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Assessing Nebraska playa wetland inundation status during 1985–2015 using Landsat data and Google Earth Engine

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Abstract Playa wetlands in Nebraska provide globally important habitats for migratory waterfowl. Inundation condition is an important indicator of playa wetland functionality. However, there is a lack of long-term continuous monitoring records for playa wetlands. The objective of this study was to determine a suitable index for Landsat images to map the playa inundation status in March and April during 1985–2015. Four types of spectral indices—negative normalized vegetation index, Normalized Difference Water Index (NDWI), modified NDWI, and Tasseled Cap Wetness-Greenness Difference (TCWGD)—were evaluated to detect playa inundation conditions from Landsat images. The results indicate that the TCWGD is the most suitable index for distinguishing playa inundation status. By using Landsat images and Google Earth Engine, we mapped the spring inundation condition of Nebraska playas during 1985–2015. The results show that the total inundated areas were 176.79 km^2 in spring migratory season, representing 18.92% of the total area of playa wetlands. There were 9898 wetlands inundated at least once in either March or April during the past 30 years, representing 29.41% of a total of 33,659 historical wetlands. After comparing the historical hydric soil footprints and the inundated areas, the results indicate that the hydrological conditions of the majority of playas in Nebraska have changed. The inundated wetlands are candidates for protection and/or partial restoration, and the un-inundated wetlands need more attention for wetland restoration. Wetlands in areas enrolled in conservation easements had a significantly high level of playa inundation status than non-conserved wetlands during spring migratory seasons in the past decades.These conservation easements only count for 4.29% of the total footprint areas, but they have contributed 20.82% of the inundation areas in Nebraska during the past 30 years.

Keywords Wetland · Rainwater Basin · Inundation · Tasseled Cap Wetness-Greenness Difference · Nebraska

Introduction

Playa wetlands are wind-formed, ephemeral, nearly circular depressions, with a clay layer that, when wet, ponds water (Smith 2003; LaGrange et al. 2011; Lane et al.

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2012). Most playa wetlands are geographically isolated, representing the lowest topographic position in closed watersheds (Tiner 2003). Playas provide critical ecological services in improving flood mitigation, capturing sediment, filtering surface runoff, recharging the underlying aquifer, and enhancing biodiversity (LaGrange 2005; Smith et al. 2011).

There are four defined playa complexes in Nebraska: Central Table Playas, Rainwater Basin, Southwest Playas, and Todd Valley Playas (LaGrange 2005). Playa wetlands in Nebraska provide mid-latitude stopover habitat for wetland-dependent bird species migrating through the Central Flyway. This juxtaposition along the flyway provides globally important habitats to millions of migratory waterfowl each year.

Wetland inundation condition is an essential part of wetland performance. Ponding of playa wetlands is mostly temporary or seasonal, but they provide critical ecosystem services for numerous flora and fauna that depend on wetlands for survival. Reduced ponding duration and frequency can degrade playa-dependent habitats for breeding waterfowl (Larson 1995) and migrating waterfowl (Nugent et al. 2015). Insufficient inundation will lead to inadequate habitat functions from playa wetlands during the peak of the waterfowl spring migration season (Tang et al. 2015; Tang et al. 2016). Continuous dry condition will influence plant diversity, reduce available forage, degrade dormant fauna, and reduce available habitat for migrating shorebirds and waterfowls (Smith 2003; Drahota and Reichart 2015). Therefore, an improved understanding of current inundation conditions will help determine areas where playa ecosystem management, protection, and restoration treatments might have the most success.

Satellite images are collected at a high temporal resolution and can provide important data sources for wetland inventory and monitoring. The repeated coverages enable seasonal or even monthly update of wetland conditions. Satellite data provides a less expensive and more efficient method of retrieving wetland condition compared to ground-based surveys (Rebelo et al. 2009). Satellites can regularly monitor wetland conditions, for instance, Landsat 7 sensors overpass and monitor the same area every 16 days. Satellite data is less costly and less time-consuming than aerial sensing data or ground surveys, especially over large areas (Ozesmi and Bauer 2002). The digital format of satellite data makes it easy to integrate into the Geographic Information System (GIS) (Brivio et al. 2002). The free Landsat images since 2008 have made large-area investigations easier, especially for understanding the dynamics of ecology (Woodcock et al. 2008; Kennedy et al. 2010).

Spectral indices are widely used for information extraction from satellite images. The Negative Normalized Difference Vegetation Index (NDVI) has been used for water body detection (Tucker 1979; Hui et al. 2008). Huang et al. (2014) examined a series of indices for wetland inundation detection, such as the Normalized Difference Water Index (NDWI) using band at 0.86 μm and band 1.24 μm (Gao 1996), Landsat TM short-wave infrared 1 (1.55–1.75 μm)/green band (0.52–0.6 μm) (Ozesmi and Bauer 2002), and Tasseled Cap Wetness-Greenness Difference (TCWGD) (Huang et al. 2014). They found that the TCWGD had the highest coefficient of determination of the linear relationship of inundation percentage and index. NDWI calculated using green band (0.52–0.6 μm) and near infrared band (0.76–0.9 μm) also proved to be useful in delineating open water and enhancing their appearance in digital imagery (McFeeters 1996). Xu (2006) used the modified NDWI to extract water information from Landsat images. His method replaced the near infrared with shortwave infrared and demonstrated the improvement in detecting lakes, rivers, and seawater. These indices were developed for and tested in humid areas such as the east coast of USA and the east or southeast coast part of China. No research has identified the indices and relevant thresholds to distinguish playa wetlands and other land uses. Thus, identification of a suitable index and threshold of water body detection is an important step to track playa inundation conditions from satellite data. The spatial resolution of Landsat images is 30 × 30 m. The average size of playa wetlands in Nebraska is 26,843 m^2 with a standard deviation of 126,128 m^2. There are 4701 playa wetlands less than 900 m^2, counting for 13.50% of the total number of playa wetlands in Nebraska. By considering spatial resolution of Landsat images, in order to analyze inundation changes, we only count the appearance or absence of inundation for each historical hydric soil footprint.

Many efforts have been made to document wetland inundation conditions through field survey or in situ monitoring combined with information from aircraft and satellite remote sensing (Guthery et al. 1981; Mulligan et al. 2014; Playa Lakes Joint Venture 2015; Rainwater Basin Joint Venture 2015). A variety of geospatial datasets can be used to document wetland conditions, including the National Agriculture Imagery Program (NAIP), Landsat images, digital raster graphics, the National Elevation Dataset, the Soil Survey Geographic dataset (SSURGO), the National Wetlands Inventory (NWI), Light Detection and Ranging (LiDAR), and the National Cropland Data Layer. The employment of multiple datasets can improve the accuracy and reliability of wetland condition assessment. However, wetland datasets associated with inundation status are rare since data may not be concurrent. Since playa wetlands normally do not have groundwater recharge, evaporation and precipitation could greatly influence the length of the hydroperiod and vegetation present (Smith 2003). In highly cultivated areas, due to the spatial resolution issues of the National Elevation Dataset (NED), SSURGO, and NWI data, these datasets may not be able to accurately reflect the wetland conditions due to the high degree of land modification (Tang et al. 2015). The satellite datasets provide long-term temporal information to understand wetland inundation changes. Other datasets (e.g., SSURGO, NWI, LiDAR, etc.) provide good spatial information, but they are inadequate to track the long-term temporal change of playa inundation conditions. Thus, up-to-date inundation information is essential for maintaining and managing sustained ecosystem services from playa wetlands.

