AN ASSESESSMENT OF SUAV BASED AERIAL IMAGERY:

MODELING FLUVIAL INTERACTION OF BANK ARMORING STRUCTURES IN RIVERINE SYSTEMS

by

Megan E. Tuttle

A Thesis

Submitted in partial fulfillment

of the requirements for the degree

Master of Environmental Studies

The Evergreen State College

June 2019

This Thesis for the Masters of Environmental Studies of Environmental Studies Degree

by

Megan E Tuttle

Has been approved for

The Evergreen State College

By

____

Mike Ruth

Member of the Faculty

____

Date

ABSTRACT

{Title of Thesis -- single-spaced
if on more than one line}

{Your Name}

ABSTRACT

An Assessment of sUAV Based Aerial Imagery:

Modeling Fluvial Interaction of Bank Armoring Structures in Riverine Systems

Megan E. Tuttle

Geomorphological change in riverine systems occurs across a wide range of temporal scales. Modeling change with high frequency could capture the complex behavior of the interactive dynamics between engineered structures in riverine systems. The objective of this work is to demonstrate the capability of SUAV's imagery for monitoring large scale structural projects interjected into riverine systems. The objective of this research is to capture and process imagery that could classify bank armoring structures as either successful or stable in potentially hazardous locations. In addition to capturing the structural integrity of the structures it is also proposed that this research could aid in monitoring habitat used by adult and juvenile salmonids. sUAV's provide an inexpensive way to capture large scale structural implementation and for restoration projects, bank protection methodologies, as well as general habitat monitoring.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank my faculty advisor Mike Ruth for his support in getting this project up off the ground. Mike's teachings of GIS and spatial analysis skills led my research to new heights that I could not have ever imagined. I was able to conduct concise and successful field research and data processing workflow using the skills he has equipped myself and many of his other students with.

The base of this project would not have been possible without the license provided to me by the Esri Conservation Board to utilize the Drone2Map software. I am so grateful for the Conservation Board granted me the ability to enhance the imagery captured in this research and develop models that were the foundation of my thesis.

I would also like to extend mass gratitude to my field and research advisor Jane Atha. Jane provided me with the additional tools I needed to have high accuracy in the field, direction for my research, as well as a path that was clear and concise to help me stay on track throughout. Her support helped me navigate the fluvial aspect of my research at many critical stages of the study.

I would also like to thank my husband Aaron Tuttle for his endless support not only though my thesis work but for my entire academic adventure. I am so thankful for his sacrifice of time and support in and out of the field.

In addition to those who supported me through the data collection and the processing, this whole project could not have been completed without the permission from the landowners from the sites that I flew. To Stormy and Shirley Glick as well as Cliff and Betty Perry. I could not be more thankful for your open welcome to let me fly your properties in addition to your inquisitive questioning and spark of interest in my project. Thank you for allowing me to stake out your property, leave flags, and conduct the drone overflights that are the core of this thesis.

Literature Review

Introduction

Aerial based imagery collected using sUAV's is considered cutting edge for the natural sciences. High resolution imagery such as orthomosaics and 3D models are proving as a relevant data source in habitat classification, categorization of riparian areas, and riverine hydraulic research (Arif, Gülch, Tuhtan, Thumser, & Haas, 2017). The use of sUAV's is increasing with environmental research in riverine environments due to the remote sensing capabilities. Small unmanned aerial vehicles provide less costly data than that acquisitioned by standard manned aerial vehicles for a specific research location (Science, 2012). Riverine research or monitoring locations typically have a very specific target site or research location, therefore using sUAV's to obtain site specific data increases the usage appeal. In comparison using a standard aircraft or satellite imagery increases flight time, imagery cost, and time that flight data reaches the researcher (Science, 2012). Many researchers also rely on satellite based remote sensing imagery. Satellite imagery is often outdated imagery, and can reflect older land use practices in an area (Science, 2012). The satellite imagery often does not represent real time data that sUAV's can obtain during a flight in the desired location.

