Wetland Mapping and Restoration Decision Making using Remote Sensing and Spatial Analysis: A Case Study at the Kawainui Marsh

By

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List of Abbreviations

USC	University of Southern California
UAV	Unmanned Aerial Vehicle
NFWF	National Fish and Wildlife Service
NWI	National Wetland Inventory
DLNR	Department of Land and Natural Resources
DOFAW	Department of Forestry and Wildlife
AOI	Area of Interest
LiDAR	Light Detection and Ranging
MODIS	Moderate Resolution Imaging Spectoradiometer
ETM+	Enhanced Thematic Mapper Plus
UAS	Unmanned Aerial System
DSM	Digital Surface Model
DTM	Digital Terrain Model
DEM	Digital Elevation Model
MCE	Multi-Criteria Evaluation
TIFF	Tagged Image File Format
.LAS	Log ASCII Standard
GPS	Global Positioning System
GLONASS	Global Navigation Satellite System
RTK	Real-Time Kinetic
JPEG	Joint Photographic Experts Group
VDI	Virtual Desktop Infrastructure

NIR	Near-Infrared
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Water Index
TWI	Topographic Wetland Index

Abstract

Wetlands are a unique and important ecosystem for our world by serving as one of the largest forms of carbon sequestration and storage while also housing thousands of plant and animal species. As much of Earth’s wetlands are disappearing due to human activities, conserving these natural resources has become even more crucial. Restoration, or the process of returning a degraded area to its original form, is necessary for the future of wetland ecosystems, as well as our world. In the conservation field, unmanned aerial vehicles (UAVs) are a common tool for wetland assessments. However, they are rarely used for restoration planning, which is mostly done on a larger scale using LiDAR and satellite imagery. Because wetland restoration relies on noting small changes, the flexibility of UAVs may prove to be a more useful tool. As ecosystems that connects land and water, vegetation and hydrology can vary intermittently and may require detailed planning and consistent monitoring. Although other forms of remote sensing can give us accurate DEMs and high-resolution imagery on a large scale, a UAV may be more effective for smaller study areas.

The 60-acre Kahanaiki restoration area is an ideal study area for restoration planning with a UAV. This study utilized a DJI Phantom 4 Pro V2 drone to acquire high-resolution imagery and a 3D point cloud, which was then classified into variables – streams, mudflats, plant species, urban land use, and a 0.15-meter DEM. These criteria were used in a suitability analysis to determine where restoration efforts are most likely to succeed. Along with this, high-resolution imagery of Kahanaiki and 2 other current restoration sites were created for use in future monitoring. The purpose of this study is to assist with conservation research of the Kawainui Marsh by monitoring existing restoration areas and planning ideal locations for future restoration sites. In doing so, the research determined if UAVs can be an effective tool for restoration planning for future wetland mitigation.

Chapter 1: Introduction

Wetlands are precious ecosystems that keep our air cleaner by absorbing carbon and nitrogen, while also serving as habitats to a vast amount of flora and fauna. In the last century, we have seen huge losses of wetlands as urbanization and development have increased globally. To conserve this valuable resource, restoration efforts must be put into place. Remote sensing has successfully created data to help monitor wetlands with unmanned aerial vehicles (UAVs) entering the industry quickly as technology evolves. UAVs are often applied in assessments and management, but the high-resolution imagery is not commonly used in restoration planning. This study utilized remote sensing with a UAV to acquire imagery and then an overlay analysis was done with the classified data to determine the most suitable sites for future restoration efforts in the Kawainui Marsh on Oahu, Hawaii.

1.1 Wetlands

Wetlands, which naturally connect land and water, are arguably the most important ecosystem in the world. They have the rare ability to mitigate climate change and create habitats for a vast assortment of flora and fauna. Scientists often refer to wetlands as the “kidneys of landscapes” because of their ability to extract waste and naturally clean water sources. They are one of the largest forms of carbon sequestration and storage, creating cleaner air for mankind (Ramos 2018). Wetlands also help protect human populations from extreme weather by working as flood barriers. They serve as one of the most productive ecosystems in the world by housing majority of flora and faunal taxonomic groups (Garg 2013). This includes more than 800 species of protected migratory birds globally and several thousand plant species that have evolved to survive in a unique, hydrologically changing environment (Ramos 2018).

Wetland ecosystems were first recognized for their significant value at the global level in 1971 at the Ramsar Convention in Ramsar, Iran. There, at the oldest intergovernmental environmental agreement, over 160 countries identified wetlands within their countries for the value they bring to humanity as a whole (Ramsar 2014). Today there are 2,300 Ramsar sites around the world, covering 2.1 million square kilometers.

The U.S Department of Interior, National Fish and Wildlife Service (NFWF) was the first to define wetland ecosystems in 1979, bringing forth a new and necessary wave of research. The term ‘wetland’ can be used to define an assortment of aquatic habitats, including marshes, swamps, bogs, ferns, peatland, prairie potholes, vernal pools, aquatic beds, and more (Wu 2018). Because of this, wetlands have been classified into 5 types including, marine, estuarine, riverine, lacustrine, and palustrine. These categories are defined by the plants, soils, and frequency of flooding in the area (Cowardin et al. 1979). NFWF also created the National Wetland Inventory (NWI), which was used to map and study wetlands across the country to facilitate conservation management. Open to the public, the NWI includes information on abundance, characteristics, and distribution of wetlands. Despite the importance of wetlands to local and global communities, the NWI tool has shown that the U.S. has lost hundreds of thousands of acres of wetlands due to urbanization (U.S. Fish & Wildlife Service 2019).

1.2 Restoration

Conservation management is key to successfully restoring an ecosystem, like wetlands, to its original state by minimizing the negative effects of human activity. Human developments, including urbanization, aquaculture, pollution, and controlled water sources, are quickly replacing wetland ecosystems. Evidence of this includes a loss of biological diversity, deterioration of water quality, increase in invasive plants, vegetation shrinkage, and reduced migratory bird populations.

The success of restoration efforts relies heavily on identifying appropriate areas for repair, the foundation of proper restoration planning. The first step in planning any type of mitigation is to determine the most critical location (Erickson and Puttock 2006). Restoration planning, an aspect of mitigation, includes identifying key actors, either problem areas or areas that can be easily restored. These actors are then used to define the goals and objectives. Next, a restoration plan should include mapping and an inventory of these areas or resources, as well as an understanding of the history of the area. Once the initial framework is determined, a restoration plan can be developed, implemented, and monitored closely.

Vegetation, hydrology, and soils are the basic elements that comprise all wetlands. Vegetation is one of the most sensitive actors in a wetland, and therefore a useful indicator of ecosystem health. This is due to the large diversity of species, their rapid growth rates, and direct response to environmental changes (Fennessy, Gernes and Mack 2002). Majority of the plants found in wetlands are hydrophytic, meaning they have adapted to survive in frequent and consistent flooding (Wu 2018). This study focused on the conservation and restoration of native plants, those that occur naturally in the Hawaiian Islands before human arrival. Native vegetation is a key factor in restoring an ecosystem back to its original state. Hydrology, including water depth, chemistry, and flow rates influences the health of wetland plants, and is usually the basis of criteria for mitigation site planning. Understanding the roles of vegetation and hydrology in terms of restoration efforts can influence climate science, ecology and ecosystem management, deforestation, and conservation efforts in general. Wetland restoration is relatively new to Hawai’i and each wetland within the state requires vastly different mitigation efforts (Erickson and Puttock 2006). This study will serve as an example of restoration planning in the state's largest wetland.

1.3 Study Area

The study area is the Kawainui marsh located in Kailua on the windward side of Oahu, Hawaii. Meaning "the big water", the history of the marsh dates back to 400 BC, before the arrival of Polynesians to Hawaii, when the Kawainui area was actually a bay connected to the ocean. Overtime, a natural sandbar was built, where the city of Kailua now sits, and the ocean retreated. Rainwater began to fill the bay, completely changing the ecosystem. Polynesians used

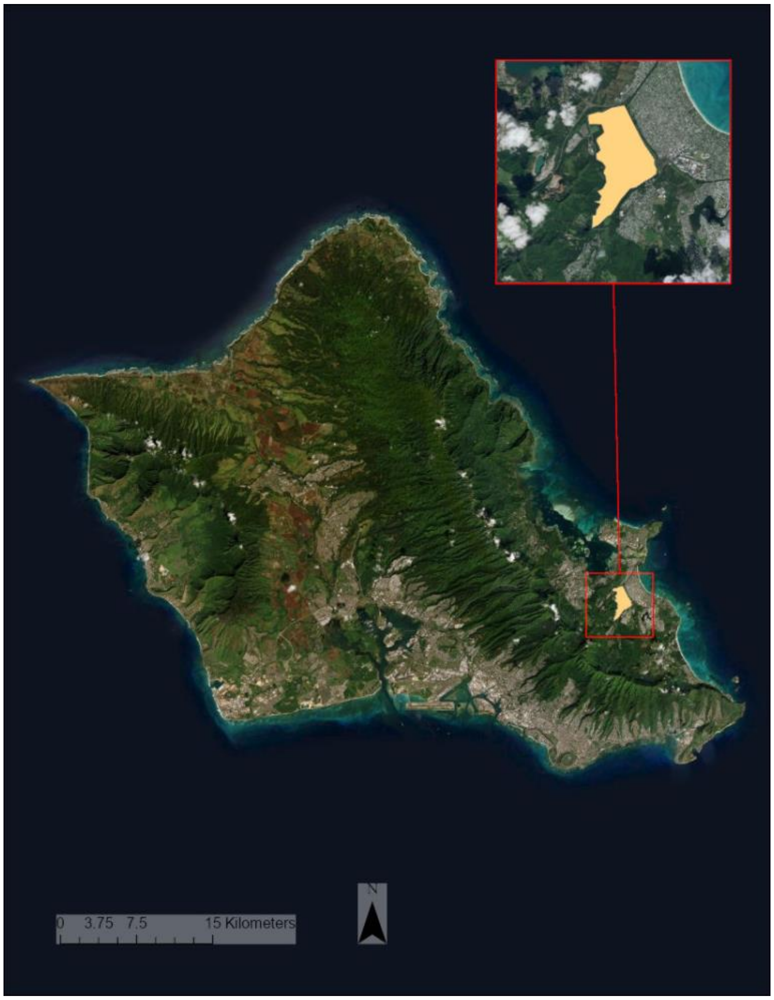


Figure 1: Location of the Kawainui Marsh on the windward side of the Island of Oahu

this newly formed lagoon for agriculture, including fish and taro. The area became a sacred oasis, so much so that 3 heiaus, Hawaiian sacred sites, were built surrounding the Kawainui area. The wetland was recognized for its cultural significance in 1962 when it became a state monument (HHF Planners 2016). It was not until 2005 that the marsh was designated as a Ramsar Wetland of International Importance. However, the State of Hawaii Department of Land and Natural Resources (DLNR) recognized its biological importance before then.

The development of the windward side of Oahu began in the 1930, quickly creating a need for conservation management of the area. A highway and tunnels were built connecting Honolulu to Kailua, making it more accessible for urbanization and growth. The County of

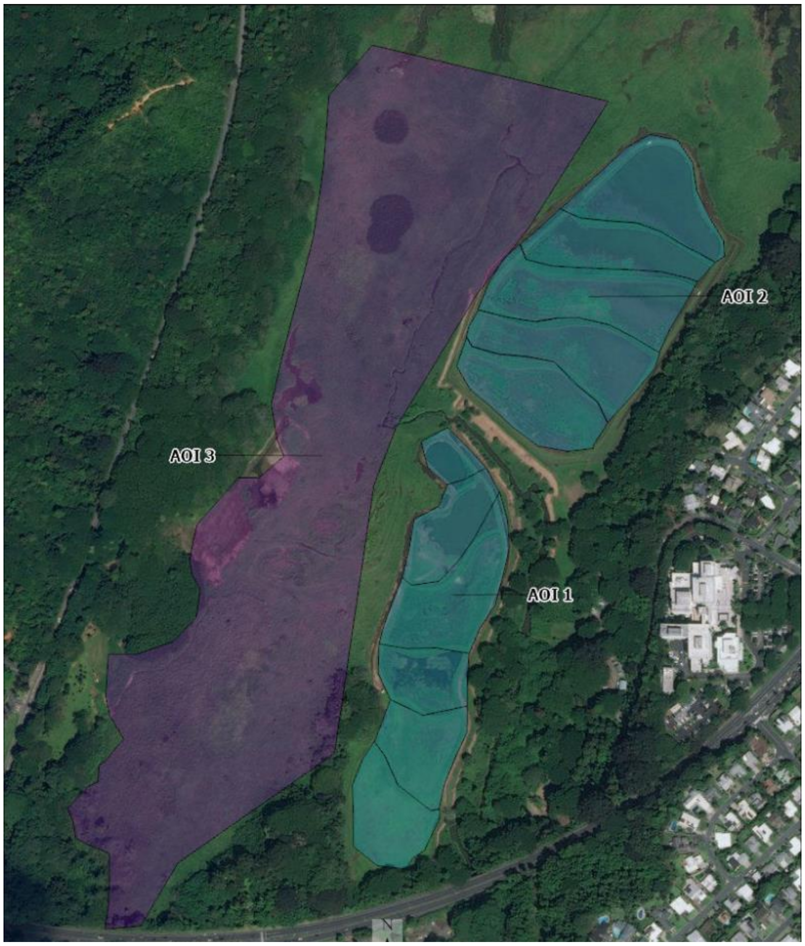


Figure 2: DOFAW's Restoration Areas of Interest within Kawainui Marsh

Honolulu and eventually the State of Hawaii worked together to create the Wetland Restoration and Habitat Enhancement Plan to restore habitats for Hawaiian water birds, migratory shore birds and waterfowl, and native fish (HHF Planners 2016). The plan, with funding from NFWF, The Castle Foundation, and the Division of Forestry and Wildlife (DOFAW) includes restoration sites on the edges of the marsh.

