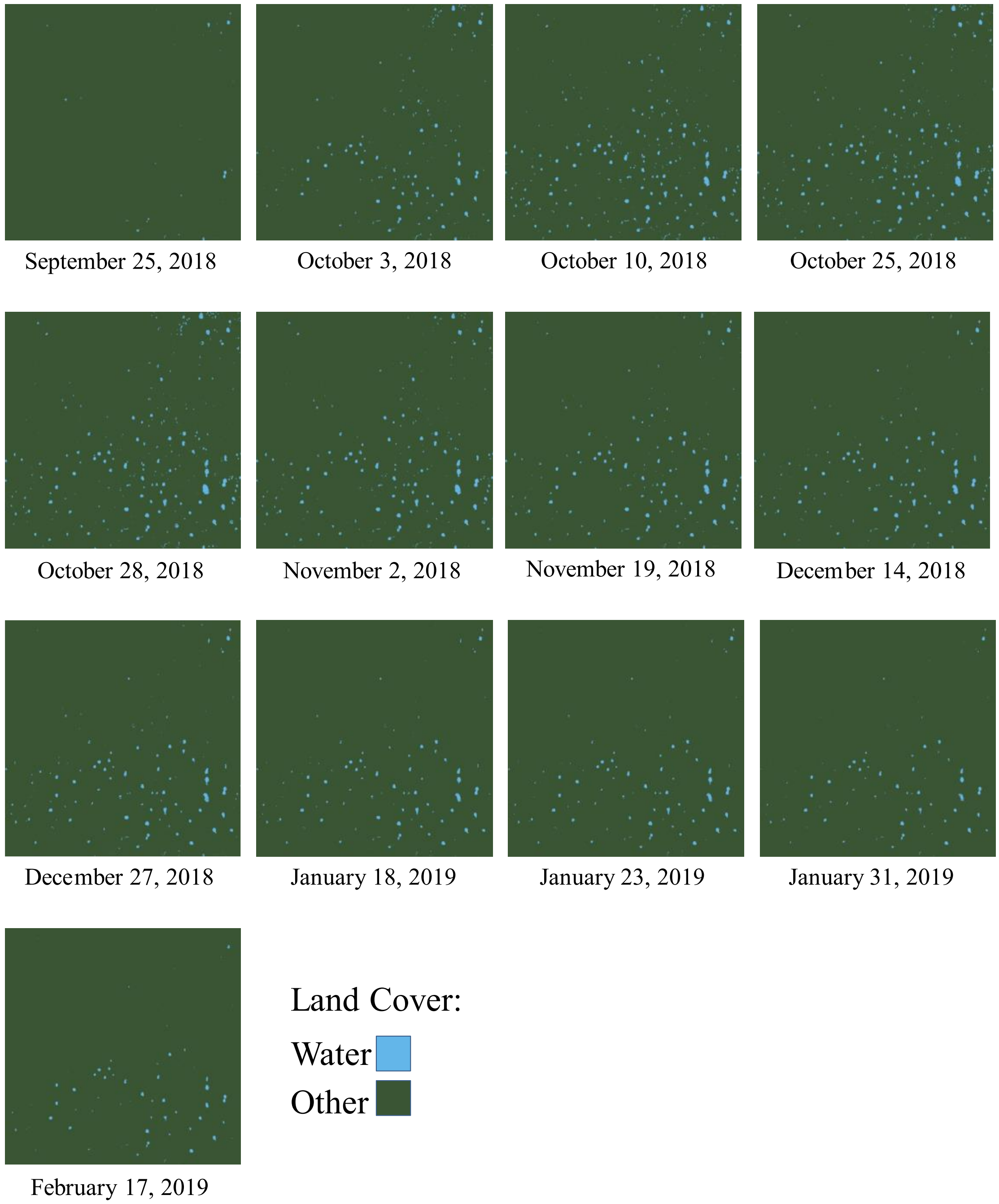

Figure 7. Map of playa lakes derived from Sentinel-2A/B satellite imagery over Region 1 between September 25, 2018 and February 17, 2019. Maps are 30km x 30km.

