Improving Wetland Determination Utilizing Unmanned Aerial Systems

by

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List of Abbreviations

AVHRR	Advanced Very High-Resolution Radiometer
CASI	Compact Airborne Spectrographic Imagery
CIR	Color-infrared
FEMA	Federal Emergency Management Agency
GeoEye	Geologic Event Volume Estimator
GPS	Global Positioning System
MODIS	Moderate Resolution Imaging Spectroradiometer
NHD	National Hydrology Dataset
NPDES	National Pollutant Discharge Elimination Systems
NRCS	National Resources Conservation Services
NWI	National Wetland Inventory
RGB	Red Green Blue
SWOT	Strength Weakness Opportunity, and Threats
UAS	Unmanned Aerial Systems
USACE	United States Army Corp of Engineer
USCWA	United State Clean Water Act
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
WOTUS	Waters of the United States

Abstract

When project proponents wish to assess a development site for jurisdictional wetland impacts, they are traditionally left with two options: a wetland determination or a delineation. A wetland determination is customarily a desktop assessment of the site including, but not limited to, the following datasets: National Wetland Inventory (NWI), National Hydrography Dataset (NHD), National Resources Conservation Services Soil Survey (NRCS), topographic maps and satellite imagery. A wetland delineation assesses the presence of hydrophytic vegetation, hydric soils and hydrology during field evaluation. The NWI is typically used to determine where existing wetlands are in order to determine if they qualify as jurisdictional wetlands. This allows project proponents to either take the appropriate avoidance measures to reduce impacts to the wetland or determine if a full wetland delineation is required to apply for a Section 404 permit. In some cases, NWI maps have not been updated for up to 30 years, and these mapped wetlands are limited by conditions that were present at the time the aerial imagery was taken.

This thesis shows that by incorporating unmanned aerial systems (UAS) into a wetlands determination, wetland specialists and project planners can capture current conditions of the development site (i.e. topography, disturbance, land cover, etc.) within efficient time frames and assess the potential extent of a wetland(s). This allows project proponents to avoid the cost and time restrictions that come from a full wetland delineation. The UAS imagery was compared to historically mapped wetlands still present; UAS improved placement of wetlands on the landscape and had on average a 76.5% overlap with delineated wetlands. Future research into buffer distances, topography, seasonality and thermal imagery could improve this overlap. With the aerial imagery from current conditions, wetland specialists can assess potential wetland extent, hydrology, highwater marks, and coarsely classify vegetative condition.

Chapter 1 : Introduction

An increasingly important issue when developing lands is wetland assessment and avoidance. Wetlands are valued as important sinks, sources, and transformers of a multitude of chemical and biological materials, as well as being valued as vital habitat for many fish and wildlife species. Wetlands have been described by scientists as the “kidneys of the landscape”. This phrase is used because wetlands typically act as downstream filters of water and both natural and human-made waste. Wetland areas are known to provide ecosystem services such as water purification, sediment and nutrient retention, groundwater replenishment and flood control (Zhang et al. 2010) which is vital to many ecosystems and human activities.

Prior to the mid-1970s, wetlands were considered to be areas where insect-born diseases such as malaria originated. Therefore, the drainage and destruction of wetlands was encouraged, with states like California and Ohio reporting up to a 90% loss in natural wetlands. Once the valuable services of wetland areas were recognized, the U.S. government supported a multitude of federal, state and private programs to preserve existing wetlands, placing a higher priority on wetlands connected to hydrology. In the U.S., the U.S. Fish and Wildlife Service (USFWS) is involved with the classification and inventory of wetlands, the U.S. Environment Protection Agency (USEPA) is involved with human activity and its impacts around wetlands, and the U.S. Army Corp of Engineers (USACE) provides guidelines to assess wetlands on the ground and gives permits for wetland destruction. The USEPA reserves a veto authority over permits given.

As defined by the USACE and the USEPA, "Wetlands are areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas"

(USEPA 1970). While some states have more stringent laws regarding wetlands, this thesis focuses on the federal guidelines established by the U.S. Clean Water Act (USCWA).

1.1 History of the Clean Water Act

In 1899 the River and Harbors Act was passed by the U.S. Congress to regulate the placement of anything that might affect navigation in navigable waters; this includes the construction of any bridge, dam, dike, wharf, pier, dolphin, boom, weir, breakwater, bulkhead, jetty or causeway (33 U.S.C. 403; Chapter 425, March 3, 1899; 30 Stat. 1151). It also stated that it shall not be lawful to excavate or fill, or in any manner to alter or modify the course, location, condition, or capacity of, any port, roadstead, haven, harbor, canal, lake, harbor of refuge, or enclosure within the limits of any breakwater, or of the channel of any navigable water of the U.S., unless the work has been recommended by the Chief of Engineers and authorized by the Secretary of War prior to beginning the same. In 1977 the USCWA was implemented to revise the River and Harbors Act. This included Section 401, which deals with water quality certification; Section 402 which deals with National Pollutant Discharge Elimination Systems (NPDES) or liquid discharge; and Section 404, which deals with placement of fills in Waters of the U.S. (WOTUS). The term WOTUS means: all waters which are currently used, or were used in the past, or may be susceptible to use in interstate or foreign commerce; all interstate waters including interstate wetlands; all other waters such as intrastate lakes, rivers, streams (including intermittent streams), mudflats, sandflats, wetlands, sloughs, prairie potholes, wet meadows, playa lakes, or natural ponds, the use, degradation or destruction of which could affect interstate or foreign commerce (USEPA 2017).

Wetlands that flow into navigable WOTUS are known as jurisdictional wetlands, which are the wetlands that are typically permitted during development. Section 404 of the USCWA establishes a program to regulate the discharge of dredged or fill material into WOTUS, including wetlands. A Section 404 permit, whether individual or general, allows for a project proponent to discharge dredge or fill materials into the WOTUS during development of a specified area within the limitations set forth for each permit. In order to comply with Section 404 of the USCWA and associated regulations, project proponents must assess the current conditions of each proposed development site before applying for an individual Section 404 permit. This can prolong project timelines and generate uncertainty for stakeholders.

Without going to the project site, many project proponents rely on wetland determinations to remotely gather data regarding the project site, which can vary in accuracy and may have long gaps between collection and development dates. For example, some NWI wetlands mapped by the USFWS in Oklahoma have not been updated since September 1981. The methods associated with determinations are known to have flaws in location and size, with the USFWS stating the following on their website for the NWI: “The Service's objective of mapping wetlands and deep-water habitats is to produce reconnaissance level information on the location, type and size of these resources. The maps are prepared from the analysis of high altitude imagery. Wetlands are identified based on vegetation, visible hydrology and geography. A margin of error is inherent in the use of imagery; thus, detailed on-the-ground inspection of any particular site may result in revision of the wetland boundaries or classification established through image analysis. The accuracy of image interpretation depends on the quality of the imagery, the experience of the image analysts, the amount and quality of the collateral data, and the amount of ground truth verification work conducted. Metadata should be consulted to determine the date of the source imagery used and any mapping problems. Wetlands or other mapped features may have changed since the date of the imagery and/or field work. There may be occasional differences in polygon boundaries or classifications between the information depicted on the map and the actual conditions on site" (USFWS 2018a).

In order to improve accuracy, wetland scientists in the past have used publicly available aerial imagery from Google and Esri to determine wetland location but are limited by the collection date and the resolution of the imagery provided (Scarpace et al. 1982). On the other hand, a wetland scientist can go out onsite and visually assess the wetland using parameters put in place by the USACE (1987) wetland delineation manual along with applicable regional supplements. A wetland delineation is a costly and time-consuming effort that requires hours of survey time and assessment to meet the manual's guidelines. It also requires a specialist that has been certified as a wetland delineator in order for the assessment to be considered as valid by the USACE.

In recent years, many studies have used UASs for surveying and monitoring natural landscapes, such as forests and rangeland (e.g. Hardin and Jackson 2005; Dunford et al. 2009; Rango et al. 2009; Breckenridge and Dakins 2011; Getzin et al. 2012). Benefits stated from these past studies include the ability to acquire aerial imagery at very high spatial resolution (<10 cm/pixel), and the ability to deploy the UAS in a convenient, timely and repeatable manner that is cost competitive when compared to traditional survey methods (Chabot and Bird 2013). The utilization of UAS can also decrease harm and injury to researchers by allowing a researcher to assess the landscape without encountering the natural hazards which may be encountered when in the field.

1.2 Traditional Methods of Wetland Determination and Delineation

Effective conservation and management of wetlands depends on the ability to collect accurate and timely data on the habitats that contain them (Finlayson and Mitchell 1999). Traditionally, project proponents have been left with a choice between a wetlands determination or a complete wetlands delineation in order to assess wetlands during project development and determine the appropriate permitting pathway under Section 404 of USCWA.

For the purposes of this thesis, a wetlands determination will be defined as the study of remotely sensed data acquired from the NWI, NHD, NRCS Web Soil Survey, Federal Emergency Management Agency (FEMA) flood maps and aerial imagery (sourced by one or more of the following: Esri, DigitalGlobe, GeoEye, i-cubed, U.S. Department of Agriculture – Farm Service Agency, U.S. Geological Survey, AEX, Getmapping, Aerogrid, Institut Geographique National, Interior Gateway Protocols, Swisstopo, or the GIS User Community). These datasets are used to determine where historic wetlands are located within a development area, as well as to determine if those historical wetlands are potentially jurisdictional wetlands. A wetlands determination allows project proponents to determine what wetlands have been historically present within a development area; however, a wetlands determination is not legally binding for project proponents and does not meet the standards set forth by the USACE for acquisition of a Section 404 permit.

Current wetlands determinations are limited by the accuracy and precision of the above-mentioned historic datasets. For example, NWI features may not capture the size and location of the associated wetlands and some areas of the country have not been mapped by FEMA, so flooding conditions are unknown. Many NWI maps in Oklahoma are 30 years old (OKGOV 2018) and the satellites used coarse resolutions of 10 m or greater. Further, wetland determinations are also limited by the environmental conditions and time frame in which the aerial imagery was captured. Consultants are unable to control the season, time-of-day, or resolution in which the images are captured (Lee and Lunetta 1995; Adam et al. 2010). This inaccuracy contributes to unknown errors of wetland placement and until a site visit occurs the wetland feature's status is not known.

In contrast, a formal wetlands delineation involves an onsite assessment of three wetland indicators as defined by the USACE' Wetlands Delineation Manual (USACE 2010):

1. Hydric soil - soils saturated, flooded, or ponded, long enough during the growing season to develop anaerobic conditions in the upper profile.
2. Hydrology – presence of water (past or present).
3. Hydrophilic vegetation - plant life growing in water, soil, or on a substrate that is periodically deficient in oxygen due to excess water.

Presence or absence of all three indicators is captured by the wetlands delineator to determine the extent of the wetland. To determine the wetland boundary, the delineator chooses a series of data points that are representative of the site. The delineator digs a soil pit at each data point in sample wetland areas and sample upland areas for vegetation and hydrology. In some regions, wetland delineations are limited to being performed during the region's growing season for delineators to fully assess vegetation characteristics. Wetland delineations are used by the USACE to assess the jurisdictional status of delineated wetlands, identify the boundaries of the delineated wetlands and are legally binding for the project proponent. However, wetlands are challenging to survey because of their often complex patchwork of flooded areas interspersed with dense vegetation, which can be laborious for a wetlands delineator to navigate and characterize at ground level. Due to the large scale of some development projects, the costs and time associated with performing a formal wetlands delineation might impede on the planning and progression of the project. Currently wetland delineation is considered to be the most accurate form of wetland assessment.

1.3 Unmanned Aerial Systems

Recent developments in UAS platforms, positional and attitudinal measurement sensors, imaging sensors, and processing approaches have opened a vast new area of opportunities in remote sensing for observation, measurement, mapping, monitoring, and management in various natural environments (e.g. forests). UAS are an ideal tool for monitoring sensitive areas and subjects that may be threatened or destroyed if monitored manually (Jones IV, Pearlstine, and Percival 2006). The use of high spatial resolution aerial imagery captured by small UAS in natural resource management is rapidly increasing (Abd-Elrahman, Pearlstine, & Percival, 2005; Laliberte, Rango, & Herrick, 2007; Rango et al., 2006; Watts et al., 2012). Improvements in technology and procedures are gradually enabling UASs to produce high-quality georeferenced orthorectified images through software programs like Pix4D. The spatial and temporal resolutions of UAS imagery are controlled by the operator/user who determines the mission parameters (e.g. time of day, season, resolution, percent overlap and flying height); this gives a significant advantage, even over traditional piloted image-capture missions. Being able to assess a landscape under controlled conditions allows for repeatable flights to be conducted over the same area in order to see changes over time. This has been accomplished in the past with other historic satellite imagery in order to assess vegetation growth or contraction (Everitt et al. 2010). Although more sophisticated image capturing sensors have been created (i.e. hyperspectral and LiDAR sensors) for smaller UASs these sensors are very expensive. Off-the-shelf three-band (RGB) cameras can provide the resolution needed for many of the current studies. This also sets a baseline for data capture that is affordable for many researchers. Inexpensive alternatives are best when considering the likelihood of a UAS failure or crash. Many over-the-counter units can be purchased for less than $1,000, which makes start-up cost for any company wishing to use UAS reasonable to maintain, and replacement costs are negligible in cases of unit failure. While the UAS model would not be meant to replace a full wetland delineation, it could be used as a planning and avoidance tool for project development. The ability to acquire up-to-date data for a project area as well as a visual from the air which could be used to assess the approximate location and size of the wetland. With some USACE districts, aerial photos are required with the submission for a permit; however, due to the time gaps in image capture and project dates the USACE may not accept aerial photos or satellite images in lieu of a full delineation. If UAS imagery could be utilized as an alternative to historic images both project proponents and USACE would have the opportunity to use the most current data for the assessment of the Project Area.

1.4 Motivation and Goals

Wetlands are highly protected sites that require detailed information in order to accurately assess the conditions currently present. Historical datasets are by nature inaccurate and make current wetland determinations limited in the information that is being provided. This leaves project proponents with little to no preplanning of site development until a full wetland delineation has occurred to assess the size and shape of potentially present wetlands. UASs have been utilized in many environmental studies to capture current conditions in a timely and cost-effective manner. The goals of this study were to: (1) improve upon current wetland determination datasets; (2) determine the accuracy of the imagery when compared to mapped

NWI wetlands and wetland delineations; and (3) determine the cost effectiveness of UAS when compared to traditional methods.

1.5 Thesis Organization

The next chapter discusses previous studies from the 1980s to the present (Section 2.1), current methods of wetland determination and delineation used as a standard for environmental consulting agencies (Section 2.2) and methods of UAS data collection (Section 2.3). Chapter 3 details the collection, processing and analysis methods used for this thesis. Chapter 4 describes the results that were developed for the case study wetlands, and Chapter 5 discusses conclusions and future research questions.

Chapter 2 : Related Work

Remote sensing of aerial imagery collected by satellites has been utilized in a number of environmental research projects involving wetlands. UAS have also become more prominent in environmental assessments. This chapter will review past studies of remotely sensed wetlands (Section 2.1), current methods used to conduct wetland determinations (Section 2.2), and the adoption of UAS for the collection of spatial data (Section 2.3).

2.1 Past Wetland Studies Using Remotely Sensed Imagery

The development of satellite remote sensing in the 1970s made researchers begin to consider using remote sensing for wetland analyses. However, only 17 papers were found to be published before the 1990s when technological advancements began to boom. Johannessen (1964) utilized aerial photography of Nehalem Bay from 1939 to 1960 to compare marsh boundaries. Johannessen recognized a circular pattern on the photos that he determined to be clumps of vegetation on mud flats that proved rapid expansion of the marshes. This is the earliest known wetland remote sensing paper. In the following years, wetland mapping and visual interpretation was developed for aerial imagery; however, this approach proved to be difficult for past researchers to use due to the inability to accurately identify wetland cover classes and plants. Scarpace et al. (1982) used digitized aerial photography to identify the wetland vegetation in marshlands by employing visual interpretation methods, with an accuracy that was determined to be 56-60%.

Color-infrared (CIR) aerial photographs were found to clearly identify vegetation types, with strongly reflective plants in near-infrared wavebands (Dale et al. 1986). Lovvorn and Kirkpatrick (1982) found that CIR photos at the 1:4800 scale can identify dominant plant species and that early September in Indiana was an optimal time for identifying dominant species because of the senescence of species in the fall. Tiner (1990) used high-altitude aerial photography with scales ranging from 1:40,000 to 1:130,000 as the primary data sources and visual stereoscopic photo interpretation for the identification, classification, and inventory of forested wetlands on a national basis in the U.S. This author concluded that CIR aerial photography from the early spring is best for detecting deciduous forested wetlands in temperate regions.

Besides the visual interpretation techniques for wetland mapping, automated unsupervised and supervised classification methods were also utilized. Supervised classification was used for high-resolution multispectral imagery from the Compact Airborne Spectrographic Imager (CASI) to classify mangroves (Green and Ellis 1998). The identified mangroves had an overall accuracy of 78.2%. The authors concluded that CASI imagery can be used to assess mangrove areas with a greater level of detail and accuracy than with satellite sensors. Unsupervised and supervised image analysis techniques were used for archived aerial CIR photographs to monitor black mangrove on the South Texas Gulf Coast of the U.S. and provided accurate results (Everitt et al. 2014, 2015).

Aerial photography has an advantage in terms of spatial resolution and data acquisition time; however, wetland studies use these data typically in narrow coastal areas or along rivers because of the generally small areas covered by these photos. In most cases, aerial photographs are combined with other satellite images to study wetlands on a regional or national scale. Aerial surveys can also be used as supplementary data for the land cover mapping in large areas based on coarse spatial resolution imagery (e.g., Advanced Very High Resolution Radiometer, AVHRR) (Rogers et al. 1997). Aerial photography techniques have been widely used in wetland studies because of their excellent advantages in terms of spatial resolution, cost and time, especially when satellite remote sensing techniques were relatively new. Because of the challenges of data acquisition for large areas by flight, aerial photography has usually been used for the mapping of small wetland areas. After the launch of satellites, especially Landsat TM, aerial photography was mainly used for assessment of the classification procedures or biomass derived from lower-resolution remote sensing methods. Satellite remote sensing data provides an effective and efficient tool for detecting water body areas and flood inundation extent over large areas. Because of the high temporal resolution and large coverage, Moderate Resolution Imaging Spectroradiometer (MODIS) has significant advantages for mapping the wetland extent and dynamics at a coarse spatial resolution (Ordoyne and Friedl 2008). Cai et al. (2005) used MODIS data to map the water body areas of Poyang Lake in China and obtained the lake surface area with an error of approximately ± 6.19%.

High spatial resolution is considered to be images with the spatial resolution of <4 m, including data from SPOT-5, IKONOS, Quickbird, WorldView, and GeoEye. Compared with medium-resolution and hyperspectral images, images with high spatial resolution have more geometry and texture information on the surface features and can be used to identify ground features more easily (Guo et al. 2017). Images with high spatial resolution provide detailed information about the ground surface and are a cornerstone of remote sensing. Because of the high price of high-resolution images (Lee and Lunnetta 1995), they are mainly used in small study areas, to explore new methods, or to verify the wetland map accuracy. Many researchers have confirmed that high resolution images have the potential to improve wetland classification accuracy (e.g. Guo et al. 2017).

2.2 Current Methods of Wetland Determination

Currently a wetland determination is deemed a routine or minimum-level of wetland assessment. This is because a consultant or wetland scientist can conduct a “reconnaissance” and characterize the scope of the work. A determination indicates where potential jurisdictional or general wetlands may be located. It involves a desktop evaluation of NWI, NHD, NRCS Soil Survey, topographic maps and satellite imagery. The following is a description of the datasets:

1. *NWI* - publicly available resource that provides detailed information on the abundance, characteristics, and distribution of U.S. wetlands. NWI data are used by natural resource managers, within the USFWS and throughout the nation, to promote the understanding, conservation and restoration of wetlands.
2. *NHD* - represents the nation’s drainage networks and related features, including rivers, streams, canals, lakes, ponds, glaciers, coastlines, dams, and stream gages.
3. *NRCS Web Soil Survey* - provides soil data and information produced by the National Cooperative Soil Survey. NRCS has soil maps and data available online for more than 95 percent of the nation’s counties and anticipates having 100 percent in the near future.
4. *Topographic maps* - general use maps at medium scales that present elevation (contour lines), hydrography, geographic place names, and a variety of cultural features. Current-generation topographic maps are created from digital GIS databases, and are branded "US Topo."
5. *Satellite imagery* – Esri base maps are typically used for these reports and includes map features on 0.3 m resolution imagery in the continental U.S. and 0.6 m resolution imagery in parts of western Europe from Digital Globe. In other parts of the world, 1 m resolution imagery is available from GeoEye IKONOS, Getmapping, AeroGRID, and IGP Portugal.