The 12 existing restoration sites within Kawainui marsh, all managed by DOFAW, are the focus of this research. The marsh is classified as Palustrine, a freshwater wetland not associated with a river or lake (Cowardin et al. 1979). Wetlands in Hawaii have a year around growing season, which make vegetation and hydrology sufficient indicators of ecological health. Wetland plants, known as hydrophytes, have developed unique evolutionary strategies for survival at a rapid pace. While hydrology is usually the driving force for restoration, it is also most confusing determinant of wetland health partly because it is uncommon to find documentation of long-term hydrological patterns in Hawaii (Erickson and Puttock 2006). The Kawainui wetland sits at the bottom of the Ko'olau Mountain range, with large amounts of annual rain water entering from the south western corner of the marsh. DOFAW has built 11 man-made ponds with a connecting water source to serve as habitats for native Hawaiian waterbirds. These areas have been split into Area of Interest (AOI) 1 and 2.

Figure 3: Aerial view of AOI 3, the Kahanaiki restoration site

The last area, AOI 3, is the Kahanaiki restoration site, shown in Figure 3. This site was recently acquired by DOFAW and is too large for one restoration project. Therefore, this area was further analyzed to determine spaces within it to focus conservation management practices. Although majority of the conservation work being done by DOFAW is to support the native bird populations, there is potential for native plant habitats that could benefit the Kawainui Marsh as a whole. This research has identified primary and secondary locations within the Kahanaiki restoration area that could be successful native plant habitats, which could in turn produce an enhanced environment for native waterbirds. This study recommends introducing native plants that are also found in the nearby Hamakua Marsh Wildlife Sanctuary in Kailua to ensure success. These plants are listed in Table 1 (Nietmann and Works 2019).

Table 1: Recommended native plant species for restoration efforts in AOI 3

Plant species
Bolboschoenus maritimus, saltmarsh bulrush*
Cladium jamaicense, uki
Cyperus javanicus, ‘ahu’awa*
Cyperus laevigatus, makaloa
Cyperus odoratus, rusty flatsedge
Cyperus polystachyos, manyspike flatsedge*
Cyperus trachysanthos, pu‘uka‘a*
Fimbristylis cymosa, tropical fimbry
Fimbristylis dichotoma, forked fimbry
Schoenoplectus tabernaemontani, giant bulrush

*Currently established in nearby Hāmākua Marsh

1.4 UAVs and Wetlands

Remote sensing, especially UAVs, are commonly used to assess ecosystem health because it can provide spatially and temporally distributed information over a variety of scales. Remote sensing is the acquisition of information from an airborne device, including satellites or aircrafts. UAVs, with their especially high spatial resolution, have recently become a popular choice for monitoring wetlands. Their value can be demonstrated due to the ability to control flight times, the ability to fly low and avoid cloud cover, and the relatively low costs and easy use (de Souza et al. 2017). Cost becomes a consideration when consistent monitoring must be completed on foot by a biologist. A full day of pedestrian surveys can be done in a few hours with a UAV. Palustrine, or freshwater, wetlands often include dense vegetation. This makes other forms of remote sensing, like LiDAR, nearly impossible (de Boisvilliers and Selve 2019). UAVs surveys can not only obtain vegetation data, but they also can acquire tree type and height data because of the high-resolution imagery they produce.

The technology and applications of UAVs has only gotten better with the introduction of applications like Drone Deploy and Pix4D. Drone deploy is a tool designed to easily map flight paths with a DJI drone. Pix4D is the leading software that takes the JPGs taken during flight and produces orthomosaics, 3D point clouds, digital surface models, and digital terrain models. These applications make the process of acquiring data relatively simple, allowing for repeatable flights over time.

This study used a UAV to monitor the current conditions of DOFAW's 11 restoration ponds in the Kawainui marsh. The native bird counts within AOI 1 and AOI 2 are relatively low, indicating that the sites are not very successful and there is no existing data to date that can be used to monitor it. The first portion of the study collected and created high resolution imagery. The information can be used by DOFAW to better manage the restoration ponds, and potentially perform UAV assessments to monitor seasonal change.

Although UAVs have become a popular tool in wetland assessments, they are not yet common in restoration site planning. LiDAR data is generally successful at restoration preparation at a large scale; however, UAVs are necessary when gathering data on a small wetland site (Klemas 2013). UAVs allow us to reach sites without invading natural systems, and gather extremely high-resolution imagery showing land cover, vegetation structure, habitat boundaries, and elevation. The photogrammetry that is generated from UAVs can identify characteristics, such as texture and color, which can be used to identify plant communities

(Boon, Greenfield and Tesfamichael 2016). This study benefits the geospatial community by understanding whether the data acquired with a UAV can properly be used to not only monitor, but to identify restoration sites.

An overlay analysis was done using data classified from the flight over the 60-acre AOI 3. The Kahanaiki area is too large for one restoration project, but again, currently there is no data to support restoration decision making. The orthomosaics from the flight were classified, a terrain analysis was completed, and a multi-criteria evaluation was performed. The study assessed streams and waterbodies, vegetation types, the location of mud flats, and urban land use to determine where DOFAW should focus their restoration efforts within AOI 3.

1.5 Research Goals

Wetlands are an extremely valuable ecosystem that have experienced significant deterioration from human development. In order to conserve these precious ecosystems, restoration should be implemented. Successful ecosystem restoration relies on thorough planning, including site selections. This research will demonstrate that airborne remote sensing is the best option for wetland assessments and restoration planning as it has qualities of both satellite imagery and aerial photography, including spatial bands, spatial resolution, temporal control, and economic value.

This study answered the following questions:

- Are there benefits of monitoring restoration with a UAV as opposed to pedestrian surveys?
- Can UAVs and spatial analysis properly perform restoration site selection?
- Where and what kind of restoration should be performed within AOI 3 of DOFAW’s land?

1.6 Thesis Organization

The thesis is organized into 5 chapters, including a related work section, the methodology, results, and discussion and conclusion. Chapter 2 outlines related works associated with wetlands, remote sensing, and site-suitability assessments. The Chapter 3 is the methods, which is broken up into research design, data description, equipment, data acquisition, post-processing of data, and the data analysis. Chapter 4 covers the results that were developed from the methods of monitoring, classifying data, and the final analysis. Chapter 5 discusses these findings, the advantages and disadvantages of UAV research, and future research.

Chapter 2: Related Work

The related work includes studies and information on wetlands and their importance to conservation, remote sensing techniques with a UAV, and site suitability assessments for freshwater wetland restoration. The restoration investigation of Kawainui marsh applied knowledge from these three categories to monitor existing restoration sites and determine future mitigation sites.

2.1 Wetlands

Wetland ecosystems play a unique role in the ecology of the Earth as they connect land and water, meaning their health can affect other ecosystems. Their importance is most commonly linked to their ability to extract waste from water sources to naturally clean runoff. Wetlands also serve the broader climate by sequestering and storing carbon. This process happens because of the anaerobic conditions found in wetland soils, which slowly decomposes carbon over time (Australia Government 2012). Along with this, wetlands serve as a habitat for biodiversity, especially migratory birds. They also protect human populations from extreme weather events by serving as a flood barrier (Ramos 2018).

The environmental movement of the 1960s-1970s helped identify the value of wetland ecosystems. Wetland conservation first gained interest in 1971 at the Ramsar Convention, the oldest intergovernmental agreement, in Ramsar, Iran. It included 160 countries who agreed to recognize wetland sites around the world for their significant value to humanity as a whole. Wetlands were distinguished because of their influence on other ecosystems, as a transitional system between dryland and water bodies. Today, there are 2,300 Ramsar sites, covering 2.1 million square kilometers (Ramsar 2014). The Kawainui Marsh was designated a Ramsar wetland of international importance in 2005, which has allowed for an increase in restoration efforts (HHF Planners 2016).

The rise in wetland regulations in the early 1990s brought about a surge of research. Globally, studies were done to determine strategies for wetland data acquisition, and especially, wetland health assessments. During this period of time, conservation organizations began to understand how quickly wetland loss was happening. It became evident that increased urbanization correlated with the decline of wetland health. Zhang et al. (2010) found that majority of the scientific articles written between 1991-2008 came from China and the United States, leaders of urbanization and therefore wetland degradation.

This burst of research, and the data that was acquired, help create a more comprehensive approach to wetland science in the U.S. The U.S. Fish and Wildlife Service helped maximize research with the creation of the NWI. NWI provides information to the public on the status and trends of wetlands, including abundance, characteristics, and distribution of wetlands in the U.S (U.S. Fish & Wildlife Service 2019). The NWI utilizes the Cowardin classification system to identify 5 main wetland types: marine, estuarine, riverine, lucastrine, and palustrine (Cowardin et al. 1979). The Cowardin system, seen in Figure 4, has become the basis for wetland research globally as well. The Department of Land and Natural Resources, Division of Forestry and Wildlife is responsible for many wetlands around the country, including the Kawainui Marsh. A portion of their responsibilities include regularly monitoring specific restoration sites through pedestrian surveys. These surveys include walking the periphery of the areas to monitor birds, vegetation, and hydrology using binoculars to monitor the interiors. The weekly pedestrian surveys are intended to make sure the restoration areas are remaining healthy. This includes bird counts, as well as habitat use within the 3 AOIs (Nietmann and Works 2019).

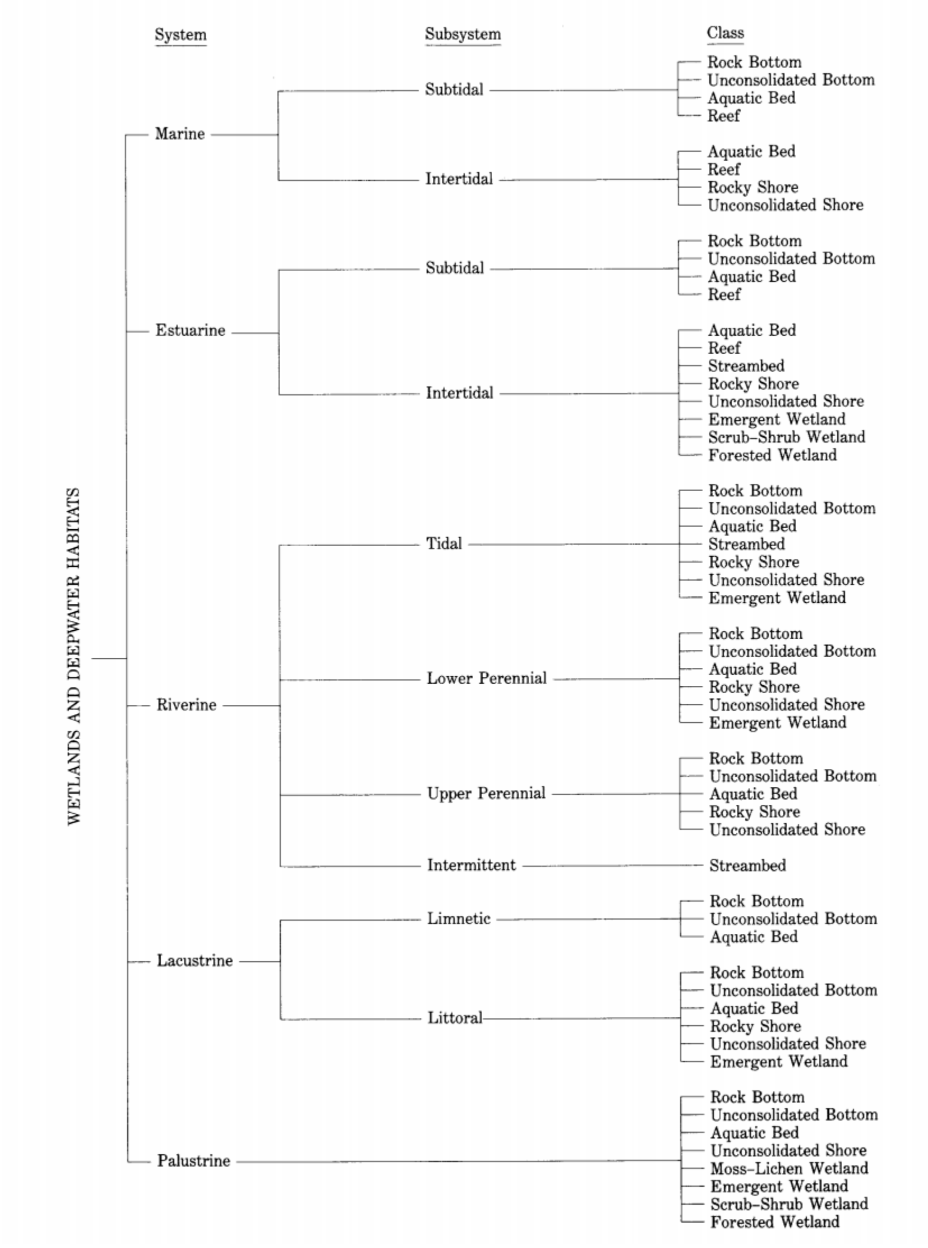


Figure 4: Cowardin System of Wetland Classification. Source: Cowardin et al, 1979

2.2 Remote Sensing

Remote sensing has greatly altered the quality and precision of data collection for all fields, but especially environmental science. A study covering wetland remote sensing between 1991-2015 demonstrated a steady increase in wetland research due to technological advancements

(Guo et al. 2017). As the technologies advanced from aerial photographs to high-resolution drone imagery, so have the quality of research and the success of conservation and restoration efforts.