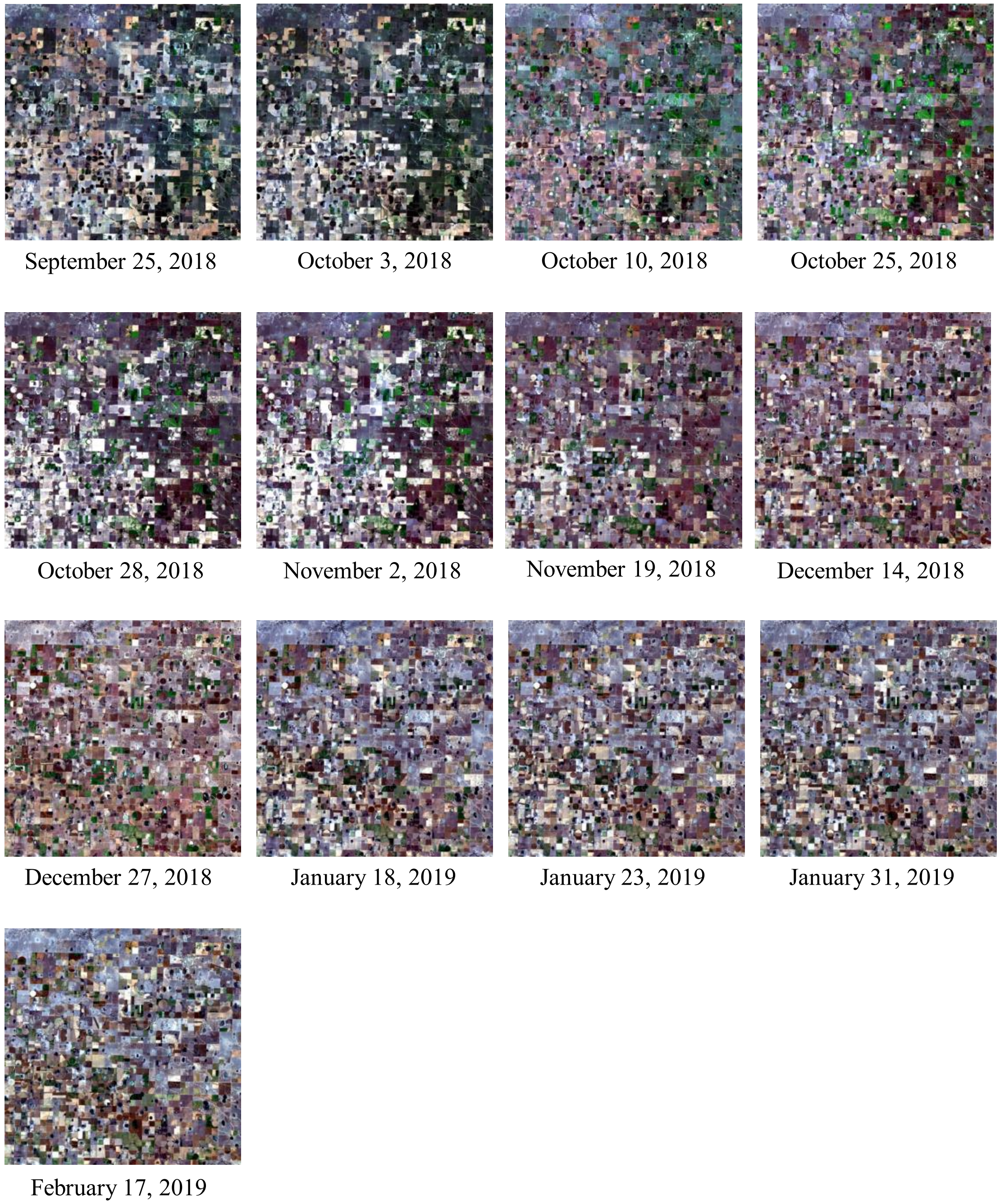

Figure 8. True color imagery derived from Sentinel-2A/B satellites over Region 1 between September 25, 2018 and February 17, 2019. Maps are 30km x 30km.

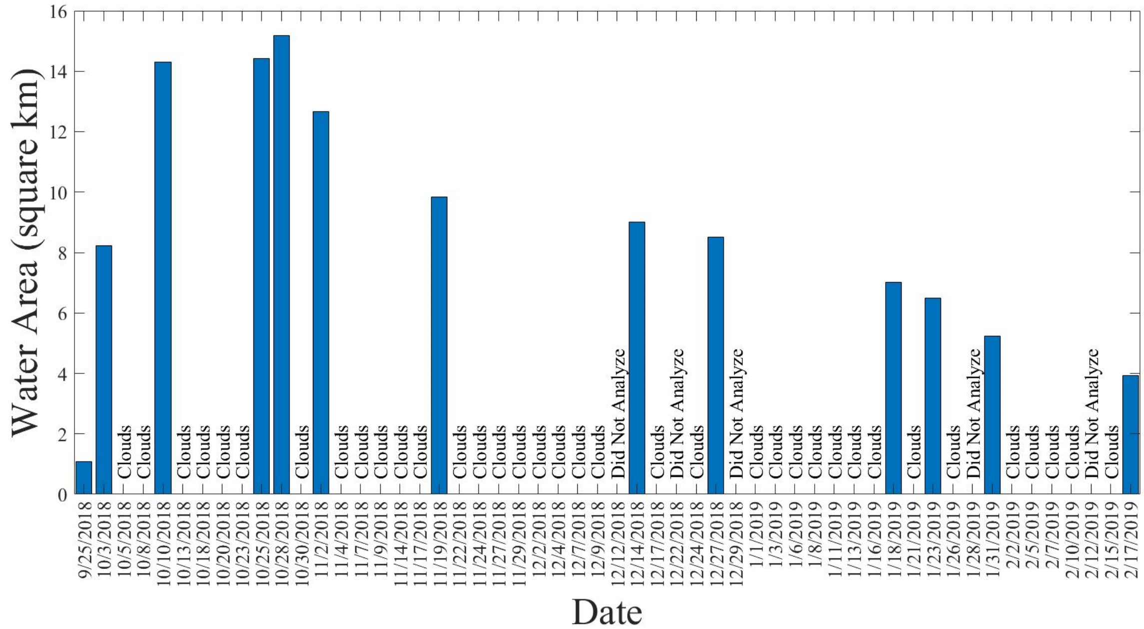

Figure 9. Playa lake surface water area over Region 1 (see Figure 2) for the period between September 25, 2018 and February 17, 2019. Missing dates are due to either cloud cover or data not being analyzed as indicated on the plot.

