

A SPATIO-TEMPORAL CHANGE ANALYSIS OF SHOREBIRD HABITAT USING
REMOTE SENSING AT STILLWATER NATIONAL WILDLIFE REFUGE, NV

By

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DEDICATION

To my partner, Kyle, who has been a constant source of support, balance, reason, and love throughout the entire process. To Cricket, my pup, who was by my side during late nights and long days working on this project. This work is also dedicated to my family and friends who have encouraged me all the way to the finish line.

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This paper would not have been possible without the knowledge and guidance of my advisor, Yoga Korgaonkar. I am also grateful for the feedback and support of my peers as we made our way through this shared educational journey. Finally, I acknowledge the original and continued sovereignty of the *Numu* (Northern Paiute) people and communities - the Native nation of the physical region in which this project was performed. I acknowledge the deep-rooted ancestral ties the *Numu* people, and Indigenous nations everywhere, have to the land and recognize that these communities continue to thrive today.

TABLE OF CONTENTS

	<u>page</u>
DEDICATION	2
ACKNOWLEDGMENTS	3
LIST OF TABLES	5
LIST OF FIGURES	6
ABSTRACT	7
ETHICS STATEMENT	8
INTRODUCTION	10
METHODS AND DATA	15
Study Area	15
Data Sources and Pre-Processing	17
Methods of Analysis	24
RESULTS	28
Indices Change Detection	30
Land Cover – Land Use Change Detection	36
DISCUSSION	40
CONCLUSION	44
LIST OF REFERENCES	46

LIST OF TABLES

<u>Table</u>	<u>page</u>
Table 1. Project data and sources	22
Table 2. Project data spatial reference information.....	23
Table 3. NDVI values and the associated change in area between study years. Proportion indicates the percentage of total area.	30
Table 4. NDVI value statistics for each study year.	31
Table 5. NDVI percent change for Stillwater NWR across the study years.....	31
Table 6. MNDWI values and the associated change in area between study years. Proportion indicates the percentage of total area.	33
Table 7. MNDWI percent change for Stillwater NWR across the study years.	34
Table 8. Distribution of land cover and percentage of gain or loss for each land cover class for Stillwater NWR between 2001-2019.	36
Table 9. Change matrix of land cover area (km ²) changes for Stillwater NWR between 2001-2019.	37
Table 10. Distribution of impervious surface coverage and percentage of gain or loss for each coverage class for Stillwater NWR between 2001-2019.....	39
Table 11. Change matrix of impervious surface area (km ²) changes for the Stillwater NWR between 2001-2019.	40

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
Figure 1. The Pacific Flyway migration corridor within the United States.	11
Figure 2. The study area - Stillwater National Wildlife Refuge.	15
Figure 3. Extent of Landsat imagery.	18
Figure 4. Extent of USGS Land Cover data.	20
Figure 5. Extent of USGS Impervious Surface data.	21
Figure 6. Flowchart of spatial analysis.	24
Figure 7. Spatial distribution of the investigated environmental factors related to shorebird habitat. (a) NDVI, (b) MNDWI, (c) Land Cover, and (d) Impervious Surfaces.	29
Figure 8. NDVI value percent change by pixel for 2001 – 2019 at Stillwater NWR.	32
Figure 9. MNDWI value percent change by pixel for 2001-2019 at Stillwater NWR.	35
Figure 10. Land cover percent change between 2001-2019 for Stillwater NWR.	38

ABSTRACT

Stillwater National Wildlife Refuge (NWR) provides critical wetland stopover habitat for thousands of breeding and non-breeding migrating shorebirds during the spring and fall seasons. Habitat loss and degradation at the refuge due to climate change and human activities are of great concern to shorebird conservation groups. Evaluations of critical habitat features utilizing GIS can be leveraged as powerful, cost-effective tools in shorebird conservation and management efforts. In this study, three years (2001, 2011, and 2019) of remote sensing data captured during the fall season were analyzed for changes in select land cover factors impacting quality of shorebird habitat: presence of surface water using the Modified Normalized Difference Water Index (MNDWI), preferred land cover types, food and shelter availability using Normalized Difference Vegetation Index (NDVI), and human disturbance using impervious surface data. Results successfully detected temporal changes in many of the select environmental factors, including sizeable increases in NDVI and MNDWI results, both in value and spatial distribution, and notable transitions between land cover classes and their represented areas. Findings support the ongoing habitat conservation efforts at the refuge and demonstrate the use of remote sensing and GIS techniques in monitoring land cover conditions related to vital migratory shorebird habitat.

Keywords: remote sensing, change detection analysis, NDVI, shorebird conservation, Stillwater National Wildlife Refuge

ETHICS STATEMENT

As advances in GIS technology progress and spatial data availability increases, the need for ethical GIS practices grows. Spatial data visualizations are very influential means of communication that are used across multiple disciplines to inform and influence decision making. Knowing the power maps have to influence federal, state, and community decision making, users of GIS must learn to identify and prevent harm that may result from their geospatial work. Some of the major ethical concerns within the field of GIS include the misrepresentation of spatial data, omission of contradictory data or results, insufficient citation of data sources, and the loss of privacy and autonomy of individuals or communities. Strategies in addressing these concerns are outlined in the GIS Code of Ethics and include the accurate portrayal of spatial data using appropriate symbols and projections, the inclusion of all data to reflect an unbiased representation of reality, the detailed and accurate documentation of data sources within metadata, and the protection of sensitive information regarding individuals, communities, and cultures. Map outputs should be repeatable by others in the field and spatial data made widely available when possible.

Ethical considerations specific to this project relate to the neutral, clear, and accurate portrayal of the GIS analysis results in all map products, the appropriate citation of other's work and data sources, and the contribution of study results to the community and other invested parties. In order to meet ethical expectations, care was taken to recognize and abide by the GIS Code of Ethics throughout the study. Spatial data sources are accounted for in a metadata table, included on map products, and intellectual sources are cited thoroughly throughout the written report. Maps and

associated data tables do not omit study results, striving to maintain neutrality. The design of the maps and related visuals were created to be simple, evident, and clear to the reader. All data is openly sourced from notable organizations, and the methodology section provided should allow for the repeatability of the study. Individuals and communities of people were not included in this specific study, so privacy concerns were low. Geospatial information, analysis, and visualization can provide solutions to many complex problems or questions, while also having the potential to harm the populations they should serve. The rigorous observance of ethics in GIS and the development of sensitivity to the impactful message maps can portray are necessary actions GIS users should take to maximize the positive benefits of geospatial technology in our communities and across the globe.

INTRODUCTION

Wetlands, defined as year-round or seasonal water saturated lands hosting a blend of aquatic and terrestrial plants, are unique features of a watershed as they function as vital habitat to numerous species, mitigate flooding impacts, and act as natural water filters (Davis 2004). These important ecosystems face ongoing threats of degradation in response to the impacts of climate change, as well as human driven loss to area and quality. Hydrologic changes, increased temperatures, and extreme weather events all threaten to throw off the sensitive balance of wetland systems and the degree to which their current features may shift will depend upon their specific environmental characteristics and geographic locations (Erwin 2009).

The Great Basin is a desert region of the western United States that spans across most of the state of Nevada and large swaths of Oregon, Idaho, Utah, and California. Unique in the broad ecologic diversity and various climate gradients present across the region, the Great Basin is geographically defined by borders of north-south mountain ranges whose winter snowpack drains down into wide, interior valley floors and their land-locked lakes, marshes, and sinks (Minckley et al. 2007; Pellant et al. 2004). The arid wetlands of the Great Basin region lie within one of the most at-risk ecoregions in the United States for land use-land cover (LULC) changes and climate variability (Chambers & Wisdom 2009).

Migratory shorebirds (order Charadriiformes) of the Intermountain West are small to medium sized wading birds that travel seasonally along the Pacific Flyway migratory corridor, a travel route spanning from the Arctic regions of Canada and Alaska, across the Great Basin region (Figure 1), ending in the southern coastal regions of Mexico and

South America (*The Flyways: Pacific Flyway* 2014). Traveling shorebirds fly for long periods as they pursue faraway breeding grounds and richer nutrition sources, only pausing along their journey at select locations called stopover sites to gain access to vital habitat resources such as food, water, and shelter (Carlisle et al. 2009; Moore et al. 2005). The wetland ecosystems scattered across the Great Basin region act as a network of crucial stopover sites for migrating shorebirds within the Intermountain West.

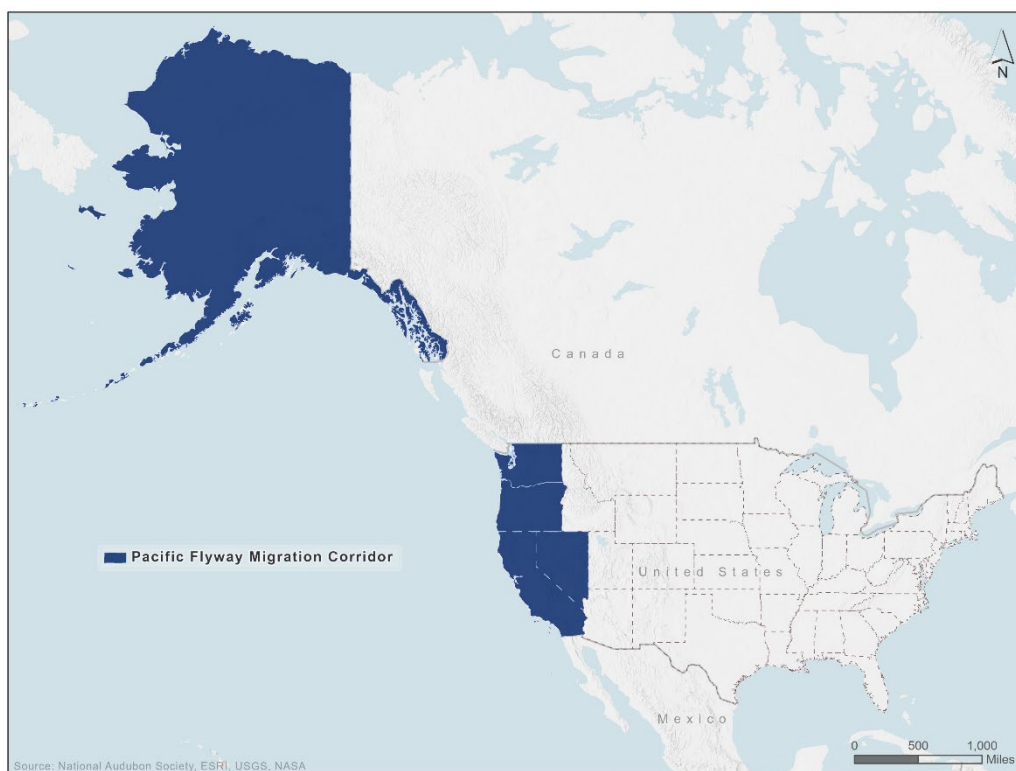


Figure 1. The Pacific Flyway migration corridor within the United States.