Wetland inundation mapping can provide geospatial information for wetland conservation programs and the assessment of effectiveness of these programs (Lang and McCarty 2009). Many recent studies have applied geospatial modeling and analysis to simulate wetland inundation dynamics using a variety of approaches in the range of landscapes and wetland types (Hess et al. 2003; Gómez-Rodríguez et al. 2010; Muster et al. 2013; Huang et al. 2014). Tang et al. (2014) developed a procedure with LiDAR data to map wetlands in three dimensions and extract key parameters of playa wetlands. These studies have contributed to the methodologies and technologies for wetland inundation mapping and accurate prediction. The historical satellite data can be coupled with the high-resolution topographic/morphometric data on playas and their watersheds to understand wetland inundation dynamics. Uden et al. (2015) coupled scenario planning and statistical modeling to predict wetland stopover habitat availability in the Rainwater Basin. However, no specific research has addressed playa wetland inundation mapping at a large temporal-spatial scale.

The objective of this study was to determine a suitable remote sensing spectral index with an appropriate threshold and then map the inundation condition for playa wetlands in the spring migratory season during the past 30 years. This study examined the performance of four different indices in wetland inundation detection, including Negative NDVI, NDWI, modified NDWI, and TCWGD. Landsat images and Google Earth Engine were used to create inundation condition maps for all playa wetlands in Nebraska in March and April spring season during 1985–2015. March and April are the peak migratory season when millions of waterfowl stage and forage on these playa wetlands in Nebraska. Lastly, we examined inundation maps for playas enrolled in the Wetlands Reserve Program and included in the National Conservation Easement Database (NCED 2016) to evaluate the inundation performance of playas enrolled in conservation easement programs located in playa wetland complexes.

Study area

The major playa complexes encompass an area of approximately 935 km^2 distributed throughout 46 counties in Nebraska (LaGrange 2005) (Fig. 1). The playa complexes in Nebraska cover four major sub-regions, including the Rainwater Basins, Central Table Playas, Southwest Playas, and the Todd Valley. The descriptive statistics of these playa complexes are listed in Table 1. The mean size for playa wetland in Nebraska is 26,843 m^2 with a standard deviation of 126,128 m^2. There are 4701 playa wetlands less than 900 m^2, counting for 13.50% of total playa numbers. The total area of these playa wetlands represents 0.3% of total playa areas. These playas are mainly located in crop landscape. Precipitation increases from west to east across the playa complexes and ranges from 38.10 to 76.2 cm (LaGrange et al. 2011).

Playas in Nebraska serve as important habitats for wildlife, particularly for migrating water birds. Since the European settlement from the 1850s, the majority of playa wetlands have been drained and filled to facilitate row-crop agriculture production. Due to the intensive human activities, both the wetland numbers and areas have been significantly reduced. Playa wetlands experienced a rapid loss of wetlands before the 1960s and then have been in a relatively slow degradation process during the past half century (Nugent et al. 2015).

In the 1960s, the US Fish and Wildlife Service and Nebraska Game and Parks Commission recognized the value of these wetlands and began purchasing wetlands in fee title as Waterfowl Production Areas (WPA) and Wildlife Management Areas (WMA). As part of the 1986 US Department of Agriculture Farm Bill, the swapbuster provision was implemented. This provision required producers to not drain wetlands if they are enrolled in the Farm Program. In the early 1990s, the

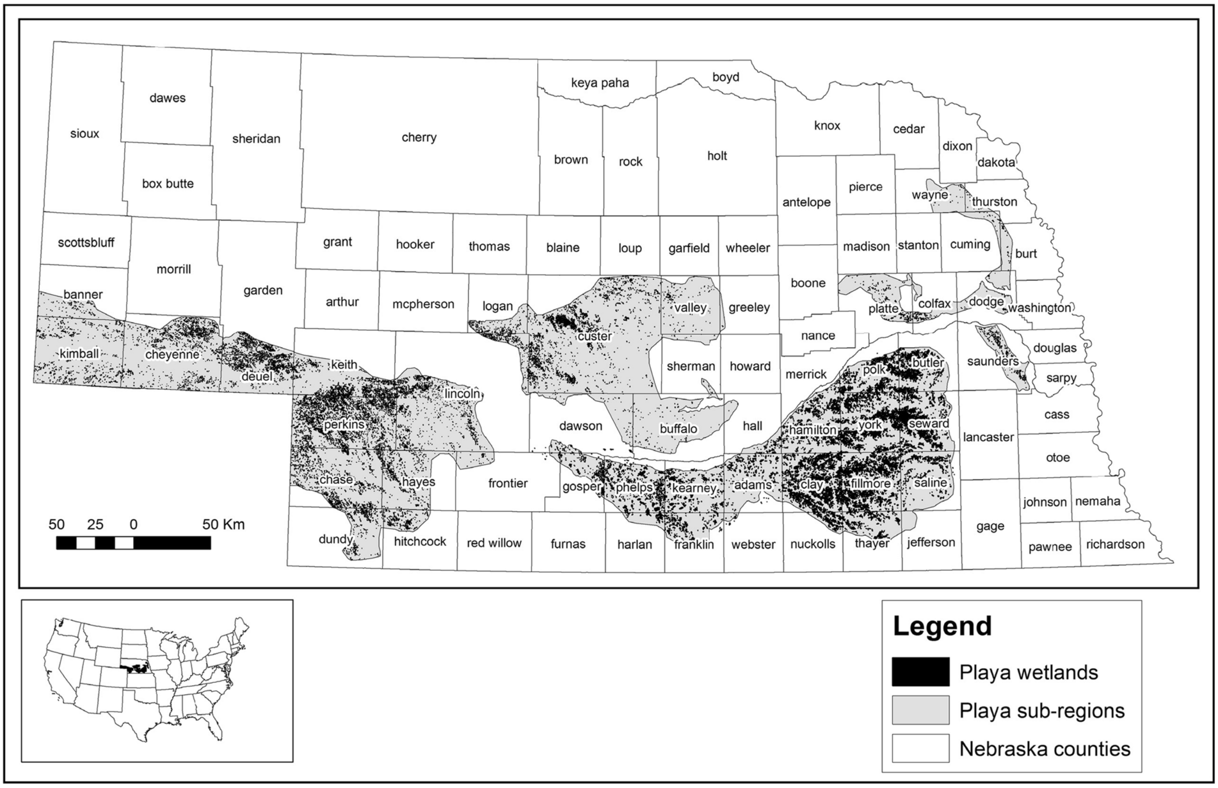


Fig. 1 Location map of playa wetlands, within defined playa wetland complexes, in Nebraska

Wetlands Reserve Program was introduced and has resulted in 94 easements on private lands in Nebraska.

Data sources

The playa wetland dataset for Nebraska is a combination of the Playa Lakes Joint Venture's wetland data (http://pljv.org/for-habitat-partners/maps-and-data/maps-of-probable-playas/) and the Rainwater Basin Joint Venture's wetland data (http://rwbjv.org/). The playa wetland dataset was developed from multiple datasets, including the NWI, SSURGO, and satellite imagery.