Using Small Unmanned Aerial Vehicles in Science

Before recently there has been a stereotype around sUAV's used as highly technical devices primarily for militia style reconnaissance missions and undercover missions. The categorization of sUAV's as highly capable devices has been a factor in discouraging state agencies and conservation groups from using so-called "drones" for imagery acquisition. Skepticism from the general population has also been a concern from state agencies. However, the use of drones has just recently been adopted by Washington state agencies such as the Department of Fish and Wildlife. With countless parameters of public informational meetings and press releases before every flight conducted the department has begun to integrate flights into restoration and project research.

Small unmanned aerial vehicles have dropped in cost. The lower cost makes them more affordable for state agencies and conservation groups. Limiting factors such as funding and privacy restrictions have been the reason sUAV's have not become as prevalent in current environmental research. Due to the lowering cost and public acceptance, the continued use of sUAV's could lead to monitoring techniques that will reduce research and monitoring costs for state agencies and conservation groups (Science, 2012).

In recent years the use of sUAV's has excelled in the engineering world to create digital elevation models (Martínez-Carricondo et al., 2018). Digital elevation models or DEM's are used to survey a landscape and run spatial analysis on areas of interest. Using sUAV's in correlation with large scale engineering projects integrated into natural systems is a developing method used as a communication tool for the public as well as other state agencies. Developing surface orthomosaics of a desired project site for both post monitoring of a project as well as defining areas of concern pre-project construction is developing into the standard practice. Due to previous cost restraints periodic monitoring of sites was the only viable option due to high cost and minimal people to survey sites from the ground. Data collection using traditional ground survey methods was not as easily quantified compared to the newly developing methods of frequent image acquisition using sUAV's(Martínez-Carricondo et al., 2018). A site can be flown using an sUAV multiple times per year and the data can be compared with higher frequency than was once collected using traditional methods of aerial photography or direct observation by ground-based survey methods.

As a result of using sUAV's more frequently and for pre and post monitoring efforts of engineering projects in natural systems, researchers are able to generate highly detailed reports of restoration efforts and quantify their success. Modeling natural systems response to a foreign manmade structure requires rigorous image acquisition of high frequency (Thumser, Haas, Tuhtan, Fuentes-Pérez, & Toming, 2017). Geomorphological change in natural systems, particularly riverine systems, occurs on a frequent temporal basis. Small unmanned aerial vehicles can help to determine practices for restoration projects and structural implementation. The imagery can help generate models of structural response, structural integrity after several hydraulic cycles, and fluvial interaction with a structure could lead to critical information obtained to providing evidence of successful restoration and structural implementation (Thumser et al., 2017).

Bank Armoring Structures

Bank armoring structures or "hard-armoring" structures are a common amenity in most Pacific Northwest rivers. Due to the complex geomorphological cycles and the intensity of the precipitation events. Riverine systems in western Washington often have complex meandering paths that threaten private entities and state infrastructure such as roads and bridges. To protect these entities from the river, the implementation of bank armoring structures are designed to redirect the river channel and flow to a less destructive path. Bank armoring structures are often constructed from large angular rock called “rip rap”, steel bulkheads, and concrete creating a less dynamic composition to the bank than was generated in the natural system (Li & Eddleman, 2002).

Bank protection methods dating from the 1960’s and 1970’s were designed with the sole intent to protect a landowner’s property or public infrastructure. Aquatic and terrestrial habitat were of less concern then due to further research of unknown impacts not yet obtained. The immediate protection from a rip rap implementation or a solid concrete wall was successful and was categorized as viable (Li & Eddleman, 2002). The impacts resulting from the hard-armoring structures were unknown due to minimal monitoring and expense of imagery acquisition. Though some structures implemented with the hard- armoring design still remain, many have succumbed to scouring and erosion due to their lack of complexity (Li & Eddleman, 2002). Reduction in vegetation and increased smooth surfaces increase approach velocities in the hydraulic path around the project implementation and create focused toe erosion and scour. The increased velocity scours under the structure and over a temporal scale of 30- 50 years generates a structurally unstable site (Li & Eddleman, 2002). Watersheds that have experienced the effects of non-dynamic bank protection structures are experiencing decreased geomorphological structure due to the removal of native vegetation species (Vespia et al., 2017). Bank protection structures and reduction in riparian density are all drivers in amplifying flood intensity.