Birds face many hazards during migration flights including increased nutritional demands, variations in environmental conditions, unfamiliar habitats, physical and environmental barriers, and increased competition with fellow migratory birds (Carlisle et al. 2009). Shorebird species are of particular concern to bird conservationists

because of their continued, documented decline in populations and the ongoing loss or degradation of their critical wetland habitats (Shuford et al. 2002). Many studies have projected that wetland habitats will decrease in area, quality, and abundance in response to the effects of climate change, potentially resulting in changes to shorebird population sizes, species composition, and migration timing (Sofaer et al. 2016; Haig et al. 2019). A 2013 U.S. Shorebird Conservation Plan for the western U.S. pinpoints freshwater availability and water resource competition as their most critical issues facing shorebird habitat conservation across the Intermountain West (Western Hemisphere Shorebird Reserve Network n.d.).

Remote sensing and Geographic Information Systems (GIS) can be used to investigate landscape characteristics over time and determine variables influencing habitat quality through mapping. Conservation research into habitat condition and quality using remote sensing and GIS has become more accessible with the advances in GIS technologies and increased access to high quality satellite imagery. Map products created using these tools can serve a variety of purposes in state and federal land use decisions regarding environmental conservation, planning, and design.

Across the globe, many studies have been performed to evaluate changes in LULC composition of natural habitats, and the reliant species, using remote sensing and GIS techniques. Wetland habitats were investigated for change using remote sensing and GIS in the Tian et al. (2019) survey of waterbird habitat between 2000-2015 in the West Songen Plain of China. This study investigated four environmental factors associated with waterbird resource requirements by utilizing Landsat satellite imagery to perform an object-oriented land cover classification, normalized difference moisture

index (NDMI) analysis, and normalized difference vegetation index (NDVI) analysis in conjunction with field survey data to ultimately create a habitat suitability assessment which revealed declines in high quality waterbird habitat areas in the study region. In a similar study, Tang et al. (2016) performed a time change analysis of LULC changes using remote sensing to evaluate winter habitat suitability for migrating waterfowl in China's Poyang Lake region using object-oriented LULC classification, NDVI analysis, spatial density of water bodies, and the density of urban development and roads. Analysis results showed decreases in size and distribution of water bodies in the study area, creating larger wetland areas which provide more suitable habitat for migratory waterfowl in the region. Researchers validated their geospatial results with waterbird population counts. Teng et al. (2021) analyzed the distribution of hydrologic conditions in the Poyang Lake region of China using remote sensing images and GIS to perform a normalized difference water index (NDWI) analysis to investigate relationships between freshwater habitat availability and waterbird occurrence. Their study concluded that suitable habitat for wintering geese decreased as the winter season progressed, better informing waterbird distribution models and wetland management plans for the Poyang Lake region. Nosakhare et al. (2012) investigated LULC changes in Maryland's Eastern Shore watershed and its associated wetland using remote sensing images and a supervised classification technique to quantify long-term relationships in LULC as part of a conservation strategy for the region. The study documented land cover changes across many classifications, most notably their results demonstrate a decline of coastal wetland areas which was attributed to climate change and the growth of local invasive species. Osborne, Alonso & Bryant (2001) used satellite imagery and GIS data layers to

create a predictive model for Great Bustards, a vulnerable grassland bird species in central Spain, resulting in GIS generated habitat and species distribution maps to be used for conservation efforts.

While many research projects have evaluated habitat changes using a variety of remote sensing and GIS techniques, there is a lack of published research evaluating change in wetland habitats of the Great Basin using GIS analysis. The objective of this study is to evaluate spatio-temporal changes in LULC properties related to migrating shorebird habitat at the Stillwater National Wildlife Refuge (Stillwater NWR), a subset of wetlands and lakes within the Lahontan Valley wetlands complex in northern Nevada, over an 18-year period using remote sensing and GIS analysis techniques. The goals of this study are to (1) map key LULC characteristics between 2001-2019 related to migratory shorebird habitat requirements and (2) quantify any spatio-temporal changes for the investigated metrics. The findings of the study will support the need for current baseline data at the Stillwater NWR and the associated conservation efforts targeted at migrating shorebirds in the region.

METHODS AND DATA

Study Area

Stillwater NWR lies in the Lahontan Valley at the terminus of the Carson River, near the town of Fallon, in north-central Nevada (39.59400, -118.43460) (Figure 2). The approximately 80,000-acre refuge was established in 1948 and is a U.S. Fish and Wildlife managed federal conservation area for migratory birds. The refuge consists of fresh to saline wetlands intermixed with small ephemeral lakes that lie within a larger complex of managed conservation areas spanning across the valley and into the north at Pyramid Lake (U.S. Fish and Wildlife Service 2000). The Lahontan Valley wetlands, including Stillwater NWR, were designated as a site of hemispheric importance to migratory shorebirds of the Pacific Flyway by the Western Hemisphere Shorebird Reserve Network in 1988 owing to the more than 250,000 shorebirds documented in the valley annually (Western Hemisphere Shorebird Reserve Network n.d.).

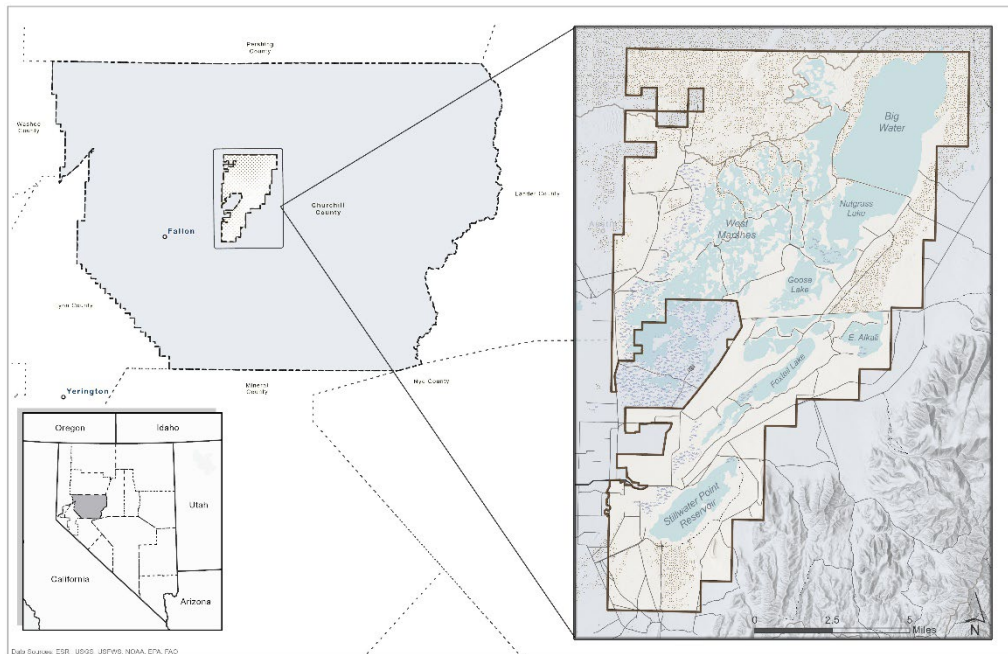


Figure 2. The study area - Stillwater National Wildlife Refuge.

Water levels at the refuge fluctuate across seasons and years, dependent upon the snowpack levels in the nearby mountain ranges and local agricultural use. During dry years the wetlands and lakes are maintained at minimum levels through a federal water rights acquisition program created in 1990 allowing conservation groups to purchase private water rights from local farmers to rehabilitate and preserve the important wetlands of the Lahontan Valley (Oring, Neel and Oring 2013; Ise & Sunding 1998). Federal and State entities, as well as local conservation groups, have purchased approximately 30,000 acre-feet of private water rights to date (The Nature Conservancy 2022). The water supplementation has bolstered the wetlands of the refuge, which have experienced severe area and quality loss since European colonization of Nevada, estimated by researchers that approximately 86% of original wetland habitat lost in the Lahontan Valley by 1987 (Skudlarek 2006).

In a 34-year survey of shorebirds seen across the Lahontan Valley wetlands during spring and fall migration periods, populations were documented in numbers over 20,000 individuals in 94% of survey years and in numbers over 100,000 in 24% of survey years (Senner et al. 2021). These results demonstrate the great number of shorebirds dependent on the wetland habitats at Stillwater NWR and across the Lahontan Valley. Another shorebird survey conducted between 1949 -1977 at the refuge counted shorebird population sizes ranging between 23,000 to 133,000 individuals at Stillwater NWR, depending on the year, with peak shorebird numbers of over 300,000 individuals between 1978-1987 across the entire Lahontan Valley wetlands (Neel & Henry 1996). Additionally, the variety of habitats present at Stillwater NWR provide resources to a variety of shorebird species, including 11 shorebird

species deemed critically or very important for conservation efforts to the Intermountain West (Oring, Neel and Oring 2013). Two shorebird species, the American Avocet (*Recurvirostra americana*) and Long-billed Dowitchers (*Limnodromus scolopaceus*), are a conservation priority as they utilize the Lahontan Valley wetlands during fall and spring migration periods in numbers exceeding 10% of their total global populations (Senner et al 2021).