2.2.1 Aerial Imagery

Remote sensing became popular with the use of aerial imagery, which led to classification techniques of vegetation mapping. The earliest account of remote sensing in wetland research is Johannessen's use of aerial imagery to study tidal marshes along the Oregon coast. He used imagery taken in 1939 and compared it to photos from a flight in 1960 to determine that colonies or marsh plants are indicators of wetland expansion (Johannessen 1964).

2.2.2 Satellite Remote Sensing

The introduction of satellite imagery allowed for valuable data to be obtained on a large scale. Satellite remote sensing has allowed for conservationists to model ecosystem change over time and better plan restoration efforts. Data with coarse spatial resolution first became available with the Moderate Resolution Imaging Spectoradiometer (MODIS) from NASA's Aqua and Terra Satellites, which took orbit in 1999. Coarse spatial resolution refers to data with a pixel size greater than 250 meters. These satellites included 36 spectral bands, 7 of which were designed for land monitoring (Guo, et al. 2017). The U.S. Fish and Wildlife Service's NWI datasets were created with coarse spatial resolution, which may limit the ability to make clear decisions. In the same year, medium spatial resolution became available as Landsat TM/Enhanced Thematic Mapper Plus (ETM+) took to the sky. This data, found between 4-30 m resolution, is used to classify wetland vegetation, understand carbon stock of wetlands, and create water quality estimations from reflections (Guo et al. 2017). Soon after that, data with high spatial resolution became available. With data found at less than 4 meters, researchers could see the geometry and surface textures creating better invasive species monitoring and understanding carbon/nitrogen intake of the soil, water, and vegetation in wetland ecosystems (Guo et al. 2017). Research from this revolutionary satellite imagery was short lived, with only a few studies conducted, as LiDAR became available soon after.

2.2.3 LiDAR

As wetlands are complex ecosystems with thick vegetation, varying elevations, and periodic flooding, LiDAR can be a more useful tool for information gathering than satellite remote sensing. LiDAR uses lasers to monitor the earth’s surface and has the ability to provide high accuracy data for the production of Digital Elevation Models (DEMs). The introduction of accurate DEMs allowed for better terrain analyses, which became the focus of many wetland studies. High-resolution LiDAR data became the basis for planning and understanding restoration of wetland ecosystems.

Although wetland research greatly benefitted from LiDAR data, dense vegetation presents a challenge for wetland mapping. This was de Boisvilliers and Selve’s (2019) argument for utilizing an UAV to analyze the hydrology of a wetland. Their study was done as part of a restoration project on the Mou de Pleure bog in France, a site with physical and financial barriers. The vegetation around and within the bog made terrestrial surveys impossible and prohibited accurate terrain models with LiDAR. They were able to georeference a point cloud of ground control points and created a more accurate Digital Terrain Model (DTM) using UAV imagery. This DTM was then used to extract contours to map the rivers and streams using the Watershed tool and simulate water flow within the area. (de Boisvilliers and Selve 2019). Additionally, the benefits of reduced cost and scalability have led to an increase in wetland research using UAV survey techniques.

2.2.4 Unmanned Aerial Systems (UAS)

Agriculture paved the way for data collection with a UAV as much of the research originating in large scale farming. De Souza et al's (2017) study on skips in sugarcane plantations in Brazil is just one of the many examples. They used a UAV to better manage crops with controlled revisit flights to see change over a short amount of time. The orthomosaics of the plantation were then classified and extracted into vector data to identify crop rows.

Boon, Greenfield and Tesfamichael (2016) were early to use a UAV to assist in a wetland delineation, the most precise wetland assessment. The high-resolution imagery is necessary for obtaining surface derivatives used to calculate water accumulation and slope for studying hydrology. They could view texture and color, allowing for the classification of plant communities. The researchers considered the wetland delineation with a UAV a success because of the low cost of acquiring and processing data, which tied into the temporal scalability of the research. They were not constrained by scheduling flights as data collection with a drone is fairly simple and efficient compared to a pedestrian survey or a manned aircraft (Boon, Greenfield and Tesfamichael 2016).

Another example of UAV use in agriculture can be found in Rokhmana's (2015) study in Indonesia, where he created better flight planning strategies. While using a drone to assess gaps in vegetation, he found that wind was affecting the quality of the output images. The research tested if expanding the photo overlap would help the problem. By taking more photos, overlapping at 85%, the photomosaic was clear and without gaps (Rokhmana 2015). The technology associated with UAV data collection may not be perfect, but the ease and accessibility can be maintained with thoughtful flight planning. Applications such as DroneDeploy, which assists with sufficient flight planning, and general interest can bring more necessary research on wetland ecosystems, which is especially useful in conservation and restoration.

The previous studies using UAVs will be used as resources in determining best practices for data collection and data processing. Along with this, they will be used to understand the types of projects that utilize UAVs and why. It is evident from these studies that UAVs are commonly used in ecosystem assessments and management, but rarely used for restoration planning.

2.3 Site-Suitability Analysis

The purpose of restoration is to design and restore functions of historical wetland ecosystems. This may include removing invasive species, removing bulkheads and fill, grading elevation, creating flush channels, and germinating of native plants (Klemas 2013). With multiple variables, a site-suitability analysis is the most comprehensive strategy for identifying restoration sites. Multiple articles identified the importance of planning and design, as well as identification of goals, for the success of restoration. One of the most valuable outcomes of using GIS for wetland conservation is the ability to identify sites for restoration efforts. Wetlands are spatially complex and temporally variable, meaning high-resolution imagery is critical for a proper site-suitability analysis (Klemas 2013).

Hydrology is a major component of restoration efforts; therefore, many site assessments focus on watershed patterns. Russel, Hawkins and O'Neil (1997), early pioneers of site-suitability analyses, focused their study on hydrologic factors to identify an area's wetness index. The potential for saturation and the surrounding land use were main attributes for selection mitigation sites. Another study, by Van Lonkhuyzen, Lagory, and Kuiper (2004) focused on hydrology, as well as soil and historic condition of the land. Nearby vegetation was given the second most weight, followed by land use. All of the data was converted to rasters and Raster Overlay was used to calculate areas with the most potential for restoration.

The interest in hydrology led to the importance of accurate and detailed DEMs. Russel, Hawkins, and O'Neill (1997) found this to be the main component in their study on a restoration site selection in the San Luis Rey River watershed in southern California as wetlands tend to form a continuous descent from upland regions to a body of water. With the introduction of LiDAR data and sub-meter accuracy, DEMs became a large focus of site-suitability research. Elevation data significantly improves accuracy of wetland mapping (Klemas 2013). Small-scale DEMs allowed for precise slope values, which became the focus for both Ouyang, et al and Uuemaa, Hughes and Tanner (2011, 2018). Ouyang, et al (2011) studied DEMs to calculate slopes and water movement speeds as variables in their restoration site selection in the Yongdinghe River in northern China. Uuemaa, Hughes and Tanner (2018) used DEMS to study similar attributes, as well as water accumulation in the Waituna Lagoon Catchment on the southern coast of South Island, New Zealand. The DEM was the major component in their assessment as it helped calculate potential flood zones, accessibility for restoration, and flatter topography with water flows. By visualizing a change in slope, values for importance of criteria could be assigned, normalized, and integrated into the evaluation data.

Accurate DEMs of small-scale areas became possible with the use of UAVs and their applications. A Digital Surface Model (DSM) can be built using post-processing applications, such as Pix4D. This information is the basis for the Digital Terrain Model (DTM), classified vector data that distributes points related to elevation over a surface. Various ArcGIS geoprocessing tools allow for this information to be presented as a Digital Elevation Model (DEM) to be used in further analysis (Zietara 2017).

The introduction of high-resolution LiDAR data also created valuable soil and vegetation data, becoming the basis for most terrain analysis. Uuemaa, Hughes and Tanner (2018) performed a multi-criteria evaluation (MCE) focusing on soil, underlying geology, low topography, and available land. Similarly, Klemas (2013) used remote sensing to compare land cover vegetation structure habitat boundaries, and other biophysical characteristics to identify potential restoration sites. It is evident that wetlands in the same Cowardin class may be affected by different variables. These studies show the importance in planning specific restoration strategies and understanding the attributes of a wetland prior identifying mitigation sites.

Chapter 3: Methodology

The methods of this research include using an Unmanned Aerial Vehicle (UAV) to acquire a tiled orthomosaic and raw data of the current restoration efforts in the Kawainui wetland. This information was shared with the State of Hawaii DNLR DOFAW to use in their conservation and management plans. The study also used portions of the acquired data to perform a site-suitability analysis of potential mitigation sites within the 60-acre area that is managed by DOFAW.

3.1 Research Design

The research methods can be divided into two parts. The first is to use a UAV to acquire high-resolution imagery which is stored as a TIFF raster format for each of the existing restoration sites. The currently managed restoration sites include 11 ponds that are used as bird nesting habitats. Ponds 1-6 are within AOI 1 and ponds 7-11 are within AOI 2. Prior to this study, there was no existing data of these ponds, therefore high-resolution imagery was created for future use in restoration monitoring. The total acreage for the ponds within AOI 1 and AOI 2 is 37 acres.

The second part of the research includes restoration planning for DOFAW’s recently acquired 12th site, Kahanaiki restoration area. This 60-acre site, AOI 3, was also flown with a UAV to acquire imagery and the features were classified. However, because the site is too large for one type or restoration project, a site-suitability analysis was completed with this data to determine where DOFAW should focus their attention. Features considered include vicinity to streams, location of mud banks for nesting, native plant habitats, and vicinity to urban land use.

Figure 5: AOI 1 & AOI 2, The Restoration Ponds at Kawainui Marsh

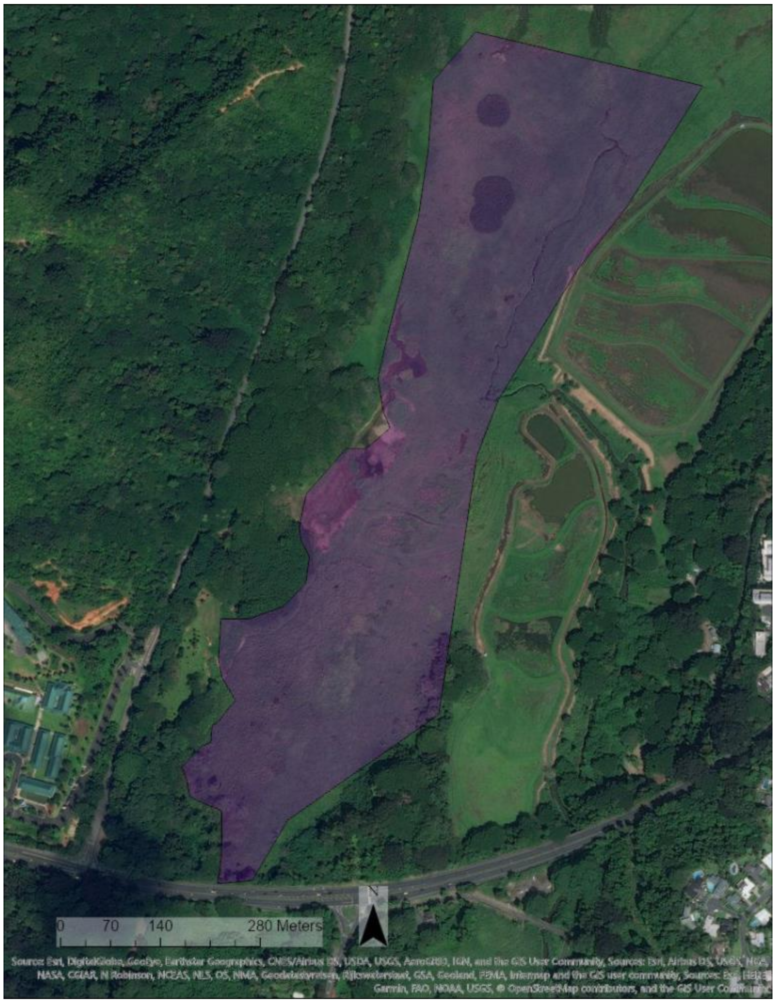


Figure 6: AOI 3, Kahanaiki Restoration Area at Kawainui Marsh

3.2 Data Description

The data acquisition was done through remote sensing using a DJI Phantom 4 Pro V2 drone. It was administered for three separate flights, covering a total of 97 acres. Flights of AOI 1 and 2 were done to build an orthomosaic that was generated as a TIFF raster. Flight 3 also produced a TIFF raster, as well as 3D point clouds in .las format.