Integration of Vegetation

Bank protection methodologies used for current projects have evolved from the project implementations used historically. Many state agencies once favored the previous hard armoring methods due to the reinforcement properties and sheer strength variables (Li & Eddleman, 2002). Value in integration of vegetation into riverine armoring structures has become more prevalent in the past decade. Projects referred to as “biotechnical hybrids” and “green or soft armoring” have become mandatory in design proposals required by both state agencies and conservation groups. Biotechnical bank protection projects include the use of various native plant and tree species as well as large woody material designed to mimic natural riverine morphology as a bank protection methodology (Li & Eddleman, 2002). The Washington State Department of Fish and Wildlife has adopted this method and aims to increase habitat quality for both aquatic and terrestrial species by requiring the design of these structures to now include such features. Using sUAV’s to determine the value of riparian areas and integrated biotechnical armoring methods on a temporal scale is a developing research methodology.

Because most river systems in the western Washington are currently altered by anthropogenic impacts, the biological impacts on habitat loss is often secondary thought. The implications of critical habitat loss are infinite, however the most prevalent are invasive vegetative encroachment, shade resistant foliage, controlled flood regime, and lack of sediment transport. These processes and their relations all define a threatened or unhealthy watershed (Brooks et al., 2004). The need for heterogeneity in bank material, vegetation, and spatial allowance is essential for a healthy watershed. Meandering channels that are unaltered by bank armoring structures provide critical habitat to species throughout the Pacific Northwest. Their ecosystem function as wildlife corridors, spawning grounds for salmonids, as well as protected riparian zones are indispensable to maintain an effort for ecological balance. If healthy riverine systems are not continually identified and are continually degredated by human impact, complex habitat and biodiversity is at risk (Schook et al., 2017).

A healthy watershed consists of a heterogeneous composition of characteristics. Plunge pools, diverse vegetation, wetlands, and braided channels are characteristics logistically vital to the reduction of erratic seasonal flow dynamics. Current research in the hydrological community has illuminated the importance of environmental stochasticity and vegetative variation within riverine ecosystems (Vespia et al., 2017). The role of high disturbance flow regimes plays an extensive role in the distribution and recruitment of new growth vegetation (Hession & Curran, 2013). After a high flow event, sediments transported provide a foundation for new recruitment, seed dispersal, and root stock transport (Vespia et al., 2017). Areas with the highest new growth establishments rates are those with the deposited nutrient rich sediments transported by the flood waters, often referred to as pointbars and islands (Vespia et al., 2017). In riverine systems, mass disturbance sites as described previously play an integral role as nursery grounds for new plant development (Vespia et al., 2017).

Integrating vegetation with bank armoring structure designs increases root composition complexity, terrestrial habitat, aquatic habitat, and the strength of implemented bank armoring structures (Li & Eddleman, 2002). Although failure of bioengineered structures is plausible, increased ability of engineers to calculate the strength of these structures continues to advance. Analysis demonstrates that the vegetative methods are decreasing flow degradation as well as providing ecosystem services to river communities (Li et al., 2002). Vegetation by nature is self-healing, thus allowing for further recruitment and replacement if scoured by high water events. Using bank stabilization as mitigation for high flow events reduces vegetative complexity, while vegetation provides the environmental advantage of stream coverage, temperature reduction, water quality, fluvial roughness, and increase of water retention capacity in anthropogenically influenced areas (Konsoer et al., 2015).