Though these surveys establish the importance of the wetland ecosystems of Stillwater NWR, and generally of the Lahontan Valley, migratory shorebird populations are experiencing documented declines across the northern hemisphere. Rosenberg et al. (2019) estimate a 29% net loss in total bird abundance across North America since the 1970's, and specifically a 37% decrease in migratory shorebird populations in the same period. Senner et al. (2021) indicate that their survey of Nevada Department of Wildlife (NDOW) shorebird counts may suggest that use of the Lahontan Valley wetlands is currently in decline, with seasonal population counts decreasing since 1991, though researchers recommend continued surveying of the valley to verify the decline is real.

Data Sources and Pre-Processing

This study investigated spatio-temporal LULC changes at the Stillwater NWR over two decades utilizing roughly 10 year interval periods of 30-meter resolution Landsat satellite images for the years 2001 (Landsat 7), 2011 (Landsat 5), and 2019 (Landsat 8), acquired from the United States Geological Survey (USGS) National Land Imaging Program (USGS Landsat Missions 2022) (Figure 3), during the fall migration period when water levels are low and relatively stable for comparison between years (Shuford, Page and Stenzel 2002). The decision to use Landsat 5 images for the 2011

analysis and Landsat 8 images for the 2019 analysis in place of using Landsat 7 images for all study years was due to the permanent Scan Line Corrector failure in the Landsat 7 satellite imagery, which created data gaps in all images collected since June 2003 (Landsat Missions 2022).

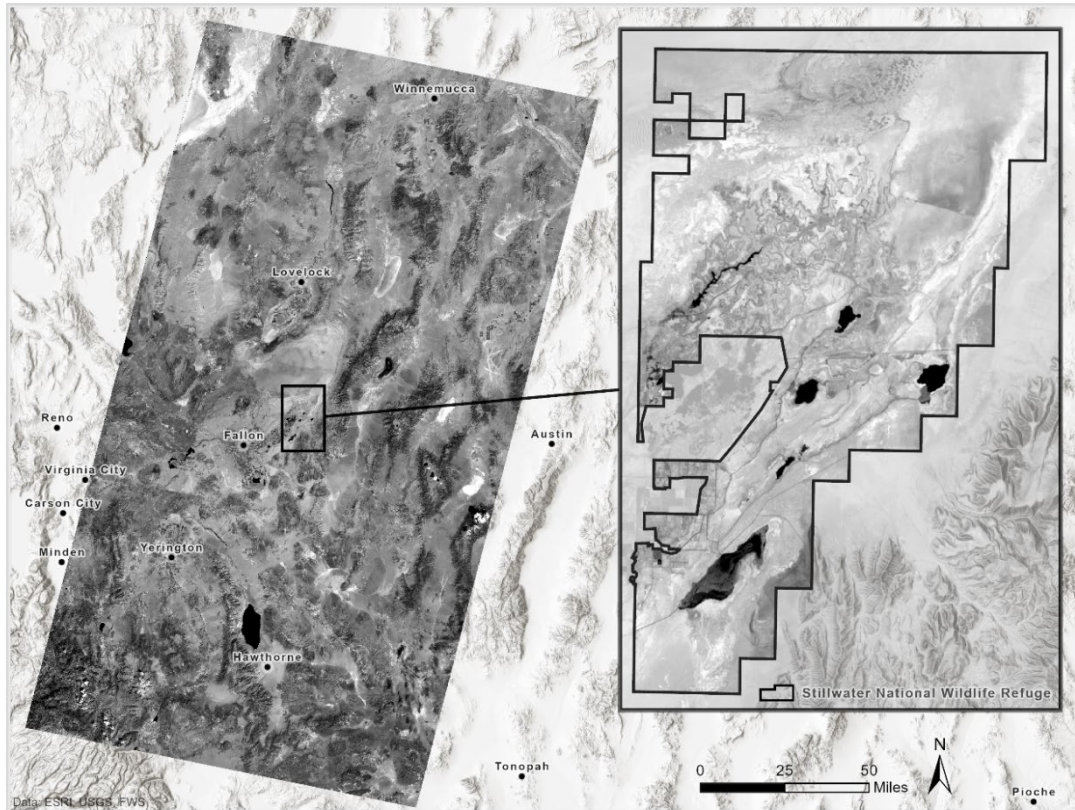


Figure 3. Extent of Landsat imagery.

Two cloud-free images were acquired for each year's fall migration period, approximately August until mid-September, and pre-processed for further analysis using ArcGIS Pro. The scenes were reclassified to remove No Data values, then merged into one seamless image covering the entire study area using the Mosaic to New Raster tool. This process was repeated for each subsequent study year. The scenes were

calibrated to Top of Atmosphere (TOA) Reflectance through the processes of conversion to at-sensor radiance and then solar correction. The TOA Reflectance measures the proportion of reflected solar radiance from the measured surface, in this case the surface of the Earth, allowing for improved comparison of Landsat images across time and sensors making it an appropriate technique for this study (Young et al. 2017). Once TOA calibration was complete, each scene was clipped to the extent of the study area as defined by the U.S. Fish and Wildlife Service's National Wildlife Refuge Boundaries layer.

Conversion to at-sensor radiance was performed using Equation (1):

$$P\lambda' = M_p * Q_{cal} + A_p \quad (1)$$

Where:

$P\lambda'$ = TOA planetary reflectance without solar angle correction

M_p = Band-specific multiplicative rescaling factor

Q_{cal} = Quantized and calibrated standard product pixel values (DN)

A_p = Band-specific additive rescaling factor

Solar Correction was performed using Equation (2):

$$P\lambda = \frac{P\lambda'}{\sin(\theta_{se})} \quad (2)$$

Where:

$P\lambda$ = TOA planetary reflectance with solar angle correction

$P\lambda'$ = TOA planetary reflectance without solar angle correction

θ_{se} = Local sun elevation angle

Land cover and impervious surface datasets at 30-meter resolution were obtained for the study area's extent for years 2001, 2011, and 2019 from the USGS National Land Cover Database. The recently updated and released land cover and impervious surface datasets, estimated by the USGS to have a 91% accuracy (USGS 2021), are classified into 20 land cover classifications (Figure 4) and include percentage of urban imperviousness per pixel (Figure 5). Land cover data was reclassified during the analysis into five categories reflecting migratory shorebird habitat preferences, from most suitable to least suitable, as indicated by previous shorebird studies. Metadata and sources for all datasets used in the analysis can be found in Table 1 and Table 2.

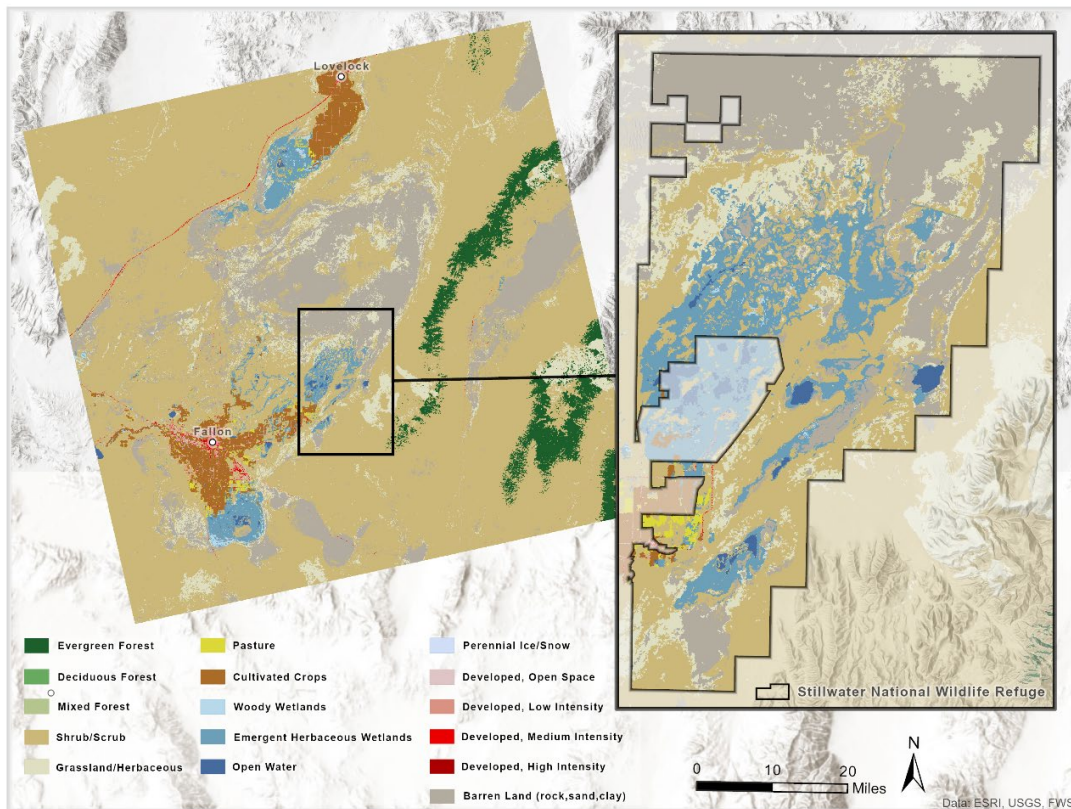


Figure 4. Extent of USGS Land Cover data.