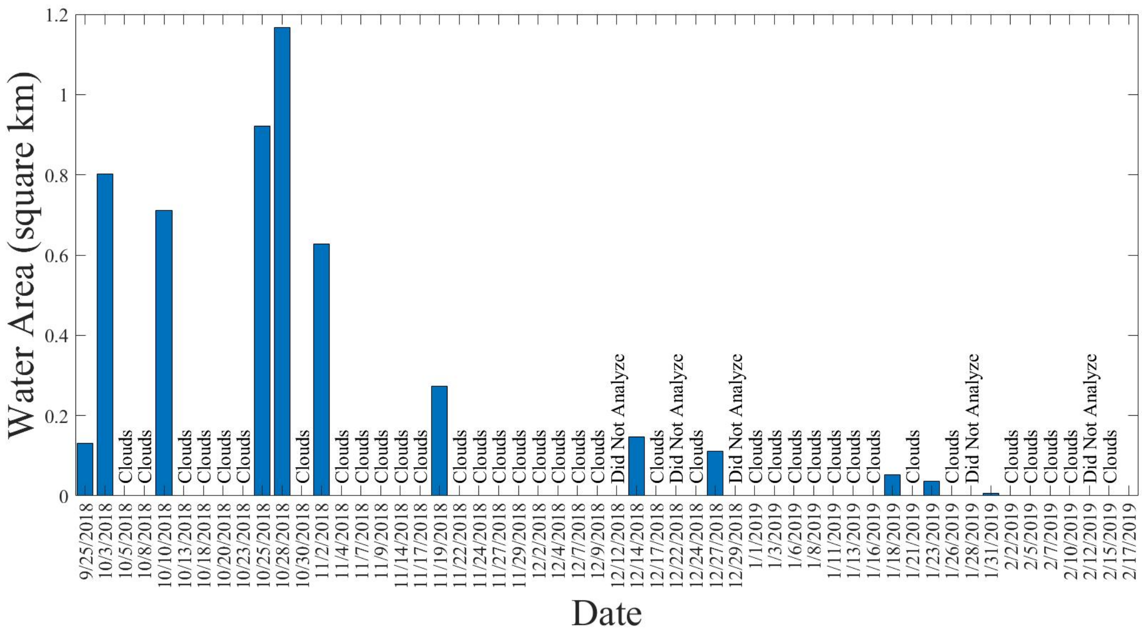

Figure 10. Playa lake surface water area over the Small Pond subsection of Region 1 for the period between September 25, 2018 and February 17, 2019. Missing dates are due to either cloud cover or data not being analyzed as indicated on the plot.

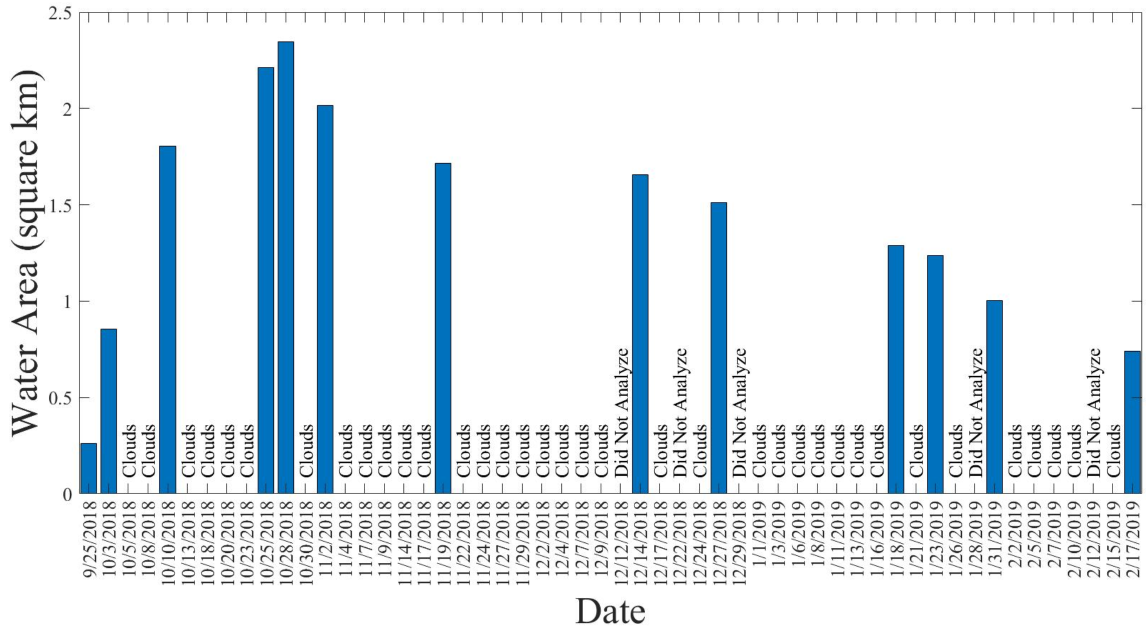

Figure 11. Playa lake surface water area over the Large Pond subsection of Region 1 for the period between September 25, 2018 and February 17, 2019. Missing dates are due to either cloud cover or data not being analyzed as indicated on the plot.