One meter USDA NAIP imagery is available in some states of the U.S. Additionally, imagery at different resolutions has been contributed by the GIS user community.

6. *LiDAR Data* - While LiDAR is a more accurate tool, it is cost prohibitive as many LiDAR devices cost up to $10,000 and the state of Oklahoma does not have publicly available high-resolution data at this time.

After these datasets are considered, the scientist determines existing wetlands and “potential jurisdiction wetlands”. Potential jurisdictional wetlands would be an area that exhibits one or more of the three wetland criteria found in a wetland delineation. These features allow a project proponent to appreciate the conditions and choose if a Section 404 permit is necessary or can be avoided (Lyon and Green1992). If the client determines that wetlands will need to be assessed before development then, the only option to them is to hire a wetland delineator to do an onsite assessment of the site.

There are two main problems with the wetland determination. One is that the data is not likely to represent current conditions. Figure 1 shows a sample wetland, using Google Earth Pro with a 30 cm per pixel resolution but image taken on 02/25/2014 and Esri base maps with a 0.5 m per pixel resolution and imagery that was collected on 04/01/2016. If a researcher is looking to assess a wetland they are left with a choice between the two images: is the resolution or the date that is the most current and therefore more likely to represent any modifications that have occurred more important?   The second flaw comes from the NWI maps, because years or even decades may have passed from the date of assessment compared to the original date the map was prepared. The associated wetland that was mapped in Figure 2 was mapped in September, 1981, which when this thesis was written would be a 37-year difference in dates. It is unlikely that a wetland that was mapped 37 years ago would represent current conditions on the site.

Figure 1. Google Earth images versus Esri base maps

Figure 2. Esri base map with NWI mapped wetland overlaid on top of the basemap**.**

2.3 The Use of UAS for the Collection of Spatial Data

The process of capturing aerial imagery using a manned aircraft is a time consuming and costly endeavor. Project proponents will incur the costs of hiring an aircraft, pilot, and insurance.

They will also need to plan the missions (i.e. study areas, buffers, transect distances), plan a flight time, determining the optimal resolution of the imagery, and obtaining the necessary photographic equipment (Falkner and Morgan 2002). The correct weather conditions for flights are also considered, if unfavorable conditions such as fog, high winds, or rain appear on the day of the flight, pilots and scientists will be grounded until favorable conditions occur. Even though no flight has taken place many aviation companies will still charge a daily fee for having the vehicle on standby. This leads to unneeded losses in time and money. No matter which vehicle (fixed-wing, helicopter, or UAS) is being used to capture aerial images, mission planning processes are similar for proper image acquisition, with the main differences being the height and speed at which the missions are flown.

Paine and Kiser (2012) provides an excellent list of variables that need to be addressed before any aerial photography mission. The mission will incorporate the altitude that must be maintained, the percent overlap of the images, the pattern that will be flown, the angle of the camera, the appropriate focal length, and the proper photography equipment to be acquired before the flight. The focal length, flight lines and desired overlap, in combination with the size of the area and chosen detail in output, determine the altitude of the mission and number of images that are required to produce imagery suitable for the desired scale (Paine and Kiser 2012). Typical overlap in UAS mission plans is 80% while manned aerial vehicles require 60% overlap for forward lap in the flight line and 30% on the side lap of each series of flight line photographs. For 2D maps the flight path looks similar to a lawn mowing pattern, and for 3D maps the flight path initially flies the same pattern as a 2D map; however, it then flips the pattern 90 degrees to cross over the original pattern so that a cross-hatch pattern is created. The 3D map allows for digital elevation models to be created in programs such as Pix4D. The variables set forth during the mission planning process need to be maintained during the flight to ensure accurate results (Ahmad et al. 2013).

Mission planning differs between UAS and traditional aircraft. Mission planning software that can be downloaded on iPhone and android phones can provide the UAS operator with preliminary aerial imagery to use as a basemap to select the area that will be flown. These missions can be created before the operator arrives on site or directly once a visual ground assessment has occurred. The operator can then input the desired flight parameters such as altitude and overlap percentage, as well as the camera details such as camera angle. The software will create a flight path that covers the selected area, with precise points at which images will be taken in order to gain the desired outputs. The mission is then uploaded to the UAS via a Wifi link from the phone to the UAS and the mission begins when the operator starts the mission within the application. The progress of the mission can be monitored on the computer in real-time as the UAS completes the mission (Berteska and Ruzgiene 2013; Gademer et al. 2009).

Unlike UASs, planes and helicopters need to go through safety checks, repeated fuel up, and can only take off once clearance is granted. These aircraft are limited by the available airports in the area, which can be several miles from the study area, and could mean a considerable time lag before images are captured. If refueling is needed to complete the mission costs could continue to increase. On the other hand, most kinds of UASs can be taken to the site, and within minutes, be launched and begin imagery collection. All missions will require ground control points (GCPs), and these will need to be determined. GCPs can be temporary markers or existing features on the ground that can be seen within the aerial photograph. The purpose of GCPs is to provide locations on the image that can be precisely identified on the ground (Campbell and Wynne 2011). The coordinates of the locations can be obtained through the use of

Global Positioning System (GPS) receivers in the field before, during, or after the mission. The coordinates of the GCPs are used during post-processing to georeference the images to the Earth's surface. However, algorithms are being developed that might render GCPs unnecessary in the future (Xiang and Tain 2011).

As with most methods, there are advantages and disadvantages to the utilization of each. The light weight makes the UAS manageable to transport and assemble, but this light weight will also make them more vulnerable to winds during flight that would not affect manned aerial vehicles. Changes in wind, either direction or speed, can cause the UAS to pivot on its pitch, roll, or yaw axis, all which can change the angle of the camera (Watkins et al. 2006). While wind altered photos can be corrected it is best to plan for ideal weather conditions to save time in post processing.

This last section has provided insight into the methods for preparing, obtaining, and processing aerial imagery for mapping and monitoring purposes. Information on image overlap, the use of mission planning software and GCP ensure proper coverage of the site. This information served as a reference in the preparation for the data collection methods used for this thesis.

Chapter 3: Methodology

This chapter describes the methods used in this thesis project. The case study locations are introduced (Section 3.1), followed by a description of the equipment used to complete the study (Section 3.2). The final section (Section 3.3) discusses data acquisition by UAS, field data acquisition and post-processing of data for analysis.

3.1 Case Studies

The flights for the case studies occurred in May, June and July of 2018. The case studies for this thesis consisted of 15 mapped NWI wetlands in Oklahoma. Four were located near Meeker, OK, one was found in Pawnee, OK and ten were located near Roosevelt, OK. Meeker, OK is located within the Northern Cross Timbers sub-region of the Cross Timbers ecoregion, Pawnee, OK is located in the Cross Timbers Transition sub-region of the Great Plains ecoregion and Roosevelt, OK is located in the Red Prairie sub-region of the Central Great Plains ecoregion (Woods et al. 2005). The Northern Cross Timbers sub-region is characterized by mosaics of oak savanna, scrubby oak forest, eastern red cedar (*Juniperus virginiana*), and tall grass prairie. Areas within the ecoregion are used primarily for livestock farming, with cropland being less extensive than in other ecoregions found in Oklahoma (Woods et al. 2005). The four case study sites found near Meeker, OK are used in a seasonal rotation for grazing cattle. The Cross Timbers Transition sub-region is characterized by rough plains that are covered by prairie grasses and eastern red cedar, scattered oaks, and elms. Terrain and vegetation are transitional between the less rugged grass-covered ecoregions to the west and the Northern Cross Timbers sub-region to the east. Rangeland and livestock production is the primary land use (Woods et al. 2005). The Red-Prairie sub-region is characterized by mostly mesquite-buffalograss (*Buchloe dacryloides Nutt. Engelm*) communities with gypsum outcrops. Wheat (*Triticum sp.*) is the main crop, but unfavorable lands are maintained as rangelands. Like the sites in Meeker, OK, the Pawnee and Roosevelt case study areas are used for cattle grazing with seasonal rotations.

3.2 Equipment

A DJI Phantom 3 Professional (DJI, Shenzhen, China) was used for imagery acquisition on all case studies. The device is a commercial “all-in-one solution” quadcopter. In addition to the aircraft itself, it consists of a built-in camera with a three-axis gimbal, remote control, a mobile application for the aircraft and camera control, and information about the state of the aircraft. The camera sensor is an RGB Sony Exmor 1/2.3” CMOS with lens FOV of 94◦, 20 mm focal length, f/2.8 focal ratio, and focus to infinite. The image resolution of the camera is 4,000 × 3,000 pixels (Table 1).

3.2.1 Systems and Software

The Phantom 3 Pro UAS (Figure 3) (DJI, Shenzhen, China) was chosen for this thesis project due to accessibility, affordability, and compatibility with the mission planning software (Pix4Dcapture). As seen in Table 1, the UAS with all accessories weighs approximately 1,280 g and has a diagonal length of 350 mm. The UAS can have a flight time of 23 minutes (mins) with a pristine lithium battery that is fully charged; however, this can be limited by subpar batteries or adverse weather conditions. The UAS remote control unit operates between 2.400 and 2.483 GHz with a range of 3.1 mi (5 km) in unobstructed areas that are free of interference.

Table 1. List of field equipment and specifications

System Specifications	
Aircraft - Phantom 3 Pro by DJI	
Weight (Battery & Propellers Included)	1280 g
Diagonal Size (Propellers Excluded)	350 mm
Max Ascent Speed	5 m/s
Max Descent Speed	3 m/s
Max Speed	16 m/s (ATTI mode)
Max Tilt Angle	35°
Max Angular Speed	150°/s
Max Service Ceiling Above Sea Level	19685 feet (6000 m)
Max Flight Time	Approx. 23 mins
Operating Temperature Range	32° to 104°F (0° to 40°C)
Satellite Positioning Systems	GPS/GLONASS
Hover Accuracy Range	Vertical: ±0.1 m (with Vision Positioning) ±0.5 m (with GPS Positioning) Horizontal: ±0.3 m (with Vision Positioning) ±1.5 m (with GPS Positioning)
Gimbal	
Stabilization	3-axis (pitch, roll, yaw)
Controllable Range	Pitch: -90° to +30°
Max Controllable Angular Speed	Pitch: 90°/s
Angular Control Accuracy	±0.02°
Remoter Control	
Operating Frequency	2.400 - 2.483 GHz
Max Transmission Distance	FCC Compliant: 3.1 mi (5 km) CE Compliant: 2.2 mi (3.5 km) (Unobstructed, free of interference)
Operating Temperature Range	32° to 104°F (0° to 40°C)
Battery	6000 mAh LiPo 2S
Transmitter Power (EIRP)	FCC: 20 dBm CE: 16 dBm MIC: 16 dBm
Operating Current/Voltage	1.2 A@7.4 V
Video Output Port	USB
Mobile Device Holder	Apple iPhone 7s
Camera	
Sensor	1/2.3” CMOS Effective pixels: 12.4 M (total pixels: 12.76 M)
Lens	FOV 94° 20 mm (35 mm format equivalent) f/2.8 focus at ∞
ISO Range	100-1600 (photo)
Electronic Shutter Speed	8 - 1/8000 s
Image Size	4000×3000
Still Photography Modes	Single Shot Burst Shooting: 3/5/7 frames

	Auto Exposure Bracketing (AEB): 3/5 bracketed frames at 0.7 EV Bias Timelapse
Max Video Bitrate	60 Mbps
Supported File Systems	FAT32 (≤32 GB); exFAT (>32 GB)
Photo	JPEG, DNG (RAW)
Video	MP4, MOV (MPEG-4 AVC/H.264)
Supported SD Cards	Micro SD Class 10 or UHS-1 rating required
Operating Temperature Range	32° to 104°F (0° to 40°C)
Other equipment	
GPS Receiver	Trimble Geo &X Handheld Model 88161 Trimble TerraSync 5.9 Software
Computers, Systems, and other software	Dell HP Precision 7720 Esri ArcGIS 10.5 software Pix4Dcapture mapping services Pix4D Desktop 4.2.27 software USFWS wetland Mapper SanDisk Micro USB 32GB

Figure 3. Phantom 3 Pro UAS by DJI
(Source: https://www.dji.com/phantom-3-pro)

Images were collected via a SanDisk micro USB 32 GB. The Gimbal Roll Arm Motor (Figure 4) by DJI is a 3-axis gimbal camera mount that secures the camera to the Phantom 3 Pro UAS, providing stabilization for the camera should the UAS experience movements in “pitch”, moving front to back; “rolling”, moving side to side; or “yaw”, moving left to right (Figure 5). Without stabilization, such movements on a camera would cause the camera to tilt, roll, and pan.

Figure 4. Pro gimbal camera roll arm and camera
(Source: http://ww.dji.com)

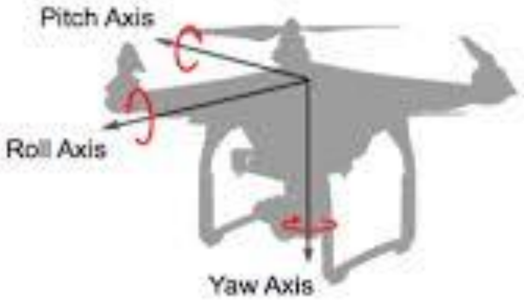


Figure 5. Example of pitch, roll and yaw on UAS.
(Source: https://developer.dji.com/mobile-sdk/documentation/introduction/flightController_concepts.html)

The Pix4dcapture ISO phone application supports 18 UAS models, from DJI and Parrot, including the Phantom 3 Pro. This makes Pix4Dcapture ideal for mapping with no additional equipment requirements (Draeyer and Strecha 2014). This application has specific programing for the as-is Phantom 3 Pro by DJI, which allowed easy interface between the pilot and the program with no adjustments needed. By using Pix4Dcapture, it allows the UAS pilot to plan the mission (Figure 6), wireless upload it to the UAS, monitor the progress of the UAS during flight, and land the UAS at the GPS point where the mission began. The pilot selects the total area, drawing a square or polygon, to be flown based on Google Earth imagery or Google Street Map. The pilot can select altitude, percent forward overlap and lateral overlap in order to gain the desired resolution or adjust flight times. Higher altitudes and decrease percent overlap will decrease flight time however resolution will also decrease.

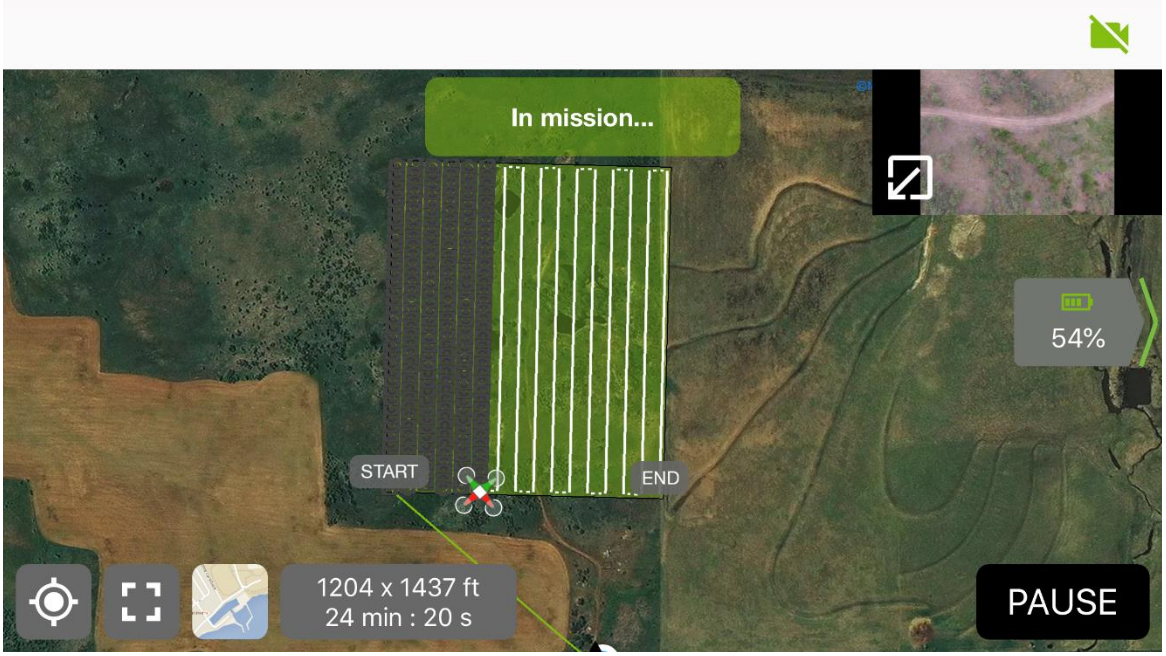


Figure 6. Example of Pix4Dcapture mission
(Source: http://www.aerialpicture.co.za/the-pix4d-mapper-capture-app/)

3.2.2 Trimble GPS Receiver

A Trimble Geo 7X Series GPS receiver was used to collect the coordinates of the sampled locations for each of the wetlands and ground control points on the aerial imagery. The Geo 7X unit is a handheld unit that provides centimeter accuracy. While higher levels of accuracy are considered more ideal, wetlands are a dynamic feature with fluctuations in growth based on seasonal or yearly weather variability. Therefore, this level of accuracy was deemed adequate for the purposes of this thesis. Trimble's TerraSync 5.9 software installed on the GPS receiver allows the unit to communicate with satellites and record positional data. The interface allows the user to collect point, line, or area data, add attributes to the data, and store it in files for download.

3.2.3 Software systems

NWI wetland mapper provided by the USFWS was reviewed to record if the wetland was mapped and what year the wetland was most recently mapped, the wetland mapper was last modified on May 1, 2018. It is important to note that this mapper is used to produce reconnaissance level information on the location and size the features associated with the mapper (USFWS 2018b)

Trimble's GPS Pathfinder Office version 5.60 is a software platform installed on the Dell HP Precision 7720 for use with the Trimble GPS receiver. The software allows the user to upload data from TerraSync to the computer. GPS Pathfinder Office is used to perform post-data correction by acquiring positional data from local base stations and improving the positional accuracy of data collected with the GPS receiver. GPS Pathfinder Office also transforms data files into shapefiles for use in the ArcGIS 10.5 software (Trimble Navigation Limited 2018). Esri's ArcGIS 10.5 software was used to perform the data analysis for this study.

Pix4Dmapper 4.2 was used to stitch together all of the images that were collected during the UAS flights. Pix4Dmapper can process images taken from any angle from aerial or terrestrial, manned or unmanned platforms. During processing this system allows for automatic processing templates, optimization of internal camera parameters, such as focal length, principal point of autocollimation and lens distortions, to compensate automatically for change in brightness, luminosity and color balancing, and assess the accuracy and quality of projects with a quality report. For this thesis the main output that was assessed from this system was the orthomosaic image. Orthomosaic generation is the automated process for orthorectifing the raw imagery and mosaicing adjacent images into one single large image. This process generated a georeferenced image and optionally a digital surface model in various formats. The orthomosaic is a 2D map. Each point contains X, Y and color information. The orthomosaic has a uniform scale and can be used for 2D measurements (distance, surface).

Google Earth is used as a base map in Pix4Dcapture and provides preliminary basemap imagery for mission planning. Google Earth was used to analyze existing imagery for comparison between Esri base maps and UAS captures images in this thesis project.

3.3 Data Acquisition

The data acquisition via UAS and ground truthing occurred from May to July 2018 in locations near Meeker, Pawnee and Roosevelt, OK.

3.3.1 UAS Data Acquisition

Prior to flights, permission to access the land was obtained and NWI wetland mapper was reviewed to determine if the existing wetlands to be flown were currently mapped. If the wetlands were not mapped, they were eliminated from the sample set. To prepare the UAS for data collection, Pix4DCapture was opened on the ISO 9 iPhone 7, where the camera and flight parameters were entered in the application. The data for this study was collected at an altitude of 40 m to avoid collisions with vegetation, which varied in height at each case study site. Percent overlap for acquisition was set at 80% forward overlap and 80% lateral overlap between images; the average flight speed was 0.5 m/s. Data collection was RGB at a high spatial resolution (2 inches per pixel). While LiDAR data is more accurate than RGB, this study was limited by the cost of a LiDAR camera. Publicly available LiDAR data at the time of this thesis provides a resolution of 10 m for the state of Oklahoma. This resolution would not provide robust indicators of smaller slope changes found in areas with less distinct elevation changes. Next, a rectangle was drawn over a portion of the case study area, with some flights encompassing multiple mapped wetlands. This rectangle produced a preview of the flight path. Then the flight path was created and uploaded to the UAS. Finally, a home point for the UAS was logged within Pix4Dcapture and the UAS was launched via the application. The UAS uses the home point for automatic landing at the end of the mission, or if the mission needs to be paused for battery change. The time each flight took was recorded as well as time of day and cloud cover.