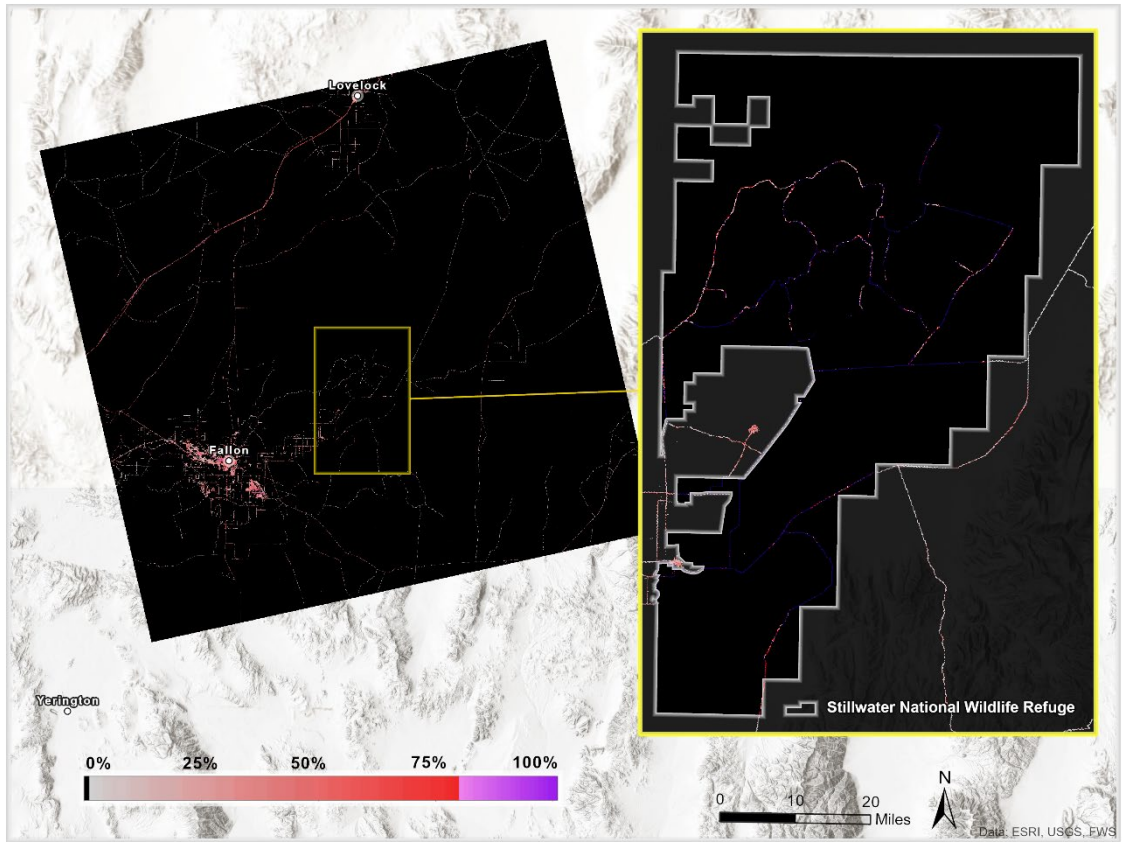


Figure 5. Extent of USGS Impervious Surface data.

Table 1. Project data and sources.

Name	Year	Author	URL
FWS Boundaries	2021	U.S. Fish and Wildlife Service	https://www.fws.gov/gis/data/CadastralDB/links_cadastral.html
LE07_L1TP_042032_20010831_2016 0929_01_T1	2016	U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	https://earthexplorer.usgs.gov/
LE07_L1TP_042033_20010831_2016 0929_01_T1	2016	U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	https://earthexplorer.usgs.gov/
LT05_L1TP_042032_20110920_2016 0830_01_T1	2016	U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	https://earthexplorer.usgs.gov/
LT05_L1TP_042033_20110920_2016 0830_01_T1	2016	U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	https://earthexplorer.usgs.gov/
LC08_L1TP_042032_20190825_2019 0903_01_T1	2019	U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	https://earthexplorer.usgs.gov/
LC08_L1TP_042033_20190825_2019 0903_01_T1	2019	U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center	https://www.fws.gov/gis/data/CadastralDB/links_cadastral.html
National Land Cover Database (NLCD) 2001 Land Cover	2021	U.S. Geological Survey (USGS)	https://www.usgs.gov/centers/eros/science/national-land-cover-database
National Land Cover Database (NLCD) 2011 Land Cover	2021	U.S. Geological Survey (USGS)	https://www.usgs.gov/centers/eros/science/national-land-cover-database
National Land Cover Database (NLCD) 2019 Land Cover	2021	U.S. Geological Survey (USGS)	https://www.usgs.gov/centers/eros/science/national-land-cover-database
National Land Cover Database (NLCD) 2001 Impervious Surface	2021	U.S. Geological Survey (USGS)	https://www.mrlc.gov/data?f%5B0%5D=category%3Aurban%20imperviousness&f%5B1%5D=region%3Aconus
National Land Cover Database (NLCD) 2011 Impervious Surface	2021	U.S. Geological Survey (USGS)	https://www.mrlc.gov/data?f%5B0%5D=category%3Aurban%20imperviousness&f%5B1%5D=region%3Aconus
National Land Cover Database (NLCD) 2011 Impervious Surface	2021	U.S. Geological Survey (USGS)	https://www.mrlc.gov/data?f%5B0%5D=category%3Aurban%20imperviousness&f%5B1%5D=region%3Aconus
National Land Cover Database (NLCD) 2019 Impervious Surface	2021	U.S. Geological Survey (USGS)	https://www.mrlc.gov/data?f%5B0%5D=category%3Aurban%20imperviousness&f%5B1%5D=region%3Aconus

Table 2. Project data spatial reference information.

Name	Coordinate System	Geodesic Model	EPSG	Projection	Spatial Resolution	Geometry
FWS Boundaries	NAD 1983	WGS84	4269	-	-	Polygon
LE07_L1TP_042032_20010831_2 0160929_01_T1	WGS84	WGS84	32611	WGS 84 UTM Zone 11N	30-m	-
LE07_L1TP_042033_20010831_2 0160929_01_T1	WGS84	WGS84	32611	WGS 84 UTM Zone 11N	30-m	-
LT05_L1TP_042032_20110920_2 0160830_01_T1	WGS84	WGS84	32611	WGS 84 UTM Zone 11N	30-m	-
LT05_L1TP_042033_20110920_2 0160830_01_T1	WGS84	WGS84	32611	WGS 84 UTM Zone 11N	30-m	-
LC08_L1TP_042032_20190825_2 0190903_01_T1	WGS84	WGS84	32611	WGS 84 UTM Zone 11N	30-m	-
LC08_L1TP_042033_20190825_2 0190903_01_T1	WGS84	WGS84	32611	WGS 84 UTM Zone 11N	30-m	-
National Land Cover Database (NLCD) 2001 Land Cover	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-
National Land Cover Database (NLCD) 2011 Land Cover	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-
National Land Cover Database (NLCD) 2019 Land Cover	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-
National Land Cover Database (NLCD) 2001 Impervious Surface	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-
National Land Cover Database (NLCD) 2011 Impervious Surface	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-
National Land Cover Database (NLCD) 2011 Impervious Surface	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-
National Land Cover Database (NLCD) 2019 Impervious Surface	WGS84	WGS84	4326	Albers Conical Equal Area	30-m	-

Methods of Analysis

To quantify changes in land cover conditions associated with shorebird habitat, a variety of geospatial analyses were performed to evaluate key environmental factors related to shorebird ecological needs, including food and shelter availability (Normalized Difference Vegetation Index (NDVI)), surface water availability (Modified Normalized Difference Water Index (MNDWI)), preferred habitats (land cover classes), and human disturbances (impervious surfaces) in accordance with current research. A visual workflow of the methods used in this study is shown below in Figure 6.

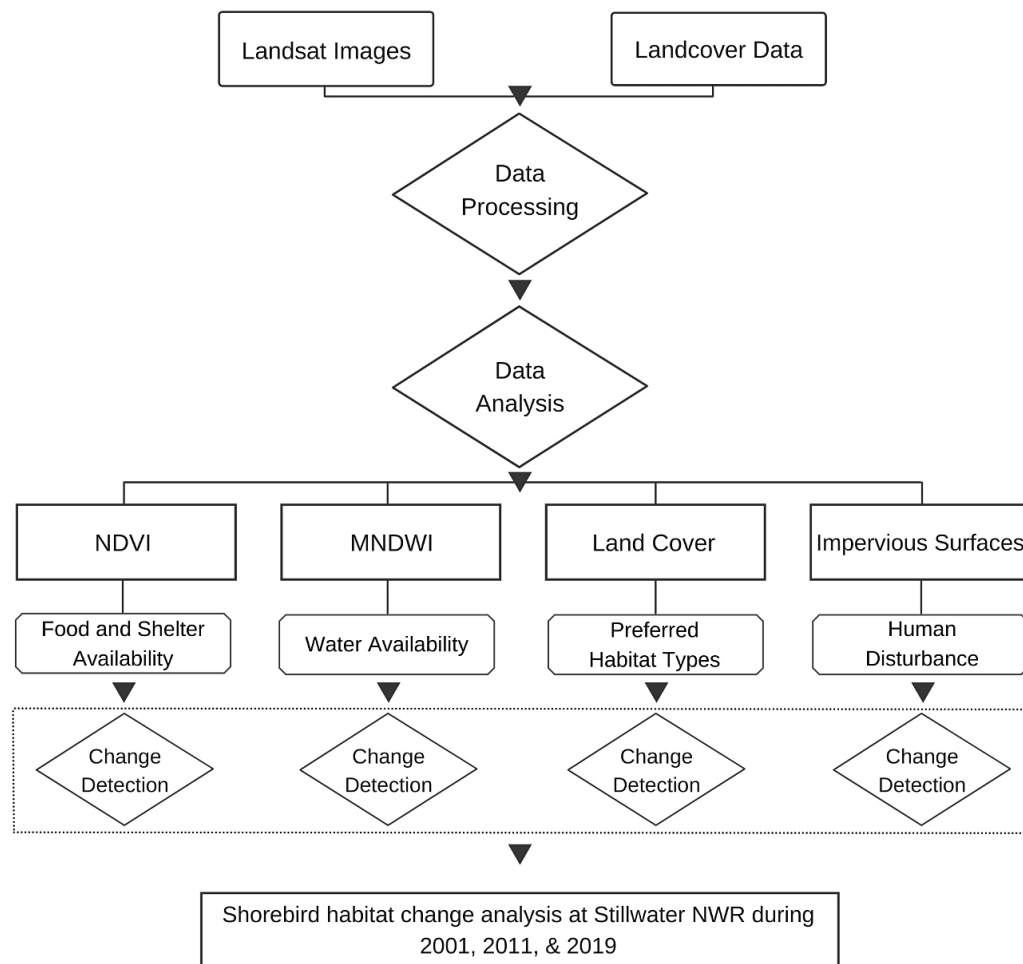


Figure 6. Flowchart of spatial analysis.