The orthomosaic of AOI 3 was used to classify data including:

- Streams/Waterbodies
- Vegetation

- Mud flats (native bird habitats)
- Urban land use
- DEM

These datasets, as well as slope identified from the 3D point cloud were used in a restoration site-suitability analysis.

3.3 Equipment

Achieving the goal of high-resolution imagery is relatively simple, when using cutting-edge equipment and analysis systems. All of the data for this research was acquired through remote sensing using DJI Phantom 4 Pro V2. The aircraft includes a built-in camera with a 3-axis gimbal (pitch, roll, and yaw), a remote control, and a mobile application for aircraft. This advanced DJI drone is only made better with the flight planning and photo processing technologies that were built for it. The aircraft and the applications used to support it will be acquired through my employer, SWCA Environmental Consultants.

3.3.1 Unmanned Aerial Vehicle

The DJI Phantom 4 Pro V2 was used for all of the data acquisition. The 1,374-gram drone includes GPS/GLONASS satellite positioning systems, enabling real-time kinematic (RTK) to enhance precision of the data. The LiPo 4S batteries have a max charging power at 160 W, where they hold a 30-minute flight time; 4 batteries were used for the data acquisition. Along with this, a Humeless 1.5 kW battery was used to charge batteries in between flights. A total of 7 batteries were used for all 3 areas of interest.

The camera attached to the aircraft is a 1-inch 20-megapixel camera with a non-rolling shutter that will capture JPEGs onto a SanDisk micro SD USB 64 GB at the time of the flight. The camera remained securely facing straight down during flight. The 3-axis gimbal is what allows stability by preventing it from moving front to back (pitch), moving side to side (roll), or moving left to right (yaw).

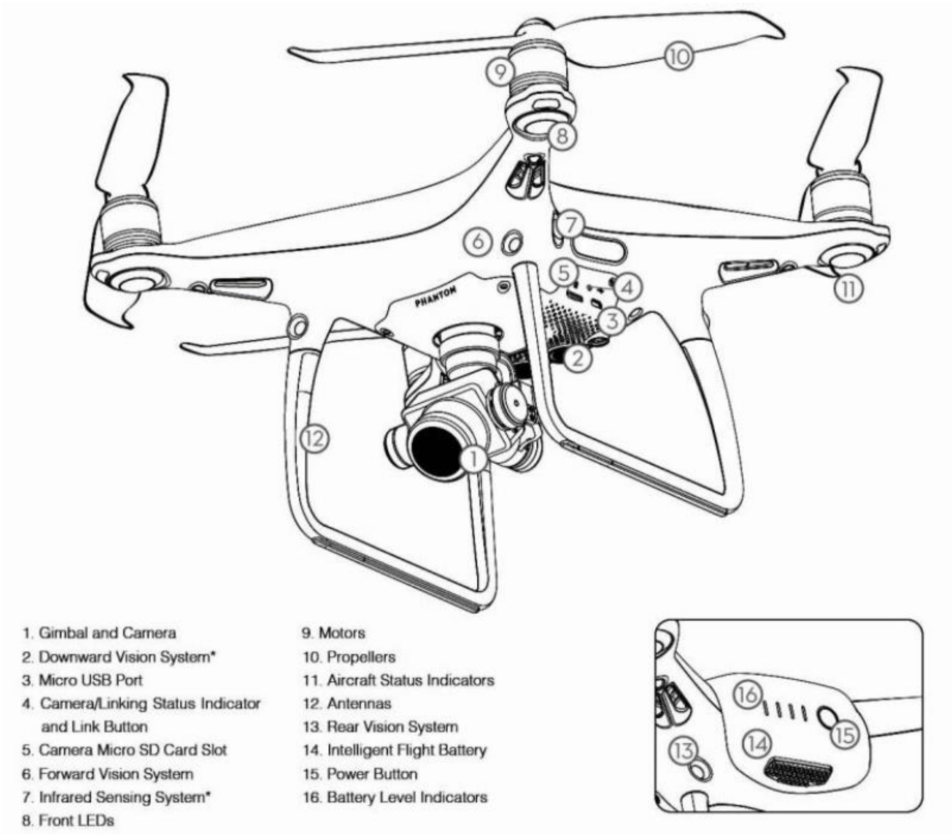


Figure 7: The elements of a DJI Phantom 4 Pro V2. Source: Moon 2018

3.3.2 Systems and Software

The flights were planned with DroneDeploy, a PC/iOS/Android application designed to work with DJI products. It allows for a streamlined flight planning process and optimized flight time in the field. The application uses a Google Maps basemap and allows the user to manually draw the flight area. The flight elevation was recorded at 150 ft. and, based on the size of the AOI, DroneDeploy determined the number of JPGs necessary to cover the area. The UAV automatically followed the plan created once connected to a DJI drone, after a safety check list is completed. The drone was followed visually and within the DroneDeploy application throughout the flight. Figure 8 shows a screenshot of DroneDeploy during its mission over AOI 3.

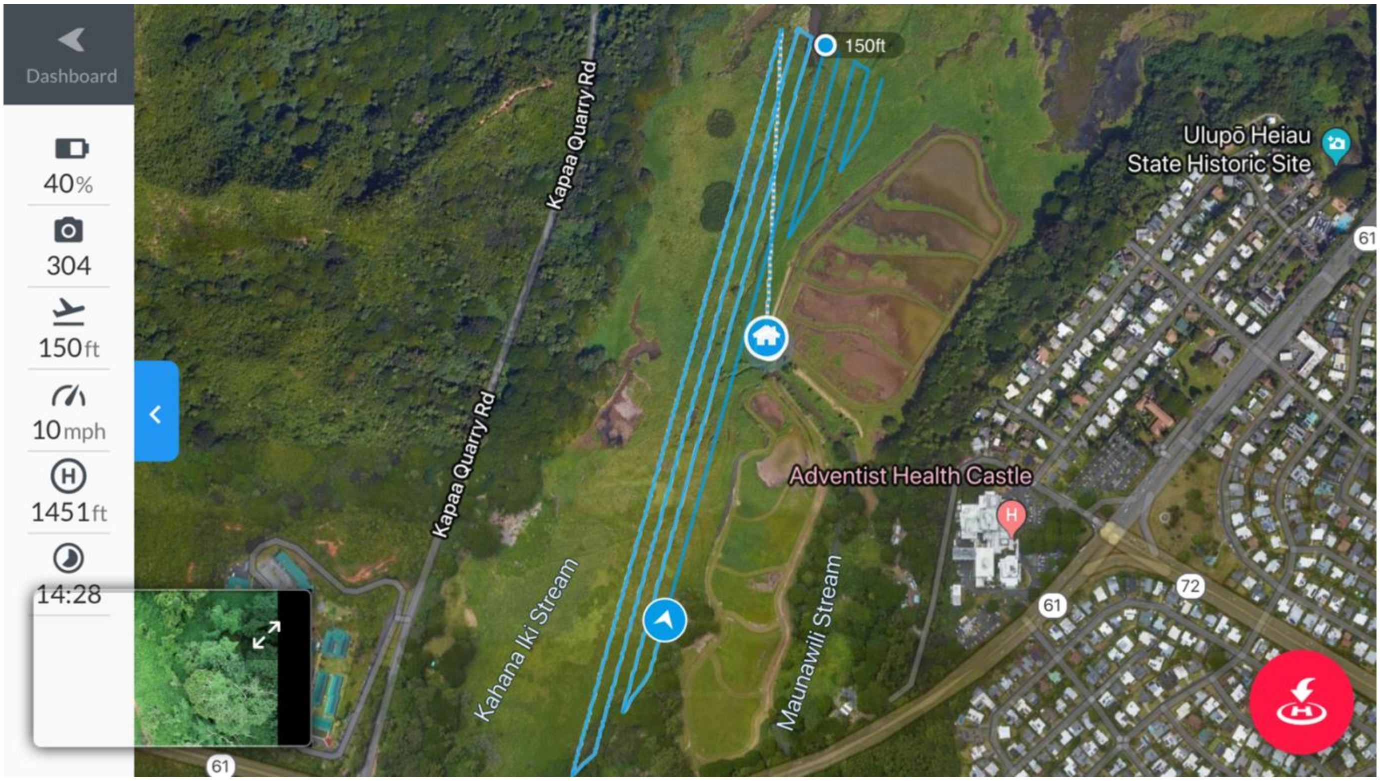


Figure 8: A screenshot of DroneDeploy during its mission over AOI 3

After the flight was completed, Pix4Dmapper 4.2 was used to process the data. Pix4Dmapper is the leading software used to produce orthomosaics, 3D point clouds in LAS format, digital surface models, and digital terrain models (the point clouds minus the vegetation/above ground objects). Pix4D stitched together the uploaded JPEGs to create an orthomosaic.

3.4 Data Acquisition

Data from the 12 restoration sites was acquired in 3 separate flights, totaling about 200 acres with buffers. Originally, data from all three areas was collected in one day, however the flight over AOI 3 had to be repeated a few weeks later due to a boundary issue. The total time to complete the 3 flights, plus travel in between, was 4-5 hours. Restoration ponds 1-6 (AOI 1) and restoration ponds 7-11 (AOI 2) each cover about 18-19 acres. The 12th restoration site, AOI 3, was done in one flight, however 3 battery changes were necessary mid-flight as the AOI is 60 acres. Batteries can easily be changed mid-flight as the UAV automatically returns to its source location when the battery hits 16%. The battery was changed, and the aircraft returned to the exact location of the flight where it left.

A flight plan is a necessary step in the acquisition process in terms of safety and data accuracy. To prepare the flights DroneDeploy was used with ISO 10 iPhone 8 with an assumed 150 ft. elevation. The AOI was mapped in the application with a 50-meter buffer on the boundaries to ensure coverage and overlapping images at the edges of the site. An 80% overlap between images was set to prevent fuzzy images from environmental conditions, such as wind. The flight path was then be uploaded to the UAV by plugging the iPhone 8 into the UAV remote's mounting station. Information was transferred automatically to the DJI application. The aircraft then moved to the designated height from the source location and towards the project site. Once there, photographs began as it moves in a diagonal pattern across the site.

The source location of each flight was1ocated 300 ft. from the waterbird nests. Figure 9 is a photo taken from the source location for AOI 3. The flights were done at 150 ft. to ensure high resolution imagery. Based on standards set by DOFAW, a flight was first tested at 400 ft. to determine how the native birds would react. When there were no noticeable disturbances, the UAV moved down to 150 ft. elevation. A DOFAW biologist was present during the flights to monitor the birds. The restoration ponds created 621 JPEGS within AOI1 and 678 JPEGS within AOI2. The flight over AOI 3 created 1,696 JPEGS. The JPEGs were collected with a separate SanDisk micro SD USB 64 GB for each flight.

Figure 9: A photo taken from the launch site, or source location, for AOI 3. The source location must be located at least 300 ft. from any potential Hawaiian waterbird nesting areas.

3.5 Post-Processing Data

Pix4DMapper was used to stitch and georeference the JPEGs into photomosaics and 3D point clouds which were used for analysis. The program locates points within each photo to triangulate their positions to match the images. This process took approximately 10-15 hours for all three areas. The 80% overlap minimized any potential errors in this process. The intended 150 ft. elevation created photomosaics with a .5 inch, or .15-meter, resolution. An RGB orthomosaic as a TIFF raster was downloaded for all 3 AOIs. A 3D point cloud in .las file format was also created of all areas. This study only utilized the 3D point cloud for AOI3. Pix4D classified a 3D point cloud using the merged raster DSM to build a DTM.

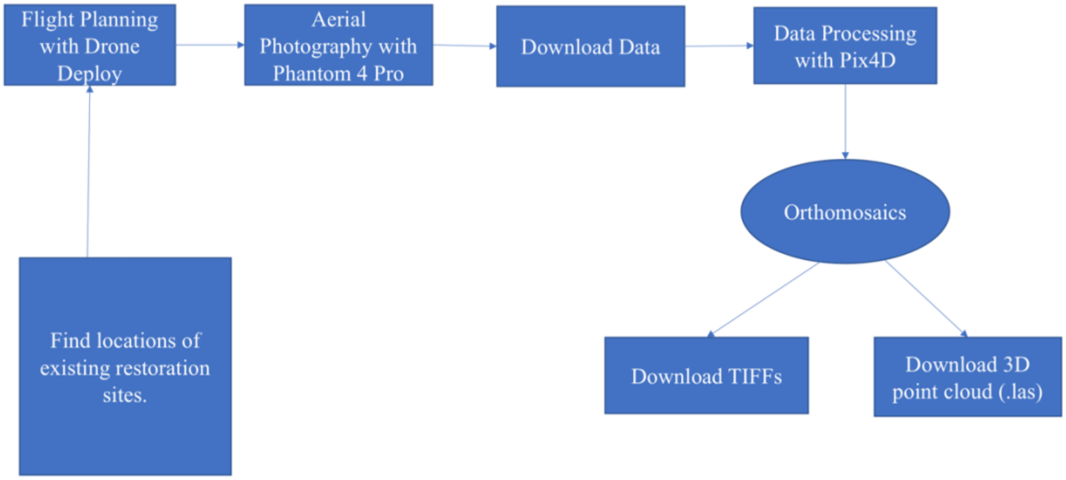


Figure 10: UAV data acquisition and post-processing workflow

3.6 Data Analysis

The data analysis portion of the thesis included taking the data captured with the UAV to monitor existing restoration sites and plan for future restoration sites. The analysis included first projecting the orthomosaics into WGS 1984 UTM Zone 4. Next, the orthomosaic of AOI 3 was classified to create attributes of interest within the site. This information was compiled and given to DOFAW to help with restoration management. Finally, the classified polygons and the 3D point cloud was used to perform a terrain analysis and a raster overlay as part of a site-suitability analysis to determine the best locations for future restoration efforts within AOI 3.