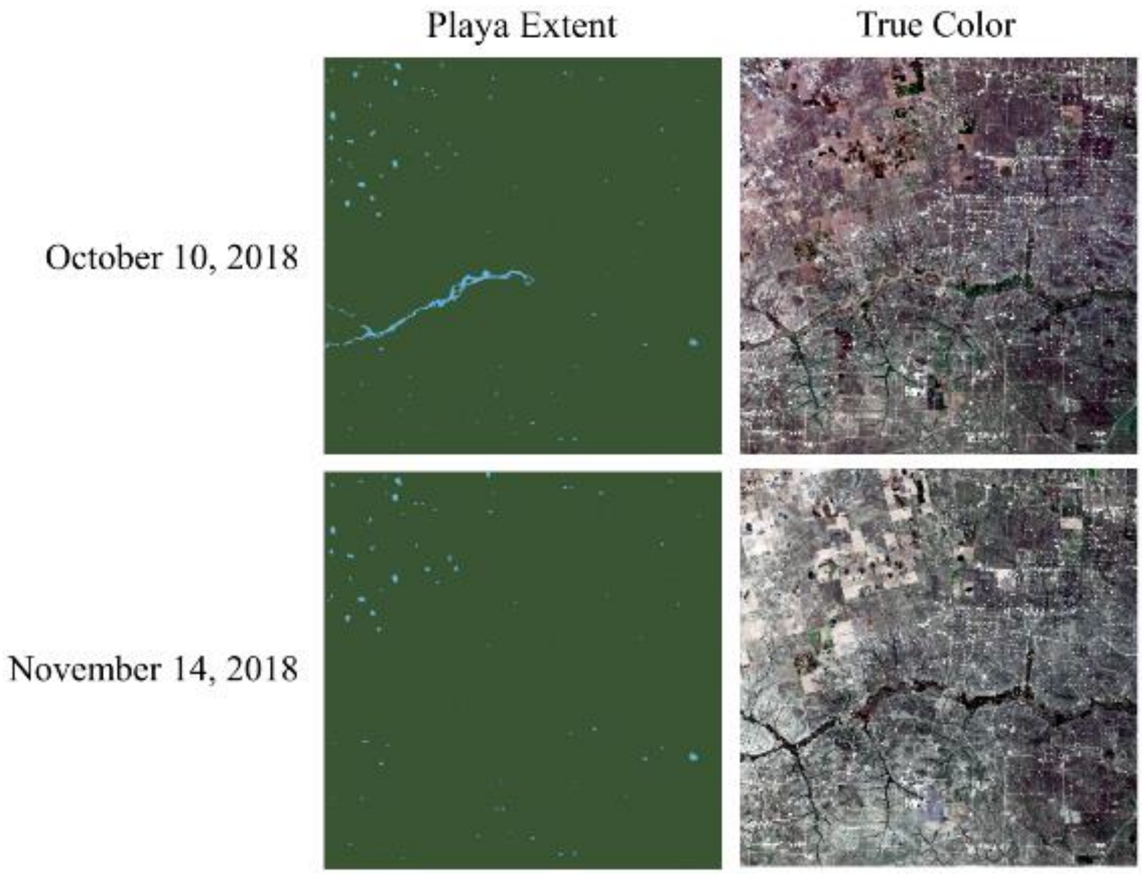

Figure 12. Map of playa lakes and the flooded Centralia Draw derived from Sentinel-2 satellite imagery over Region 2 (Karst) on October 10, 2018 and November 14, 2018. Maps are 30km x 30km.