Satellite images were obtained from the Landsat satellites (http://landsat.gsfc.nasa.gov/). This research uses seven bands with wavelength ranging from 0.45 to 2.35 μm at a 30-m resolution of the Landsat TM, ETM+, and OLI images from Landsat 5, Landsat 7, and Landsat 8, respectively, every March and April from 1985 to 2015. All satellite data were from the Landsat archive

Table 1 Descriptive statistics for playa wetland complexes in Nebraska

Sub-region	Area (km^2)	Total number	Number of wetlands (less than 900 m^2)	Mean (m^2)	Median (m^2)	Standard deviation (m^2)
Todd Valley	7.88	893	93	8826.29	3882.1	16,503.90
Central Table Playas	24.50	4712	1168	5200.23	2020.62	12,160.30
Southwest Playas	74.75	16,293	3228	4587.68	2062.12	8171.29
Rainwater Basin	826.87	11,707	0	70,408.49	25,997.1	210,339.66
Other	3.06	54	1	56,576.33	27,159.36	99,534.08
Total	934.46	33,659	4490	27,762.56	5140.45	128,214.46

(http://eros.usgs.gov/about-us/data-citation). The satellite images collected in this study cover the entire playa wetland regions of Nebraska, including path/row 28–33/31 and path/row 29–31/32, which were selected to monitor wetland inundation conditions.

The NCED is a national database of conservation easement information, compiling records from land trusts and public agencies throughout the USA (NCDC 2016). It provides important information for government and land trust agencies to conserve private land, including playa wetlands in Nebraska.

The Rainwater Basin Joint Venture conducts low-altitude aerial habitat surveys every spring (RWBJV 2015). Color infrared aerial photography is annually collected by the Rainwater Basin Joint Venture to conduct The Annual Habitat Survey (AHS). Imagery is collected during the peak of waterfowl migration and has been collected annually since 2004. The AHS delineates playa inundated area and playa hydric vegetation area. This high-angle imagery is photo-corrected with low-angle imagery and provides the ground-truthed wetland habitat condition for Rainwater Basin wetlands in recent springs. This data delineates two types of wetland information: inundation areas and hydric vegetation areas. The AHS data were interpreted from color-infrared aerial photography and necessary field verification. This study used the AHS data for field trip route determination, index validation, and threshold adjustment.

The NAIP acquires aerial imagery during the agricultural growing seasons in the continental US NAIP image is available as Digital Orthophoto Quarter Quad at a resolution of 1 m. In Nebraska, NAIP was collected with four bands (blue, green, red, and near-infrared portions of the electromagnetic spectrum) in the years of 2009, 2010, and 2012. NAIP was used to verify the inundation maps produced by the satellite imagery. In addition, the 30-cm high-resolution base map was provided by ArcMap 10.2 (ESRI Inc., Redlands, CA) (http://opendata.arcgis.com/datasets/47e29caf595d4841a8d0d6069cbb24eb_3?filterByExtent). The base map includes the TerraColor imagery updated in September 2014 for the study area.

Methods

Methods to determine the index and threshold

Three major steps were used to determine the most suitable remote sensing index and reach the appropriate threshold in terms of identifying inundation for playa wetlands.

Field surveys were conducted on March 12, 21, and 28, and April 4, 2015, to create shapefiles of surveyed land covers. These days have few clouds when Landsat satellite passes by during spring 2015. Thirty playa wetland sites were sampled, and field surveys were conducted. Three land cover categories were observed: inundated playa (surface water was present), dry playa that was cultivated, and dry playa with hydrophytes present. Seventeen sites were inundated playas, seven sites were dry playas that were cultivated, and six sites were dry playas with hydrophytes. Some dry historical playa footprints were converted to agriculture land, and some just empirically lack water. For each wetland survey, we prepared a series of base maps, including NAIP images, ArcMap online maps, and AHS maps, to identify water bodies large enough (i.e., 30 m × 30 m) to be observed on satellite imagery. A 900-m Range Finder Laser Distance Meter was used to determine the ponded surface area of the water body. Field observations for each playa were documented, such as hydric vegetation, wildlife present, surrounding land uses, and visible hydrologic modifications if observed. Each sampled water body was near-circle or has elongated shape and was larger than 4047 m^2 (approximately 0.4047 ha), in order to make sure at least one pixel (900 m^2) of Landsat image pixel fell into the water layer completely. The comparison between the samples of inundated playas, dry playas that were cultivated, and dry playas with hydrophytes was conducted to select the suitable index for inundation detection of playa with a range of land covers.

Landsat 8 data collected on the same date as field surveys was classified using four remote sensing indices (Negative NDVI, NDWI, modified NDWI, and TCWGD) to compare their performance distinguishing among the three land cover classes determined during field surveys. The spectral information of each pixel was extracted to distinguish the three land classifications—inundated surface water, cultivated land, and dry hydrophyte. By analyzing their value ranges of each wetland condition, the most suitable remote sensing index was selected for revealing playa inundation status. The criterion was to examine whether there was a threshold value from the index, which could differentiate the water from cultivated land and dry hydrophytes. Four types of remote sensing indices for water body detection, including Negative NDVI, NDWI, modified NDWI, and TCWGD, were compared in this study (Table 2).

These indices were calculated using the Top of Atmosphere Reflectance of Landsat. Five of playa polygons were marked as inundated status if water body conditions were observed during the field survey on March 21, 2015. Even though a small portion of a playa polygon has a water body, a value of "1" was given to this playa polygon's attribute table to identify as an active inundated wetland. Otherwise, if the water body condition was not observed for a playa polygon, a value of "0" was given to its attribute table to indicate a non-inundated wetland. Land cover polygons of 30 sample sites were digitized as shapefiles through ArcMap 10.2 (ESRI Inc., Redlands, CA). Google Earth Pro (Google Inc., Mountain View, CA) was used to convert shapefiles into Keyhole Markup Language (KML). KML was then imported into the fusion table through Google Drive (Google Inc., Mountain View, CA) and loaded on Google Earth Engine (Google Inc., Mountain View, CA) to clip the Landsat 8 images. The four indices were calculated using the Top of Atmosphere Reflectance of Landsat for 167 water body pixels, 191 agricultural pixels, and 46 dry hydrophyte pixels. The threshold values of the indices for water body detection subsequently were analyzed based on sampled pixels in field surveys. Boxplots are a graphical representation of the statistical distribution of the data (min-max, mean, quartiles). Boxplots were used to examine the statistical distribution in each land use, and the thresholds for water body detection were selected based on significant data difference.

We compared four indices and thresholds with the AHS data from the Rainwater Basin area. The indices and their associated thresholds were used to generate the inundation map from historic Landsat images and validate the results with past ground-truthed wetland records from AHS. The thresholds were further adjusted according to the AHS data. Inundation condition, compactness, and area were calculated for each playa/water body using the AHS data. The compactness value and shape area were calculated for each playa polygon (Li et al. 2014). These two criteria could help select the similar-shaped natural inundation area as square-shaped Landsat pixel. Compactness value calculation formula is 4π × area / squared perimeter, and the lower the compactness value (range from 0 to 1), the higher the aspect ratio and the lesser the possibility to be detected by the square-shaped pixel from Landsat images. The comparable shape of inundation needs to meet one of the following three conditions: area is >900 m^2 and compactness value is >0.25; area is >1500 m^2 and compactness value >0.1; or area is >2700 m^2. Field survey-based thresholds might have limited the representation of different shapes of ponded water bodies. During the years that AHS data are available from 2006 to 2011, five Landsat scenes could be compared. In the years 2006, 2008, 2009, and 2011, Landsat images had little cloud cover and could be compared to AHS data. There are five Landsat scenes with less than 20% wetland footprints covered by cloud or snow during spring season: 2006/2/15, path 29, row 32; 2006/2/22, path 30, row 32; 2008/3/15, path 30, row 32; 2009/3/11, path 29, row 32; 2011/4/2, path 29, row32. All of the playas in Nebraska were covered by these scenes.