3.6.1 Data Classification

The UAS imagery is in WGS 84 so first the orthomosaics was projected to WGS 1984 UTM Zone 4 to ensure the highest accuracy for creating raw data. WGS 1984 UTM Zone 4 is the common projection within Honolulu County. The 3 bands (RGB) were uploaded into ArcGIS Pro for each flight. The Composite Bands tool was used to display the maps. The orthomosaic was displayed with a white background, showing no values, therefore, shapefiles of each area, supplied by DOFAW, were used to clip the surface layer for further analysis. At this point, the final imagery for AOI 1 and AOI 2 was complete.

Next, the Classification Wizard was used to provide a guided workflow to classify streams/waterbodies, native vegetation, mud flats, and urban land use of AOI 3. Classification is the process of sorting pixels into individual categories based on their values. ArcGIS Pro's Classification Wizard is a stream-lined tool that allows a user to easily identify land use and land cover from remotely sensed imagery. There are two different approaches to classification, supervised and unsupervised, with the main difference being the way in which the pixel classes are assigned. The first step of supervised classification includes manually selecting pixels in a particular pattern. The rest of the pixels in that category are assigned based on the same characteristics. An unsupervised classification groups pixels based on reflective properties; these groups are called clusters. Once the clusters have been created, classes are then manually assigned. Unsupervised classification is usually done when there is not enough visible knowledge about the data.

A supervised classification was used for this research, meaning the outcomes depended on the object-based training samples provided by the user. These classes included streams/watersheds, vegetation, mud flats, and urban land use. The classification of streams/watersheds located any areas showing signs of water routes to give insight into the hydrological patterns of the area. The mudflats were also classified as flat areas with little water and plant groups. The only visible urban land use in AOI 3 is a nearby road, which was created as a separate feature in the geodatabase. Along with this, some blackout spots were present in the imagery, signifying areas where Pix4D did not properly capture data. These backout spots, shown in Figure 11, were created as polygon features to rule them out in the final analysis.


Figure 11: A blackout spot, or area with “No Data” created from Pix4D

With the assistance from local botanists at my place of work, the vegetation within AOI 3 was classified into taxonomic groups. Areas with native plant species were meant to highlight potential sites for restoration, however no native plants were found in AOI 3. Therefore, feature classes were created showing areas of specific botanical features, including Non-Native Mixed Forest, Lau’ae patches (a non-native fern), and non-native mixed Papyrus and unidentified fern. The rest of the area was identified as mixed non-native plants. The outcome of the classified raster was then converted into vectors showing each of the 4 categories as raw data. The new datasets and the orthomosaic were exported into a file geodatabase. This geodatabase, as well as the imagery, were shared with DOFAW to use in restoration management, and to possibly compare with future flights.

Classification of the 3D point clouds was also needed to be completed to understand elevation within AOI 3. To do this, a .las dataset was first created in ArcCatalog, and the Make LAS Dataset Layer tool was used to evaluate the point clouds. The .LAS Dataset to Raster tool was used to convert the point clouds into a precise DEM. With the original photos taken at 150 ft., the DEM has a resolution of 0.15 meters, or 0.5 feet. This small resolution was then spatially aggregated to remove potential errors in the analysis. To do this, first Raster Calculator was used to create the DEM raster as an integer. Next, Majority Filter was used to replace the raster pixels based on bordering neighboring cells. This tool allowed for the 4 neighboring cells to create a corner while the replacement threshold was set to half to create more extensive filtering. Finally, the Resample tool changed the spatial resolution of the raster dataset by creating new pixel sizes. A 10-meter spatial resolution was resampled using a cubic technique, which determines the new value of a cell based on a smooth curve through the 16 nearest input cell centers. This new 10-meter DEM was used for the rest of the analysis to eradicate any extreme elevations due to vegetation. The Slope tool created a new raster showing slopes that may be used to determine the accessibility to specific restoration sites. Slope is an important attribute because restoration sites will need to be accessed by foot, and possible with large machinery.

3.6.2 Site-Suitability Analysis

The final analysis utilized the acquired data to determine potential areas for restoration within AOI 3. The streams and drainages, slopes, mud flats, and urban environments were given specific buffers, and then converted back into raster with the Polygon to Raster tool. The DEM was utilized to determine accessibility for DOFAW biologists, and possibly machinery, to perform and monitor restoration efforts. Areas with slopes under 20% are necessary for restoration work. Mitigation efforts also need to be within 50 feet from a water source and at least 40 feet away from mudflats as they are popular nesting grounds for birds. While areas within 30 feet from urban land use are not ideal for restoration. Buffers correlating with this criteria were created for the water source, mud flats, and land use.

After specific criteria was set for each feature, the data was combined to create one final map showing suitable sites for native plants. The raster calculation became complicated as some factors needed to be included, while others needed to be excluded from the analysis. The Erase tool was used to eliminate the buffered roads, buffered mudflats, and blackout spots from the AOI 3 boundary. This updated site and the buffered water polygons were transformed into surface layers with the Polygon to Raster tool. Finally, the Combine tool was used to merge the buffered water, the layer with roads, mudflats, and blackout spots erased, and the slopes under 20%. Since the rasters were all weighted equally, with a score of 1, each combined pixel is given a score of 1, 2, or 3. The outcome includes primary locations, or those that meet all 3 criteria, and secondary locations, those that meet 2 of the 3 criteria for potential restoration within AOI 3.

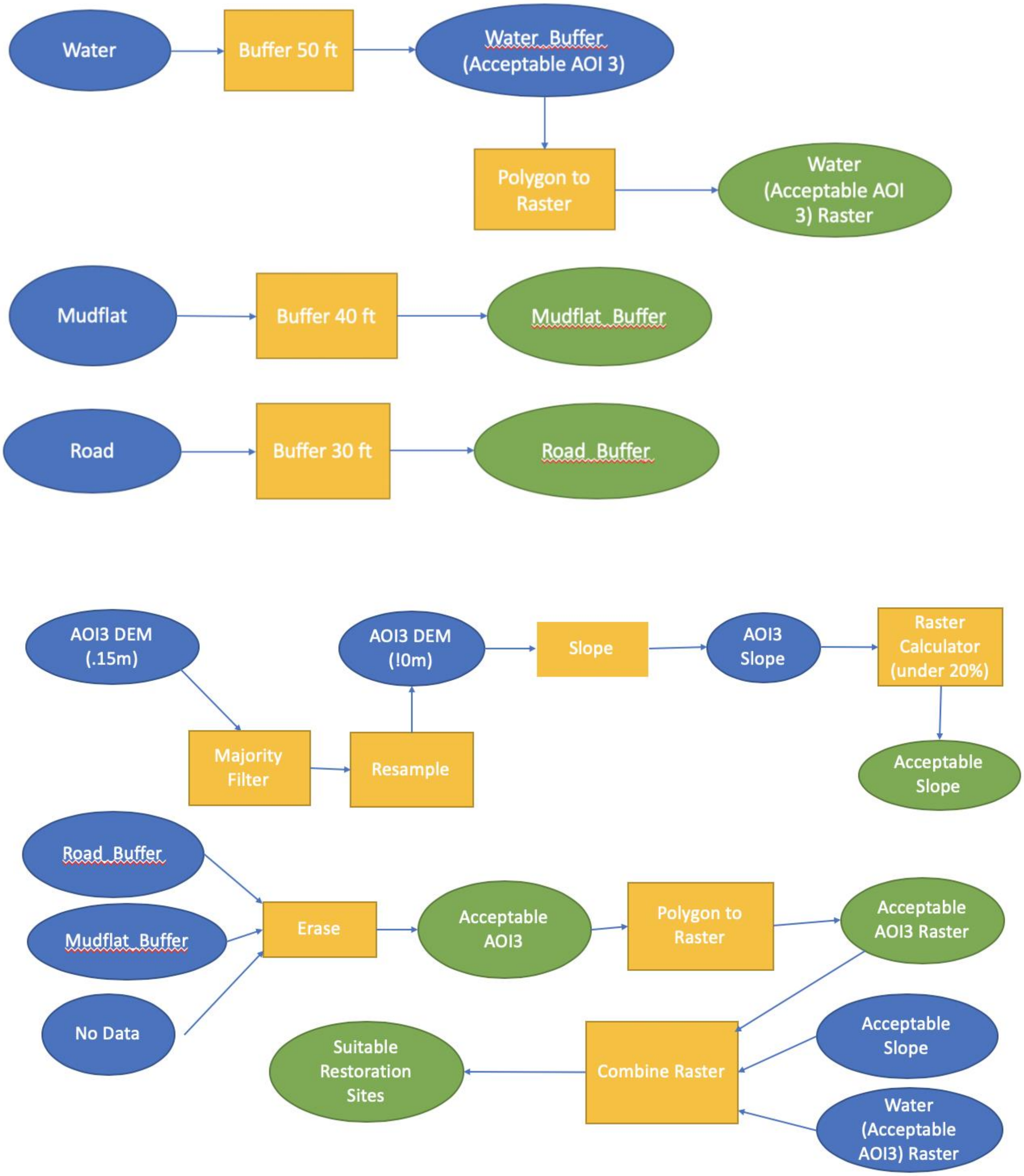


Figure 12: Model of the Restoration Site Suitability Analysis of AOI 3

Chapter 4: Results

This chapter details the results of the methods documented in Chapter 3 to create, classify, and analyze data to plan for restoration efforts. The research goals, which were outlined earlier, include: (1) examine the differences between restoration monitoring with a UAV as opposed to pedestrian surveys; (2) perform restoration site selection with spatial analysis from UAV data collection; (3) recognize the location and types of restoration that can be done.

4.1 Monitoring

The first goal of the study was to compare traditional wetland monitoring techniques, including pedestrian surveys and analysis of existing data, to UAV data collection. This relates to the quality of that data, which is determined by its usefulness and accuracy. As consistent monitoring of the sites is required, data quality is an important consideration, along with the variable of time. The time it takes to complete observations and the seasonality of data collection can vary greatly between wetland monitoring techniques.

4.1.1 Data Quality and Time

The quality of data created from the UAV flights is significantly better than what is currently being used. The existing imagery of the restoration sites can be found through Google Maps or Esri's Image Clarity Basemap; these are not regularly updated and are not acceptable for consistent monitoring. Pedestrian surveys, although can accurately identify changes near the boundaries of the areas of interests, cannot clearly view the interior of the restoration sites. Site monitoring with the Phantom 4 Pro V2 allowed for RTK, meaning no ground truthing was necessary and an 85% overlap of images was programmed to account for wind. With these controls, the imagery of all 3 areas were built with a resolution of 0.15 meters, or 0.5 inches. This type of clarity allows for incredibly accurate and comprehensive monitoring of the restoration sites. The accuracy of the data also helped create the best DEM of the Kahanaiki Restoration Area to date.

Another benefit of using a UAV to monitor restoration areas over the traditional pedestrian surveys is the amount of time dedicated to the task. The data acquisition and processing of all 3 areas took approximately 12-15 hours total. Accessibility of UAV data collection is an important consideration as well. After completing all three site in one day, it was evident that the data from AOI 3 did not cover the entire area. A second flight was quickly and easily scheduled to take place early one morning to make up the lost data. This would not have been possible without the ease and convenience of UAV data collection.

4.1.2 AOI 1 and AOI 2

The data collection for AOI 1 and AOI 2, the restoration ponds at Kawainui Marsh, took place on September 6 at 8:00 am. It was sunny, partly cloudy day. it was fairly windy with gusts reaching 30 knots. The two sites had separate flight plans but took about 2 hours to complete, including a battery change at each site. Figures 15 and 16 show the imagery created from these flights.

The data collection of AOI 1 created 621 JPGs and covered 37 acres. Pix4D was able to calibrate 100% of the images, which allowed for more photos to overlap creating higher accuracy and better results. Figure 13 shows the number of overlapping images computed for each pixel in the orthomosaic of AOI 1.