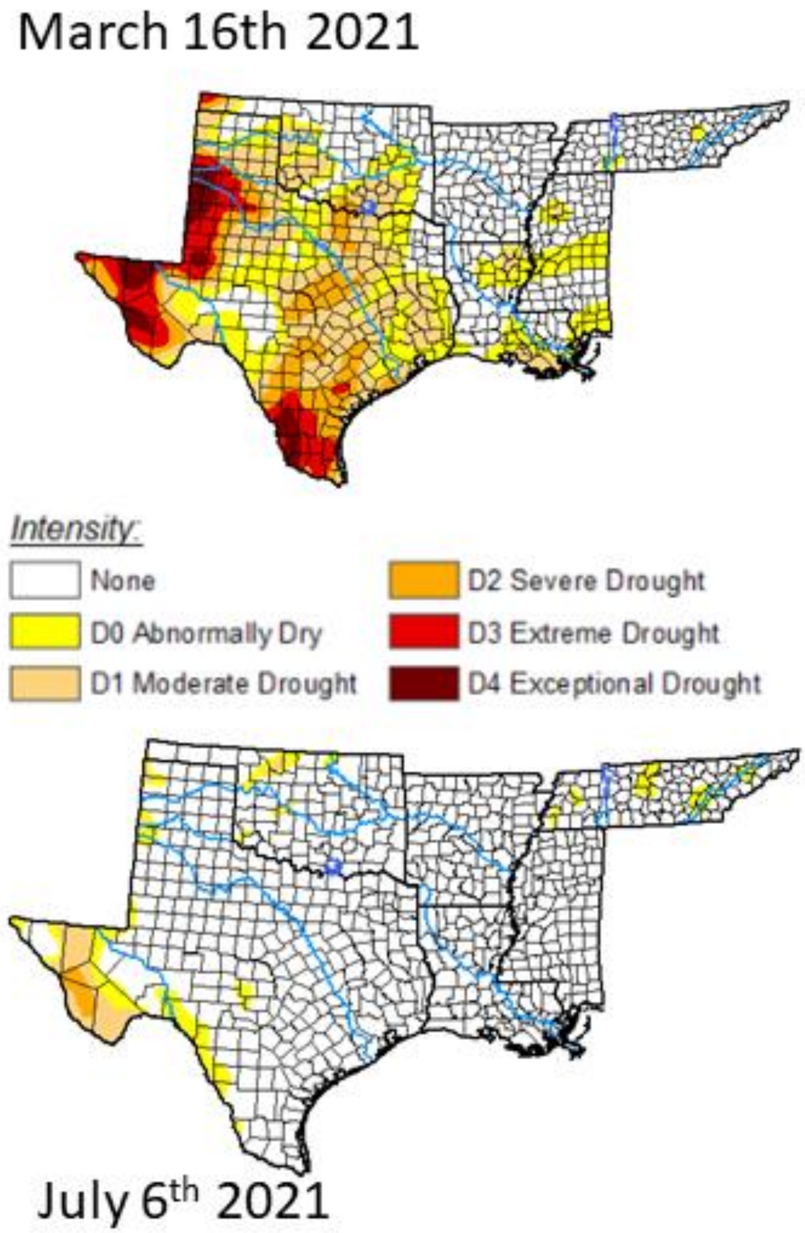

Figure 13. US Drought Monitor for March 16, 2021 (top) and July 6, 2021 (bottom).

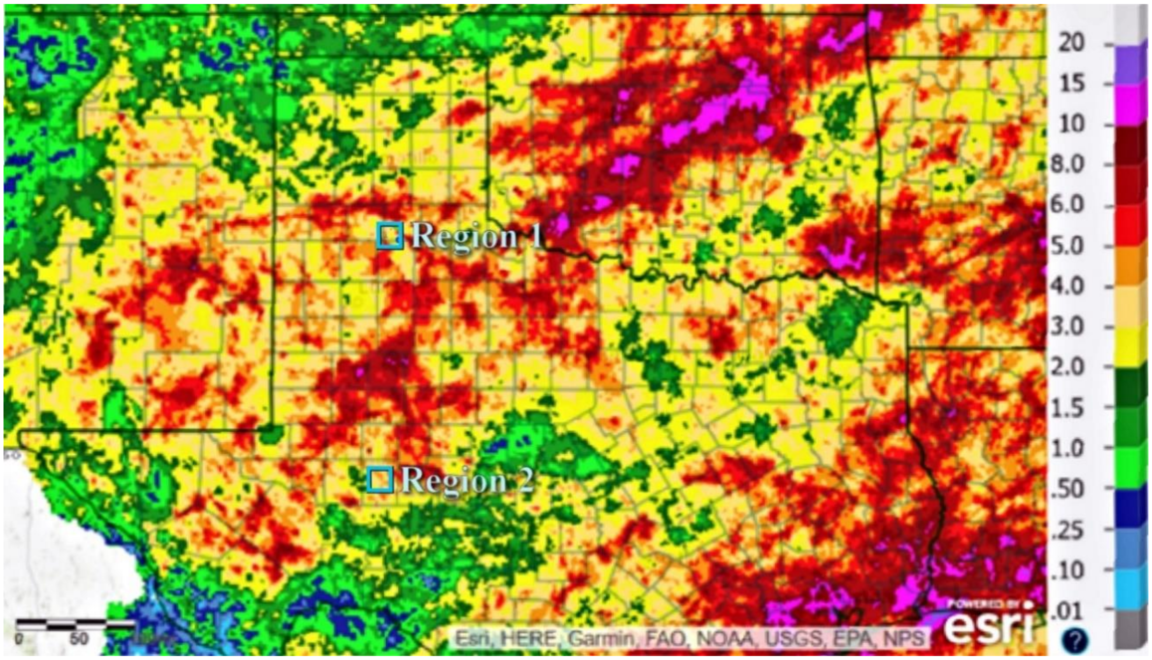

Figure 14. Radar estimated precipitation in Texas and surrounding states for June 2021. Map courtesy of the National Weather Service Advanced Hydrological Prediction Service https://water.weather.gov/precip/).