In wetland habitats plants are associated with increased densities and diversity of insects and aquatic invertebrates, important food sources for shorebirds, and the plants themselves act as part of the diet of many species (Webb et al. 2010). Varying densities of vegetation have been shown to provide shorebirds a variety of resources besides food, such as shelter to rest, visual cover from predatory species, and nesting habitat for certain species (Conway et al. 2005). Normalized Difference Vegetation Index (NDVI) analysis is a commonly used index to estimate the distribution of vegetation, vegetative status, and spatial coverage. NDVI values range from -1.0 to +1.0, and resulting values correspond to levels of chlorophyll densities, or the greenness of plants, with very low values (-1.0 – 0.1) indicating non-vegetated lands such as water, ice, rock and bare land, while moderate to high values (0.2 – 1.0) representing vegetation in various states of health and spatial densities (USGS 2018). NDVI analysis was performed in this study using Landsat imagery to represent the distribution of plants, and assumes the index is an indicator of food resources and habitat availability for shorebirds at the Stillwater NWR during the fall migratory period (Tang et al. 2016; Tian et al. 2019; Tian et al. 2008).

NDVI was calculated for each year's Landsat imagery using Equation (3):

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (3)$$

The presence of surface water in the form of fresh and saline wetlands and lakes at the Stillwater NWR, and across the Great Basin, provide the necessary component of stopover habitats that shorebirds require to complete their migration and breeding periods (Haig et al. 2019, Barbaree et al. 2020). Climate shifts in temperature and precipitation, resulting in changes to the hydroperiod, exacerbated by water diversions for human and agricultural use can result in degradation to the quantity and quality of wetland habitats, impacting the suitability of these habitats for migratory shorebirds (Haig et al. 2019). The Modified Normalized Difference Water Index (MNDWI) is an index developed by Xu (2005) that is used to extract available surface waters from the surrounding environment. Compared to the Normalized Difference Water Index (NDWI), the MNDWI more accurately discriminates between surface waters and non-water areas such as built lands, soil, and vegetation, by substituting the short-wave infrared band for the near infrared band in the NDWI equation (Xu 2006). MNDWI values range from -1.0 to +1.0 and resulting values correspond to land without surface water (-1.0 – 0) and land with water (0 – 1.0), though the threshold value of 0 has been found to be generally insufficient for interpretation in urban environments (Chen et al. 2020). MNDWI analysis was used in this study to extract the availability of surface waters for migrating shorebirds at Stillwater NWR as studies suggest that decreased water levels are related to less suitable habitat and decreased shorebird populations (Barbaree et al 2020).

MNDWI was calculated for each year's Landsat imagery using Equation (4):

$$MNDWI = \frac{P_{Green} - P_{SWIR}}{P_{Green} + P_{SWIR}} \quad (4)$$

Land cover types reflect a variety of resources and ecosystem functions to migrating shorebirds. Wetland marshes, mudflats, and open water shorelines with intermediate densities of vegetation indicated high shorebird abundance in Webb et al. 2010 study of the Rainwater Basin region of Nebraska. Another 2005 Texas study found that shorebird nest and hatchling success increased when nests were placed in locations with plant cover, though certain shorebird species did not discriminate when choosing a nesting location (Conway et al. 2005). Migrating shorebirds have demonstrated dependence on the adequate availability of various types of surface waters and generally preferred water bodies with a range of water depths, which may be related to the diversity of food and territory that mixed depth water bodies provide (Andrei et al. 2008). Once preferred land cover types were identified through previous shorebird habitat research, the USGS Land Cover data was reclassified into the following categories: wetlands representing the most preferred habitat followed by herbaceous, agricultural, open water, and finally barren land/scrub.

Developed lands and their associated impervious surfaces are found anywhere that humans inhabit or recreate, and the resulting changes to the landscape can result in decreased area of potential habitat, disturbance to hydrologic processes, and introduction of noise disturbances which all can affect the quality of avian habitat (Bryce, Hughes and Kaufmann 2002, Shuster et al. 2005). The USGS impervious surface landcover data was used in this study to represent levels of human disturbance to migratory shorebirds at Stillwater NWR. The impervious surface data was reclassified into four categories for analysis, indicating percent of the raster cell represented by impervious surfaces (0-25%, 25-50%, 50-75%, and 75-100%).

After establishing the targeted environmental factors and processing the datasets with the appropriate analyses, a change detection assessment was performed for each dataset between 2001 – 2011, 2011 – 2019, and 2001 – 2019. The resulting raster datasets were reclassified and mapped to reflect change direction and severity of change of each factor under consideration. Percent change was tabulated for each dataset and classified datasets were evaluated for direction of movement between class types. The change detection analysis results will be used to determine temporal land cover changes at the Stillwater NWR over the study period, evaluating the current conditions of shorebird habitat factors during the fall migratory period and the effects of ongoing conservation efforts at the refuge.

RESULTS

Remote sensing data analyzed over time can illustrate long-term changes in the composition of certain environmental characteristics, providing data that can be used in evaluation of habitat quality and quantity. This study investigated three periods of LULC data and remote sensing images representing the Stillwater NWR with the goal of exploring spatio-temporal changes in environmental factors related to shorebird habitat. Temporal changes in MNDWI (surface waters), NDVI (vegetation), land cover types, and impervious surfaces (human disturbances) are illustrated in Figure 7. Study results were mapped from 2001 to 2019 and the resulting spatial distributions display evident increases in the values of NDVI and MNDWI as well as transitions between land cover classes, but no notable changes in impervious surfaces can be visually identified.

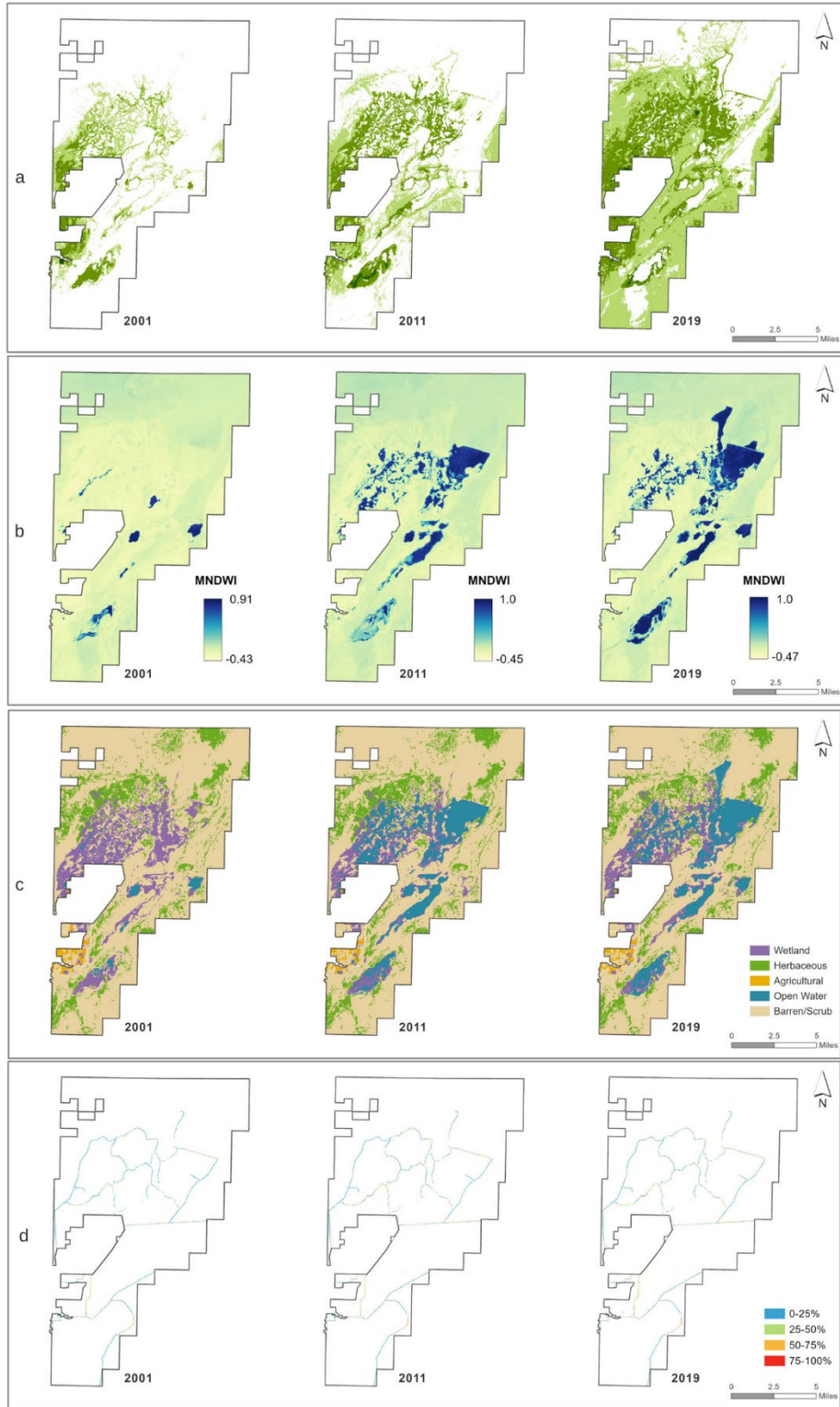


Figure 7. Spatial distribution of the investigated environmental factors related to shorebird habitat. (a) NDVI, (b) MNDWI, (c) Land Cover, and (d) Impervious Surfaces.