Visual inspection of water body presence was added during the process to make sure the natural inundations are detectable which means that at least one 30 m × 30 m box was contained within the inundated water polygon. Thresholds were adjusted based on comparison between

Table 2 Spectral indices used to classify wetland inundation status for playas in Nebraska

Spectral index	Formula[a]	Reference
Negative NDVI	(Red − Near Infrared) / (Red + Near Infrared)	(Tucker 1979; Hui et al. 2008)
NDWI	(Green − Near Infrared) / (Green + Near Infrared)	(McFeeters 1996)
Modified NDWI	(Green − SWIR 1) / (Green + SWIR 1)	(Xu 2006)
TCWGD	Tasseled Cap Wetness − Tasseled Cap Greenness	(Kauth and Thomas 1976; Crist and Cicone 1984; Huang et al. 2014)

[a] Band formula refers to Landsat 8 band illustration and will be adjusted according to the USGS illustration if the formula needs to be applied to other Landsat series (http://landsat.usgs.gov/band_designations_landsat_satellites.php)

the index threshold detection and the AHS records. Since there are limitations of field survey data in temporal and spatial dimensions, further validation and evaluation selecting and adjusting the indices and their relevant thresholds are necessary to identify the most suitable index and threshold for the detection of wetland water bodies. Thus, we compared the inundation results from four indices and thresholds with the AHS data in the Rainwater Basin area.

Methods to map wetland inundation

This study used the Google Earth Engine (Google Inc., Mountain View, CA) to host, visualize, and analyze all Landsat data. Google Earth Engine is used to combine a multi-petabyte catalog of satellite imagery and geospatial datasets with planetary-scale analysis capabilities (Gorelick 2013). It provides all Landsat images and can examine earth surface changes, document trends, and quantify differences. In this study, spatial analyses were computed by the remote server provided by Google Earth Engine. The terabyte-scale large datasets do not need to be downloaded to the local computers, which frees up space on local computers and improves the effectiveness of geospatial analysis. In addition, through integration with other services, Google Earth Engine is able to convert data for formats compatible with Google Earth Pro and ArcGIS. Therefore, we integrated Google Earth Engine and ArcGIS to analyze and monitor inundation conditions of playa wetlands in Nebraska. The primary process of geospatial analysis included five steps: (1) selecting suitable Landsat series images for calculating wetland inundation conditions; (2) calculating satellite image raster data in Google Earth Engine; (3) converting comma separated value (CSV) format data derived from Google Earth Engine outcomes to shapefile format in ArcGIS; (4) merging actual inundation maps calculated by Google Earth Engine based on different time period criteria; and (5) overlaying the merged actual inundation maps with the playa wetland dataset in ArcGIS.

By using the criteria to select suitable Landsat images, including cloud coverage, snow coverage, and the date of the image, the presence of clouds, cloud shadows, and snow can significantly complicate the classification of land (Zhu and Woodcock 2012). In order to simplify the data processing, images without cloud or snow covering playas were selected as suitable images. Also, images with some clouds or snow that did not overlay wetlands were selected as suitable images based on the user's image interpretation experience. Based on these criteria, 86 March images and 125 April images were selected over the past 30 years.

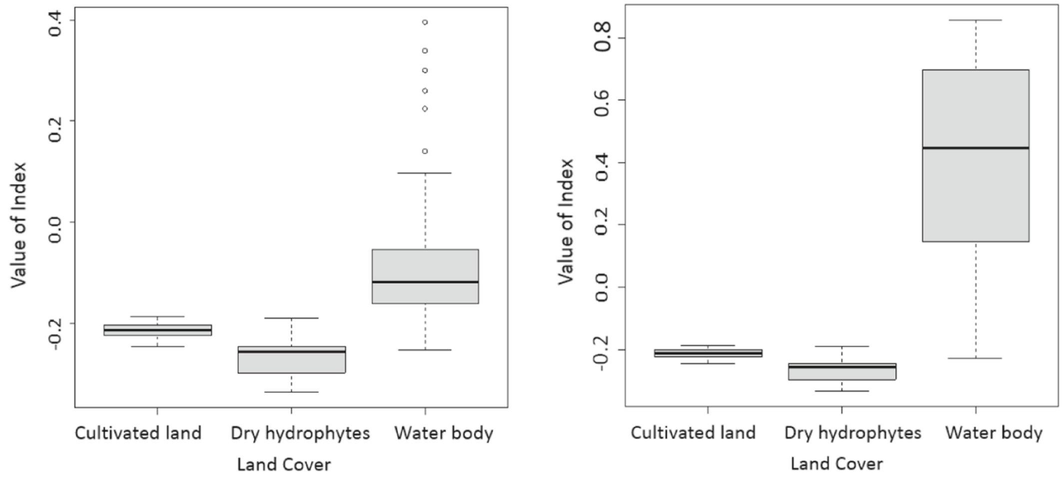
The pixels with water body features were converted to points in which each point represented an area of 22.7 m × 30 m. Points were merged with the wetland boundary layers to map inundated wetlands. If an area was inundated at least once during the past 30 years, we classified the wetland as an inundated wetland. The cumulative map of inundation for the 30-year period was overlaid with the playa wetland datasets to examine the existence of functional wetlands and to compare playas in the NCED to assess the performance of wetland conservation lands.

Results

Index and threshold determination

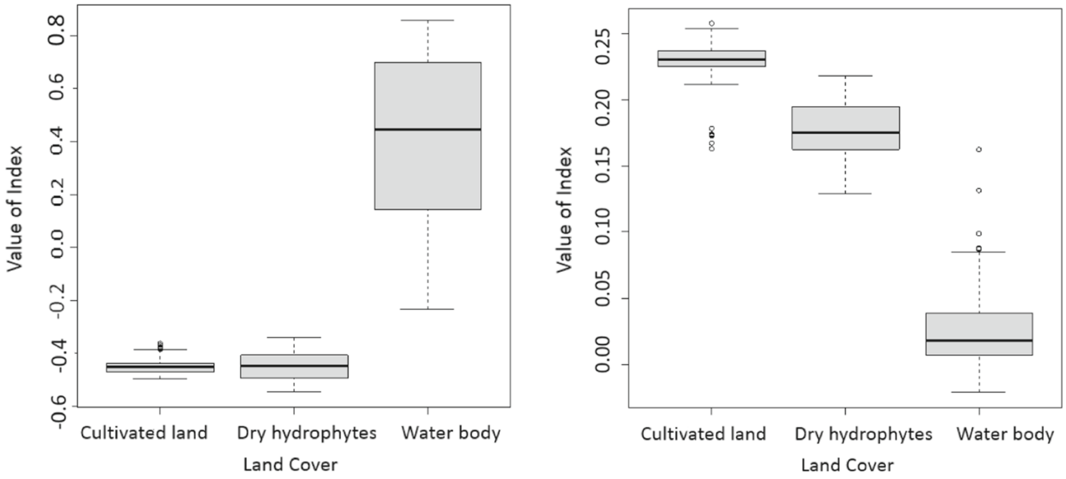
Based on the distribution of the data, four indices all had the ability to differentiate water bodies from cultivated land and dry hydrophytes (Fig. 2). The modified NDWI and TCWGD can obviously distinguish the value ranges of water with other two types of land use, including cultivated land and dry hydrophytes. The thresholds of modified NDWI and TCWGD, therefore, were determined as suitable indices.