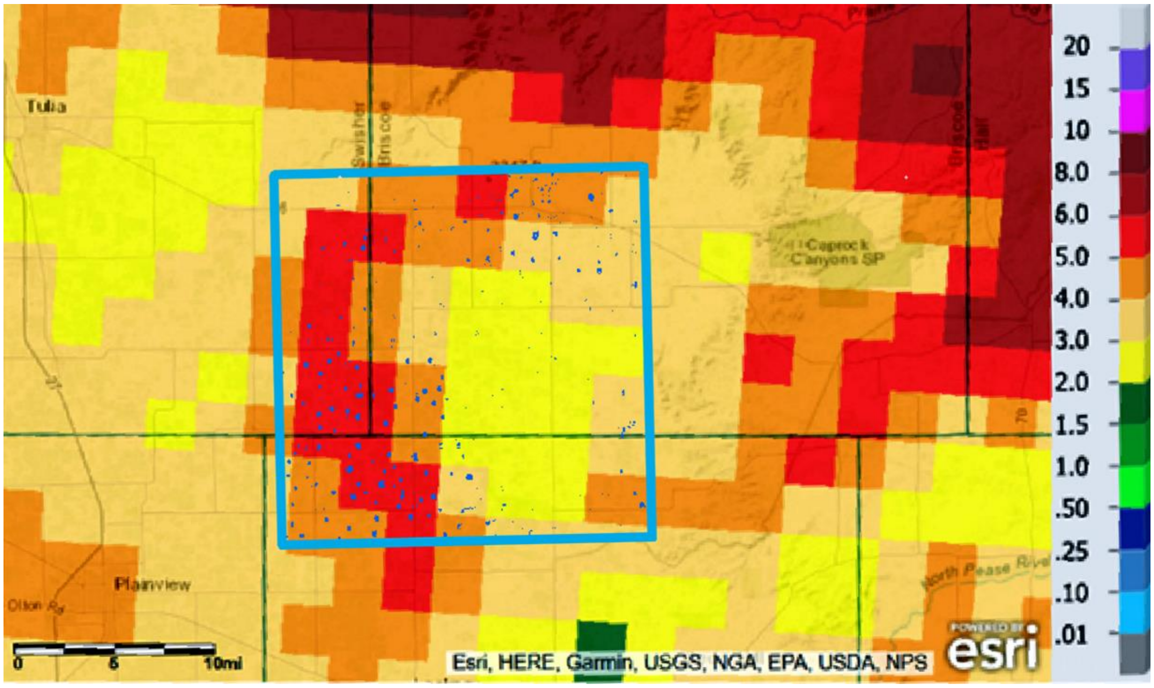

Figure 15. Radar estimated precipitation for Region 1 (blue square) from June 15 to July 14, 2021. Playa extent within Region 1 for July 9, 2021 is shown in dark blue. Map courtesy of the National Weather Service Advanced Hydrological Prediction Service https://water.weather.gov/precip/).