Indices Change Detection

The change in NDVI values at the Stillwater NWR during the study period is summarized in Table 2. Between 2001 – 2019 the NDVI values range from -0.87 at the lowest to 0.78 at the highest, and mean value doubled from 0.06 in 2001 to 0.12 in 2019 (Table 3). The study area’s lowest index value of -0.87 is close to the lowest possible index value of -1, typically indicating non-vegetated areas such as water, snow, and bare ground. The peak NDVI values for all study years vary between 0.73 to 0.78, indicating higher vegetation cover density. Over the study period vegetation cover has changed across the refuge and is visualized in the change detection map of Figure 8. The most significant change across study years is in the non-vegetated areas, represented by the -1.0 – 0.9 values range, which transitioned from representing approximately 82% of the study area in 2001 to 40% of the study area in 2019. Between 2001-2019 non-vegetated areas decreased by 51%, low vegetation index value areas (0.1-0.19) increased by 220%, moderate vegetation index value areas (0.2-0.49) increased by 265%, and high vegetation index value areas (0.5-1.0) increased by 3,373% as shown in Table 4.

Table 3. NDVI values and the associated change in area between study years. Proportion indicates the percentage of total area.

2001			2011			2019		
NDVI Values	Area (km ²)	Proportion	NDVI Values	Area (km ²)	Proportion	NDVI Values	Area (km ²)	Proportion
-0.32-0.9	276.51	82.85%	-0.55-0.9	235.43	70.55%	-0.87-0.9	134.64	40.34%
0.1-0.19	40.34	12.09%	0.1-0.19	57.91	17.35%	0.1-0.19	129.27	38.74%
0.2-0.49	16.61	4.98%	0.2-0.49	35.24	10.56%	0.2-0.49	60.65	18.18%
0.5-1.0	0.26	0.08%	0.5-1.0	5.14	1.54%	0.5-1.0	9.16	2.74%
Total	333.73		Total	333.73		Total	333.73	

Table 4. NDVI value statistics for each study year.

Year	Min	Mean	Median	Max
2001	-0.32873	0.06192	0.04992	0.7898
2011	-0.55616	0.08163	0.05756	0.73156
2019	-0.8734	0.12118	0.1127	0.75474

Table 5. NDVI percent change for Stillwater NWR across the study years.

NDVI Values	2001-2011% change	2011-2019% change	2001-2019% change
-1.0-0.9 (non-vegetated)	- 14.85%	- 42.81%	- 51.31%
0.1-0.19 (low)	43.54%	123.23%	220.43%
0.2-0.49 (moderate)	112.11%	72.11%	265.06%
0.5-1.0 (high)	1,850.51%	78.09%	3,373.72%

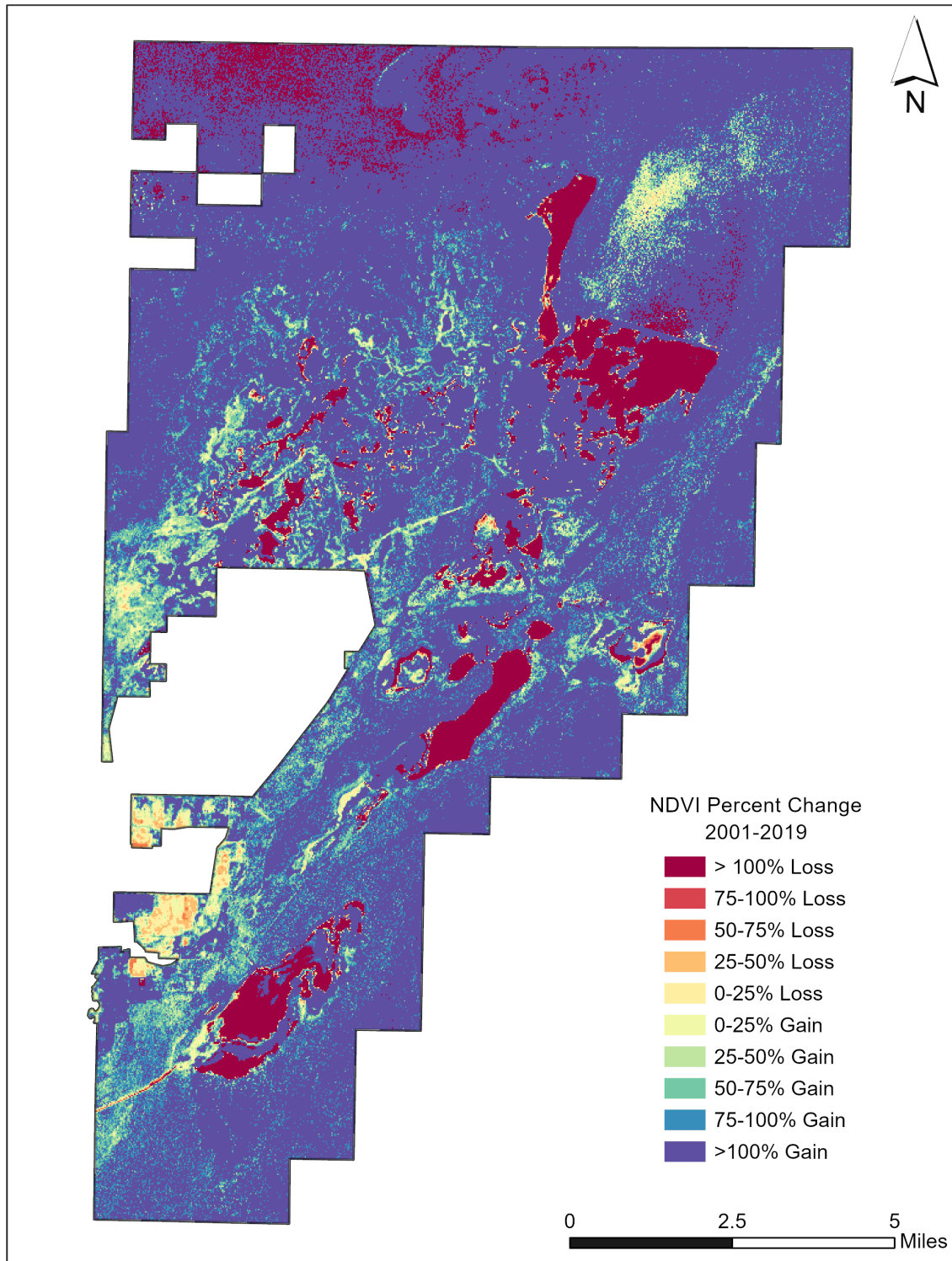


Figure 8. NDVI value percent change by pixel for 2001 – 2019 at Stillwater NWR.

Change of MNDWI values between study years is illustrated in Table 5. In this study the MNDWI values were interpreted with a threshold value of 0, meaning all pixels with values between -1.0 – 0 were understood to represent non-water areas and all pixels with values above 0 representing water. Utilizing the 0 threshold to delineate water bodies has been shown to have an approximate accuracy of 99.85% and an underestimation of water areas of less than 2% in prior research (Xu 2006). In 2001, 98.15% of the study area was represented by non-water land, pixels with values less than 0, and by 2019 this value had decreased to 87.17%. Areas with values above 0, surface water, transitioned from representing 1.85% of the study area in 2001 to representing 12.83% in 2019 (Figure 9). Across the study period of 2001-2019 image pixels representing water bodies increased 594%, implying more surface water availability in the study area by 2019 (Table 6). Many of the existing wetlands and lakes are visually larger by 2011 and continue to expand into 2019, including the regions surrounding Nutgrass Lake to the east, moving south near Foxtail Lake and Stillwater Point Reservoir, and to the west marshes.

Table 6. MNDWI values and the associated change in area between study years. Proportion indicates the percentage of total area.

MNDWI Values	2001		2011		2019	
	Area (km ²)	Proportion	Area (km ²)	Proportion	Area (km ²)	Proportion
≤0 (non-water)	327.57	98.15%	296.60	88.87%	290.92	87.1%
0-1 (water)	6.16	6.16%	37.13	11.13%	42.81	12.83%
Total	333.73	-	333.73	-	333.73	-

Table 7. MNDWI percent change for Stillwater NWR across the study years.