3.3.2 GPS Data Acquisition and Wetland delineation

Wetland delineation data for this thesis was collected with the Trimble GPS receiver. A formal wetlands delineation was completed as an onsite assessment of three wetland indicators (Section 1.2) as defined by the USACE Wetlands Delineation Manual (USACE 2010): hydric soil, hydrology and hydrophilic vegetation. Presence and/or absence of all three indicators was captured via the USACE Wetland Delineation Manual and the Midwest Regional Supplement (USACE 2010) to determine the extent of the wetland. A series of data points that are representative of the site were chosen and paired with wetland areas and upland sites. The wetland border was recorded via the Geo 7X Trimble unit. The time each delineation required was recorded as well.

3.3.3 Esri Base Maps and Google Earth Imagery Acquisition

Esri base maps are available online (www.arcgis.com) and can be used seamlessly with ArcGIS 10.5 desktop software. Google Earth imagery was acquired via conversion of GIS shapefiles of wetlands to KMZ files and uploaded to Google Earth 7.1. Both imagery datasets were used for comparison with UAS acquired imagery. These datasets were chosen due to the common use of the systems within wetland determination reports and other remotely sensed reconnaissance reports.

3.4 Post-Processing Data

3.4.1 UAS Post-Processing

As covered in Section 3.2.2, UAS data consists of several hundred images that need to be georeferenced and stitched together in order to be useful. Pix4DMapper software allows users to stitch and georeference aerial imagery into maps. The points were located and matched throughout the uploaded imagery to triangulate their positions in a manner that minimized the errors between the points. Since the imagery has GPS information in an Exchangeable Image File Format file, georeferencing occurred during the reconstruction of the imagery. An output resolution of 15 cm was chosen for the project at hand. While the flight height of 40 m could have yielded a resolution of 2 cm, a 15 cm resolution was selected to assess the processing and analysis time. A higher altitude (120 m) could have been flown to obtain 15 cm resolution imagery.

3.4.2 GPS Post-Processing

Ground-truthed data collected with the Trimble GPS receiver can have errors due to overhead vegetation that interferes with satellite signal, or proximity to water. Differential correction was performed within Trimble's GPS Pathfinder Office software to correct errors that occurred in the field. The differential correction process uses positional data from base station providers in the area that is downloaded by the software. The base station records its location at fixed intervals and compares it to the position of the control location to calculate the positional error for the reading at that specific time. The time of day that the data collected by the GPS receiver is cross-checked with the positional error data, applying positional error corrections to data that were collected at corresponding times of day. The data files are converted to shapefile format in GPS Pathfinder Office after differential correction (Dustin 2015).

3.5 Data Analysis

Processed orthomosiacs and wetland delineation polygons were uploaded into ArcGIS 10.5 for analysis. While Google Earth imagery cannot be uploaded into ArcGIS, a comparison of resolution, and capture dates at similar scales was made.

3.5.1 Visual Comparison of UAS, Esri, and Google Earth Imagery

The UAS imagery is in WGS 84 and is projected to NAD 1983 UTM Zone 14 N using the Project tool in ArcGIS. The NAD 1983 was used due to Oklahoma being divided into two state plane systems, which would have added unneeded complications. NAD 1983 UTM Zone 14 N encompasses most of the state of Oklahoma (Figure 7) the conversion of the data from the geographic coordinate system to a projected coordinate system allows measurements to be calculated on the data. The UAS, Esri, and Google Earth imagery of the study site was opened and visually examined. Ocular inspections of the imagery sets were performed, making note of differences that can be seen in each, such as differences in season, clarity and if the image registered the wetland in its entirety. After they were processed, supervised and unsupervised classification was used to determine the wetland's current extent and the surrounding vegetation. Ten training classes were used to determine wetland extent, and isoclustering unsupervised classification was used to classify the surrounding vegetation into three distinct vegetation classes (forest, grassland, and bare ground).

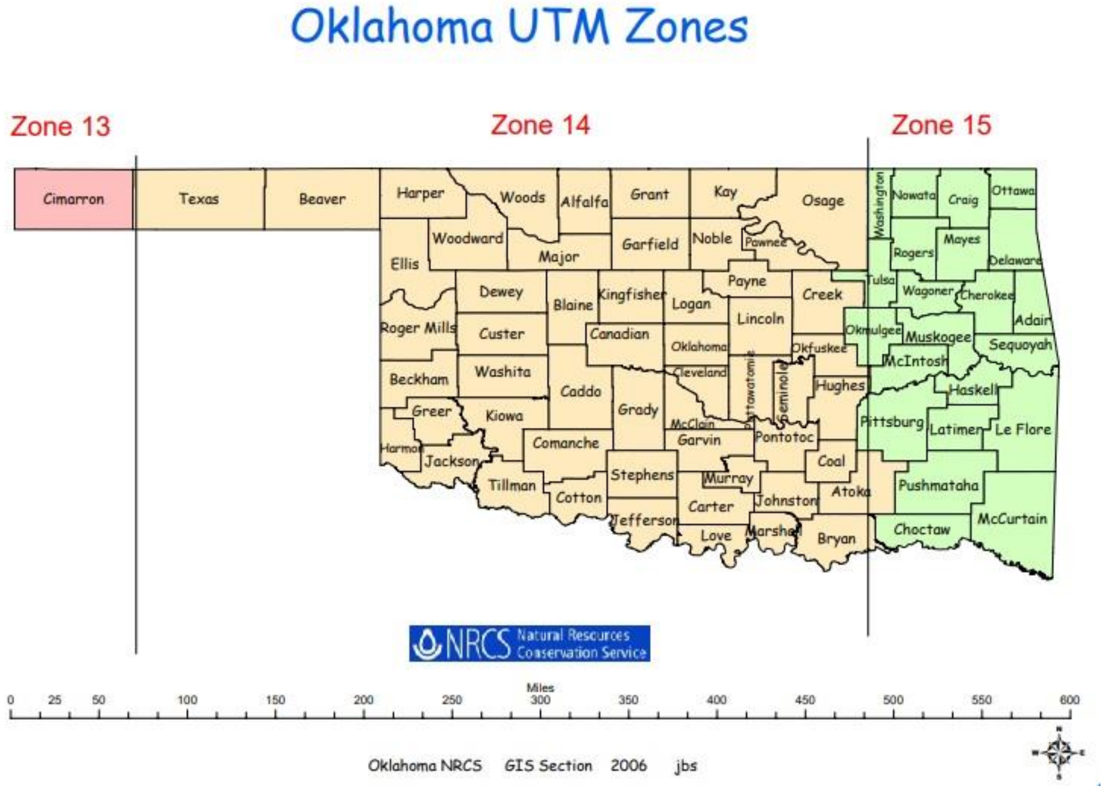


Figure 7. Oklahoma NAD 1983 UTM zones (Source: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_001664.pdf

NWI wetland data was downloaded from the USFWS wetland mapper website for the state of Oklahoma. The case study wetlands were then selected and extracted from the statewide dataset. The Calculate Geometry tool in ArcGIS measured the total number of acres for the UAS imagery, NWI imagery and the GPS collected data. The calculated acreages from the UAS and

NWI imagery were then compared to the measurements captured with the GPS receiver during the wetland delineation. Since wetland delineation is the highest form of wetland assessment, this will be considered the truest measurement for current conditions. In order to assess the accuracy of the UAS method versus the ground truth delineation of the wetland 200 accuracy assessment points were created for each site. After accuracy assessment points were created, they were input into the Compute Confusion Matrix Tool.

3.5.4 Cost/Benefit Analysis

The potential cost savings, when comparing UAS to traditional surveying techniques, was noted in Chapter 2 and in order to assess this the mobilization time, flight times, and processing times were recorded for all sites, as well as the time it took to perform a wetland delineation on each site. The hourly rates of an UAS pilot and a certified wetland delineator were captured and used with a 3.0 multiplier. These rates are compared to determine the financial differences of the UAS to traditional wetland delineation. The total hours spent collecting and processing data collected with the UAS and GPS receiver were tallied in order to determine the total labor cost for each method of data acquisition. These estimates were compared to estimate the potential labor savings benefits of the UAS. A SWOT (strength, weakness, opportunity, and threat) analysis was also performed using the results of the financial and labor benefits to evaluate the efficacy of using UAS technology for the purposes of wetland determination. Information discussed in the literature review of Chapter 2 was also considered in the SWOT analysis.

Chapter 4: Results

This chapter details the results of the methods documented in Chapter 3 to assess the differences between UAS mapped wetlands and traditionally used data. As outlined earlier the goals of this study were to: (1) improve upon current determination datasets; (2) determine the accuracy of the imagery when compared to mapped NWI wetlands and wetland delineations; and (3) determine the cost effectiveness of UAS when compared to traditional methods.

4.1 Accuracy of UAS and Existing data

The UAS-collected imagery was visually compared to Google Earth and ESRI imagery available through ArcGIS Online in ArcGIS 10.5. The dates and resolution of the various imagery data sets were first compared for relevance (Tables 2 - 4). Zooming in on the imagery increases the amount of detail that can be seen. The resolution of the imagery determines the amount of detail that can be observed before the imagery appears blurred or pixelated.

Table 2. Capture dates for imagery data in Meeker, OK case studies**.**

Imagery Source	Capture Date	Resolution
UAS	5/27/2018	5 cm
Google Earth	2/25/2014	15 cm
Esri World Imagery Basemap	4/21/2016	50 cm

Table 3. Capture dates for imagery data in Pawnee, OK case study.

Imagery Source	Capture Date	Resolution
UAS	1/15/2018 and 6/10/2018	5 cm
Google Earth	2/25/2014	15 cm
Esri World Imagery Basemap	4/2/2016	50 cm

Table 4. Capture dates for imagery data in Roosevelt, OK case studies**.**

Imagery Source	Capture Date	Resolution
UAS	7/1/2018	5 cm
Google Earth	10/14/2017	15 cm
Esri World Imagery Basemap	7/10/2016	50 cm

Fifteen UAS missions were flown around NWI mapped wetlands (Figures 10 - 23). Because wetlands are most accurately delineated during the growing season, flying during the times when wetland delineations could take place concurrently seemed ideal. A full wetland delineation was completed on each site in accordance with the USACE Wetland Delineation Manual (USACE 1987) and the Midwest Regional Supplement (USACE 2010).

Weather plays a large role in current wetland size and status. Figures 8 and 9 show the yearly variability in Oklahoma's precipitation and temperature, due to this, historic weather conditions were considered for each year that imagery was captured. Weather has an accumulative effect on wetlands; therefore, the three months preceding the capture dates were considered to see if the months had high or low temperatures and rainfall. Table 5 details the weather conditions present in Meeker, OK during 2014, 2016 and 2018. Likewise, Tables 6 and 7 detail the weather conditions present for the capture dates as shown in previous tables for Pawnee and Roosevelt, OK.

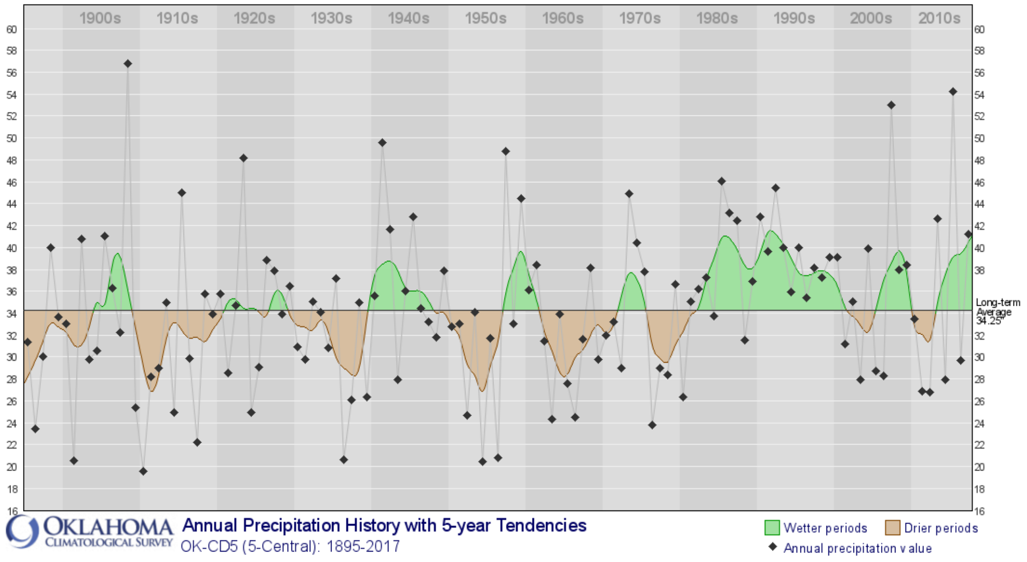


Figure 8. Oklahoma annual precipitation from 1895-2017
Source : http://climate.ok.gov/

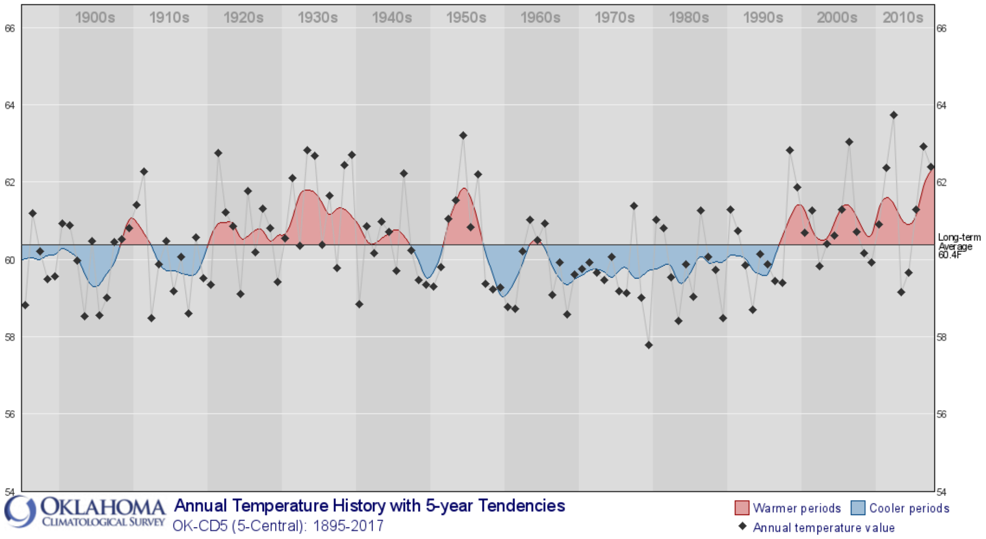


Figure 9. Oklahoma annual temperature from 1895-2017
Source: http://climate.ok.gov/

Table 5. The average maximum, mean, and minimum temperatures and rainfall totals for Meeker, OK three months prior to imagery capture dates**.**

Google Maps	December 2013	January 2014	February 2014
Max temp (F)	62	60	62
Mean temp (F)	40	41	41
Min temp (F)	24	17	18
Precipitation (in.)	0.47	0.01	0.11
Esri Base Map	February 2016	March 2016	April 2016
Max temp (F)	70	70	75
Mean temp (F)	49	56	62
Min temp (F)	36	42	51
Precipitation (in.)	1.68	0.91	4.48
UAS Mapping	April 2018	May 2018	June 2018
Max temp (F)	72	80	83
Mean temp (F)	54	74	77
Min temp (F)	34	64	70
Precipitation (in.)	2.11	4.14	3.99

Table 6. The average maximum, mean, and minimum temperatures and rainfall totals for Pawnee, OK three months prior to imagery capture dates.

Google Maps	December 2013	January 2014	February 2014
Max temp (F)	60	54	54
Mean temp (F)	35	36	36
Min temp (F)	14	8	13
Precipitation (in.)	0.66	0.05	0.48
Esri Base Map	February 2016	March 2016	April 2016
Max temp (F)	65	74	73
Mean temp (F)	47	55	61
Min temp (F)	34	40	49
Precipitation (in.)	0.26	2.52	4.61
UAS Mapping	April 2018	May 2018	June 2018
Max temp (F)	75	82	84
Mean temp (F)	54	75	79
Min temp (F)	35	64	70
Precipitation (in.)	2.05	8.87	4.83

Table 7. The average maximum, mean, and minimum temperatures and rainfall totals for Roosevelt, OK three months prior to imagery capture dates.

Google Maps	April 2016	May 2016	June 2016
Max temp (F)	75	80	92
Mean temp (F)	63	69	80
Min temp (F)	50	58	69
Precipitation (in.)	6.06	4.82	2.61
Esri Base Map	August 2017	September 2017	October 2017
Max temp (F)	89	86	77
Mean temp (F)	79	75	64
Min temp (F)	70	63	50
Precipitation (in.)	9.04	6.66	1.69
UAS Mapping	April 2018	May 2018	June 2018
Max temp (F)	73	89	96
Mean temp (F)	57	77	84
Min temp (F)	41	64	71
Precipitation (in.)	1.44	2.80	1.46

The UAS imagery was collected at an altitude of 40 m during May, June and July of 2018, with one additional flight of the Pawnee case study occurring in January 2018. The UAS imagery improved resolution and increased clarity. The Google Earth imagery, captured in February 2014, is relevant to the extent that it shows the wetlands; however, there is a four-year gap between the time these images were captured and the time at which this thesis was written. The Google Earth imagery was captured during the winter months, which does not allow the user to assess any of the vegetation patterns that exist in the growing season. The Esri base maps had the lowest resolution of all the imagery; however, this imagery was captured during the growing season. Each NWI wetland was plotted on the Esri base map and Table 8 shows the NWI acreages and capture dates for each of the fifteen case studies. The USFWS Wetland Mapper was last updated May 1, 2018.

Table 8. NWI mapped wetlands attributes

Case Study ID	Wetland Type	Classification*	NWI Acreages	Date of mapping
1	Freshwater pond	PubHh	1.32	03/80
2	Freshwater pond	PubHh	0.44	03/80
3	Freshwater Pond	PubHh	0.20	03/80
4	Freshwater Pond	PubHh	0.94	03/80
5	Freshwater Pond	PubHh	0.33	03/81
6	Freshwater pond	PubHh	0.63	03/83
7	Freshwater pond	PubHh	1.67	03/83
8	Freshwater Pond	PubHh	1.39	03/83
9	Freshwater Pond	PubHx	0.51	03/83
10	Freshwater Pond	PubFh	0.73	03/83
11	Freshwater pond	PubHh	0.35	03/83
12	Freshwater pond	PubHh	0.12	03/83
13	Freshwater Pond	PubFh	0.11	03/83
14	Freshwater Pond	PubHx	0.67	03/83
15	Freshwater Pond	PubFx	0.5	03/83

* See next page for classification description.

The NWI data that has been collected shows that all of the wetlands flown where consistent in type and classification. There is a range of 35-37 years between the mapping of these wetlands and the preparation of this thesis. The case study NWI wetlands range from 0.33 acres to 1.67 acres in size (Table 8). The Cowardian classification (USEPA 2002) code used by the USFWS and reported in column 3 of Table 8 states that all wetlands for this thesis include the following traits:

- *P - PALUSTRINE*: The Palustrine System includes all nontidal wetlands dominated by trees, shrubs, persistent emergents, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5 ppt. It also includes wetlands lacking such vegetation, but with all of the following four characteristics: (a) area less than 8 ha (20 acres); (b) active wave-formed or bedrock shoreline features lacking; (c) water depth in the deepest part of basin less than 2.5 m (8.2 ft) at low water; and (d) salinity due to ocean-derived salts less than 0.5 ppt.
- *UB - UNCONSOLIDATED BOTTOM*: Includes all wetlands and deep-water habitats with at least 25% cover of particles smaller than stones (less than 6-7 cm), and a vegetative cover less than 30%.
- *H - Water Regime Permanently Flooded*: Water covers the substrate throughout the year in all years.
- *h - SPECIAL MODIFIER Diked/Impounded*: These wetlands have been created or modified by a man-made barrier or dam that obstructs the inflow or outflow of water.
- *F - Water Regime Semipermanently Flooded:* Surface water persists throughout the growing season in most years. When surface water is absent, the water table is usually at or very near the land surface.