The average value of modified NDWI for water is much higher than that for other land cover types. The minimum modified NDWI value of water is higher than the maximum modified NDWI of other land cover types. Also, the average TCWGD of water is much lower than that of other land cover types, and the maximum TCWGD of water is lower than the minimum TCWGD of other land cover types. Also, the average TCWGD of water is much lower than that of other land cover types. Therefore, the threshold value was set as −0.23, the minimum value of water surface, for modified NDWI, and 0.1 for TCWGD, respectively. Two outliers were shown in the boxplot of TCWGD. The selected threshold of 0.1 was able to detect 98.8% of the pixels as water features. The pixel value of the modified NDWI higher than −0.23 means that the pixel is water surface other than dry wetlands, and the pixel value of TCWGD lower than 0.1 means that the pixel is water surface. The threshold for TCWGD was not selected based on the maximum value of water since there are only 2 pixels with value higher than 1.3 and these two



Negative NDVI

NDWI



Modified NDWI

TCWGD

Fig. 2 Performance of four indices for water body classification

values are apparently outliers. The threshold was selected as 0.1, the third highest value.

And when the threshold is adjusted further, two standards were employed to modify the threshold: First, the number of inundated wetlands detected by the thresholds should be close to the number of inundated detectable wetlands from AHS. Second, based on the number of inundated footprints from the new candidate thresholds, the two indices should generate similar results.

Evaluation and adjustment of the index and threshold

The thresholds selected for modified NDWI and TCWGD were based on the comparisons to field survey in the spring season of 2015. Since there are limitations of field survey data in temporal and spatial dimensions, further validation is necessary to adjust the indices and their relevant thresholds and thus identify the most suitable for the detection of wetland water bodies. Therefore, we used the number of inundated wetland footprints detected by the thresholds to compare with the number of inundated wetland footprints from the AHS during 2006–2011. The comparison could help modify the thresholds for a better ability of water body detection of playa wetlands.

This study designed two-step procedures to adjust the thresholds. First, the number of inundated wetlands detected by the new thresholds should be close to the number of inundated detectable wetlands from AHS.

For TCWGD, a series of values were examined from the 100th percentile (maximum) of the water body to the 96th percentile at the 0.05% interval. For modified NDWI, a series of values were examined upwardly from 0 percentile (minimum) of the water body to the 9th percentile at the 0.2% interval. The difference of intervals for these two indices was caused by their different value scales. Each index may have a few new candidate thresholds, which could deliver a low difference between the number of inundated footprints from Landsat and AHS. Second, based on the number of inundated footprints from the new candidate thresholds, the two indices should generate similar results. The final thresholds were selected based on the least absolute difference from the number of inundated footprints revealed by the two new candidate thresholds. They both reflect similar conditions as AHS. The best threshold value of TCWGD is 0.095, and the best threshold value for modified NDWI is −0.147 (Table 3).

According to Table 3, the best threshold value of TCWGD is 0.095 and the best threshold value for modified NDWI is −0.147. After adjustments, the number of inundated footprints determined by the index-threshold methods is closer to the number of inundated footprints detected by the AHS. The least absolute difference between the number of inundated footprints detected by TCWGD and the number of inundated footprints detected by AHS is 53 footprints, which is half of the least absolute difference compared to the modified NDWI. Therefore, the TCWGD index with a threshold of 0.095 has the best ability to differentiate the water from dry hydrophytes and cultivated land. The pixel value of TCWGD lower than 0.095 indicates that the pixel is water surface.

Distribution of available Landsat images for playa inundation detection

We examined all scenes that covered the study area during 1985–2015. There are 1549 senses in total that were examined for the study area. Only 211 senses are available for wetland mapping. It indicates that over 86% of images were affected by clouds or snow cover. The distribution indicates that neither total number of images for each scene nor images of each scene in each month period (i.e., March and April) are sufficient to monitor wetland changes from year to year. The distribution of available Landsat images for playa inundation detection in March and April during 1985–2015 is listed

Table 3 Determination and adjustment of thresholds for TCWGD and modified NDWI

TCWGD		Modified NDWI (MDWI)		20,006 (1) inundated footprints		2006 (2) inundated footprints		2008 inundated footprints		2009 inundated footprints		2011 inundated footprints		Difference (TCWGD -AHS)[a]	Difference (MDWI -AHS)[a]
Percentile	Threshold	Percentile	Threshold	TCWGD	MDWI	TCWGD	MDWI	TCWGD	MDWI	TCWGD	MDWI	TCWGD	MDWI		
0.9855	0.097	0.028	−0.204	128	193	107	153	190	179	109	173	267	449	58	426
0.985	0.096	0.054	−0.150	125	130	105	108	187	146	107	111	264	261	53	109
0.9845	**0.095**	**0.056**	**−0.147**	**122**	**127**	**104**	**108**	**185**	**146**	**105**	**111**	**260**	**260**	**53**	**107**
0.984	0.094	0.058	−0.145	122	127	104	108	183	146	101	110	256	255	57	111
0.9835	0.093	0.06	−0.143	119	127	100	107	180	144	101	109	249	250	60	116
0.977	0.088	0.062	−0.141	104	122	85	106	163	140	91	108	214	247	92	116

Bold row represents new threshold with the least difference value compared to historical records from the Annual Habitat Survey

[a] Difference represents the sum of each year's absolute value of TCWGD—Annual Habitat Survey (AHS) or modified NDWI—Annual Habitat Survey (AHS)

in Table 4. In March, the most productive scene is path 31/row 32, of which 13 images are useable, while only 4 images are useable in path 33/row 31 for the past 30 years. In April, the easternmost scene of path 28/row 31 is the most productive scene, of which 21 images are useable. Both path 32/row 31 and path 33/row 31, which cover the western playa wetlands in Nebraska, only have 9 images respectively.

Playa inundation status in March and April during 1985–2015

The playa inundation status in March and April during 1985–2015 was mapped in Fig. 3. There were 9898 wetlands inundated at least once in either March or April during the past 30 years, representing 29.41% of total 33,659 historical wetlands. The total inundated areas derived from the merged March and April data from 1985 to 2015 were 176.79 km^2. Compared with the total areas (934.46 km^2) of playa wetlands, we only detected inundation on 18.92% of total areas at least once in March or April over the last 30 years. The actual inundated area on each wetland was a small portion of the total area of playa footprints. In March, 115.83 km^2 of footprints was inundated, representing 12.40% of total areas, and 154.21 km^2 of footprints that represented 16.50% of total areas was inundated in April.