MNDWI Values	2001-2011% change	2011-2019% change	2001-2019% change
≤0 (non-water)	-9.45%	-1.92%	-11.19%
0-1 (water)	502.06%	15.31%	594.22%

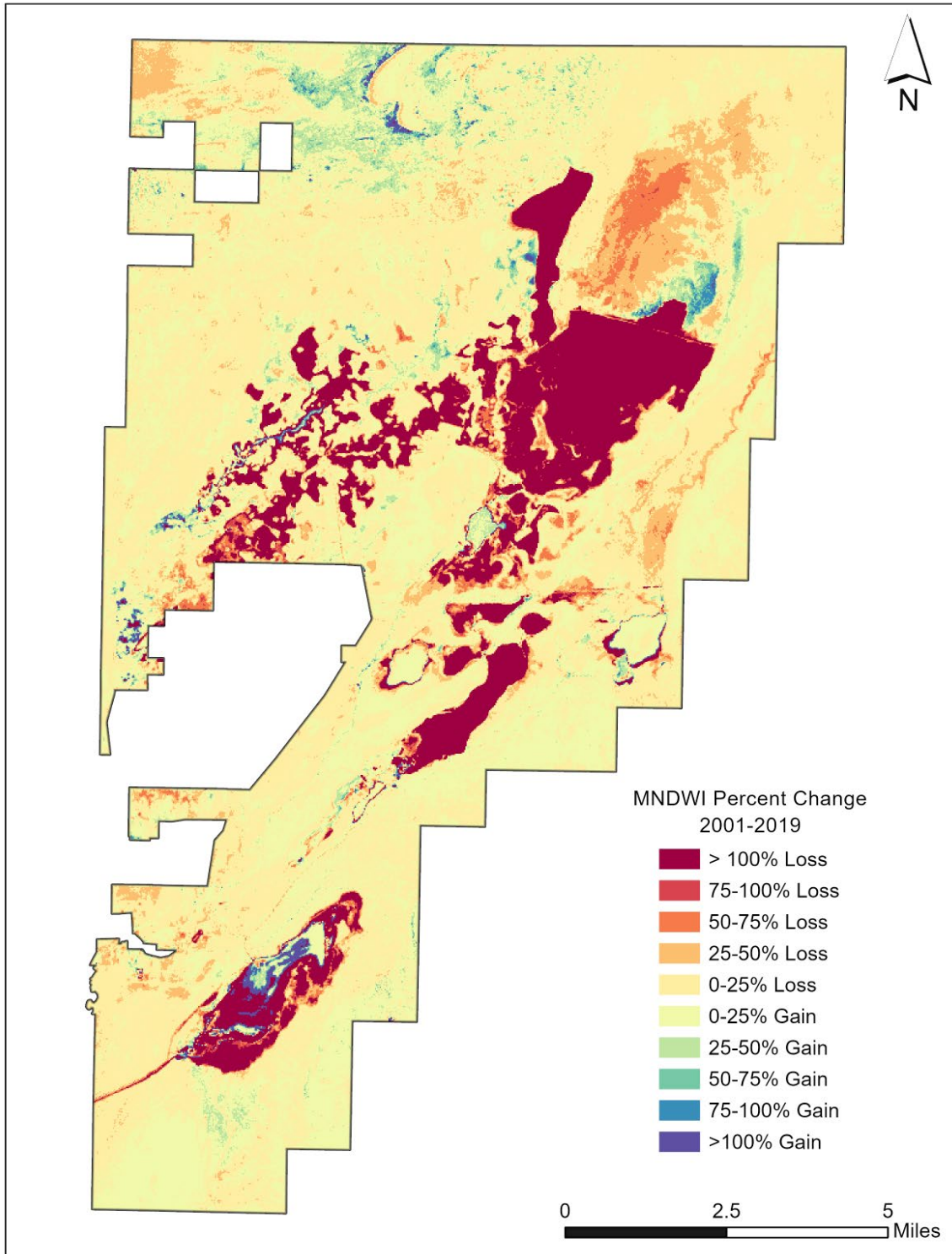


Figure 9. MNDWI value percent change by pixel for 2001-2019 at Stillwater NWR.

Land Cover – Land Use Change Detection

Table 7 summarizes the spatial distribution of land cover classes and the percent change for each class across study years. Change detection analysis of classified land cover between 2001 and 2019 reveals an approximate 1,019% increase in the open water class across the refuge implying expansion of standing water bodies and decreases of 29% in the wetlands class, 8% in the herbaceous class, 12% in the agricultural class, and 7% in the barren/scrub class. Wetlands decreased from representing 14.68% of the study area in 2001 to 10.41% in 2019, demonstrating a total area loss of 14.2 km². Mirroring the results seen in the MNDWI analysis, open water increased from representing 1% of the study area in 2001 to representing 11.59% in 2019, indicating an increase in areas of standing water of 35.16 km². Between 2001 to 2019, approximately 16 km² of wetland area and 18 km² of barren/scrub were converted to open water, and approximately 4 km² of herbaceous land changed to the barren/scrub class (Figure 10). Conversion to the open water class occurred primarily in the 2001 – 2011 period with a +1,012 percent change observed across the study period at a rate of area growth of approximately 2 km² per year. The transition between land cover classes is shown in the change matrix (Table 8).

Table 8. Distribution of land cover and percentage of gain or loss for each land cover class for Stillwater NWR between 2001-2019.

Land Cover Class	2001		2011		2019		2001-2011 % Change	2011-2019 % Change	2001-2019 % Change
	Area (km ²)	Proportion	Area (km ²)	Proportion	Area (km ²)	Proportion			
Wetlands	48.89	14.68%	30.57	9.18%	34.69	10.41%	-37.47%	+13.49%	-29.04%
Herbaceous	48.60	14.59%	47.91	14.38%	44.65	13.40%	-1.41%	-6.80%	-8.12%
Agricultural	3.27	0.98%	2.70	0.81%	2.85	0.86%	-17.38%	+5.57%	-12.78%
Open Water	3.45	1.04%	38.36	11.52%	38.61	11.59%	+1,012%	+0.65%	+1,019.20%
Barren/Scrub	228.91	68.72%	213.57	64.11%	212.31	63.73%	-6.70%	-0.59%	-7.25%

Table 9. Change matrix of land cover area (km²) changes for Stillwater NWR between 2001-2019.

From/To	Wetlands	Herbaceous	Agricultural	Open Water	Barren Scrub
Wetlands	-	0.0765	0	16.0290	0.0342
Herbaceous	0.2187	-	0	1.1421	4.4856
Agricultural	0.0036	0.0513	-	0	0.4833
Open Water	0.1422	0.0072	0	-	0.0261
Barren/Scrub	1.5786	1.7658	0.1206	18.1638	-

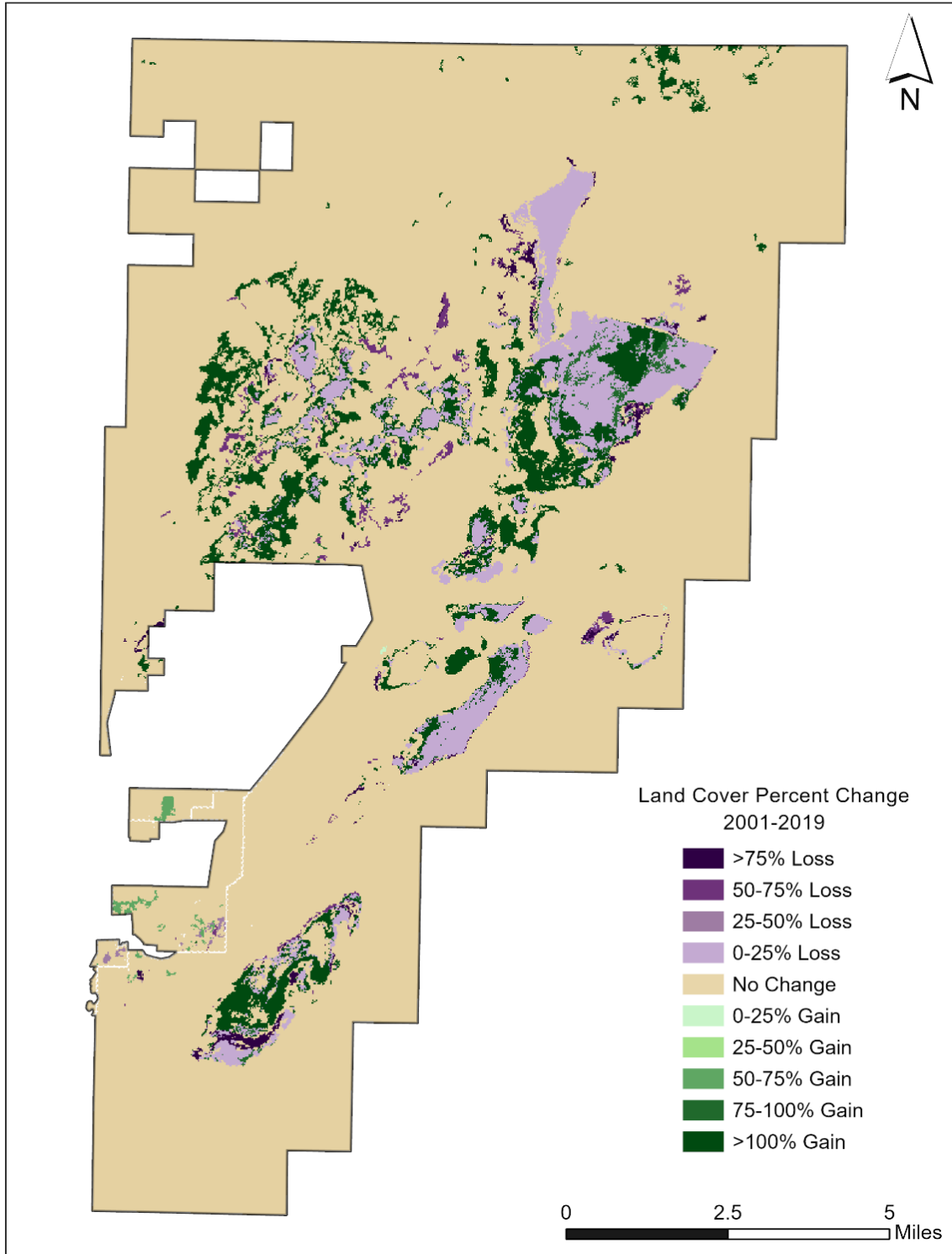


Figure 10. Land cover percent change between 2001-2019 for Stillwater NWR.