- *x - SPECIAL MODIFIER Excavated:* This modifier is used to identify wetland basins or channels that were excavated by humans.

4.2 Comparison of NWI, Delineation, and UAS Collection Methods

From the flight, delineation and NWI data, there are noticeable differences in the size (Table 9) and placement of the wetlands (Figures 8 – 22). There was greater overlap between the NWI and the delineation data compared to the UAS data; however, between the three data sets the highest percent overlap was found between the delineation data and the UAS collected imagery. Overall the UAS mapped wetlands offer more conservative measurements of area than the full delineation.

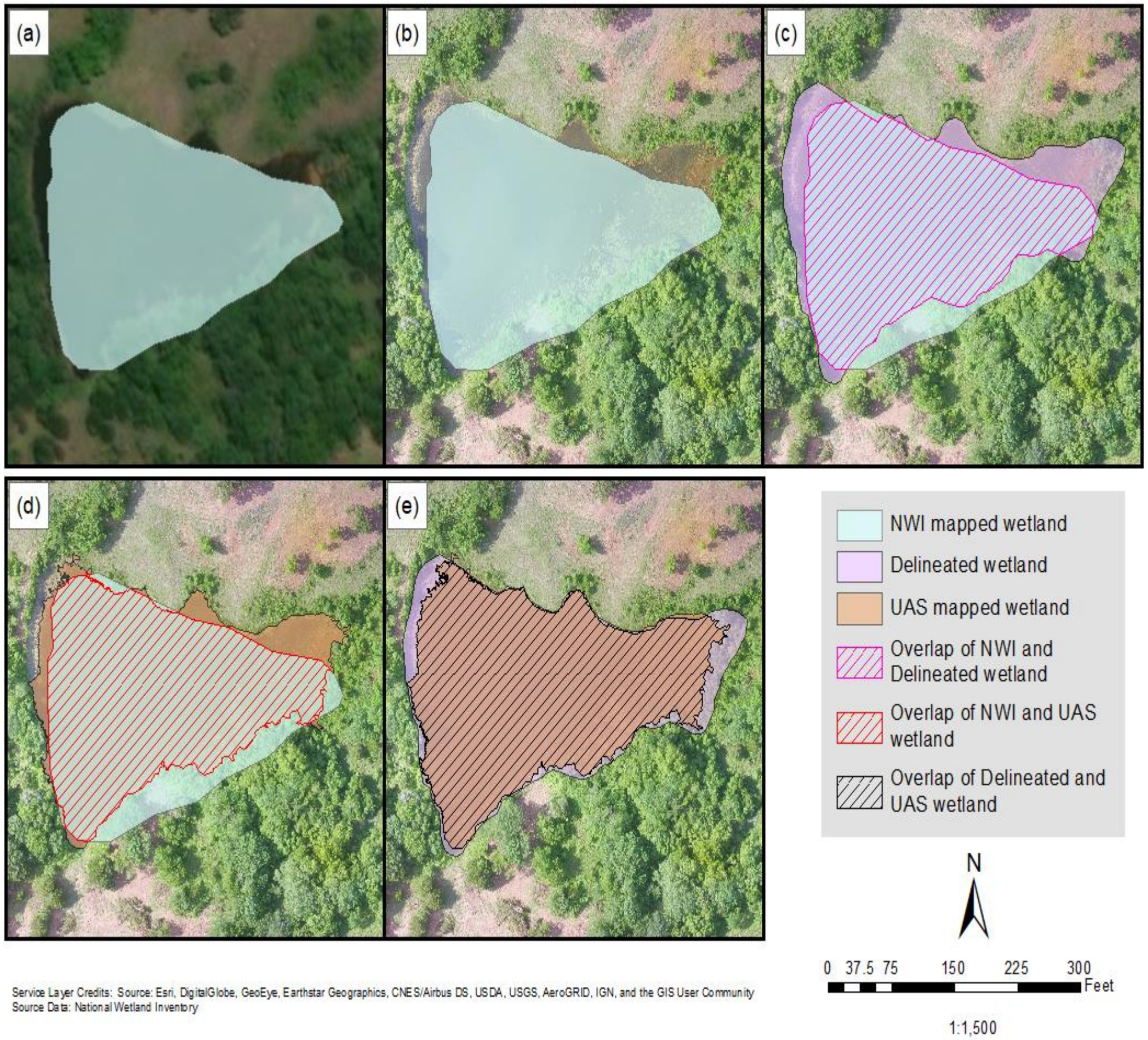
Table 9. Acreages calculated from NWI, Delineation, and UAS collection methods.

Case Study ID	NWI Acreages	Delineation	UAS
1	1.32	1.47	1.29
2	0.44	0.67	0.49
3	0.20	0.35	0.34
4	0.94	2.34	1.80
5	0.33	0.87	0.62
6	0.63	0.81	0.73
7	1.67	0.87	0.72
8	1.39	1.68	1.24
9	0.51	0.86	0.75
10	0.73	0.65	0.65
11	0.35	0.67	0.54
12	0.12	0.23	0.1
13	0.11	0.27	0.2
14	0.67	0.59	0.29
15	0.5	0.06	0.005

The following case studies document the time, weather conditions and vegetation present at the time of data collection. The wetlands were split into 3 categories: wetlands without obstruction; wetlands with canopy cover/blue green algae; and wetland with exposed bed. From these three categories 98.3%, 93.4% and 85% accuracy, respectively, was calculated.

4.2.1 Case Study #1

Case Study #1 was flown on May 28, 2018 from 5:00 to 5:25 p.m. with a total flight time of 25 minutes and 36 seconds; the flight collected data for Case Study #2 concurrently. Weather conditions were clear skies with winds of 8-12 miles per hour. Delineation of the wetland took place from 5:30 to 9:10 p.m. (i.e. 3 hours and 40 minutes). The wetland was surrounded by Blackjack oak (*Quercus marilandica*), Post oak (*Quercus stellate*), and green briar (*Smilax sp.*). Prominent wetland species that were present included Rufous bulrush (*Scirpus pendulus*), Sago Pondweed (*Stuckenia pectinate*) and blue green algae (*Cyanobacteria sp.*). Figure 10a displays the Esri basemap, captured in April 2016, and the historic NWI mapped wetland (1.32 ac), captured in March 1980. There is a 36-year time lapse between these two data sets. With the coarse imagery provided at the 1:1,500 scale, the NWI mapped area does not fully represent the 2016 extent of the wetland; however, the placement is centered over the present wetland. In Figure 10b the resolution is increased but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 10c shows the delineated area (1.47 ac) and historic wetland overlap, which indicates a 7.6 % increase in wetland size from NWI. Figure 10d shows the wetland area determined by supervised classification via UAS imagery (1.29 ac) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is a 2.27% decrease in wetland size. The UAS collected data provides a more conservative estimate than a full delineation, the delineation shows a small increase in wetland size when compared to the historic data captured 37 years ago, while the UAS method indicates a small decrease. Finally, Figure 10e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-nine percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 87.7% of the delineated area.

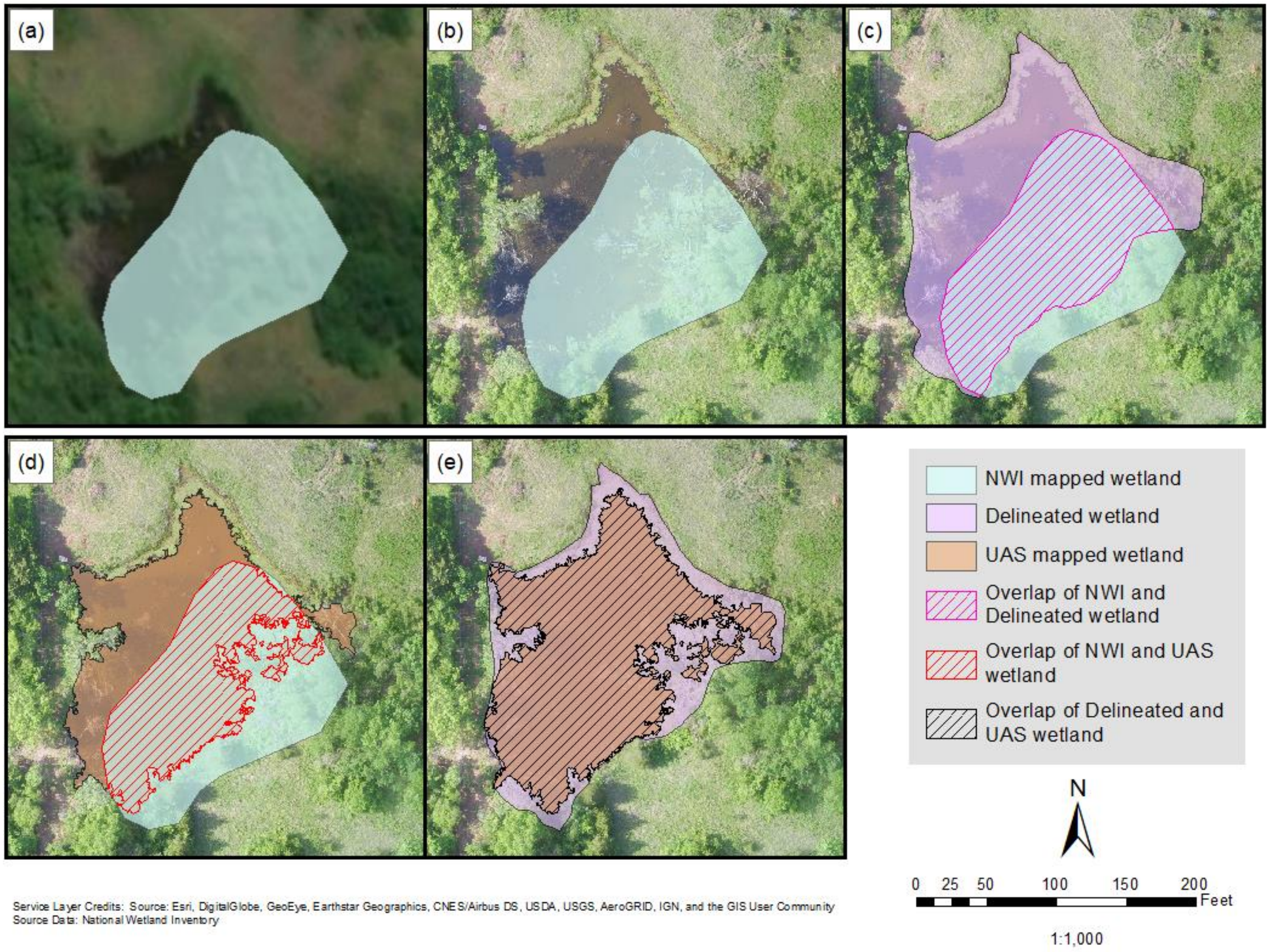


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 10. Case Study # 1 in Meeker, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.2 Case Study #2

Case Study #2 was flown on May 28, 2018 from 5:00 to 5:25 p.m. with a total flight time of 25 minutes and 36 seconds; the flight collected data for Case Study #1 concurrently. Weather conditions were clear skies with winds of 8-12 miles per hour. Delineation of the wetland took place from 9 to 10:30 a.m. on May 29, 2018 (i.e. one hour and 30 minutes). The wetland was surrounded by Blackjack oak, eastern red cedar, and green briar. Wetland species that were present included blue green algae, but disturbance was present around the shore and other vegetation was removed. Figure 11a displays the Esri basemap, captured in April 2016, and the historic NWI mapped wetland (0.44 acres), captured in March 1981. There is a 35-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,000 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 11b the resolution is increased and the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 11c shows the total delineated area (0.67 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 52% increase in wetland size. Figure 11d shows the wetland area determined by supervised classification via UAS imagery (0.49 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is a 11% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show an increase in wetland size when compared to the historic data captured 37 years ago. Finally, Figure 11e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-nine percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 73.1% of the delineated area.

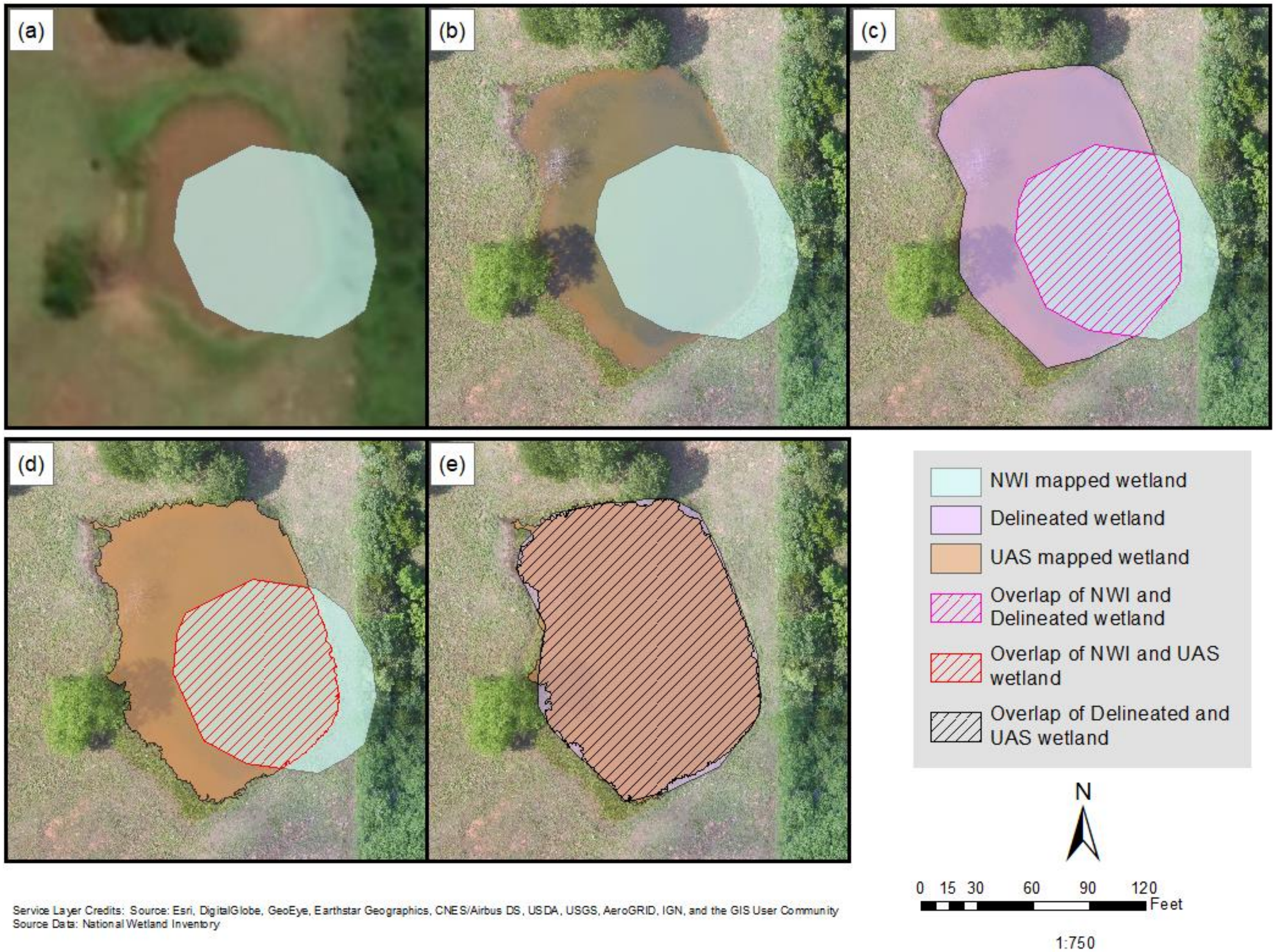


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 11. Case Study # 2 in Meeker, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.3. Case Study #3

Case Study #3 was flown on May 28, 2018 from 2:30 to 2:58 p.m. with a total flight time of 28 minutes and 3 seconds; this flight also collected the data for Case study #4. Weather conditions were clear skies with winds of 7-12 miles per hour. Delineation of the wetland occurred took place from 11 to 11:30 a.m. (i.e. 30 minutes). The wetland was surrounded by pasture land, switchgrass (*Panicum virgatum*), sideoats grama (*Bouteloua curtipendula*), hairy grama (*Bouteloua hirsute*), and bermuda grass (*Cynodon dactylon*). No wetland species were present. Figure 12a displays the Esri basemap, captured in April 2016, and the historic NWI mapped wetland (0.20 acres), captured in March 1981. There is a 35-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:750 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 12b the resolution is increased but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 12c shows the total delineated area (0.35 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 75% increase in wetland size. Figure 12d shows the wetland area determined by supervised classification via UAS imagery (0.34 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is a 70% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 37 years ago. Finally, Figure 12e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-nine percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 97.1% of the delineated area.

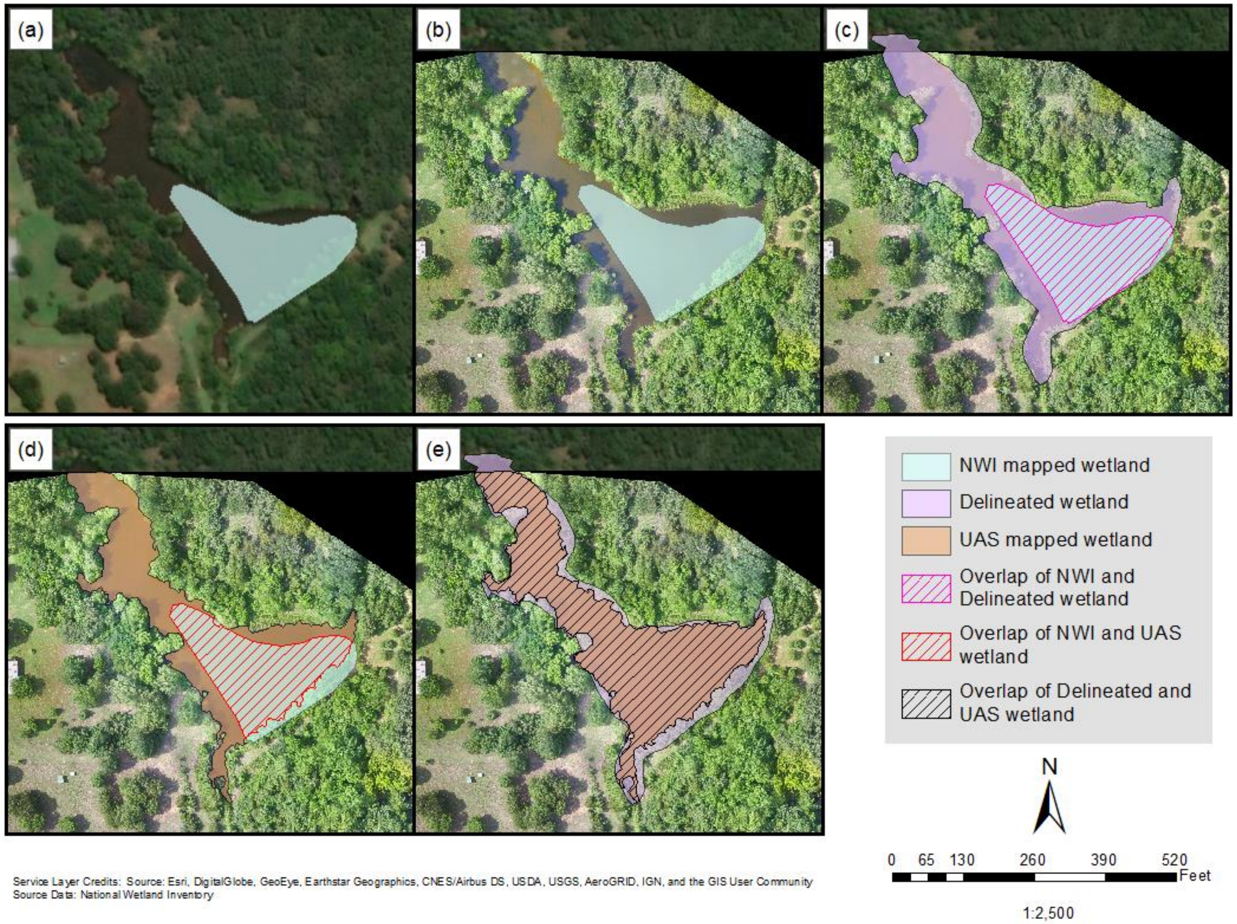


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 12. Case Study # 3 in Meeker, OK**: (**a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.4 Case Study #4

Case Study #4 was flown on June 6, 2018 from 5:26 to 5:36 p.m. with a total flight time of 10 minutes and 10 seconds. Weather conditions were clear skies with winds of 5-12 miles per hour. Delineation of the wetland took place from 2:45 to 5:10 p.m. (i.e. two hours and 25 minutes). The wetland was surrounded by Blackjack oak, eastern red cedar, and green briar. Wetland species that were present included Rufous bulrush and Shoreline sedge. Figure 13a displays the Esri basemap, captured in April 2016, and the historic NWI mapped wetland (0.94 acres), captured in March 1981. There is a 35-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:2,500 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 13b the resolution is increased but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 13c shows the total delineated area (2.34 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 264% increase in wetland size. Figure 13d shows the wetland area determined by supervised classification via UAS imagery (1.80 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is a 189% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 37 years ago. Finally, Figure 13e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-nine percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 87.8% of the delineated area.