While any of the historical hydric soil footprint was inundated once from the available Landsat images in March and April during 1985–2015, we count this footprint as an inundated wetland. The total number of inundated wetlands in the merged inundation map was 9898, while the total number of playa wetlands in Nebraska was 33,659. Approximately 30% (29.41%) of total wetlands were identified as functional wetlands in spring migratory season during the past 30 years (Fig. 3). Over 7000 wetlands (7052 in March and 7938 in April) were identified as functional wetlands in each month period, representing 20.95 and 23.58% of the total number of wetlands, respectively.

The total number of conservation easements within this playa wetland complex is 126. Among them, there are 121 easements overlaid with the functional wetlands, indicating that at least 96% of existing wetlands in conservation easements provided ponded habitat during spring migration. The total area these conservation easements is 40.13 km^2, while the contemporary ponding within 121 easements is 36.81 km^2.These conservation easements only count for 4.29% of the total footprint areas, but they have contributed 20.82% of the inundation areas in Nebraska during the past 30 years.

Discussions

Our results indicate that only a small portion of playa wetlands pond water more than once in spring during the past 30 years. The total inundated wetland numbers and areas only account for a relatively small portion of total playa wetlands in Nebraska. We did not examine inundation during the other months of the year, so it is possible that some of the playas that were not inundated in March and April were inundated at other times of the year. Prior to this study, the AHS data was the only information to determine playa spring inundation conditions in the Rainwater Basin, one of four playa wetland complexes throughout Nebraska. Tang et al. (2015) found that 13.3% of areas within the Rainwater Basin hydric soil footprints SSURGO dataset ponded water during the spring migration. The Rainwater Basin Joint Venture (2013) documented that the current ponding frequency under average moisture conditions was only 17.7%. This study examined the inundation status of playa wetlands to a larger landscape level and thus provided the first scientific report on playa-ponded habitat in Nebraska. Although inundation condition is just one of three diagnostic characteristics for wetland delineation (including wetland vegetation, hydric soils, and wetland hydrology), the lack of inundated land in wetlands is an important signal that helps determine playa hydrological conditions during spring migratory

Table 4 Distribution of available Landsat images for playa inundation detection in March and April during 1985–2015

	P28 R31	P29 R31	P29 R32	P30 R31	P30 R32	P31 R31	P31 R32	P32 R31	P33 R31	Total
March	8	12	12	10	9	8	13	10	4	86
April	21	12	12	16	12	16	18	9	9	125
Overall	29	24	24	26	21	24	31	19	13	211

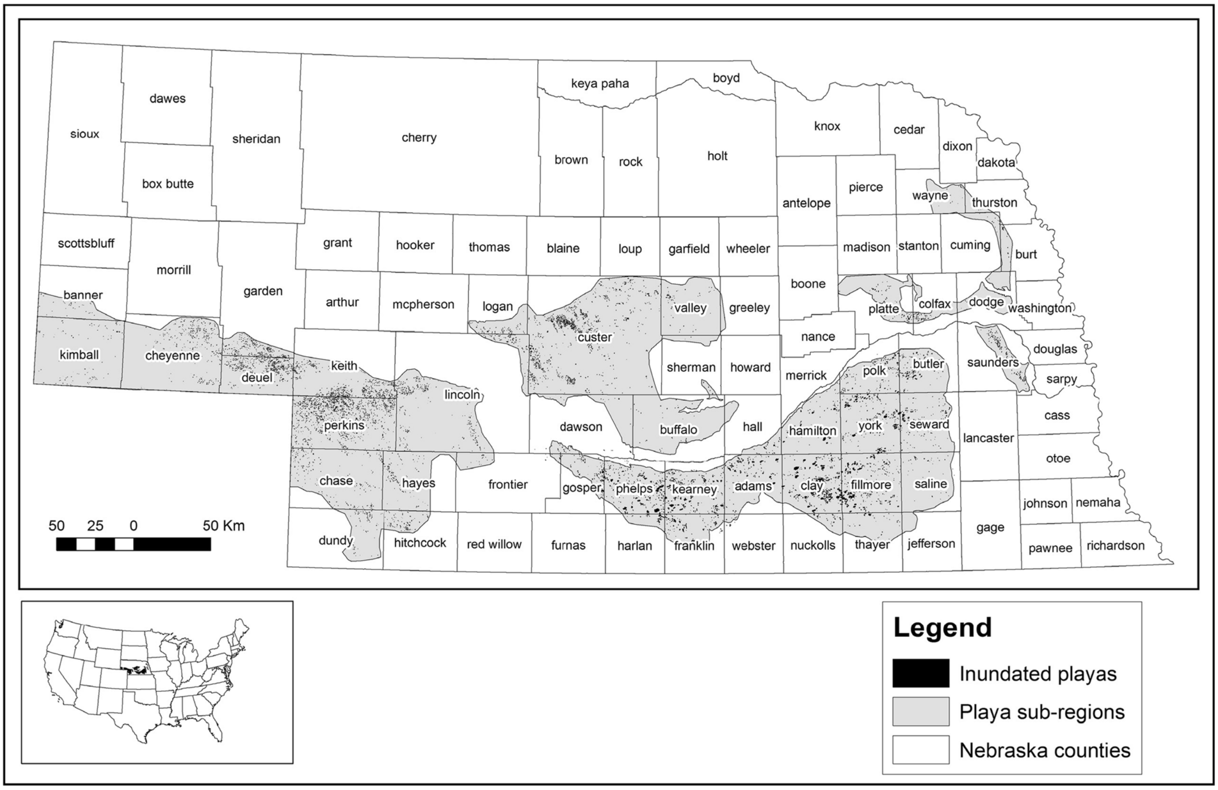


Fig. 3 Inundated playa wetlands in Nebraska in spring season during 1985–2015

seasons. Yet, the Wetlands Reserve Program has conserved wetland habitat that does pond spring water. Furthermore, the results support the previous findings that conservation programs influence land use and improve wetland functions (Tsai et al. 2007; Webb et al. 2010; Smith et al. 2011). The findings of this study also verified that wetland conservation easements in Nebraska have high rates of success in ponding water during spring migration.

This novel use of Landsat images and Google Earth Engine to capture spatial features for long-term playa wetland monitoring at landscape scale can help future conservation approaches. The method provides new insight on playa inundation conditions during the past decades. Many previous studies have developed methodologies for wetland mapping (e.g., Kuzila et al. 1991; Hess et al. 2003; Woodcock et al. 2008; Kennedy et al. 2010; Gómez-Rodríguez et al. 2010; Muster et al. 2013; Huang et al. 2014). However, most of the previous research has focused on wetland mapping accuracy and had deficiencies in monitoring long-range environment. To date, there are more than 1549 Landsat images for nine scenes available that cover the playa wetlands in Nebraska in spring over the past 30 years. However, the total size of all images is extremely large. Yet, Google Earth Engine allows users to analyze satellite data online through remote servers and returns outcomes as small-sized data format files. The index and its threshold determined in this study provide an important tool for playa inundation detection. Unlike other water bodies in large lakes and rivers, depths of playas range from centimeters to over 1 m. Since playa wetlands are shallow, frequently vegetated, and exposed to high winds that suspend sediment throughout the water column, their signatures are different than other palustrine water bodies. The index and its threshold provide a simple algorithm to analyze playa inundation conditions from long-term Landsat image datasets.