Figure 15: Imagery of AOI 1

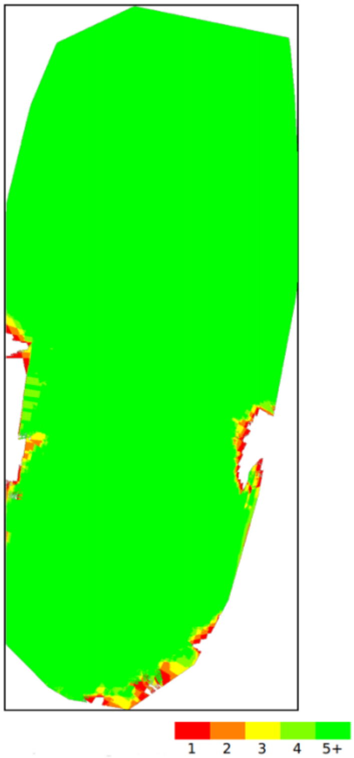


Figure 13: Number of Overlapping Images in AOI 1

The data collection of AOI 2 created 678 JPGs and covered 41 acres. Pix4D was able to calibrate 93% of the images with fewer overlapping images around the border of the site, which served as a buffer for the ponds. Figure 14 shows the number of overlapping images computed for each pixel in the orthomosaic of AOI 2.

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community, Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 16: Imagery of AOI 2

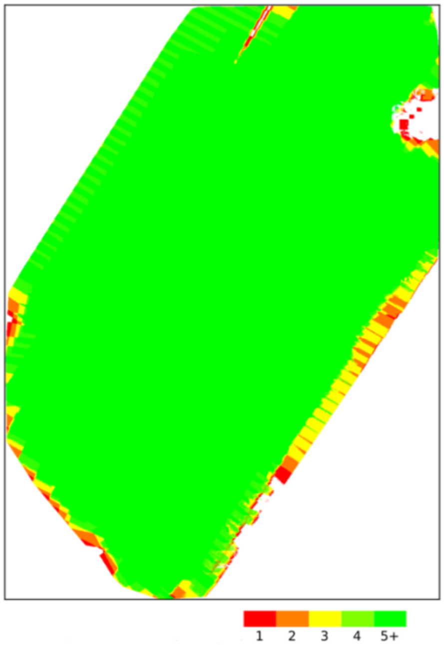
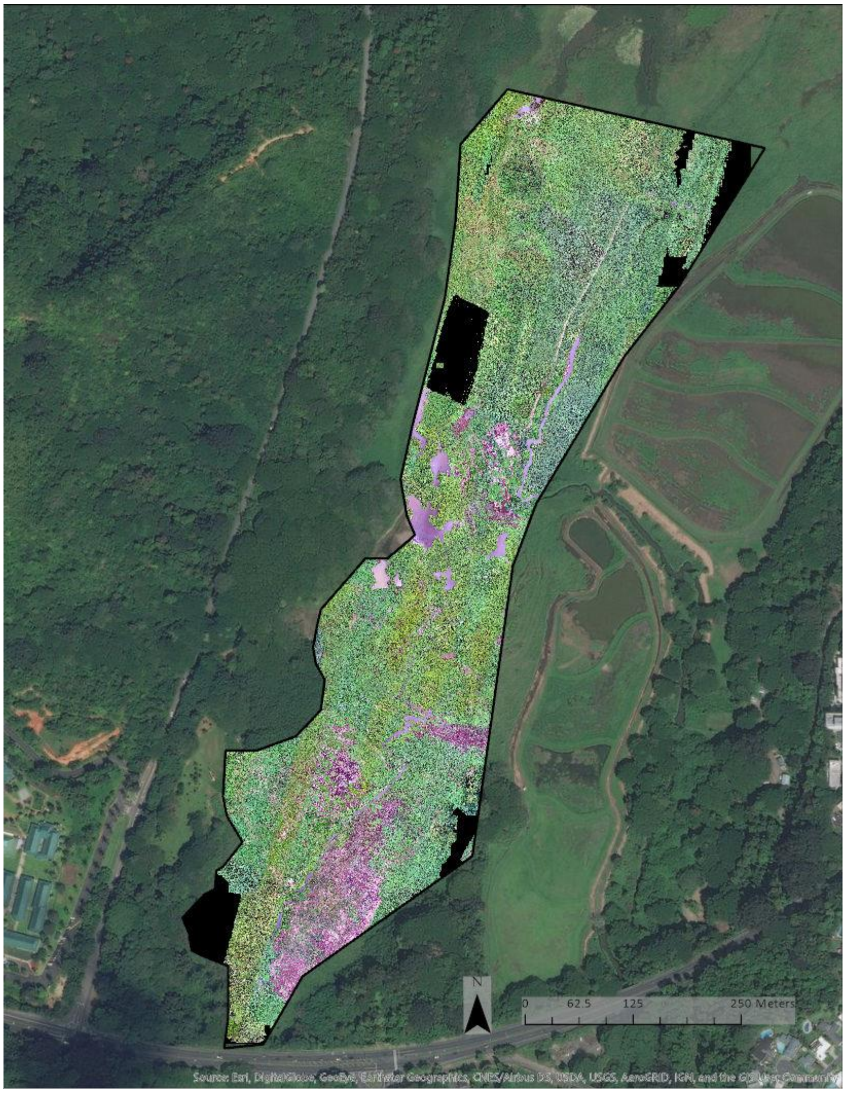


Figure 14: Number of Overlapping Images in AOI 2

4.1.3 AOI 3

The data collection for AOI 3, the Kahanaiki Restoration Area took place on September 23 at 8:00 am. The conditions were overcast with rain in the surrounding areas. The project site was dry with low winds. The flight took 2 hours to complete, including 3 battery changes. The 1,696 JPGs covered the 85-acre project site. Pix4D combined the images in 4 hours with 77% calibration. Figure 17 shows the number of overlapping images, with low numbers mostly at the edge of the area and near any missing photos. The areas with poor imagery overlap created blackout spots, shown in Figure 18, the final imagery of AOI 3.

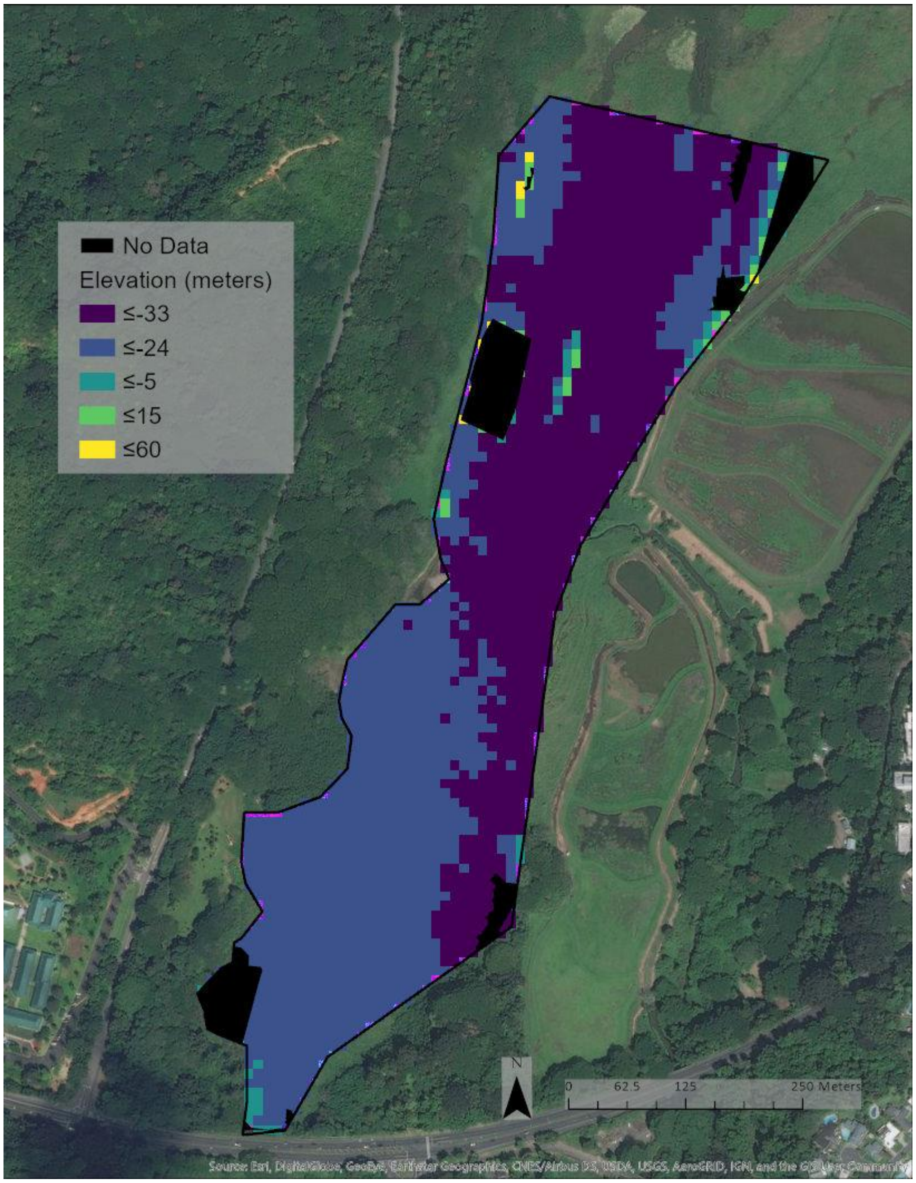


Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 18: Imagery of AOI 3

Figure 17: Number of Overlapping Images in AOI3

A 3D point cloud of AOI 3 was also created using Pix4D. The process of converting the 8 tile .las file into a DEM is outlined in Chapter 3. A spatial resolution of .5 inches was created showing subtle changes in elevation. The DEM was spatially aggregated into a raster dataset with a resolution of 10 meters to alleviate errors. This surface layer was then used to visualize elevation within in the site.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 19: Digital Elevation Model of AOI 3

4.2 Data Classification and Analysis

The final goals of the project including classifying imagery from data collected with a UAV and to determine potential restoration areas. This portion of the research was completed using data from AOI 3 with the intention of narrowing locations where native plants will flourish.

First, the ArcGIS Pro Classification Wizard was used to identify features of interest for a multi-criteria evaluation of the Kahanaiki Restoration Area. The supervised classification computed pixels showing precise locations of the mudflats and streams or water. Urban land use was initially included in the classification; however, none were found within the buffered project site. Therefore, the nearby roads were created as features in the geodatabase as a precaution for the analysis. Specific plant species were also identified; although, majority of the area was covered by mixed non-native plants showing no dominant species. The plant groups that were able to be definitively identified included non-native mixed forest, Lau'ae (non-native fern), and non-native Papyrus mixed with an unidentified vine. Although there were no identified native plants to use in the final analysis, data of the non-native plant groups was included in the geodatabase for DOFAW to use in future research.

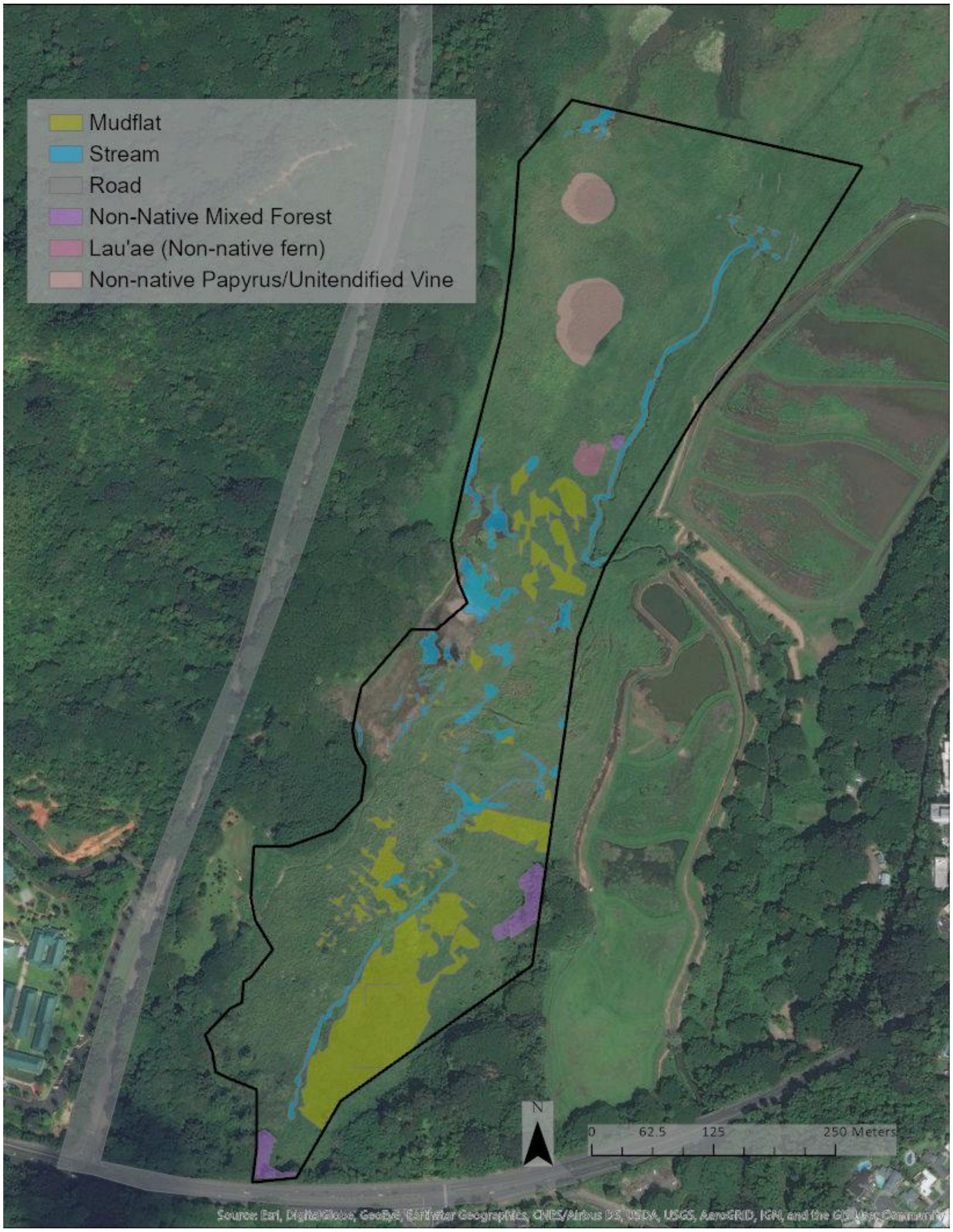


Figure 20: Classified features found within AOI 3

Another important element of the restoration site analysis was the slope within AOI 3. Because a large portion of this area is below sea level, slope can be critical in terms of accessibility for mitigation work. Figure 21 shows the percentage of slope that was calculated from the 10-meter DEM. There are gradients ranging from less than 1% to more than 60%. However, majority of the area has a slope of less than 20% incline.