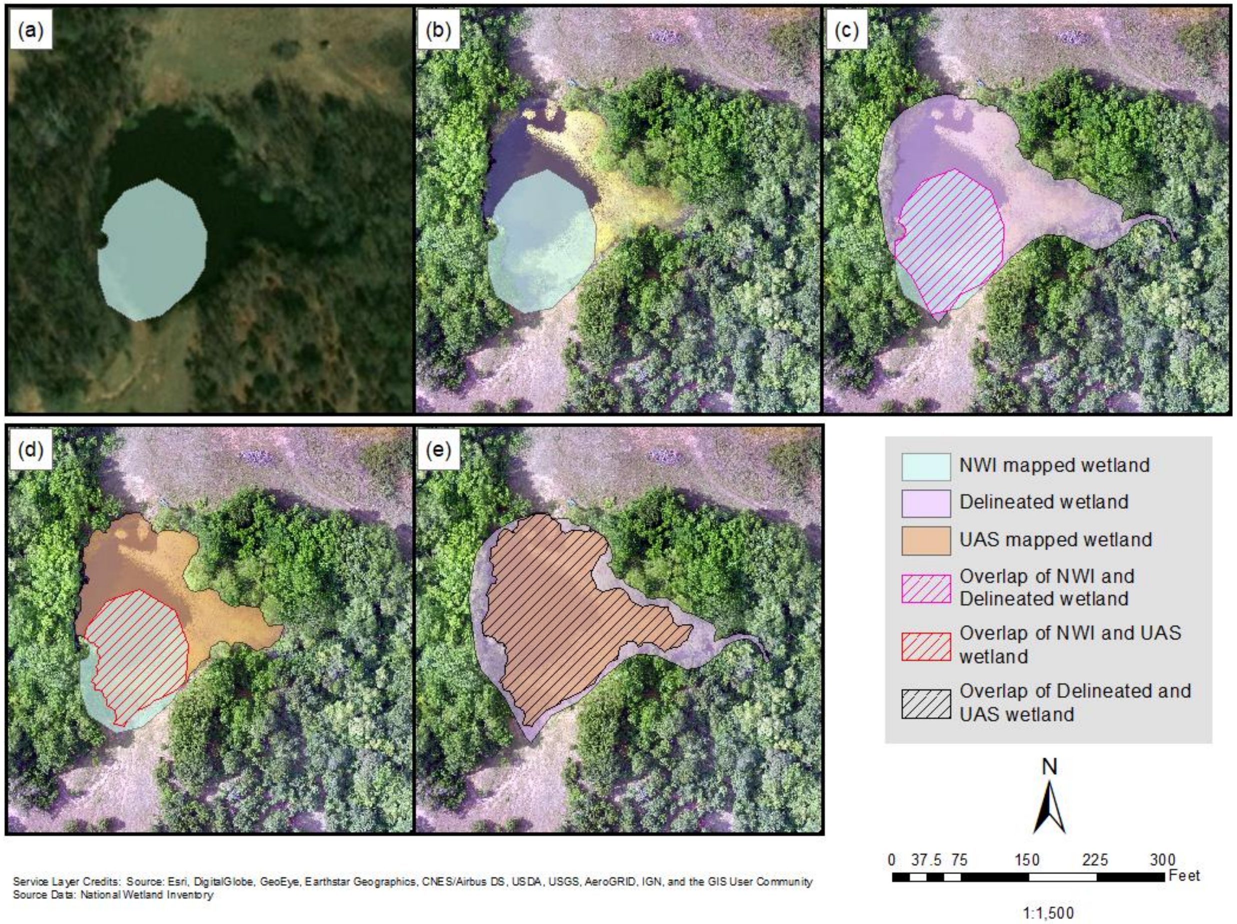


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 13. Case Study # 4 in Meeker, OK**:** (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.5 Case Study #5

Case Study #5 was flown on June 6, 2018 from 5:26 to 5:36 p.m. with a total flight time of 10 minutes and 10 seconds. Weather conditions were clear skies with winds of 5-12 miles per hour. Delineation of the wetland took place from 2:45 to 5:10 p.m. (i.e two hours and 25 minutes). The wetland was surrounded by Blackjack oak, eastern red cedar, and green briar. Wetland species that were present included Rufous bulrush, Shoreline sedge, and blue green algae. Figure 14a displays the Esri basemap, captured in April 2016, and the historic NWI mapped wetland (0.33 acres), captured in March 1981. There is a 35-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,500 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 14b the resolution is increased but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 14c shows the total delineated area (0.87 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 163% increase in wetland size. Figure 14d shows the wetland area determined by supervised classification via UAS imagery (0.62 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 87.9% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 37 years ago. Finally, Figure 14e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-nine percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 87.8% of the delineated area.

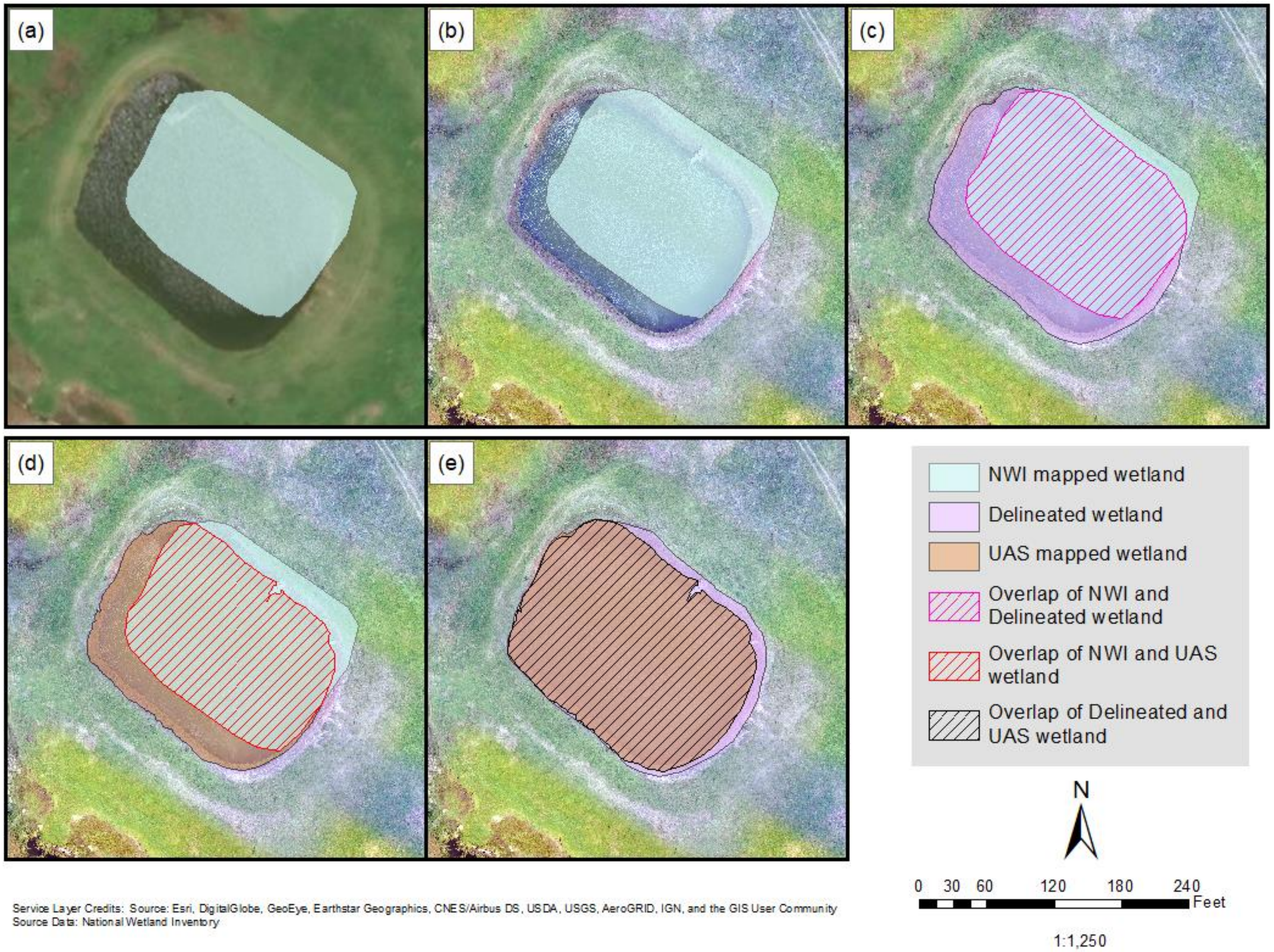


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 14. Case Study # 5 in Pawnee, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.6. Case Study #6

Case Study #6 was flown on June 21, 2018 from 11:30 to 11:42 p.m. with a total flight time of 12 minutes and 46 seconds. Weather conditions were overcast skies with winds of 5-12 miles per hour. Delineation of the wetland took place from 11 to 11:30 a.m. (i.e. 30 minutes). The wetland was surrounded by pasture land with little bluestem (*Schizachyrium scoparium*), Indian grass (*Sorghastrum nutans*), big bluestem (*Andropogon gerardii*), switchgrass (*Panicum virgatum*), sideoats grama (*Bouteloua curtipendula*), hairy grama (*Bouteloua hirsute*), and blue grama (*Bouteloua gracilis*) bermuda grass (*Cynodon dactylon*). Figure 15a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.63 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,250 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 15b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 15c shows the total delineated area (0.81 acres) and historic wetland overlap, with the delineation method indicating a 28.6% increase in wetland size. Figure 15d shows the wetland area determined by supervised classification via UAS imagery (0.73 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 15.9% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show an increase in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 15e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 90.1% of the delineated area

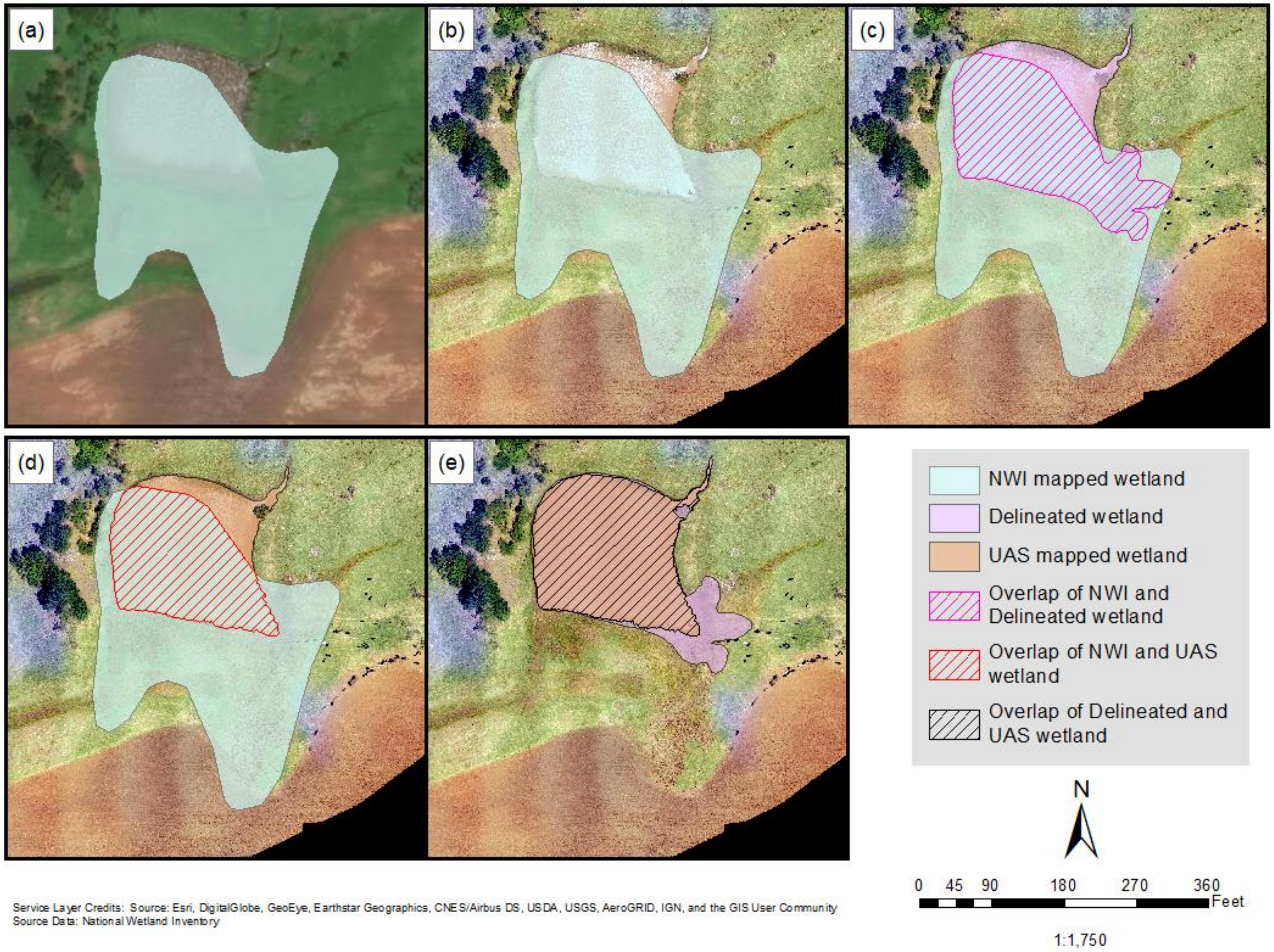


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 15. Case Study # 6 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; Figure (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.7 Case Study #7

Case Study #7 was flown on June 21, 2018 from 12:15 to 12:25 p.m. with a total flight time of 10 minutes and 13 seconds. Weather conditions were 20% cloud cover with winds of 8-15 miles per hour. Delineation of the wetland took place from 12:30 to 1:27 p.m. (i.e. 57 minutes). The wetland was surrounded by pasture land, with little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. No wetland species were identified. Figure 16a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (1.67 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,750 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 16b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 16c shows the total delineated area (0.87 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 47.9% decrease in wetland size. Figure 16d shows the wetland area determined by supervised classification via UAS imagery (0.72 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 56.9% decrease in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked decrease in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 16e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 82.8% of the delineated area.

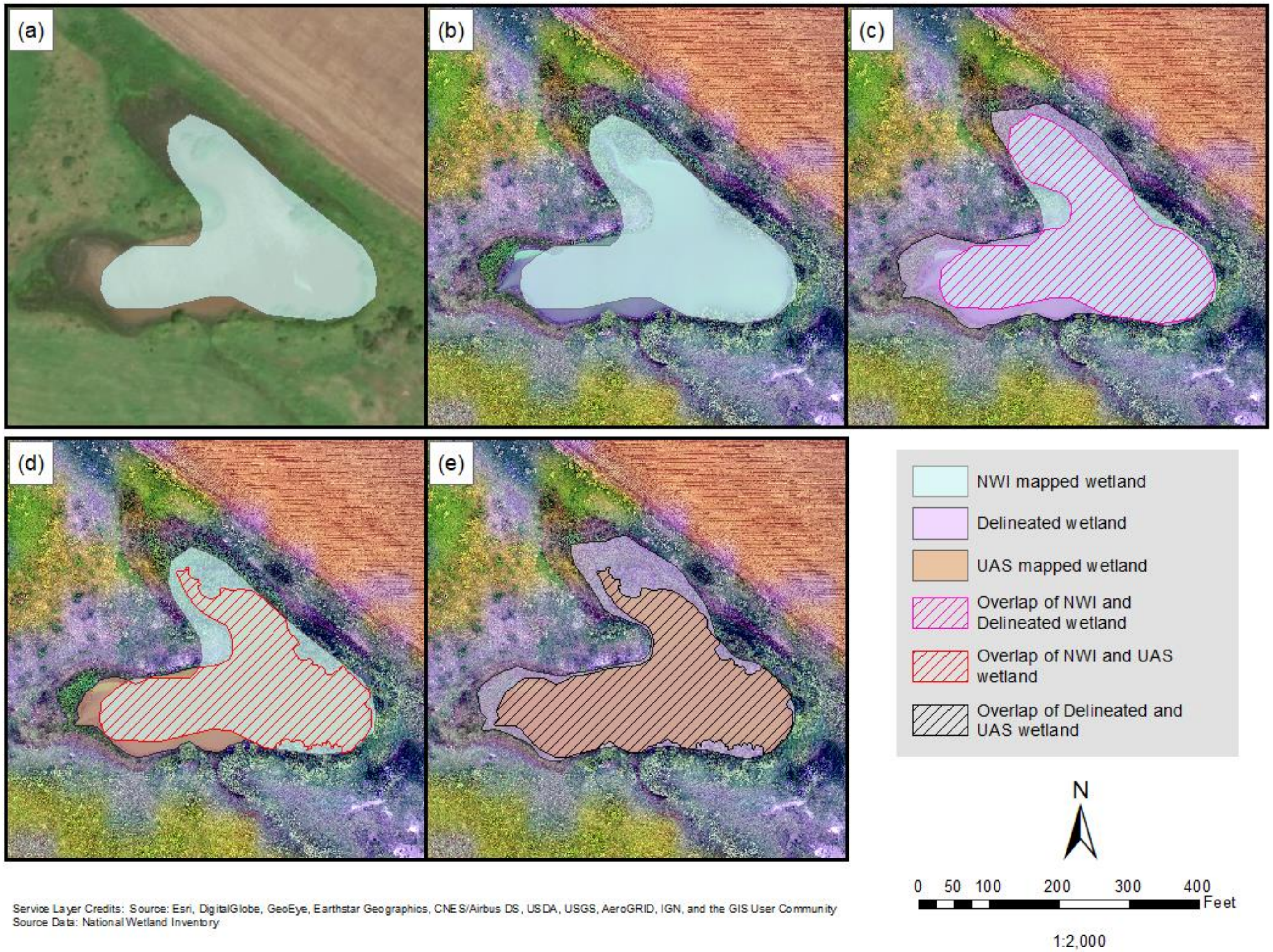


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 16. Case Study # 7 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.8 Case Study #8

Case Study #8 was flown on July 1, 2018 from 11:30 to 12:22 p.m. with a total flight time of 52 minutes; this flight also collected data for Case Studies #9 and #10. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 9:00 to 9:25 a.m. (i.e. 25 minutes). The wetland was surrounded by pasture land, with little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. No wetland species were identified. Figure 17a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (1.39 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:2,000 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 17b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 17c shows the total delineated area (1.68 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 20.9% increase in wetland size. Figure 17d shows the wetland area determined by supervised classification via UAS imagery (1.24 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 10.8% decrease in wetland size. The UAS collected data provides a more conservative estimate than a full delineation, with the delineation showing an increase in wetland size and UAS mapped area showing a decrease in size when compared to the historic data captured 35 years ago. Finally, Figure 17e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 80.6% of the delineated area.