However, the limitations of satellite imageries in wetland inundation monitoring should be recognized. The previous studies have identified the challenges (Gluck et al. 1996; Ozesmi and Bauer 2002; Zhu and Woodcock 2012). The overlapped spectral signatures of different wetland types make them difficult in separation (Gluck et al. 1996). In our field surveys, we found that playa wetlands tend to be green and brown-colored water bodies due to their shallowness and effects from agriculture runoff. In addition, weather condition is an important factor determining the inundation of playa wetlands. Hydrologically, the incoming water sources for playa wetlands are precipitation and runoff, and the two outgoing pathways of water are infiltration and evapotranspiration (Smith 2003). In the agricultural setting, irrigation could provide additional runoffs into playas. The dynamics of playa inundation conditions were not reflected on the maps, but the inundation map actually recorded the most likely areas with ponding water based on the available temporal and spatial satellite data.

This study only mapped these playa wetlands with at least one time of inundation status shown on the available Landsat images during the past 30 years. However, due to cloud or snow conditions, the Landsat images were not repeatedly available for playas; thus, annual variations were not able to be discovered due to the unmatched temporal-spatial satellite data. Many of Landsat images are influenced by cloud or snow coverage. The influence of clouds and their shadows on satellite data causes problems for interpreting data, including biased estimation, misleading land cover classification, and false detection of land cover change (Zhu and Woodcock 2012). Zhang et al. (2004) reported that approximately 66% of the surface of the earth is annually covered by clouds. In this study, a large portion (approximately 80%) of Landsat images was affected by cloud or snow coverage. Given data limitations due to cloud or snow coverage, the annually wetland change detection would be impossible to achieve. Thus, all of inundated areas identified in 211 images were dissolved into a single merged inundation map. The inundated areas identified from the available Landsat images represent the inundated areas where ponded water appeared at least once during the past 30 years. The Landsat images did cover all of the playa wetlands multiple times in either March or April during the past 30 years. Whenever a playa wetland was inundated once during the past 30 years, we count this wetland as an inundated wetland. Even if a playa wetland is inundated multiple times, it still counts as an inundated wetland. This study only counts the inundation status as "presence" or "absence." In fact, during the 30 years, the least coverage area by the Landsat data has at least 13 scenes available for analysis.

This study only examined the relatively larger-sized playa wetlands with an area above 900 m^2. Because the spatial resolution of a large portion of satellite imagery is low (20–30 m), it is technically difficult to identify small or long, narrow wetlands (Ozesmi and Bauer 2002). The original inundation information was represented by points derived from the raster data. Although all points were located in the playa wetlands, part of the area they represented may be not completely within wetland boundaries. Some small-sized wetlands that contained a small amount of water were not able to be mapped in this study. Although they did not hold a large amount of water, they still served as fully functional wetlands and provide important habitat for migratory birds and other wildlife. The number of inundated footprints less than 900 m^2 that have been detected is 247 while the total number of footprints that are less than 900 m^2 is 4490. The number percentage of inundated footprints among wetlands that is less than 900 m^2 is 5.5%. The total area of inundated footprints that is less than 900 m^2 is 0.17 km^2, while the total area of inundated footprints is 519 km^2. The area percentage of inundated footprints that is less than 900 m^2 among all inundated footprints is 0.03%. Furthermore, the total area of footprints that is less than 900 m^2 is 2.78 km^2, and the total area of footprints is 934 km^2. The percentage of footprints less than 900 m^2 among all footprints is 0.3%. The small-sized playa wetlands are ecologically important and are contributing to the inundation areas, but they were not able to be identified through Landsat images. Though Landsat could only monitor the inundations larger than 900 m^2, the number of these large wetlands is 99.7% of the entire playa footprint area and it holds much more water than smaller inundated playas. This study addresses those medium and large playas aiming to provide more historical and monitoring data of them. The Playa Lakes Joint Venture (2015) established the playa decision support system to prioritize the protection of playas that are larger than 4047 m^2 (approximately 1 acre in USA). Large wetlands have more opportunities to hold water during dry periods due to their large catchments. Small wetland footprints less than 1 acre are more likely to be either dry or cultivated. In this study, the higher percentage of the total number of functional wetlands than the percentage of total inundated areas means that more small-sized wetlands were inundated during the past 30 years. Therefore, it is extremely important to monitor the inundation of larger playas (>900 m^2) during the spring migratory season to make sure that they are able to provide ecosystem services.

Conclusion

This study uses inundation data collected from field surveys and ground-truthed AHS data to select the most suitable remote sensing spectral index and associated threshold for the detection of playa wetland inundation. Our proposed spectral index provides several advantages of information interpretation from Landsat images, including easily integrating with GIS data and less time-consuming than aerial survey and field survey. This study used field survey data and AHS data to determine the most appropriate index and its threshold for playa inundation detection. We concluded that the Tasseled Cap Wetness-Greenness Difference (TCWGD) has the best ability for detecting inundation conditions of playa wetlands. The continuity of free Landsat images makes long-term and large-area investigations possible, especially for understanding the dynamics of land cover changes and habitat loss. More high-resolution imageries, such as Earth Remote Observation System A and B, Quickbird, GeoEye, and Worldview, could be considered for wetland monitoring research.

By using the available cloud-free Landsat data, this study analyzed the playa inundation status in spring seasons during the past 30 years. From the inundation mapping results, we concluded that large portions of playa wetlands were not inundated in spring migratory seasons during the past decades. The findings of this study confirmed that there is a dramatic difference in inundation status of playas enrolled in easements vs. those not enrolled. The conservation easements had a high level of playa inundation status across Nebraska. This study also used the cutting-edge platform, Google Earth Engine, to process big satellite data. Inundated wetland maps derived from Landsat images serve as an important database for continuous wetland monitoring on long-term and large-area dimensions. However, the limitations of Landsat data should be identified. Due to the majority of the cloud-covered Landsat imageries which were not used in analysis, the map only indicates that these playas were shown at least one time of inundation condition during the past 30 years. The spatial and temporal variations of these playa inundation conditions were not counted in this study.

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References

Brivio, P. A., Colombo, R., Maggi, M., & Tomasoni, R. (2002). Integration of remote sensing data and GIS for accurate mapping of flooded areas. *International Journal of Remote Sensing, 23*(3), 419–441.

Crist, E. P., Cicone, R. C. (1984) Application of the tasseled cap concept to simulated thematic mapper data(transformation for MSS crop and soil imagery, Photogrammetric Engineering and Remote Sensing *50*, 343–352

Drahota, J., & Reichart, L. (2015). Wetland seed availability for waterfowl in annual and perennial emergent plant communities of the Rainwater Basin. *Wetlands, 35*, 1105–1116.

Gao, B.-C. (1996). NDWI—a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment, 58*, 257–266.

Gluck, M. J., Rempel, R. S., Uhlig, P. (1996). *An evaluation of remote sensing for regional wetland mapping applications* (No. 137). Sault Ste. Marie: Ontario Forest Research Institute.

Gómez-Rodríguez, C., Bustamante, J., & Díaz-Paniagua, C. (2010). Evidence of hydroperiod shortening in a preserved system of temporary ponds. *Remote Sensing, 2*(6), 1439–1462.

Gorelick, N. (2013). Google Earth Engine. In *EGU General Assembly Conference Abstracts* (Vol. 15, p. 11997).

Guthery, F. S., Bryant, F. C., Kramer, B., Stoecker, A., Dvoracek, M. (1981). Playa assessment study. U.S. Water and Power Resource Series, Southwest Region, Amarillo, TX.