Impervious surfaces were estimated as percent coverage per 30 m² cell and were classified into four classes – 0-25%, 25-50%, 50-75%, and 75-100%. Distribution and percent change of impervious surfaces in the study area can be seen in Table 9. Impervious surface coverage slightly increased across the study years, with the largest increases seen in the 50 – 75% class and 75-100% class. Between 2001 – 2011, the 0-25% class decreased 13.3%, the 50 – 75% class increased 154.5%, and the 75-100% class increased 139%. During 2011-2019 the 0-25% class decreased 3%, the 50 – 75% class increased 12.4%, and the 75-100% class increased 69%. The largest conversions occurred in the 50 – 75% and 75-100% classes, with an increase of 186% and 304.3% respectively. Generally impervious surfaces represent a very small portion of the study area. The 0-25% class lost approximately 0.38 km² while the 50 – 75% and 75-100% classes gained 0.34 km² and 0.03 km² respectively between 2001 and 2011. The greatest transition between classes is seen in the lowest coverage class, 0-25%, with a total area loss of 0.46 km² and the 50-75% class with a total area gain of 0.41 km² between 2001-2019. Table 10 summarizes the transition between classes.

Table 10. Distribution of impervious surface coverage and percentage of gain or loss for each coverage class for Stillwater NWR between 2001-2019.

% Coverage	2001		2011		2019		2001-2011 % Change	2011-2019 % Change	2001-2019 % Change
	Area (km ²)	Proportion	Area (km ²)	Proportion	Area (km ²)	Proportion			
0-25%	2.88	0.86%	2.50	0.75%	2.42	0.73%	-13.31%	-3.06%	-15.96%
25-50%	0.99	0.30%	1.01	0.30%	0.99	0.30%	+2.37%	-2.49%	-0.18%
50-75%	0.22	0.07%	0.56	0.17%	0.63	0.19%	+154.51%	+12.40%	+186.07%
75-100%	0.02	0.01%	0.05	0.01%	0.08	0.03%	+139.13%	+69.09%	+304.35%

Table 11. Change matrix of impervious surface area (km²) changes for the Stillwater NWR between 2001-2019.

From/To	0-25%	25-50%	50-75%	75-100%
0-25%	-	0.0648	0.3780	0.0216
25-50%	0	-	0.0297	0.0405
50-75%	0	0	-	0
75-100%	0	0	0	-

DISCUSSION

This study evaluated environmental changes related to suitable shorebird habitat features for fall migrants at the Stillwater NWR by integrating Landsat remote sensing imagery and USGS land cover datasets with GIS spatial analysis tools. Three fall migration periods of Landsat data and land cover data were analyzed for change over almost two-decades to evaluate spatial patterns of environmental change related to shorebird habitat preferences.

Results indicate considerable changes in many of the key environmental factors evaluated at the study area over the last two decades. NDVI values increased across the study period with mean values increasing for each subsequent year's dataset, implying an increase in the spatial distribution and density of plant life across the refuge during study years. Similarly, MNDWI values increased across study years, demonstrating an increase in available standing water across the refuge. Transitions were measured between land cover classes, with the most significant changes seen in the open water and wetland classes. Open water increased by over 1,000% while wetland area decreased by 29% by 2019. Impervious surfaces exhibited no significant

change in area across the refuge over the study period and the main differences observed in the impervious surface data were transitions between coverage classes, resulting in increases in the 50-75% and 75-100% coverage classes.

The NDVI change results suggest that the status of vegetation across the refuge has improved since 2001. The growth in vegetation coverage may be related to the ongoing conservation efforts at the refuge, including the water rights acquisition which has increased the amount of incoming water to the reserve. The land cover change detection results showing expansions in standing water at the reserve are substantiated by the increased MNDWI values, implying stability between years in available water levels which may create more suitable hydrological conditions for plant life to grow (Osakabe et al. 2014). Contrary to the NDVI results, but in line with the MNDWI results, the change detection analysis of land cover classes demonstrates decreased area coverage in all vegetation classes and an increase in area of the open water class. Of the vegetation classes, the wetlands class exhibited in the largest reduction in area over the study period. Magee and Kentula (2005) suggest that, for wetland ecosystems in general, shifts in average water levels can be related to changes in the composition of wetland plant communities and large increases in water depths may favor aquatic plants over seasonally emergent or woody wetland plants, potentially explaining the observed decrease in wetland land cover as a response to increased areas of open water. An alternative explanation for the difference in NDVI and land cover results may be the probable asynchronous timing in data collection for each study year, impacting the validity of direct comparison between the NDVI and land cover results.

The results contribute to a clearer understanding of the changes in environmental conditions associated with shorebird habitat preferences over the last two decades. Through a macroscopic lens, habitat quality for migrating shorebirds appears to have improved as demonstrated by the increase in areas of standing water bodies, expansion of vegetation coverage, and the lack of significant increases in impervious surfaces. These positive changes can likely be associated with the National Wildlife Refuge designation resulting in the 40 years of ongoing conservation efforts and habitat management at the refuge. These results validate the conservation and management techniques used so far.

Though if evaluating the results of this study through a microscopic lens, there are more questions to answer regarding the suitability of shorebird habitat at the reserve. Vegetation coverage has increased, but the contradictory land cover results bring into question the type of plants present in the NDVI results. Migratory shorebirds have been associated with woody and emergent wetland plants along shorelines, on mudflats, and in shallow waters as well as herbaceous grasses used as vital habitat resources for foraging, nesting, and protection from predators (Conway et al. 2005). Land cover and MNDWI change detection results support the increase in standing water at the reserve, but do not give information on the depth, salinity, or quality of that water. Prior research has shown that shorebirds prefer, and at certain times require, varying depths of water tending towards shallower, wading depths and gradients in salinity levels (Andrei et al. 2007). The impervious surface change detection results do not illustrate a significant increase in areas of impervious surfaces at the study area, but alone cannot account for human activities currently allowed at the reserve (hunting,

boating, camping, auto tours, and walking trails). Hockin et al. (1992) review of the effects of human disturbances on birds concluded that a variety of disturbance sources including recreational activities (boating, fishing, and hunting), public access (by foot or vehicle), and industrial development can produce several, significant negative impacts for bird species including loss of habitat, reduced foraging, disrupted breeding periods, and increased nest abandonment for those affected.

While the GIS techniques presented in this study successfully quantified and mapped changes in land cover conditions at the Stillwater NWR, the results are limited by the lack of field survey data to verify land cover, vegetation, water, impervious surface spatial distribution, and their associated characteristics. Further research is recommended to fully understand characteristics of the evaluated factors including composition of the plant community, water salinity and depths, precipitation trends, and the effects of human recreational activities on shorebird behavior. New and continued shorebird monitoring at Stillwater NWR would provide vital information regarding the composition and volume of birds using the wetland ecosystems. Previous research has indicated that shorebird populations and their migration patterns may shift in response to key habitat loss and degradation as a results of climate change and water diversions (Haig et al. 2019), strengthening the importance of continued research of environmental factors related to shorebird habitat at Stillwater NWR as part of a comprehensive conservation plan for the area.

CONCLUSION

Wetland ecosystems provide a variety of resources that are vital to traveling shorebirds during migration stopover periods. Across the world wetlands are at risk of further degradation and area loss associated with the ongoing effects of climate change and human alterations of the landscape. The land-locked arid and semi-arid wetlands of the Great Basin Desert provide important wildlife habitat to traveling shorebirds as they navigate the Pacific Flyway migration corridor to and from their winter and summer grounds. The Great Basin wetland and lake habitats, such as those present at Stillwater NWR, are some of the few sources of water, food, and shelter in the desert landscape. For this reason, Stillwater NWR will be an important target for wildlife conservation in order to preserve the vitality and connectivity of the Pacific Flyway for migrating shorebirds. Wetlands across the Great Basin have experienced documented losses in area and water quality related to a variety of factors, including European colonization of the area, modern agricultural practices, and mining efforts. Over the last 32 years, conservation groups have purchased private water rights from local sellers as an effort to restore and maintain the refuge's wetlands and lakes.

This study examined land cover changes related to migratory shorebird habitat during the fall seasons of 2001, 2011, and 2019 using remote sensing images and a variety of GIS analysis techniques. Environmental features important to migrating shorebirds were established using prior research and a spatio-temporal assessment of these features were performed to establish trends, if any, in relation to suitable shorebird habitat. NDVI and MNDWI results indicate expansion of vegetation and standing water across the study period, while change detection of land cover classes

pointed to increases in open water and decreases in all vegetation classes, especially in the wetlands. Although this study was limited to fall season imagery data for three select years across almost two decades, the resulting data suggests that plant and water availability at the reserve have increased since 2001 which has the potential to provide more, better-quality habitat for shorebirds visiting the area. Changes in levels of human disturbance and land development of the study area require further investigation as significant changes were not detected in the dataset used within this study.

The findings support the viability of the GIS spatial analysis techniques for long-term, inexpensive habitat monitoring in endeavors to conserve vital ecosystems for shorebirds and waterbirds alike. Field measurements and spatial distributions of vegetation types, water depth and salinity, human disturbances, and shorebird population counts could greatly contribute to the interpretation of this study's results, and the general understanding of migratory shorebird habitat quality at the Stillwater NWR. As of spring 2021, the National Fish and Wildlife Foundation has issued a 1-million-dollar grant to conservation and management organizations, including the Lahontan Audubon Society, to increase monitoring and management of shorebirds and associated habitats at the Lahontan Valley Wetlands (*New Grant Enables Partners to Advance Shorebird Planning at Nevada Wetlands*, 2021). As the landscapes within the Great Basin change in response to altered precipitation levels, temperatures, and urbanization, studies like this project will be important tools to further inform conservation efforts as well as support the development of policies and decision-making regarding wetland habitats and the shorebirds that depend on them.

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