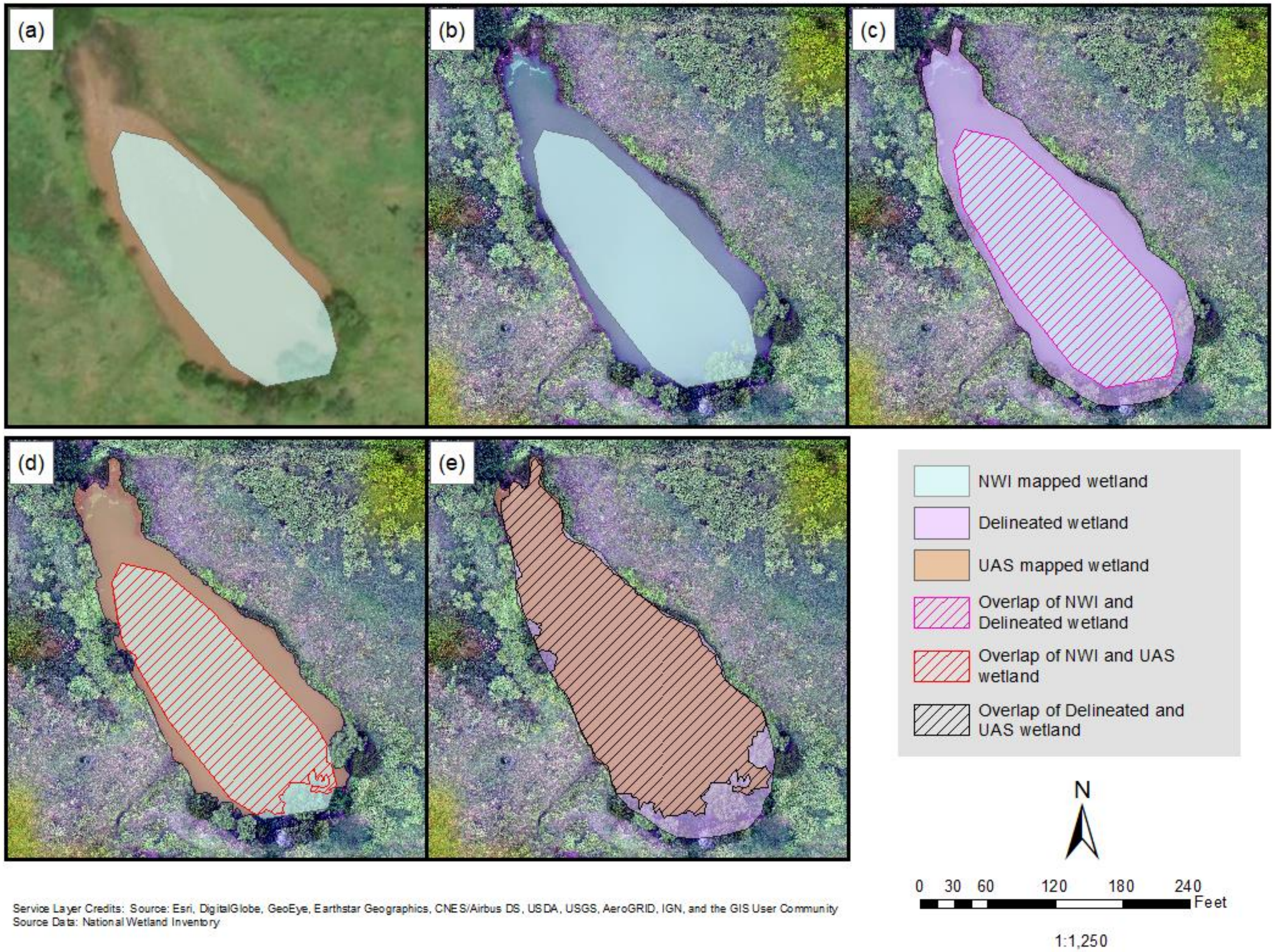


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 17. Case Study # 8 in Roosevelt, OK**:** (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.9 Case Study #9

Case Study #9 was flown on July 1, 2018 from 11:30 to 12:22 p.m. with a total flight time of 52 minutes; this flight also collected data for Case Studies #8 and #10. Weather conditions were overcast skies with winds of ≤ 10 miles per hour. Delineation of the wetland took place from 9:30 to 10:15 a.m. (i.e. 45 minutes). The wetland was surrounded by pasture land with species such as honey mesquite (*Prosopis glandulose*), little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. Wetland species included duckweed (*Lemnoideae sp.*). Figure 18a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.51 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,250 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 18b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 18c shows the total delineated area (0.86 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 68.6% increase in wetland size. Figure 18d shows the wetland area determined by supervised classification via UAS imagery (0.75 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 47.1% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 18e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-six percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 88.3% of the delineated area.

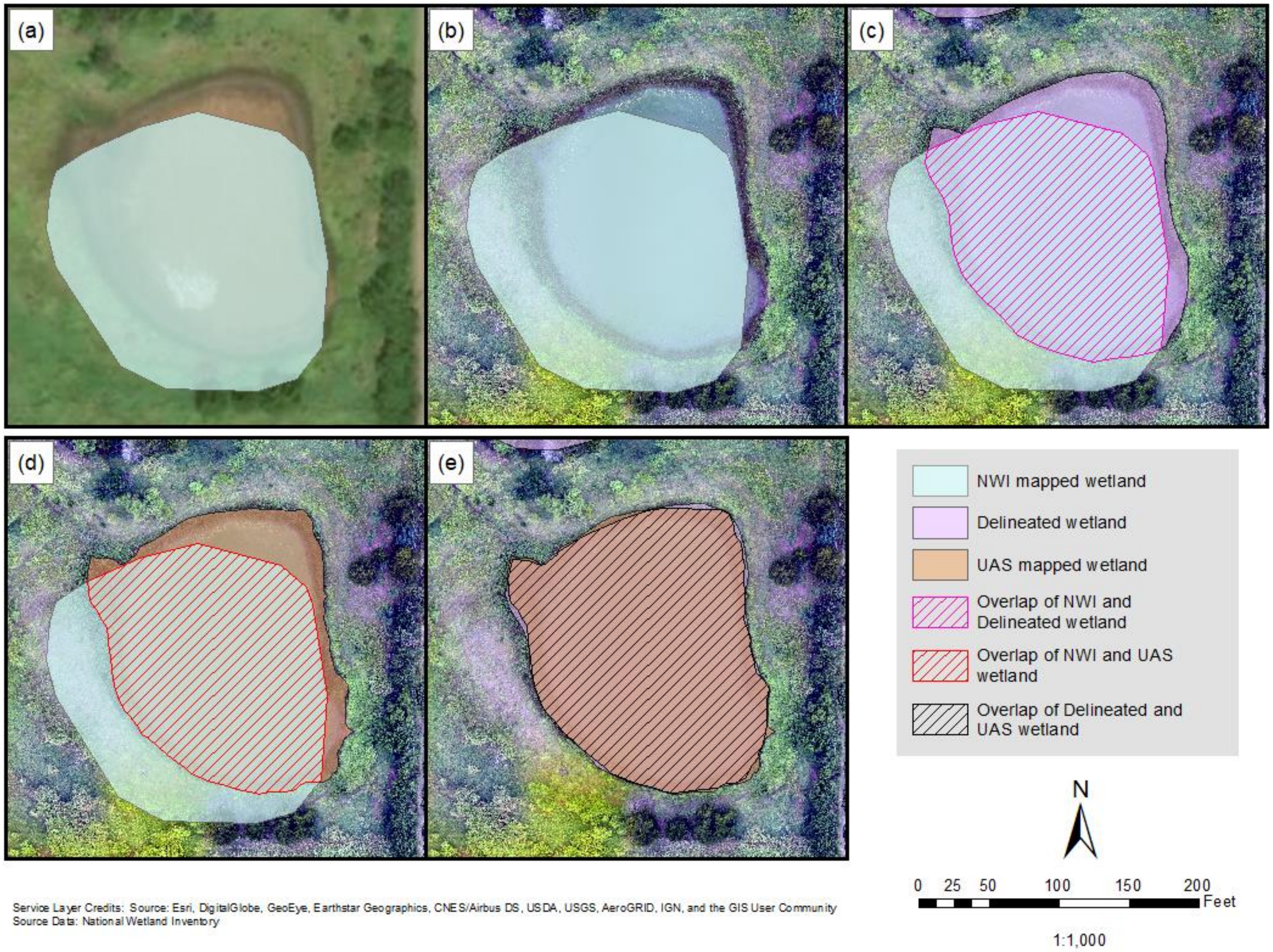


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 18. Case Study # 9 in Roosevelt, OK**:** (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.10 Case Study #10

Case Study #10 was flown on July 1, 2018 from 11:30 to 12:22 p.m. with a total flight time of 52 minutes; this flight also collected data for Case Studies #8 and #9. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 10:25 to 11:20 a.m. (i.e. 55 minutes). The wetland was surrounded by pasture land with species such as honey mesquite, little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. Wetland species included duckweed and blue green algae. Figure 19a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.73 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,000 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 19b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 19c shows the total delineated area (0.65 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 11% decrease in wetland size. Figure 19d shows the wetland area determined by supervised classification via UAS imagery (0.65 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 11% decrease in wetland size. While the UAS collected data provides the same estimation of area as a full delineation both shows a decrease in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 19e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 99.8% of the delineated area.

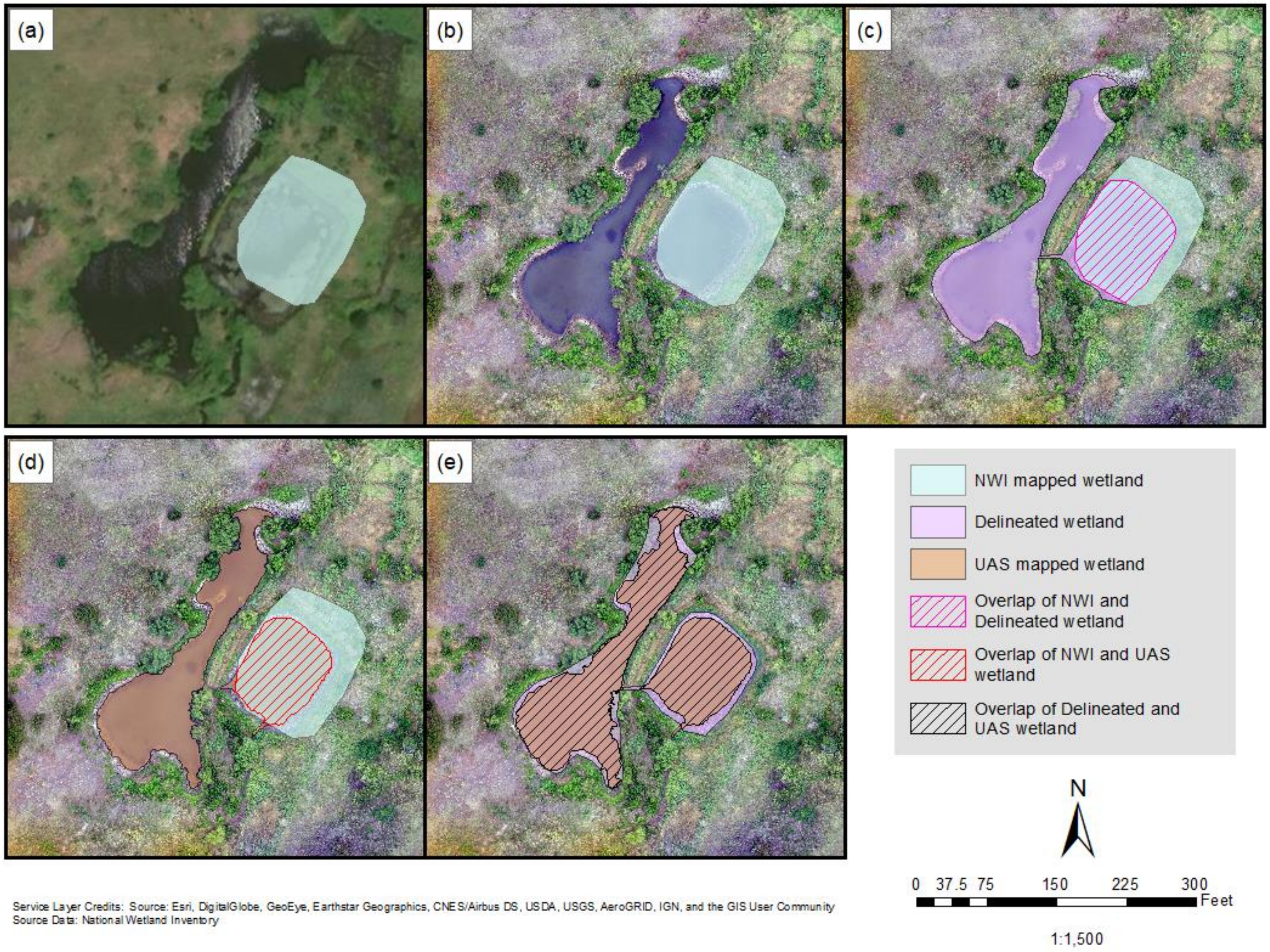


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 19. Case Study # 10 in Roosevelt, OK**:** (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results

4.2.11 Case Study #11

Case Study #11 was flown on July 1, 2018 from 12:45 to 1:48 p.m. with a total flight time of 1 hour and 3 minutes; this flight collected data for Case Studies #11 to #15. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 2:00 to 2:33 p.m. (i.e. 33 minutes). The wetland was surrounded by pasture land with species such as honey mesquite, little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. Wetland species included duckweed and blue green algae. Figure 20a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.35 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,500 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 20b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 20c shows the total delineated area (0.67 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 97.4% increase in wetland size. Figure 20d shows the wetland area determined by supervised classification via UAS imagery (0.54 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 54.3% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 20e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 80.6% of the delineated area.

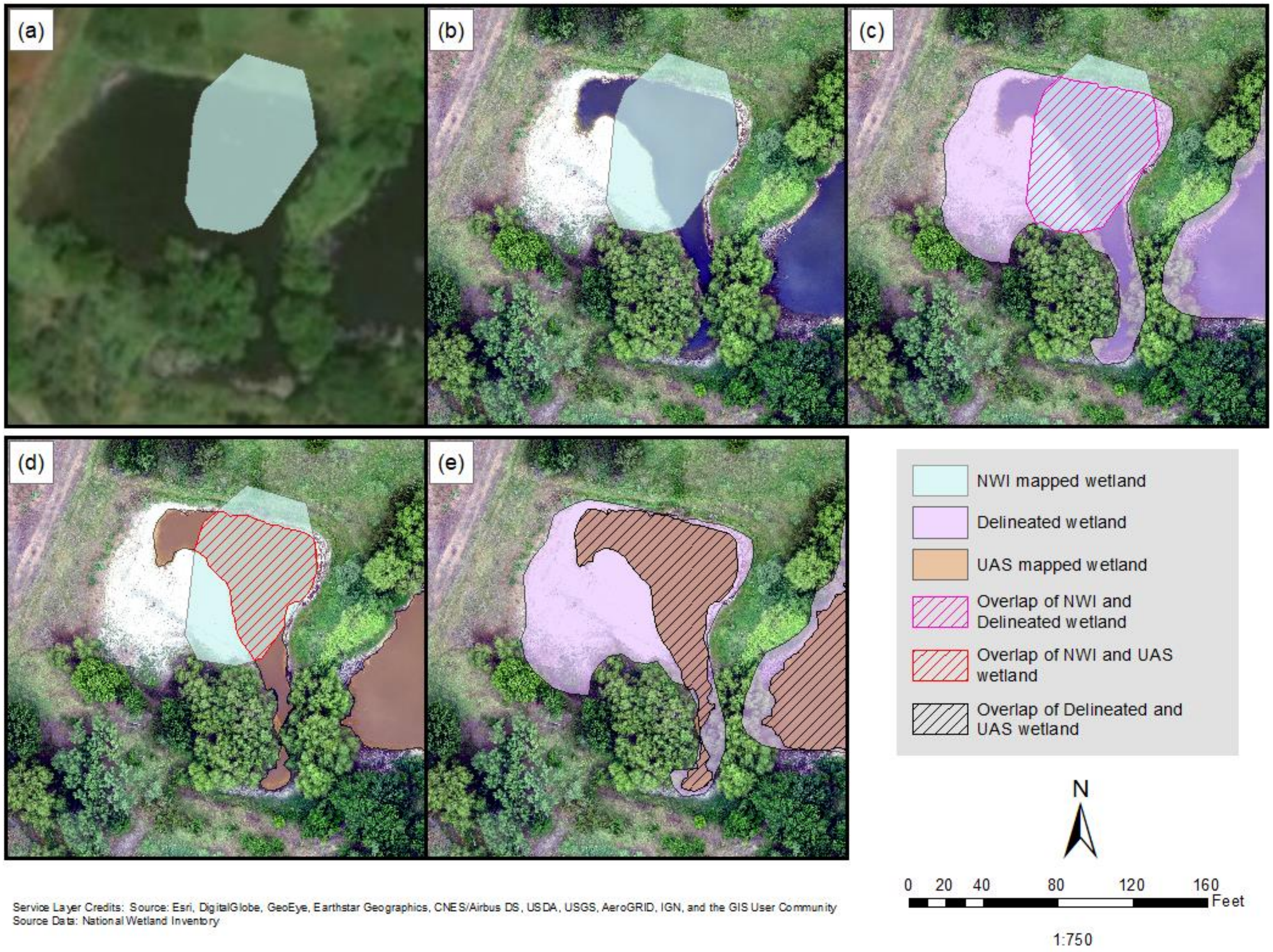


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 20. Case Study # 11 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d). UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results**.**

4.2.12. Case Study #12

Case Study #12 was flown on July 1, 2018 from 12:45 to 1:48 p.m. with a total flight time of 1 hour and 3 minutes; this flight collected data for Case Studies #11 to #15. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 2:35 to 3:00 p.m. (i.e. 25 minutes). The wetland was surrounded by pasture land with species such as honey mesquite, little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. Wetland species included duckweed and sago pondweed. Figure 21a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.12 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:750 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 21b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 21c shows the total delineated area (0.23 acres) and historic wetland overlap, with the delineation method indicating a 91.7% increase in wetland size. Figure 21d shows the wetland area determined by supervised classification via UAS imagery (0.10 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 16.7% decrease in wetland size. The UAS collected data provides a more conservative estimate than a full delineation, with the full delineation indicating an increase in wetland size and the UAS mapped wetland indicating a decrease in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 21e shows the overlap between the wetland delineation and the UAS mapped wetland. Ninety-five percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 43.5% of the delineated area.

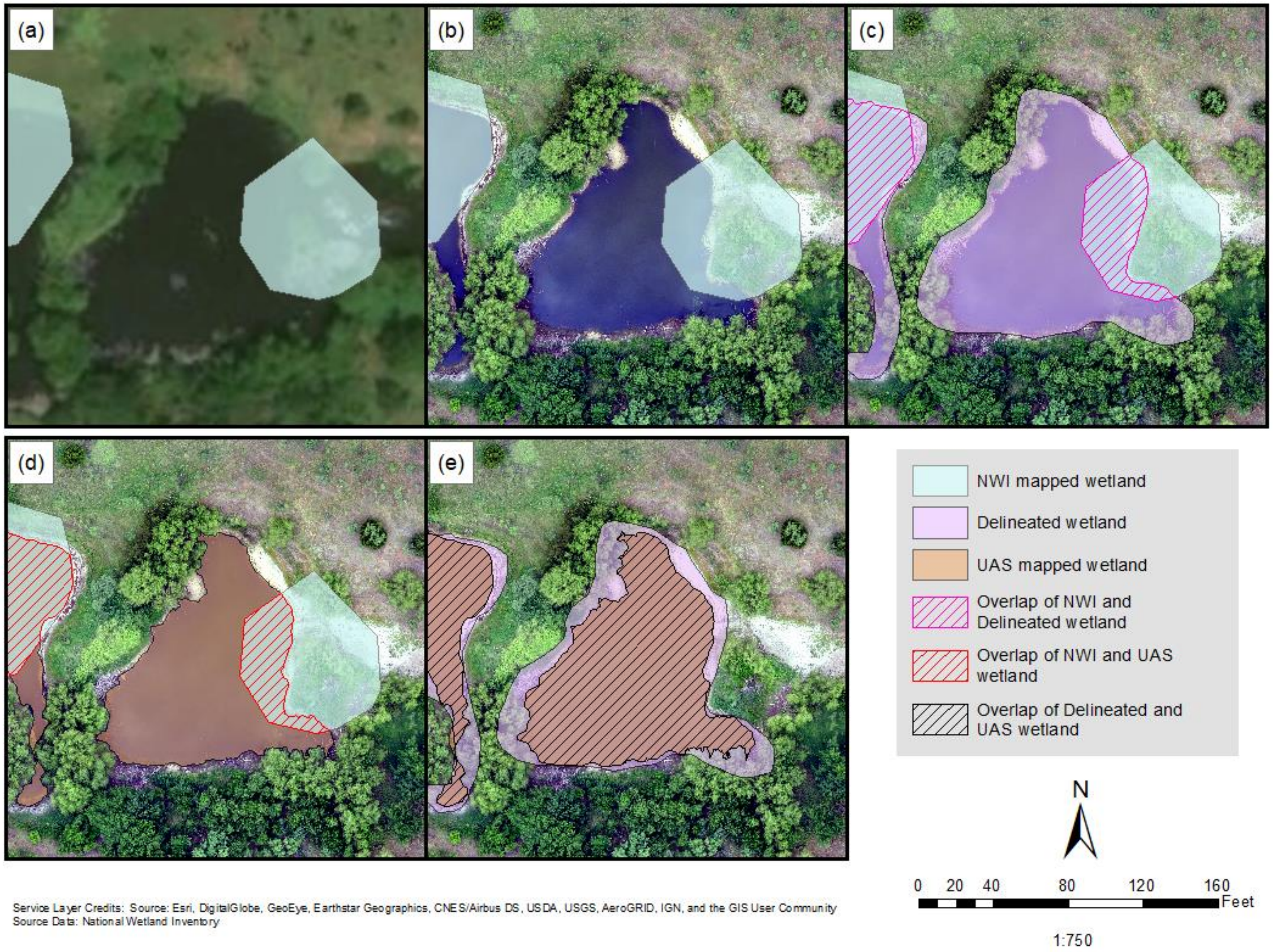


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 21. Case Study # 12 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.2.13. Case Study #13

Case Study #13 was flown on July 1, 2018 from 12:45 p.m. to 1:48 p.m. with a total flight time of 1 hour and 3 minutes; this flight collected data for Case Studies #11 to #15. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 3:10 to 3:52 p.m. (i.e. 42 minutes). The wetland was surrounded by pasture land with species such as honey mesquite, little bluestem, with Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. No wetland species were identified. Figure 22a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.11 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:750 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 22b the resolution is increased but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 22c shows the total delineated area (0.27 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates a 145.6% increase in wetland size. Figure 22d shows the wetland area determined by supervised classification via UAS imagery (0.20 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 81.8% increase in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 22e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 74.1% of the delineated area.