Hess, L. L., Melack, J. M., Novo, E. M., Barbosa, C. C., & Gastil, M. (2003). Dual-season mapping of wetland inundation and vegetation for the central Amazon basin. *Remote Sensing of Environment, 87*(4), 404–428.

Huang, C., Peng, Y., Lang, M., Yeo, I. Y., & McCarty, G. (2014). Wetland inundation mapping and change monitoring using Landsat and airborne LiDAR data. *Remote Sensing of Environment, 141*, 231–242.

Hui, F., Xu, B., Huang, H., Yu, Q., & Gong, P. (2008). Modelling spatial-temporal change of Poyang Lake using multitemporal Landsat imagery. *International Journal of Remote Sensing, 29*, 5767–5784.

Kauth, R. J, Thomas, G. S. (1976). The tasseled cap — a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. In: Proc. 10th Symposium on Machine Processing of Remotely Sensed Data, Purdue University, pp. 41–51, West Lafayette, Indiana

Kennedy, R. E., Yang, Z., & Cohen, W. B. (2010). Detecting trends in forest disturbance and recovery using yearly Landsat time series: 1. LandTrendr-temporal segmentation algorithms. *Remote Sensing of Environment, 114*(12), 2897–2910.

Kuzila, M. S., Rundquist, D. C., & Green, J. A. (1991). Methods for estimating wetland loss: the Rainbasin region of Nebraska, 1927–1981. *Journal of Soil and Water Conservation, 46*(6), 441–446.

LaGrange, T. (2005). *A guide to Nebraska's wetlands and their conservation needs* (2nd ed.). Lincoln, Nebraska: Nebraska Game and Parks Commission.

LaGrange, T.G., Stutheit, R., Gilbert, M., Shurtliff, D., Whited, P.M. (2011). Sedimentation of Nebraska's playa wetlands: a review of current knowledge and issues, Nebraska Game and Parks Commission, Lincoln.

Lane, C. R., D'Amico, E., & Autrey, B. (2012). Isolated wetlands of the southeastern United States: abundance and expected condition. *Wetlands, 32*(4), 753–767.

Lang, M. W., & McCarty, G. W. (2009). Lidar intensity for improved detection of inundation below the forest canopy. *Wetlands, 29*(4), 1166–1178.

Larson, D. L. (1995). Effects of climate on numbers of northern prairie wetlands. *Climatic Change, 30*, 169–180.

Li, W., Church, R. L., & Goodchild, M. F. (2014). An extendable heuristic framework to solve the p-compact-regions problem for urban economic modeling. *Computers, Environment and Urban Systems, 43*, 1–13.

McFeeters, S. (1996). The use of the normalized difference water index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing, 17*, 1425–1432.

Mulligan, K.R., Barbato, L.S., Seshadri, S. (2014). Playas and Wetlands Database. Texas Tech University, Lubbock.

Muster, S., Heim, B., Abnizova, A., & Boike, J. (2013). Water body distributions across scales: a remote sensing based comparison of three arctic tundra wetlands. *Remote Sensing, 5*(4), 1498–1523.

National Conservation Easement Database (NCED) (2016). National Conservation Easement Database, http://www.conservationeasement.us/about/faqs (Visited on September 20, 2016).

Nugent, E., Bishop, A., Grosse, R., LaGrange, T., Varner, D., Vrtiska, M. (2015). An assessment of landscape carrying capacity for waterfowl and shorebirds in Nebraska's Rainwater Basin. A conservation effects assessment project wildlife component assessment report. Rainwater Basin Joint Venture, Wood River, NE. 45 pp.

Ozesmi, S. L., & Bauer, M. E. (2002). Satellite remote sensing of wetlands. *Wetlands Ecology and Management, 10*(5), 381–402.

Playa Lakes Joint Venture (2015). Playa Decision Support System. http://pljv.org/for-habitat-partners/maps-and-data/playa-decision-support-system/. Accessed 22 Dec 2015.

Rainwater Basin Joint Venture (2013). The Rainwater Basin Joint Venture Implementation Plan, Grand Island, Nebraska.

Rainwater Basin Joint Venture (2015) Rainwater Basin Joint Venture, GIS Projects. Rainwater Basin Joint Venture. http://rwbjv.org/rainwater-basin-joint-venture/gis-projects/. Accessed 25 Dec 2015.

Rebelo, L. M., Finlayson, C. M., & Nagabhatla, N. (2009). Remote sensing and GIS for wetland inventory, mapping and change analysis. *Journal of Environmental Management, 90*(7), 2144–2153.

Smith, L. M. (2003). *Playas of the Great Plains*. Austin: University of Texas Press.

Smith, L. M., Haukos, D., McMurry, S., LaGrange, T., & Willis, D. (2011). Ecosystem services provided by playa wetlands in the High Plains: potential influences of USDA conservation programs and practices. *Ecological Applications, 21*, S82–S92.

Tang, Z., Li, R., Li, X., Jiang, W., & Hirsh, A. (2014). Capturing LiDAR-derived hydrologic spatial parameters to evaluate playa wetlands. *Journal of the American Water Resources Association, 50*(1), 234–245.

Tang, Z., Gu, Y., Dai, Z., Li, Y., LaGrange, T., Bishop, A., & Drahota, J. (2015). Examining playa wetland inundation conditions for National Wetland Inventory, Soil Survey Geographic database, and LiDAR data. *Wetlands, 35*(4), 641–654.

Tang, Z., Gu, Y., Jiang, W., Xue, Y., Bishop, A., LaGrange, T., & Nugent, E. (2016). Use RUSLE2 model to assess the impact of soil erosion on playa inundation and hydrophyte conditions in the Rainwater Basin, Nebraska. *Environmental Monitoring and Assessment, 188*(6), 1–15.

Tiner, R. W. (2003). Geographically isolated wetlands of the United States. *Wetlands, 23*(3), 494–516.

Tsai, J.-S., Venne, L. S., McMurry, S. T., & Smith, L. M. (2007). Influences of land use and wetland characteristics on water loss rates and hydroperiods of playas in the southern high plains, USA. *Wetlands, 27*, 683–692.

Tucker, C. J. (1979). Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment, 8*, 127–150.

Uden, D. R., Allen, C. R., Bishop, A. A., Grosse, R., Jorgensen, C. F., LaGrange, T. G., Stutheit, R. G., & Vrtiska, M. P. (2015). Predictions of future ephemeral springtime waterbird stopover habitat availability under global change. *Ecosphere, 6*(11), 215.

Webb, E. K., Smith, L. M., Vrtiska, M. P., & LaGrange, T. G. (2010). Effects of local and landscape variables on wetland bird habitat use during migration through the Rainwater Basin. *Journal of Wildlife Management, 74*(1), 109–119.

Woodcock, C. E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., & Nemani, R. (2008). Free access to Landsat imagery. *Science, 320*(5879), 1011.

Xu, H. (2006). Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing, 27*(14), 3025–3033.

Zhang, Y., Rossow, W. B., Lacis, A. A., Oinas, V., & Mishchenko, M. I. (2004). Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: refinements of the radiative transfer model and the input data. *Journal of Geophysical Research: Atmospheres (1984–2012), 109*(D19).

Zhu, Z., & Woodcock, C. E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. *Remote Sensing of Environment, 118*, 83–94.