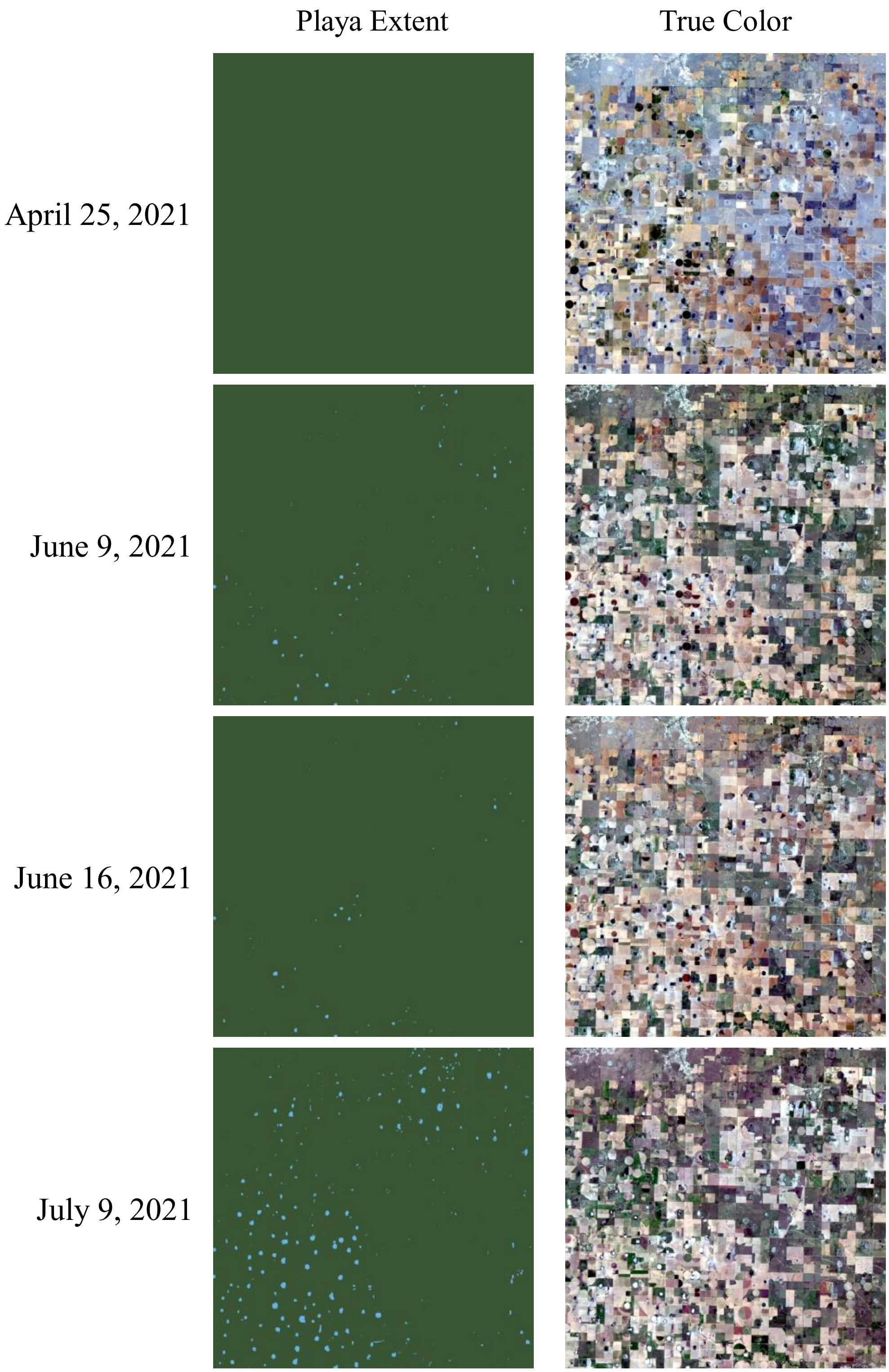

Figure 16. Map of playa lakes derived from Sentinel-2 satellite imagery over Region 1 between April 25, 2021 and July 9, 2021. Maps are 30km x 30km.

Figure 17. Google Earth image of a dry playa lake depression in the Karst geological region (Region 2). The location of this image is denoted by a yellow star in Figure 18.