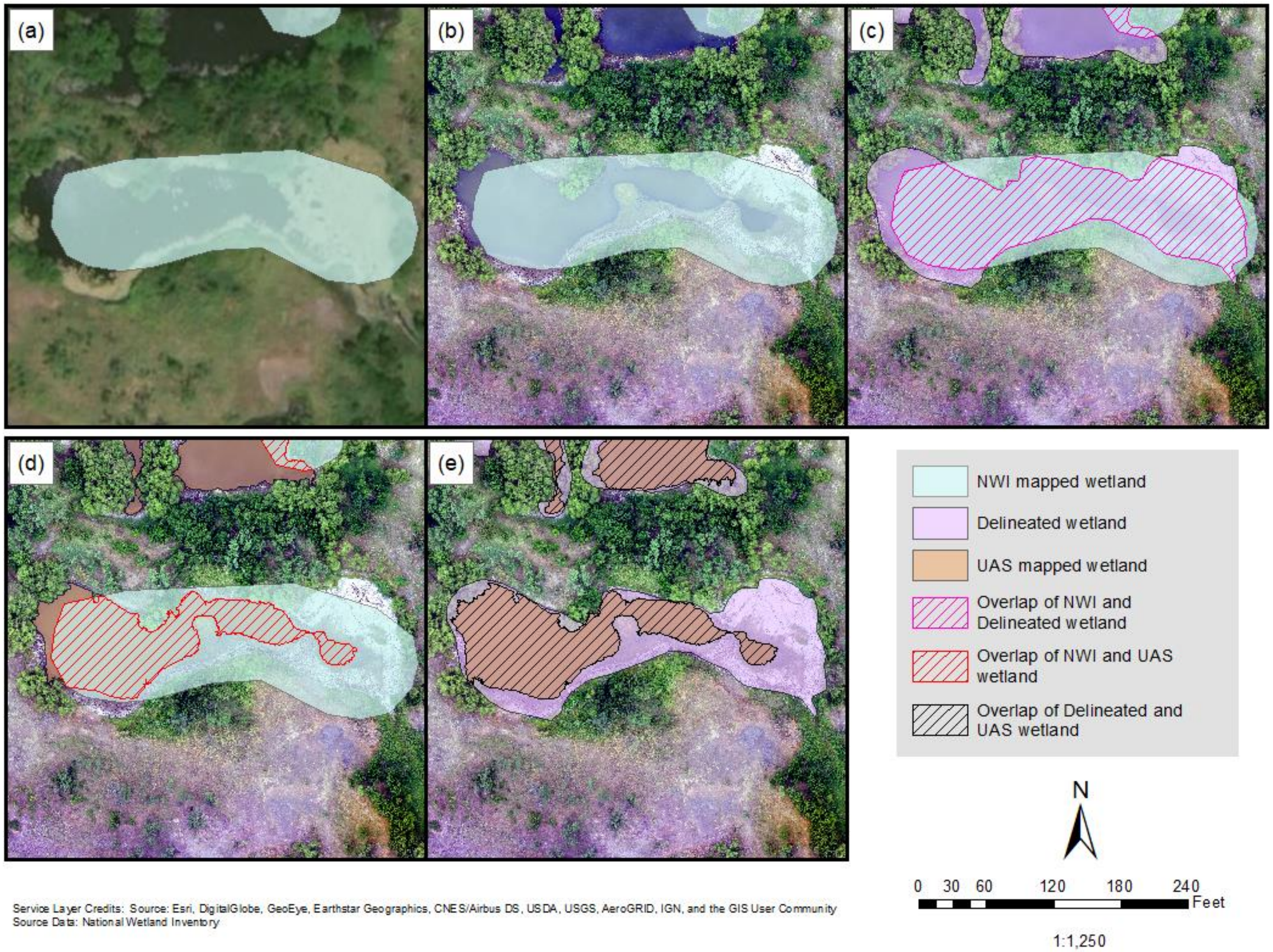


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 22. Case Study # 13 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results

4.2.14. Case Study #14

Case Study #14 was flown on July 1, 2018 from 12:45 to 1:48 p.m. with a total flight time of 1 hour and 3 minutes; this flight collected data for Case Studies #11 to #15. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 4:00 to 4:30 p.m. (i.e. 30 minutes). The wetland was surrounded by pasture land with species such as honey mesquite, little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. The only wetlands species was duckweed. Figure 23a displays the Esri basemap, captured in April 2016, and the historic NWI mapped wetland (0.67 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,250 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 23b the resolution is increased via UAS imagery but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 23c shows the total delineated area (0.59 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates an 88% decrease in wetland size. Figure 23d shows the wetland area determined by supervised classification via UAS imagery (0.29 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland versus the UAS, there is an 43.3% decrease in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked decrease in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 23e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 49.2% of the delineated area.

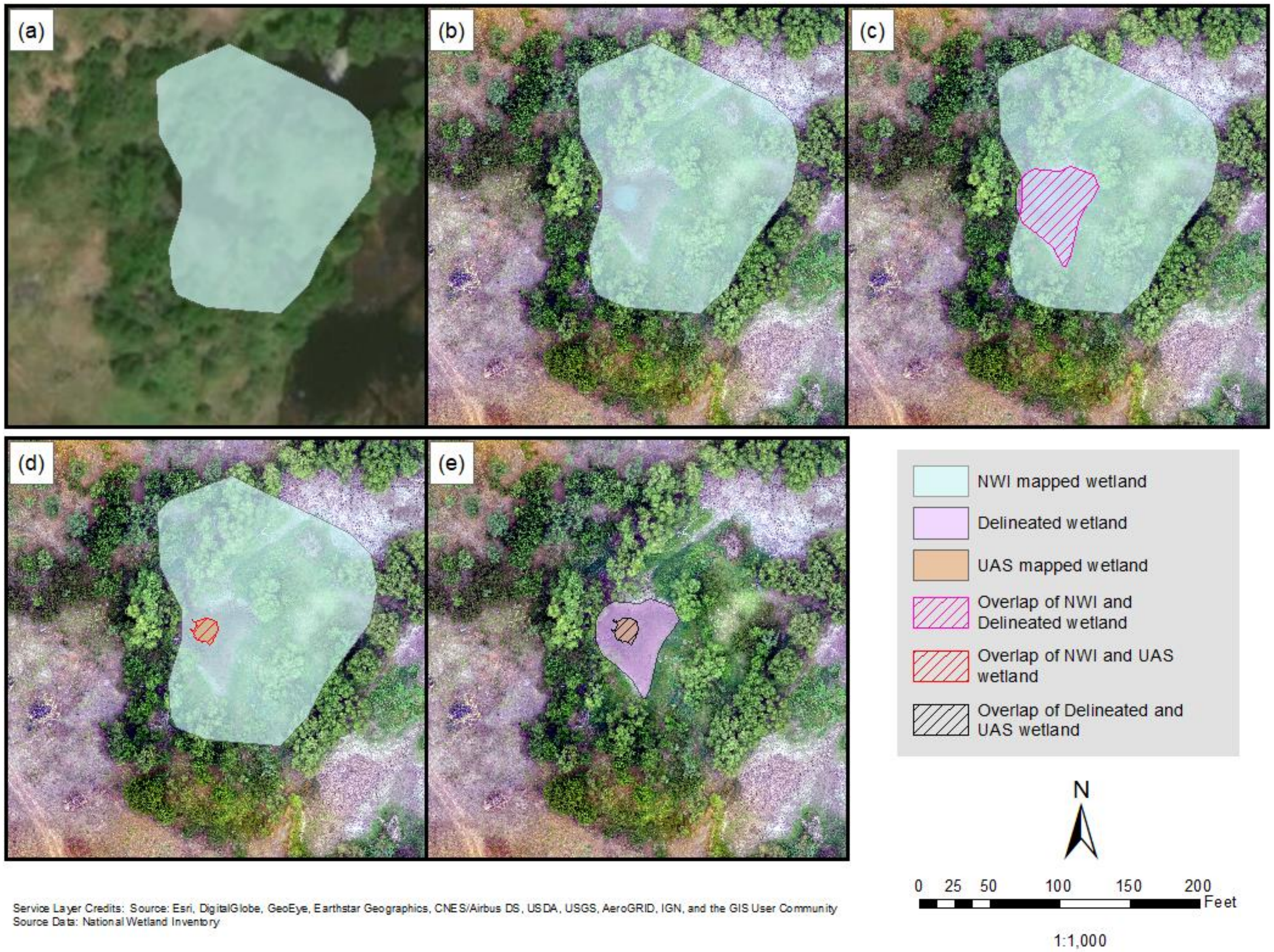


Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 23. Case Study # 14 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; (e) Overlap between Delineation and UAS mapped wetland results.

4.2.15. Case Study #15

Case Study #15 was flown on July 1, 2018 from 12:45 to 1:48 p.m. with a total flight time of 1 hour and 3 minutes; this flight collected data for Case Studies #11 to #15. Weather conditions were overcast skies with winds of ≤10 miles per hour. Delineation of the wetland took place from 4:35 to 4:58 p.m. (i.e. 23 minutes). The wetland was surrounded by pasture land with species such as honey mesquite, little bluestem, Indian grass, big bluestem, switchgrass, sideoats grama, and bermuda grass. Wetland species included duckweed and blue green algae. Figure 24a displays the Esri basemap, captured in July 2016, and the historic NWI mapped wetland (0.5 acres), captured in March 1983. There is a 33-year time lapse between these two data sets. Even with the coarse imagery provided at the 1:1,000 scale, the NWI mapped area does not represent the 2016 extent of the wetland. In Figure 24b the resolution is increased but the discrepancy between the NWI data and visual estimation of the wetland location is still present. Figure 24c shows the total delineated area (0.06 acres) and historic wetland overlap. When comparing overall acreage of historic wetland versus the delineated area, the delineation method indicates an 88% decrease in wetland size. Figure 24d shows the wetland area determined by supervised classification via UAS imagery (0.01 acres) and historic wetland overlap. When comparing overall acreage of the UAS versus the historic wetland, there is an 98% decrease in wetland size. While the UAS collected data provides a more conservative estimate than a full delineation both show a marked increase in wetland size when compared to the historic data captured 35 years ago. Finally, Figure 24e shows the overlap between the wetland delineation and the UAS mapped wetland. One hundred percent of the UAS mapped wetland area is found within the delineated area, while the UAS mapped area covers approximately 16.7% of the delineated area.



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 24. Case Study # 15 in Roosevelt, OK: (a) Esri base map with NWI mapped wetland; (b) UAS imagery with NWI mapped wetland; (c) Wetland Delineation results, NWI mapped wetland and overlap between the two; (d) UAS mapped wetland results, NWI mapped wetland and overlap between the two; and (e) Overlap between Delineation and UAS mapped wetland results.

4.3 Cost-Benefit Analysis

The time required completing the processes for working with the wetland delineation and the UAS were tallied separately and broken down into three categories, acquisition, processing, and analysis. Table 10 shows the total time required for each category using the GPS receiver and the UAS system in this study. The final tally shows a significant savings can be achieved using the UAS. Mobilization time was not taken into account as travel would have been the same for both data collection efforts. It is important to note that multiple wetlands were flown within a single mission and only one wetland at a time could be assessed with traditional delineation methods. Processing with Pix4D took place at night with limited input from the user after the template was created and images uploaded, subsequently only the time used to upload the imagery was considered for this comparison. The average salary of an entry level biologist with a multiplier of three was used to estimate the costs. There was a considerable cost and time savings when considering UAS against traditional methods. This cost analysis only considers the amount of labor for a technician to perform the work and does not consider mileage during travel nor equipment such as a soil auger, a Trimble GPS unit, vegetation field guides, rental rates from consultants for UAS use, or software costs. The costs that were omitted typically vary between consultants and/or project.

Table 10. Time required to acquire, process and analyze data collected for delineation and UAS.

	Delineation	**UAS**	**Cost of Delineation**	**Cost of UAS**
Acquisition	16 hr 30 min	3 hr 40 min	$1,023	$248
Processing	5 hr	2 hr upload/ 10 hr for Pix4D output	$310	$124
Analysis	6 hr	7 hr	$372	$434
Total	27 hr 30 min	20 hr 40 min	$1,705	$806

Chapter 5: Discussion and Conclusions

This chapter discusses the broader significance and ramifications of the results of this thesis and offers some conclusions about the use of UAS versus traditional delineation methods.

5.1 Findings

The methodology utilized in this study provided three significant findings: (1) wetland determination is inherently flawed, utilizing data that was captured over 3 decades ago; (2) new UAS methods offer ease of data acquisition in comparison to traditional methods; and (3) substantial cost savings when compared to full delineation.

When one compares all of the maps from the case studies it can noted that the level of resolution is a hindrance to the user when attempting to determine the location and extent of wetlands or isolated ponds on the landscape using Esri basemaps. The lack of resolution, control of flight conditions during image capture and the time gaps between Esri basemap capture and project dates prevents consultants from having high confidence about the true condition of the wetland. The NWI data was found to be 35-37 years old at the time of this thesis. Within each of the 15 case studies that were provided not one NWI mapped wetland matched the delineated wetland in size or placement. As seen with the confusion matrix results, the largest discrepancies were found where dried soils were exposed that would have been inundated in wetter conditions. Applying the buffer to the UAS mapped wetlands did not appear to drastically increase the overlap or the percent accuracy. While some wetlands, such as Case Study #6, had similar shape to current conditions the placement of the wetland was to the northwest while other wetlands such as Case Study #11 are drastically different when considering the true extent of the wetland. It was typically found that there was overlap with the delineated wetland and the NWI so if a true delineation is required researchers would be able to know the approximate location of the wetland if it still existed.

5.2 Advantages and Disadvantages of Using the UAS Methodology

The inexpensive UAS used to collect data for this study performed very well over water bodies which have been noted to interfere with GPS signals (Matolak 2015). The UAS platform is extremely user friendly and complete the data capture in a short period of time. It is also very easy to mobilize in a safe location and observe the mission without leaving the area around the vehicle. This limits the safety hazards that would be encountered during a traditional wetland assessment. These hazards include but are not limited to dead or dying trees, entanglement in thorny vegetation, potential biting insects that could carry disease (i.e. West Nile virus, Lyme disease, rocky mountain spotted fever, etc.) and possible drowning.

The UAS estimation of wetland area was always a more conservative measurement than what was found in a traditional wetland delineation. While the comparison of a delineation and the UAS method is a comparison of two very different types of assessments, by assessing both we were able to determine the accuracy of the UAS method, a comparison with the NWI would have entailed comparing two datasets of unknown accuracy and error. The delineation method is the most accurate assessment but is still subject to human error. The UAS method allowed for a conservative method to increase placement accuracy on the landscape over the NWI method. The average overlap between the delineation and UAS methods for wetlands located in Meeker, Pawnee, and Roosevelt OK was 86.4, 87.8, and 70.6%, respectively. If Case # 15 is considered an outlier, as there was a substantially large area that was dry pond bed, which brought the overlap down to 16.7%, this would bring the Roosevelt site up to 76.6% overlap. While wetland delineations are considered to be the highest quality determination method they are still subject to human error and dependent on seasonal and/or yearly variability. The UAS on average was typically found completely within the delineated area and the average overlap was 76.5% with all sites and 80% excluding the outlier with the complete delineated area.

An unexpected development of flying missions within the growing season was the presence of algae and pondweed floating near the edges and/or in the wetlands. The supervised classification method was not able to determine the differences between the algae and the surrounding grasslands. The supervised classification method was also not able to determine the wetland extent underneath full canopy cover nor in areas that were desiccated from the original boundary. The limitations of canopy cover/algae can be seen in Case Study #2 and the issues with desiccated areas can be seen in Case Studies #12 and #15. To correct vegetation issues it might be best to complete UAS missions during the leaf-off seasons. The following sections explore corrections that could allow for flights to occur during the growing or leaf-off seasons.

5.2.1 Supplemental buffers

As seen in all case studies, the placement of the wetland was improved by the UAS method even though this method was found to be more conservative than the full delineation. The reason for these conservative estimates was attributed to dense canopy cover and floating vegetation and to see if this could be corrected, 5, 10, 15, 20, 25, 30 and 35 ft buffers were placed around the wetlands to determine if there was an optimal distance to use to encompass the entire delineated area. By applying up to a 35 ft buffer on all sites 95% of the wetlands within this study had full coverage. Table 11 shows the overlap percentage achieved with each buffer. It can be seen that the 15 ft buffer encompasses most of the case studies with ≥ 90% overlap. However, not all wetlands were completely encompassed even when using the 35ft buffer. Because the UAS method was only assessing the open water areas of the wetland and the vegetation was not incorporated in the supervised classification method applying a buffer allowed for the surrounding plant life to be incorporated.

5.2.2 Seasonality

The season in which UAS missions occur could also increase the accuracy of the UAS method. As seen in Table 3, only Case Study #5 was flown in a season that would be considered leaf-off or non-growing (January 15, 2018). Figure 27 illustrates the difference between winter and summer UAS flights and the overlap of the delineated area found in each season. The Delineated Area of Case Study #5 was 0.87 acres, and the summer UAS mapped wetland calculated that the total area of the wetland was 0.62 acres, with an overlap of 71.3%. In contrast the winter flight allows the UAS to see through the tree canopy and determine the shoreline with greater accuracy than was achieved in the summer months. The winter UAS mapped wetland calculated the total area of the wetland to be 0.85 acres with an overlap of 97.7%. This improved the overlap of the Delineated and UAS mapped wetlands by 26.4%. While this is only one wetland, this could provide a key area of exploration for UAS wetland assessment in the future. If winter months are to be considered for flights, it is suggested that they be performed in times when the wetlands are not iced over as the classification of the wetlands could change due to inclement conditions prior to or during the flights.