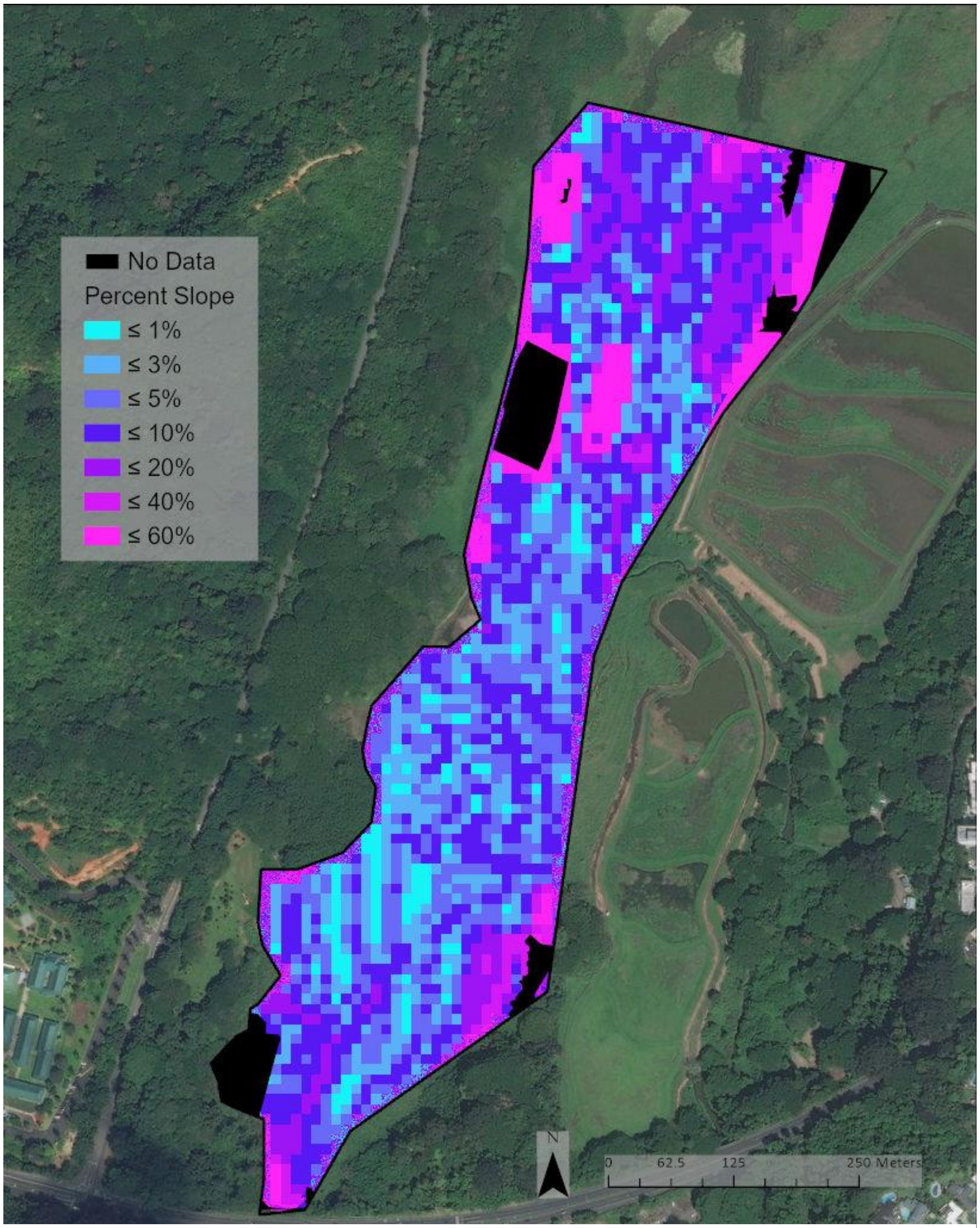
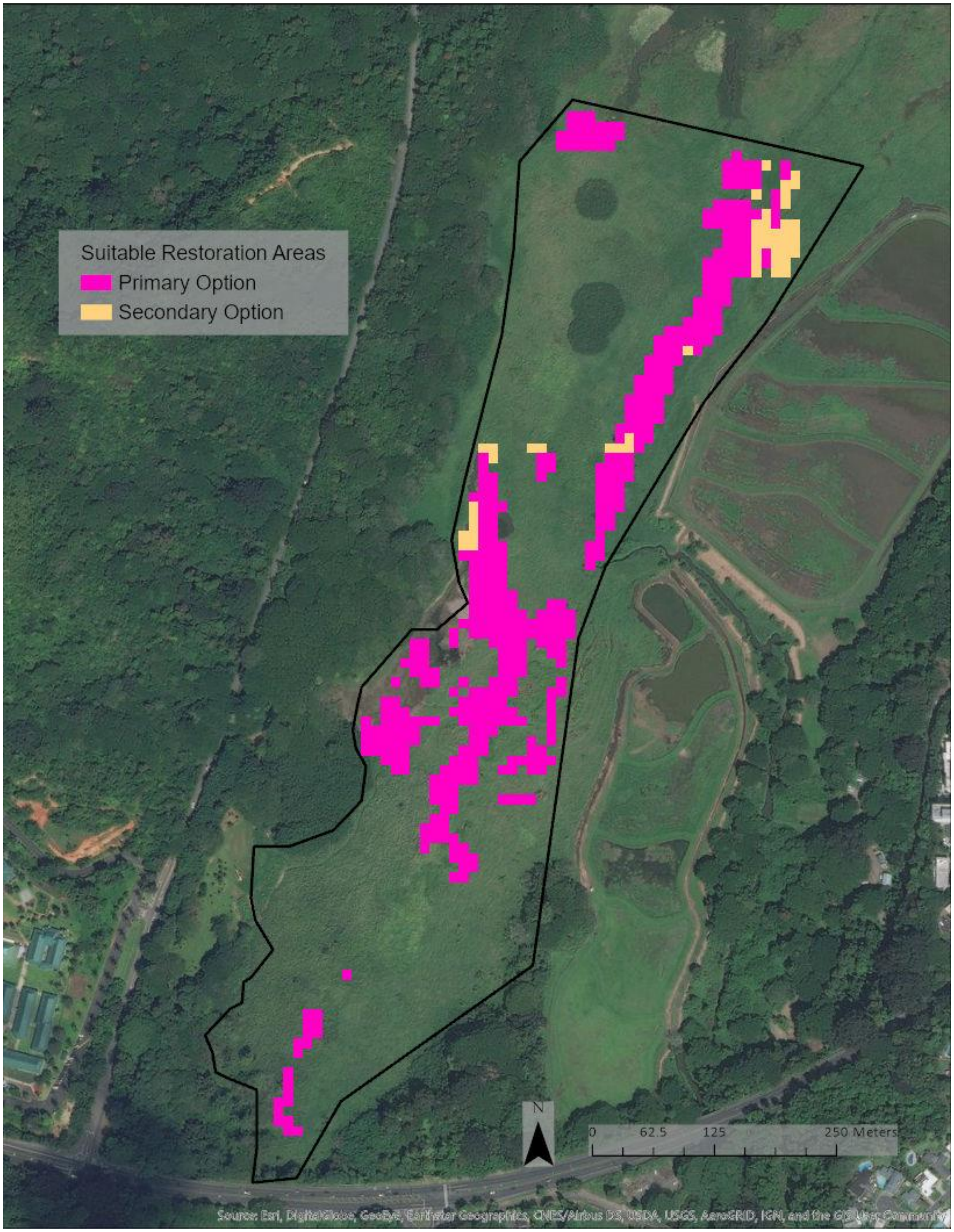


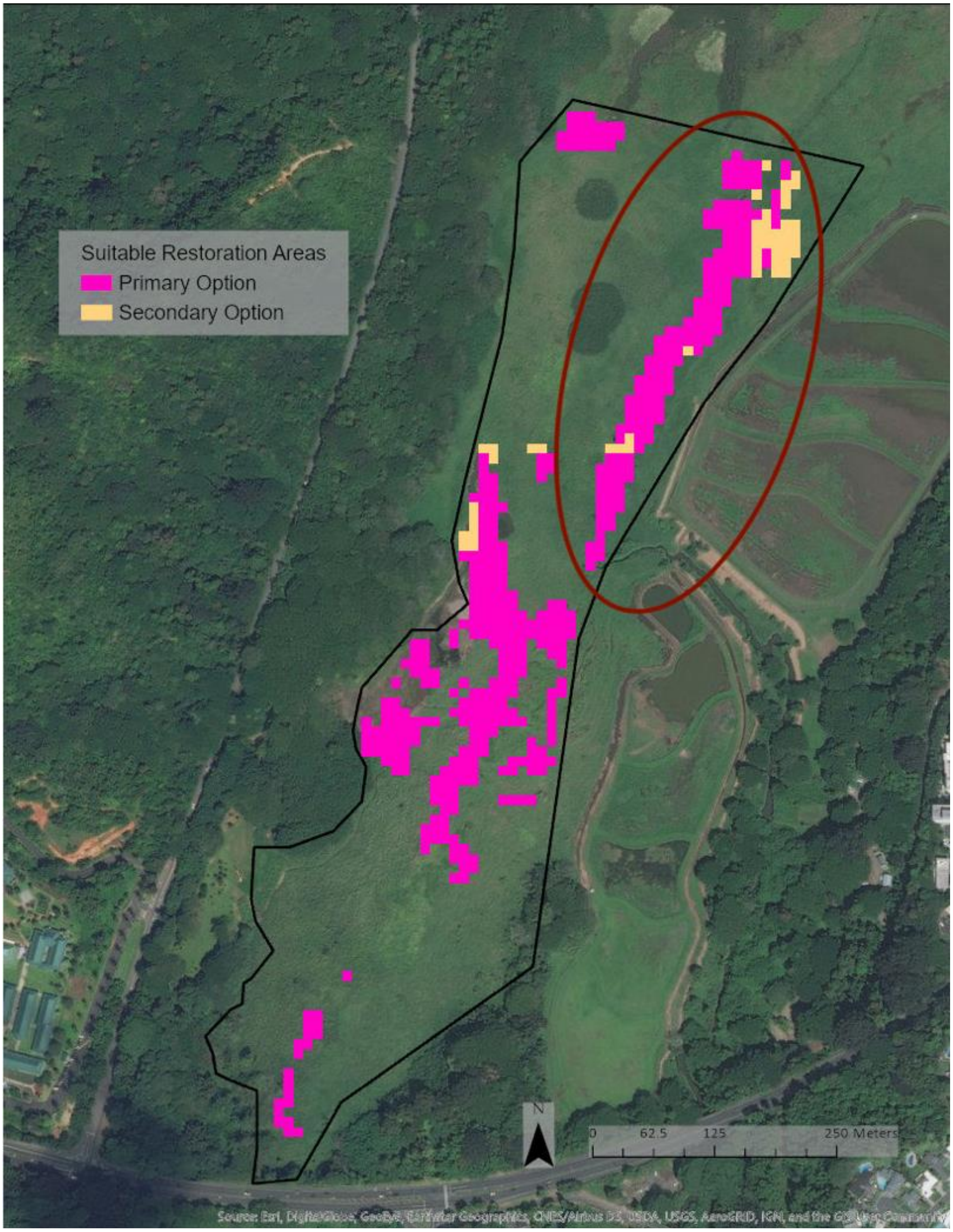
Figure 21: Percent slope within AOI 3

The final step in the analysis was to use the acquired data to perform a multi-criteria evaluation of AOI 3. The process of creating, organizing, and combining surface layers produced an output showing primary and secondary sites. Meaning, each pixel within the final, combined raster was given a score between 1-3. The 3 layers of criteria included a slope of less than 20% incline, areas with positive attributes (within 50 ft. of a water source), and sites to exclude (40 ft. from mud flats, 30 ft. from roadways, and areas with no data). These specific locations were given a score signifying how many of the conditions were met and therefore, their potential success for native plant habitation within the Kahanaiki restoration area. The most ideal sites for native plant establishment are outlined in Figure 22. This study has also outlined recommended areas within these sites to begin restoration efforts. The area highlighted in Figure 23 was chosen based on ecological factors and accessibility. The recommended site is near AOI 2, which serves as a migratory bird habitat. By planting native plants close by, the habitat could expand and attract more native birds. Along with this, there is a nearby, elevated road along the selected site making for easy access.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 22: Suitable sites for native plant establishment within AOI 3



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 23: Recommended site for native plant establishment within AOI 3

Chapter 5. Discussion and Conclusion

This chapter discusses the significance and problems with the study, including findings, advantages and disadvantages of monitoring with a UAV, and suggestions for future studies.