Bank erosion is a fundamental process that spurs platform changes along the paths of meandering rivers, contributing added sediment to the networks of channel (Konsoer et al., 2015; Rhoads et al., 2015; Langendoen et al., 2015; Best Ursic et al., 2015; Abad et al., 2015; Garcia et al., 2015). The importance of bank stability as well as erosion can have inverse effects in different locations of the watershed. In the headwaters and transitional zones, it is essential that rivers meander and erode banks to slow flows, gather sediment and nutrients to transport to the lower river to offload and stabilize healthy riverine ecosystems. Inversely, if channels are not able to migrate, potential damage to human inhabited areas will likely increase due to higher velocity of the river and larger materials transported such as large woody debris (Brooks et al., 2004). Bank stability being dependent on vegetative properties such as root systems and heterogeneous soil compositions for stability (Konsoer et al., 2015) continue to be altered due to bank armoring structures. If allowance of naturalized hydraulic processes such as the integration of biotechnical bank protection structures does not continue, then increased damage to private property and state infrastructure is imminent.

To accurately analyze bank armoring structures, it is imperative to have an established record of channel movement and structural response, as well as analysis of the interaction of the channels with the surrounding habitat. Establishing a methodology using sUAV's can determine a baseline for future data collection and later justify proposed restoration efforts in areas of anthropogenic influence (Brummer et al., 2006; Abbe et al., 2006; Sampson et al., 2006; Montgomery et al., 2006). Using sUAV's for hydraulic modeling and field investigation can be effective for investigating and compiling data regarding bank armoring structures.

The continued use of sUAV based imagery to monitor the fluvial interaction of bank armoring projects and riverine systems has the potential to introduce methodologies used to determine the success of different methodology types. Understanding the geomorphological processes of riverine systems requires multiple layers of analysis involving complex research approaches. Applying sUAV based imagery methodologies to restoration projects of any size also develops a temporal understanding of how the methods are developing over time (Thumser et al., 2017). To obtain optimum information of how riverine systems and other natural systems are responding to anthropogenic structures, it is essential to identify weaknesses in design. Small unmanned aerial vehicle-based imagery provides a low-cost solution for understanding the physical and temporal process of fluvial response to integrated structures in natural systems.

CHAPTER I

1. Introduction

Rivers in the Pacific Northwest are defined by their complex geomorphological characteristics. Stream stabilization or armoring techniques have been the desired method to refute the meandering behavior of complex riverine systems over millennia (Polvi, Wohl, & Merritt, 2014). Bank armoring structures such as the ones reviewed in this research are used to protect private property and infrastructure from the meandering behavior of the river. Engineered bank protection methods using angular riprap, bulkheads, concrete, and rock groins or riprap barbs are the most common in the Pacific Northwest.

The Satsop River and the Wynoochee River are two rivers where Washington State agencies have installed major bank armoring structures to control river channels and protect both private and state infrastructure. Each river has large bank protection structures that have been in place for a minimum of five years. Each protection structure has experienced several hydraulic cycles including abnormal high-water events through their constructed lifespan. The armoring structures analyzed for this research were all methods used by the Washington State Department of Fish and Wildlife. Each location was situationally different and required a different approach for bank protection methodology. The engineering design for protection methodology was based on flow direction, location of entity needing protection and proposed redirection of the channel. All three of these locations have experienced toe erosion and high intensity scour from recent high flow events. Though each methodology was different in design, all three of these locations were protected using a hybrid methodology consisting of riprap rock and large woody material to try and stabilize the banks. Due to time restraints and the threat of losing a privately-owned home, the mainstem Satsop River site was less complex in design than the other two research locations.

Small unmanned aerial vehicles or sUAV based photogrammetry has entered the natural sciences and engineering field as a tool that is creating a cost-effective way to concisely evaluate an areas scope of project. Small unmanned aerial vehicles have shown their capabilities of high-resolution image capture resulting in a low-cost methodology to create models used for restoration science, engineering design, or monitoring methodologies for state agencies and other private entities. The high precision image capture from currently available sUAV devices requires significantly less time to process data. The lower processing time for sUAV imagery is an incentivizing cost reduction compared to standard manned aircraft imagery (Martínez-Carricondo et al., 2018).