Table 11. Percent overlap achieved using at 5, 10, 15, 20, 25, 30, and 35 ft buffers generated around the 15 UAS mapped wetlands

Case Study	Area (ac)	5ft (ac)	% overlap	10ft (ac)	% overlap	15ft (ac)	% overlap	20ft (ac)	% overlap	25ft (ac)	% overlap	30ft (ac)	% overlap	35ft (ac)	% overlap
#1	1.47	1.39	94.56	1.43	97.28	1.46	99.32	1.47	99.93	1.47	99.96	1.47	99.96	1.47	99.96
#2	0.67	0.62	92.54	0.66	98.51	0.67	99.40	0.67	99.55	0.67	99.58	0.67	99.58	0.67	99.58
#3	0.35	0.35	100.00	0.35	100.00	0.35	100.00	0.35	100.00	0.35	100.00	0.35	100.00	0.35	100.00
#4	2.34	2.03	86.63	2.18	93.08	2.27	96.84	2.31	98.69	2.33	99.53	2.34	99.88	2.34	100.07
#5	0.87	0.71	82.05	0.78	89.73	0.81	93.68	0.84	95.98	0.85	97.23	0.85	97.92	0.86	98.38
#6	0.81	0.78	96.40	0.81	99.59	0.81	99.71	0.81	99.71	0.81	99.71	0.81	99.71	0.81	99.71
#7	0.87	0.75	86.44	0.77	88.27	0.78	89.91	0.80	91.59	0.81	93.29	0.83	95.03	0.84	96.64
#8	1.68	1.37	81.83	1.46	86.84	1.51	90.14	1.55	92.41	1.58	94.26	1.61	95.82	1.63	97.14
#9	0.86	0.80	93.30	0.83	96.17	0.84	98.00	0.85	99.29	0.86	99.99	0.86	100.32	0.86	100.40
#10	0.65	0.65	100.33	0.65	100.33	0.65	100.33	0.65	100.33	0.65	100.33	0.65	100.33	0.65	100.33
#11	0.67	0.64	95.43	0.66	99.01	0.67	99.34	0.67	99.34	0.67	99.34	0.67	99.34	0.67	99.34
#12	0.23	0.13	58.68	0.15	67.34	0.17	73.29	0.18	78.20	0.19	82.52	0.20	86.30	0.21	89.47
#13	0.27	0.24	90.30	0.27	98.90	0.27	100.27	0.27	100.27	0.27	100.27	0.27	100.27	0.27	100.27
#14	0.59	0.37	62.77	0.43	72.09	0.46	78.66	0.49	83.46	0.51	86.52	0.53	89.27	0.54	92.05
#15	0.06	0.01	24.72	0.03	45.54	0.04	64.44	0.05	78.68	0.05	87.33	0.06	92.09	0.06	93.92

Some USACE districts require that delineation take place during the growing season, so if a comparison was to be made to meet both this USACE requirement and the preference for leaf-off time periods early spring might be the better option. Lovvorn and Kirkpatrick (1982) found that aerial photographs have potential for the accurate identification of all dominant species and that early September is an optimal time for species identification due to the variation in fall colors among species. However, Tiner (1990) determined that CIR aerial photography in early spring is best for detecting deciduous forested wetlands in temperate regions. Due to this conflicting advice in the literature, research will be required for different regions to determine the optimal seasons for image capture. Buffer distances do not take into account the topography of the land surface and this leads to misperceptions in and near depressions. This causes non-uniform growth of wetlands in certain directions that cannot be handled by buffering alone. Figure 25 shows the success of this method with Case Study # 11 which had little canopy cover and therefore needed a limited buffer. Figure 26 shows Case Study # 7 which has an oddly shaped wetland and the full delineated area was not covered.

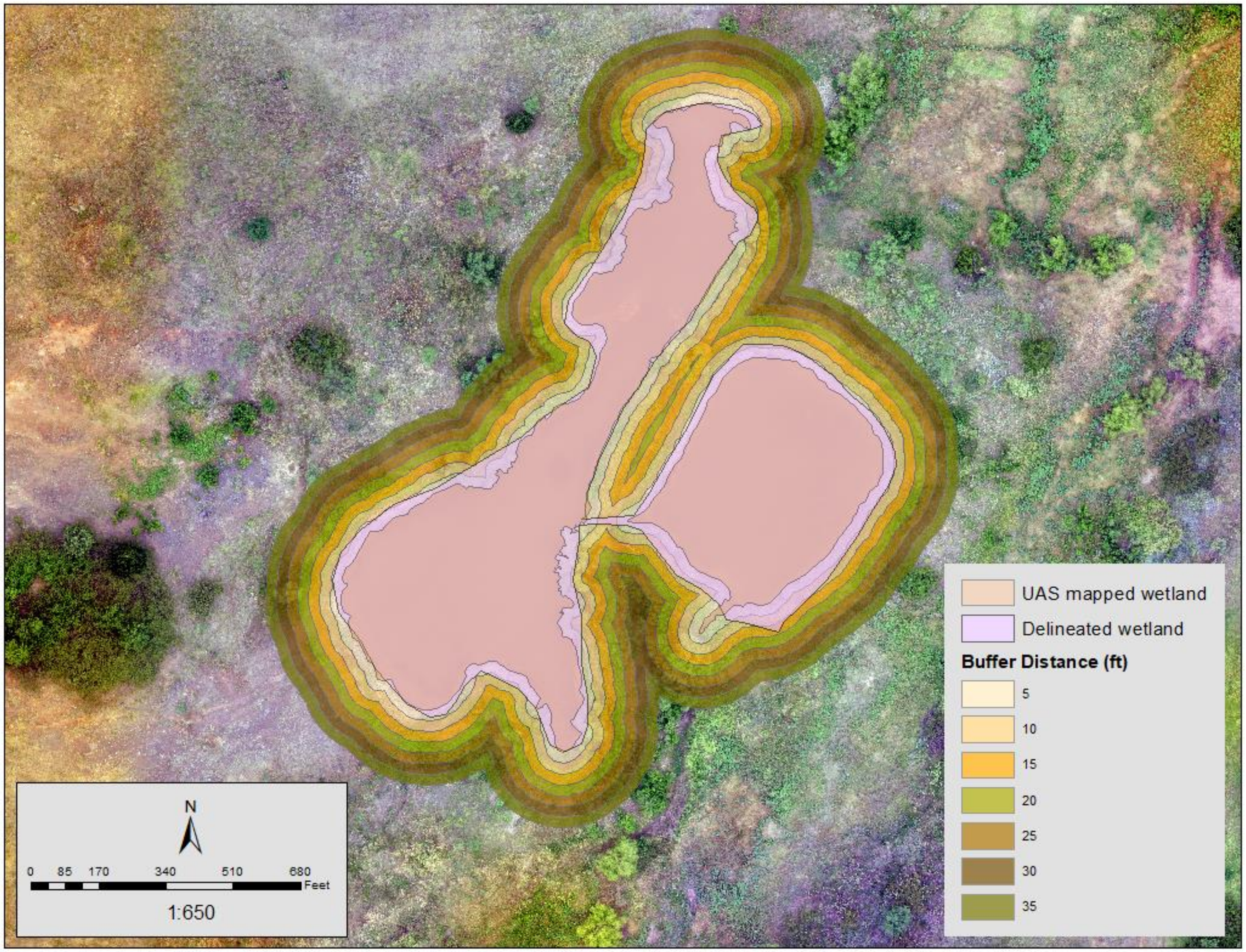


Figure 25. A map of Case Study #11 showing how the application of a buffer around the UAS mapped wetlands allowed for the delineated wetland to be fully encompassed within a 15 ft buffer.

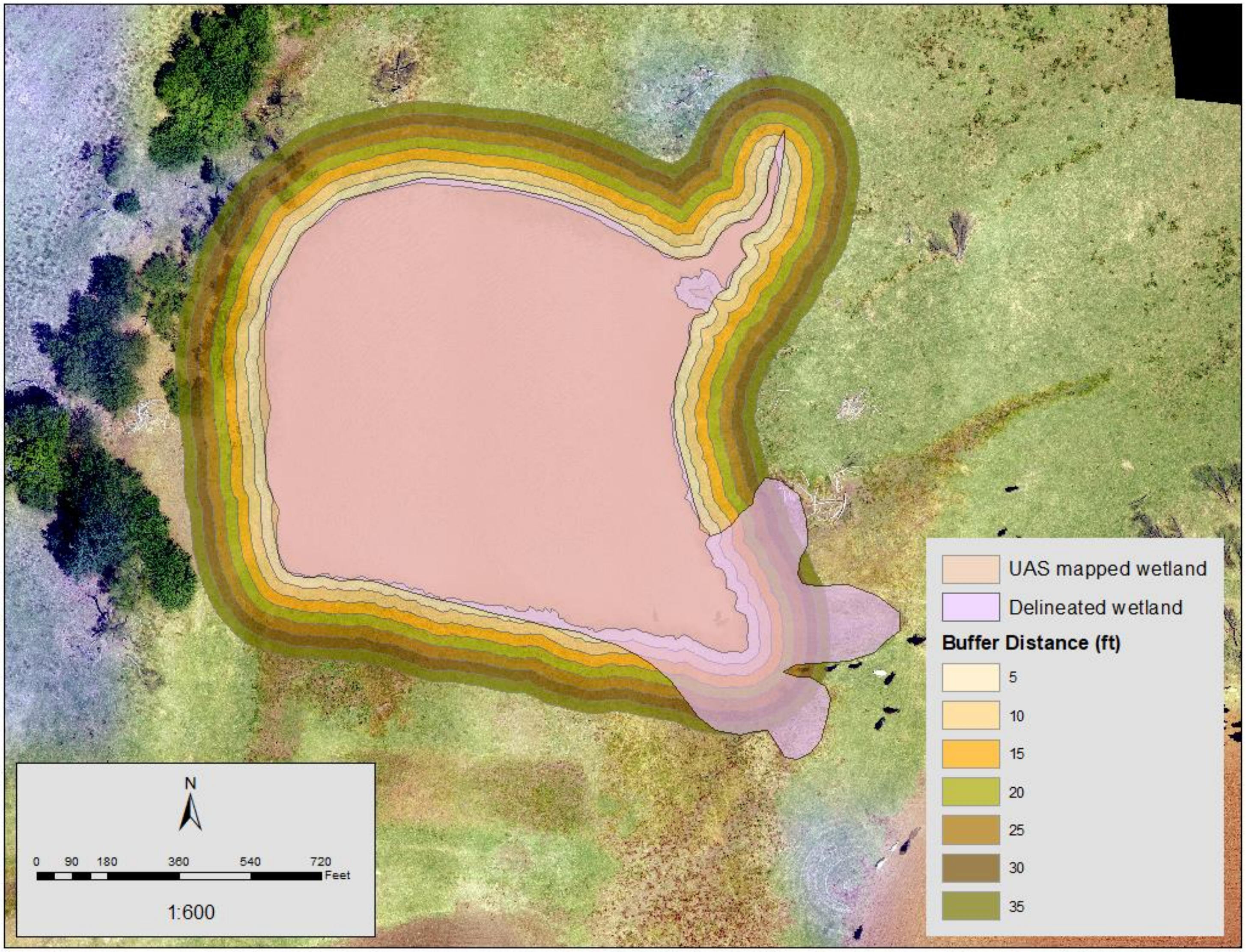
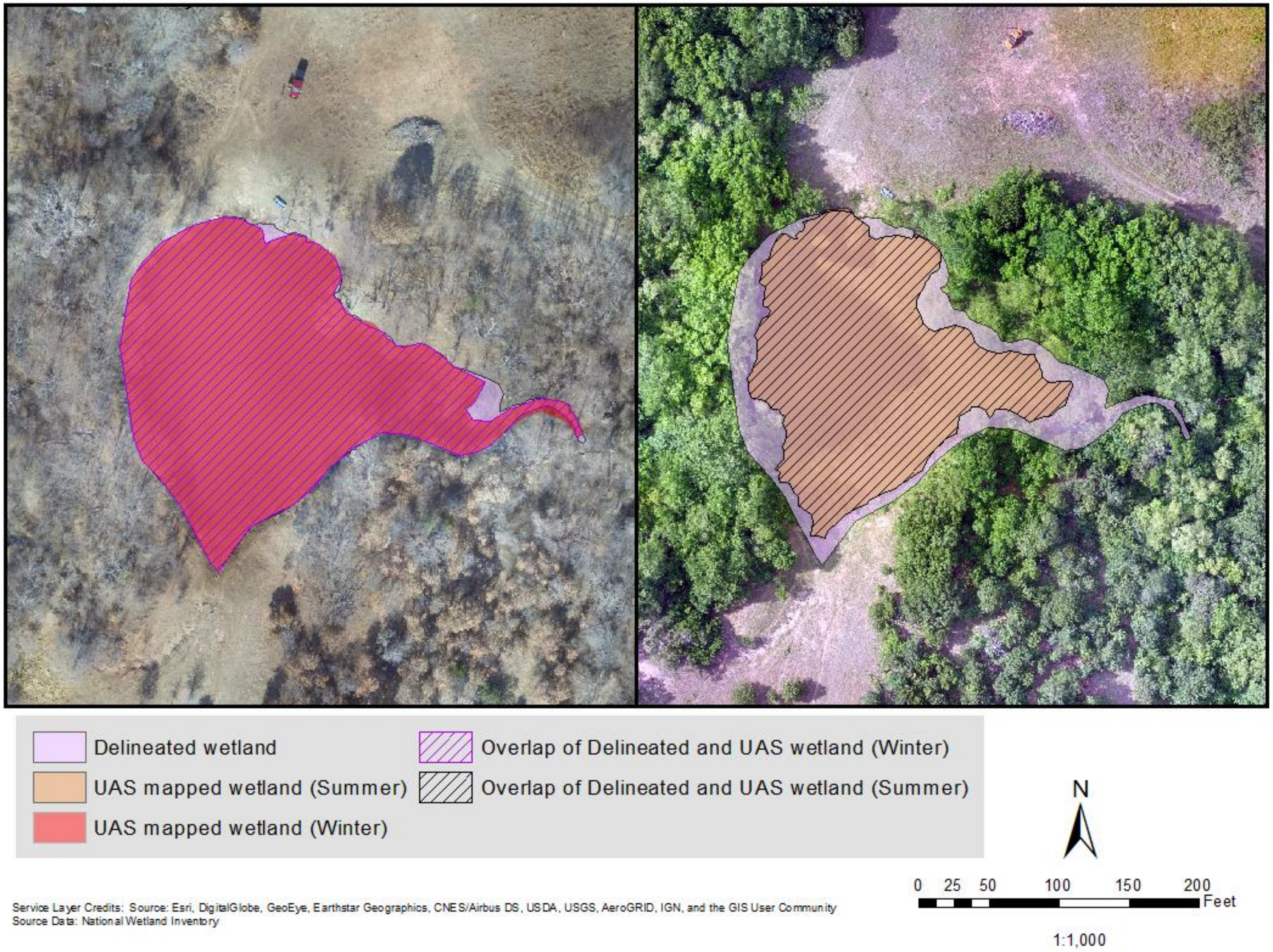


Figure 26. A map of Case Study #7 show how the application of a buffer around the UAS mapped wetlands which does not consider the topography with a 35 ft buffer**.**



Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community
Source Data: National Wetland Inventory

Figure 27. Differences in overlap between winter and summer UAS flight times and the delineated wetland for Case Study #5**.**

5.2.3 Other potential methods

Other methods that have potential for assessment of wetlands include the digital surface models that are provided in programs such as Pix4D. UASs are distinctive in this regard because satellite images do not provide these types of returns, and LiDAR technology, while accurate, is typically not cost effective for many projects. To collect DSMs, missions are typically flown in a 3D mapping grid in order to get a better understanding of the landscape. This would be best performed on areas that do not have high percentages of canopy cover. A digital surface model has elevations that are represented with the first reflected surface detected by the sensor. These first returns may be reflected by bare ground or by surface features such as trees and structures.

Figures 28 and 29 show an example of how digital surface models could be used to predict and visualize the directional growth in wetlands. Within these maps one can see the current extent of the wetland and the potential for directional growth to the north and east. Information like this provides a more accurate assessment of the site than additional buffers or different seasons.

Other potential areas of exploration would be the investigation of thermal imagery. Water tends to have a cooling effect on surrounding substrates, one could hypothesize that if flying with a thermal camera, areas that are completely saturated or in close proximity to those areas would be cooler than areas without water. However, these missions would have varying results due to the time of year and vegetation cover, similar to other methods.

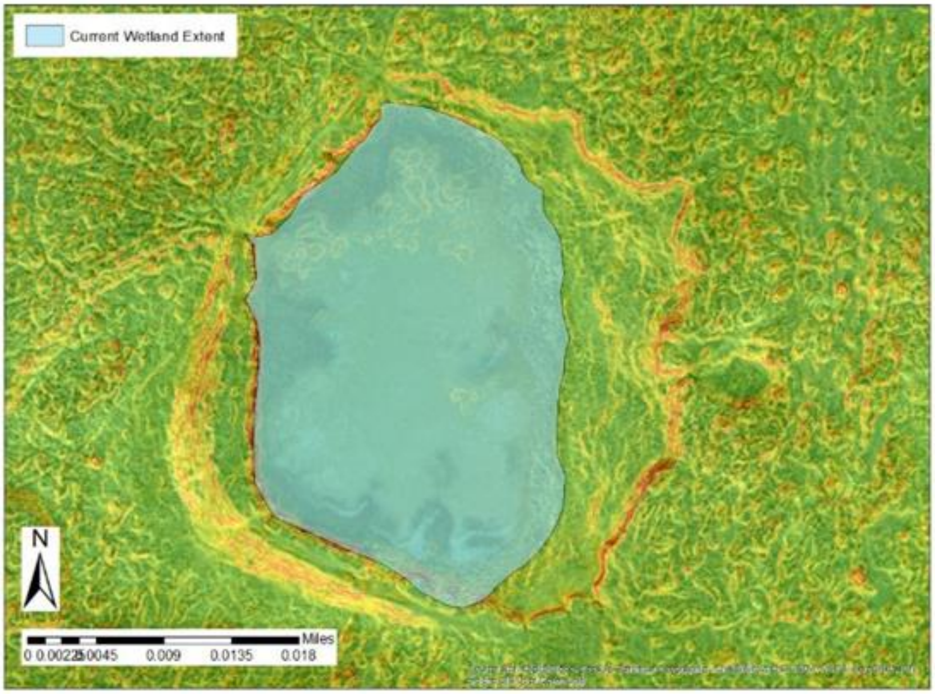


Figure 28. Slope estimate from Digital Surface Model provided in Pix4D with current wetland extent**.**

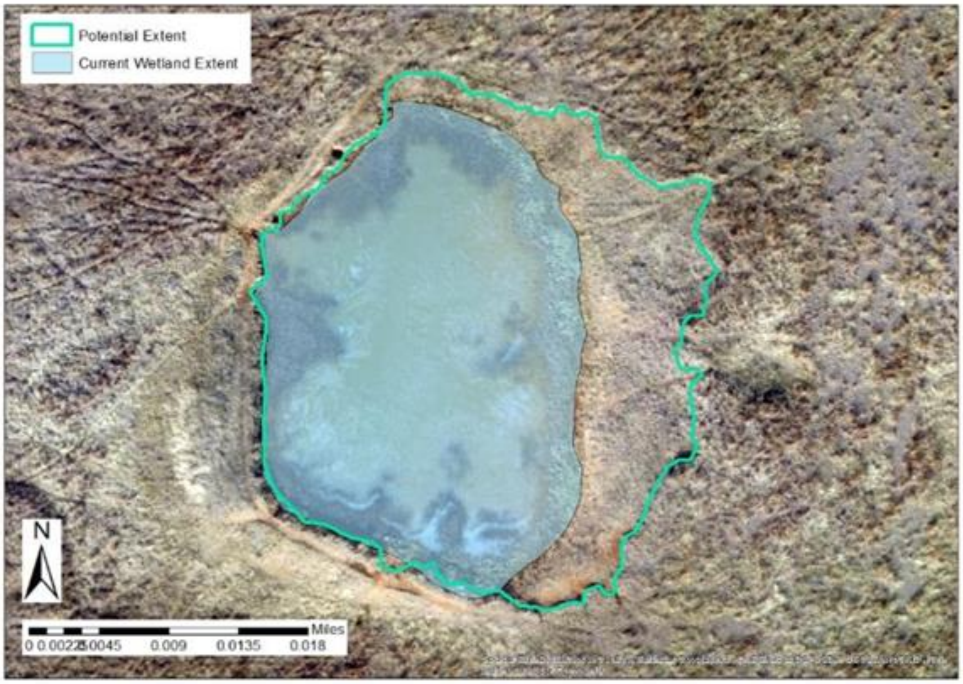


Figure 29. Wetland growth estimate from Digital Surface Model provided in Pix4D with current wetland extent.

5.3 Conclusions

Wetlands are dynamic systems with seasonal/yearly changes as seen with the rainfall differences between image capture dates. Even wetland delineations are subject to human error and the problems caused by limitations in accessibility. The increase in placement and size accuracy of the wetlands using UAS has drastically improved upon the current datasets being utilized for wetland assessment. The UAS mapped wetlands, on average, were located completely within the delineated area and the average overlap was 76.5% with all sites and 80% excluding the outlier with the complete delineated area. UAS was typically a more conservative estimate of area than a full wetland delineation. By adding up to a 35 ft buffer the UAS mapped wetlands typically encompass ≥90% of the delineated wetland. UAS is limited by canopy cover, floating vegetation, and most severely the presence of dry wetland beds and additional methods such as including buffers, seasonality of missions, assessments of topography from digital surface models, and thermal imagery have been suggested as areas of future research to build upon this work. The cost-savings of this method when compared to traditional methods reduced costs by $1,000 for labor alone; in large projects this could result in significant savings to consultants and project proponents. This method could be used as a pre-planning tool for wetland avoidance during development; however, as technological advancement continues traditional methods may well be used sparingly in favor of the rapid and cost-effective methods provided by UAS.

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