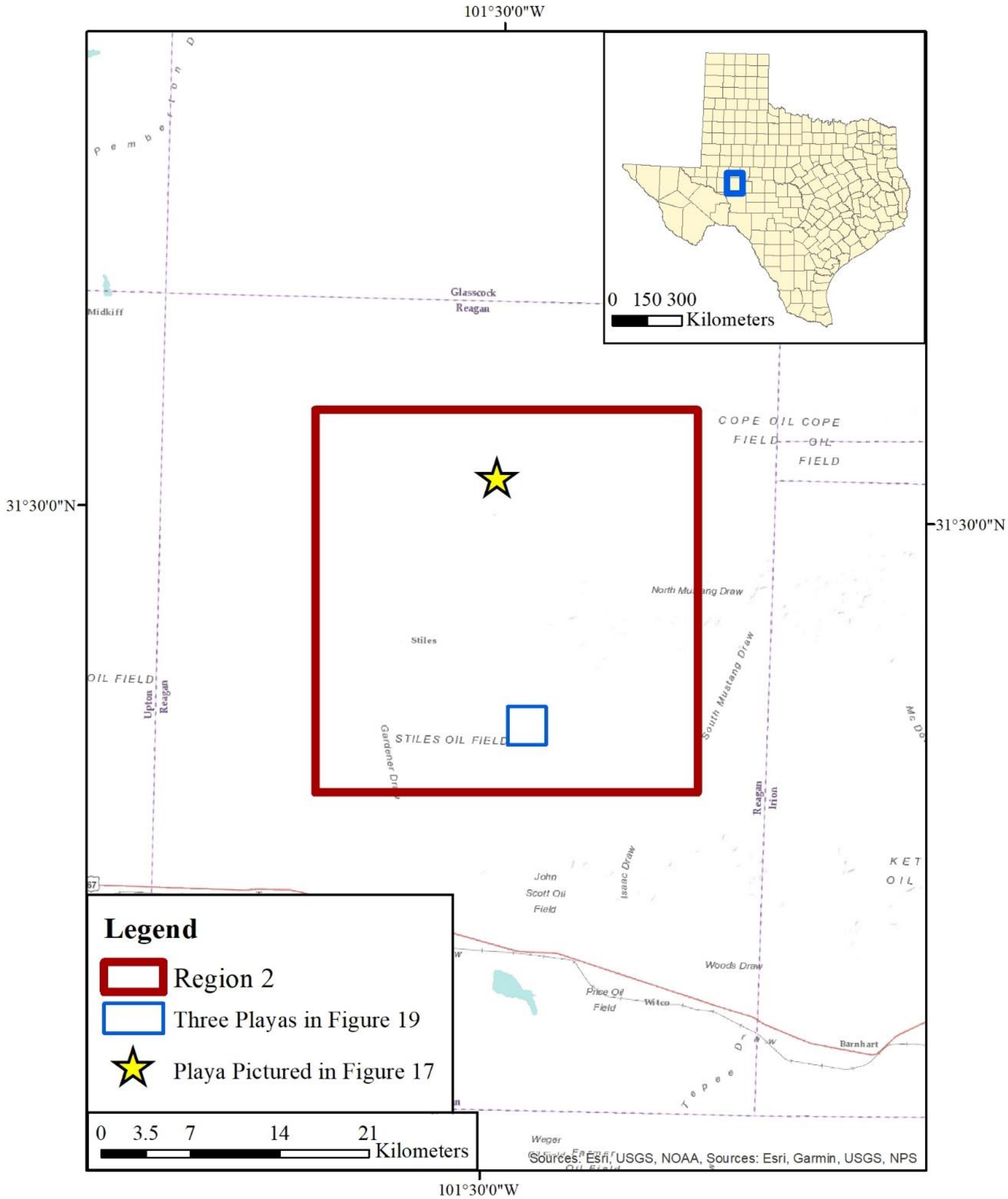

Figure 18. Close-up map of Region 2 (brown box). The small blue box delineates the location where potential playa lake groundwater infiltration was noted as shown in Figure 19.

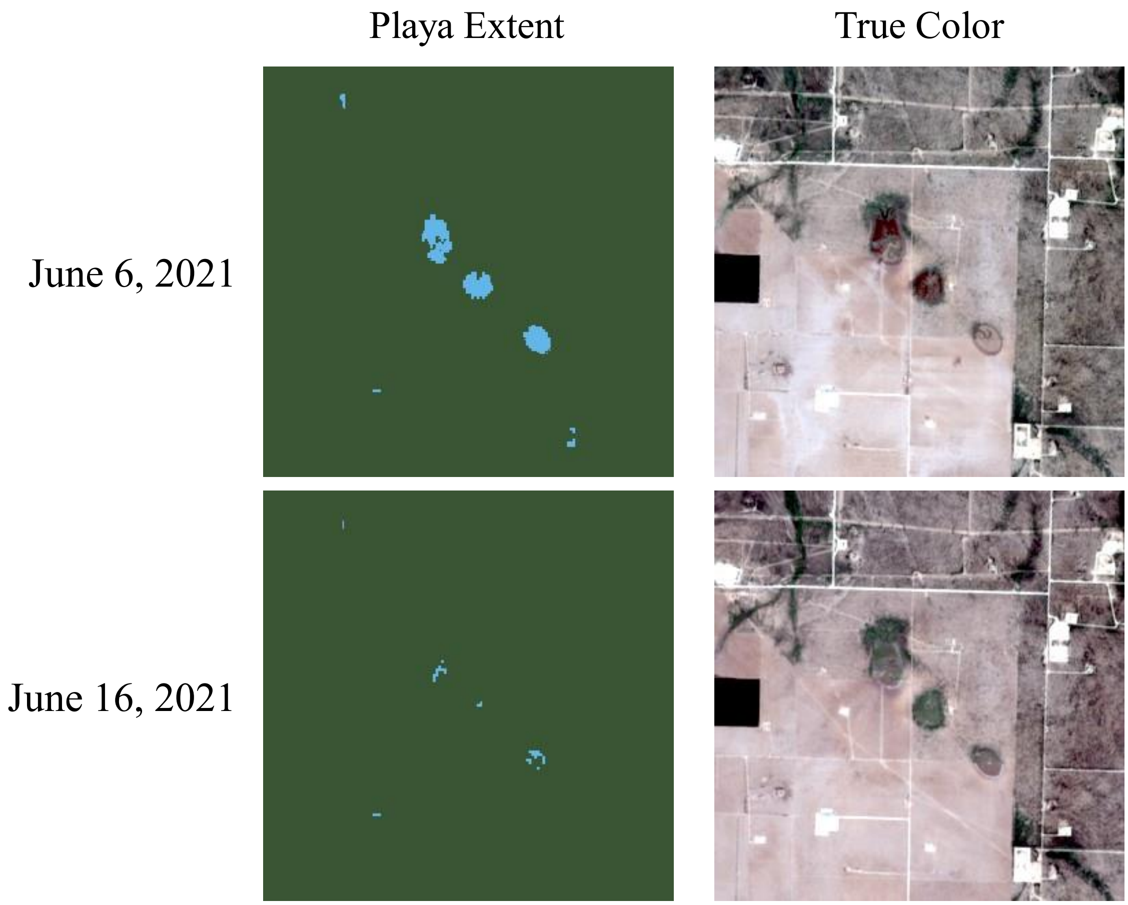

Figure 19. Map of three playa lakes derived from Sentinel-2 satellite mission imagery showing change in water extent between June 6, 2021 and June 16, 2021 in the small sub-region denoted by a blue box in Figure 18. Maps are 3km x 3km.