5.1 Findings

The methodology of the study allowed 3 research goals to be reached: (1) There are time and accuracy benefits to monitoring restoration with a UAV as opposed to pedestrian surveys; (2) a UAV and spatial analysis can successfully perform restoration site selection; (3) Mitigation efforts including native plant establishment within the specific sites outlined in Chapter 4 are recommended.

5.1.1 UAV vs. Pedestrian Surveys

Using a UAV for restoration monitoring is more advantageous than pedestrian surveys. Based on conversations with the biologist at DOFAW who is responsible for these areas, it takes at least 2 days to cover the areas by foot, or more depending on weather and how in depth the survey is. The data acquisition and processing of all 3 areas took approximately 12-15 hours total. Although the timing may seem similar, the data that is acquired with the UAV includes more precise imagery of the entire area as opposed to pedestrian surveys taken from the boundaries of the AOIs. An in-depth analysis at a .15-meter resolution is more accurate, and therefore more valuable. This accessibility can also be taken into account during seasonal changes. Pedestrian surveys may not be possible during the rainy season (November through March) as the areas can undergo extreme flooding. As monitoring must be done during this period, a UAV survey may be the only option.

5.1.2 Restoration Site Selection

The general features of AOI 3 were easily classified with ArcGIS Pro's Classification Wizard, including streams, mud banks, and urban land use as the pixels associated with these features were clearly identified. The high spatial resolution of the imagery allows for other variables to be created as new features if necessary, as well. However, the vegetation did prove to be difficult to classify. Majority of AOI 3 was clearly a mix of non-native plant species, yet there were a few sections with signs of one dominant species. These signs included difference in color, elevation, and texture. If more time were available, the study would have benefitted from identifying these sections of dominant species and performing another round of flights at lower elevations to get more precise imagery. From there, more classified vegetation layers could have been created for future research.

5.1.3 Native Plant Establishment

The study also outlined specific locations where native plant establishments are recommended within AOI 3. The original scope was to locate the native plant species and work to replenish and restore those areas. Since no native plants were found within AOI 3, the primary and secondary options for restoration focused on areas where native plants could be successful. As outlined in Chapter 2, this includes observing the hydrology and elevation changes within the wetland area. Although restoring an area without existing native species is more difficult to accomplish, it could be a worthwhile endeavor to reestablish the native bird habitat. The first criteria included was slope of less than 20% incline. This allows for easy access by foot or by machine. Next, areas within 50 ft. of a water source were determined to be the best place for plant rehabilitation. This was determined from the imagery because most plant diversity was seen along the water sources. The analysis also took into consideration sites with attributes that should be excluded. Areas within 40 ft. of the mud flats were eliminated, as these are known native bird nesting areas that take first priority, as well as areas that are 30 ft. from urban land use and roadways, which have a high potential for invasive plants. Finally, the “No Data” areas found in the data were exempt from the analysis altogether. The overlay analysis considered general characteristics where native plants may grow successfully.

5.2 Advantages and Disadvantages of UAV Data Acquisition

There are advantages and disadvantages to using UAVs as a strategy for data collection in wetlands, however it is evident that as the technology continues to develop, and with adequate survey time, drones are a successful type of remote sensing. The major advantages to using a UAV for data collection include controlled accuracy, the ease of data collection, and the cost. The orthomosaics that were created of the 3 AOIs were built with a 0.15-meter, or 0.5-inch, spatial resolution. The surface layers were incredibly detailed, where blades of grass could be seen from the imagery. When taking the short time frame for data collection and processing into consideration, this is one of the greatest benefits. This efficiency is what makes the methods repeatable. The UAV is very user friendly and can be monitored without the user moving far from the launch site. In the study, AOI 3 had to be flown twice due to problems with the boundary and the ease of the drone’s setup/breakdown allowed for a last-minute survey. The data collection process is quick, DroneDeploy is easy to use and allows for repeatable flights.

Lastly, the cost of using drones is low compared to the pedestrian surveys that are typically done in the area. The initial cost of a DJI Phantom 4 V2 is around $1000. Each photo processed in a Pix4D account comes to roughly $0.05/photo. For this research, the cost of processing totaled around $150.00. A weekly monitoring of the 3 areas may take multiple days for the DOFAW biologists to complete, making labor costs quite high. The entire data collection was done in 4-6 hours and the processing was all done overnight. This leaves more time for biologists to complete other work and high-quality data to be tracked visually with orthomosaics.

Table 2: Costs of monitoring Kawainui restoration sites with pedestrian and UAV surveys

Pedestrian Survey		
Labor Hours for Wildlife Biologist	Average Income of Wildlife Biologist	Total cost of pedestrian survey
~ 20 Hours	$62,000	~ $600

UAV Survey		
Labor Hours using Drone	Cost of Using UAV processing (not including initial cost)	Total cost of monitoring with UAV with labor
~ 6 Hours	$150	~ $330

The use of a UAV for data collection is clearly advantageous, however there are some technological issues and potential problems that may arise when weekly monitoring relies on it. The low battery life of the drone was thought out prior to completing the methods and the automatic return of the UAV to return to its launch site made the battery change process straight forward. However, it should be noted that the UAV and the DJI application had to be rebooted and reconnected after each battery change. This was not detrimental to the study but did add time to the total data collection. Another potential hindrance of UAV data collection is the inability to control data quality. Although UAVs allow for relatively easy rescheduling due to rain, wind, etc., the subtle differences in weather may impact the quality of data. There was a noticeable difference in the imagery collected on a bright, sunny day verses the overcast day. AOI 3 was covered on the overcast day where the clouds seem to mute the brightness, making the different shades of green vegetation more difficult to decipher. There were also obvious patches of dark spots in the imagery where clouds were directly overhead. On a windy day, these clouds could move quickly and potentially alter the imagery. Weather is an influence that cannot be controlled; therefore, the cameras will need to strengthen to avoid these issues. As the technology associated with the battery life and quality of cameras on drones increases, these disadvantages may lessen.

The most obvious issue seen from the orthomosaic of AOI 3 are the blackout spots where no data was collected. This is most likely due to an error imagery overlap creating errors within Pix4D during the processing. Although an 85% overlap was assigned, the application was unable to stitch specific areas of data. The Pix4D support page attributes this error to the difficulty of identifying specific characteristics within dense vegetation. This could be problematic in any wetland area, as they tend to include similar vegetative imagery. The recommendation for this is to fly higher, which could lessen the resolution.

5.3 Future Research

This research brought about other methods that could create better data and easier analysis, as well as related future studies. If the study were to be recreated with similar timeline, equipment, systems, and software an initial flight would be completed first at a higher elevation, around 300 ft. This would alleviate the potential for blackout spots and take up less processing space and time. The imagery with lower spatial resolution could then be analyzed closely and areas where more detail is needed would be identified. A second round of flights would be scheduled at a lower elevation, around 50 ft., to make the process of classification easier. This would allow for more detail at specific sites where it is necessary.

Calibration panels could also be purchased for about $50 to assist with accurate data collection if this exact study were to be repeated. They could be added to the workflow in

Pix4Dto assist in normalizing conditions during data collection. This would alleviate the difference in imagery due to weather conditions, allowing for more accurate landcover classifications. For example, the mudflats and non-native mixed forests would look more consistent across sites, despite varying reflections.

5.3.1 Multispectral Sensors

The study could also be progress with the inclusion of sensors on the UAV. Until recently, multispectral sensors have been too heavy and bulky to be used on UAVs. Along with most drone research, the agricultural industry was the first to use multispectral sensors to calculate information about their crops (Boon and Tesfamichael 2017). As the cameras found on drones have gotten better, they are able to include Near-Infrared (NIR), Red, Green, and Blue wave bands (DroneDeploy n.d.). These light sources are used to create multispectral imagery, which can then be used to calculate and accurate monitor the vegetation and wetness of wetlands. Future studies may benefit from using drones with more sensors to calculate vegetation and wetness, as well as solar irradiance.

The Normalized Difference Vegetation Index (NDVI) is the most common sensor for detecting live vegetation. It can also be used to calculate plant health by detecting the near NIR light bands that reflects off of the leaf and back into the atmosphere. The more chlorophyll, green colors, signify plant health (DroneDeploy n.d.). NDVI works by calculating values based on the amount of green light that is reflected from a pixel. Values range between -1 and +1, where negative values indicate little to no vegetation and numbers closer to +1 show higher concentrations of green, healthy, vegetation (Wu 2018). Specific plant species may also be calculated based on these reflectance values; however on-site evaluation is also necessary for complete accuracy. NDVI calculations can also be verified with multiple software. (Boon and

Tesfamichael 2017). For example, DroneDeploy, Pix4D, and ArcGIS Image Analysis all have NDVI functions if the UAV has a NIR sensor.

The ability to accurately calculate a wetland's "wetness" is also crucial to understanding its growing season. Sensors like the Normalized Difference Water Index (NDWI) and Topographic Wetland Index (TWI) can be used to learn how much water does, and could exist in an area, Wetness is easier to identify than dryness through remote sensing because of the dark, multi-spectral tone that is reflected off of water of moist soil. NDWI is similar to NDVI in that it uses a spectrum between -1 and +1 to detect water features. Negative values indicate no water, while values closer to +1 show pixels with higher amounts of wetness (Wu 2018). The calculated DEM can also be used to derive information an ecosystems vegetation and wetness by using TWI. TWI uses elevation change to calculate the tendency of a grid cell to accumulate water. The higher the TWI of a cell is, the more potential it has for the presence of water, a key metric in the area's ability to host native plants (Wu 2018).

Multispectral cameras also have sunshine sensors, which can measure solar irradiance in an area. This could be used to monitor how much sun is being absorbed at any given time, which could in turn affect wetness of the site and vegetation's response to solar energy. Understanding solar irradiance can also improve the classification accuracy when training vegetative features.

5.3.2 Seasonal Changes

Finally, one of the benefits of using a UAV to monitor and analyze a wetland is the ability to repeat the methods. It is evident that to properly manage and conserve wetlands, change needs to be monitored sufficiently. The Kawainui Marsh has distinct dry and rainy seasons in which the streams may go from completely dry to flooding the wetland. DSM can be calculated using Pix4D's 3D point cloud, therefore water depth can be monitored over time as well. Restoration decision making, such as the introduction of specific plant species, could depend on this information. Understanding this seasonal change and how it affects the vegetation and streams could be beneficial for identifying future restoration sites and native bird nesting sites, as well as potential threats, such as invasive species. Ideally, this study would be repeated at the start and end of each season, so roughly in March, May, September, and November. Recording how a place may change over time is crucial for restoration site planning, and UAV data collection makes this process accessible.

UAVs with multispectral cameras can also be used to study reforestation efforts across time using the DSM. This can be done by calculating biomass of individual plant species, as well as forested areas. The results can be compared over time to identify healthy growth or deforestation. Raster datasets showing biomass may be aggregated into voxels covering 3D space. This would allow for biomass of native vegetation to be calculated not only be how much area is covered, but by height as well, which would show accurate vegetation volumes. Biomass data is crucial to understand effects of climate change and to assist with restoration and mitigation.

5.4 Conclusions

As technology advances, and higher quality cameras become more available, UAVs may become the most practical form of wetland monitoring and restoration planning. UAVs are successful, and arguably necessary, for monitoring wetlands, especially in terms of seasonal change. The flexibility of the data acquisition with a UAV allows controlled monitoring in a shorter period of time than existing pedestrian surveys. Along with wetland monitoring, UAVs have proven to be valuable for restoration planning. This study concentrated on native plants and although none were found in the Kahanaiki restoration area, the analysis located areas where native plants could be established. It is evident that mitigation planning with the UAV requires a specific focus, whether that be native plants, invasive plants, hydrological conditions, or soil types. There is potential for more detailed data, and therefore a more accurate suitability analysis, with the inclusion of multispectral sensors. Additional sensors would allow for the inclusion of NDVI, NDWI, TWI, and solar irradiance measurements. Along with these sensors, understanding seasonal changes in a wetland area is necessary for restoration monitoring and planning.

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