Data collected using sUAV's can determine current flow pattern, hydraulic response, structural integrity, design type, and overall success of a riverine bank armoring structure. Capturing aerial imagery of the seasonal fluvial dynamics in response to the engineered structures could accurately determine effectiveness of design type in many different channel types and scenarios. Placing physically non-dynamic structures into riverine systems has been less monitored over the past several decades due to the high cost of image acquisition using manned aerial overflight methodologies and the potentially hazardous conditions influencing the structure.

The need for the introduction of more frequent monitoring has been recognized by state agencies. Using sUAV's to collect data used to determine the effectiveness and implementation of the bank protection structures has the potential for additional research applications. In addition to the methodology's application for bank armoring imagery, the sUAV also produces concise habitat imagery within the predetermined flight quadrant. Collecting data on the implementation of armoring structures and geomorphological response to the structures subsequently captures habitat data for salmonids, vegetative mosaics, and hydraulic flow patterns.

The Satsop and the Wynoochee watersheds of western Washington are in an area that has been altered by twentieth century timber harvest and agricultural practices. Flow dynamics in riverine systems are complex and often fluctuate seasonally due to precipitation and land use dynamics. After implementation, bank armoring structures are not often monitored due to high cost of imagery acquisition and limited financial resources. Often the bank armoring structures are not reviewed unless they are visibly reacting or failing, and the landowner informs authorities.

The research for this manuscript addresses the potential for using sUAV's as riverine monitoring applications. The use of sUAV's is low cost and time efficient for use in monitoring applications. Results from this research imply that sUAV's require less flight planning time than standard manned aircrafts and also enable cost efficient data processing methods. The flight time necessary to capture the entirety of a potential research location is reduced significantly in comparison to that required by a standard aircraft. The reduced overall cost and flexibility of sUAV development increases the potential to conduct monitoring, compared to traditional aerial imagery and ground-based survey methodologies.

CHAPTER II

2. Site Locations and Descriptions

The purpose of this research was to develop a method to further increase our understanding of bank armoring structures and their role in riverine systems I also wanted to identify the difference between a successful project and a project that has failed after implementation. After extensively reviewing hundreds of engineering plans and documents from the Department of Fish and Wildlife's archive, I landed on these three sites. Each site represents a bank armoring project that was either successful in protecting the landowner's home or a structural entity such as a highway. Each site had an engineering goal that was stated in either the documents or the engineering plans. The description of the engineering goal helped determine whether or not the observed structure was an effective bank armoring implementation or a failed implementation.

The purpose of using an sUAV was to capture the imagery of the bank protection structures and see whether the imagery from each flight would accurately capture the fluvial interaction of the armoring structures and current state of the structures. The intention for using a sUAV for this research was to capture any potential data that would be missed during a terrestrial survey. The results of sUAV image processing would show whether sUAV's are capable of capturing high-resolution image data. In addition, the aerial images from this research were then compared to the engineering goals developed for each project to determine whether the armoring structures were a success or detriment in the riverine environment of each study site.

Table 1 Watershed characteristics data collected using the USGS tool "streamstats." The data for this table is collected using NAD 1983 State Plane FIPS 1103.

Watershed Characteristics

	Mainstem Satsop River	West Fork Satsop River	Mainstem Wynoochee River
Basin Drainage Area	295.33 mi^2	93.91 mi^2	187.07 mi^2
Percent Canopy Coverage	59.7 %	65.8%	67.4%
Mean Annual Precipitation	117 in	123 in	133 in
Mean Basin Elevation	737 ft	1010 ft	951 ft

Table 2 Data for this table was map measured using ArcGIS Pro. The survey reaches are projected in NAD 1983 State Plane FIPS 1103 and are based off river miles not linear miles or meters. The image overlap for each flight was eighty percent.

Aerial Survey Data Collection

	Mainstem Satsop River	West Fork Satsop River	Mainstem Wynoochee River
Channel Length Surveyed	718.35m	726.55m	437.75m
Number of Photos Captured	999	999	426
Area surveyed	112302m^2	103497m^2	43316m^2

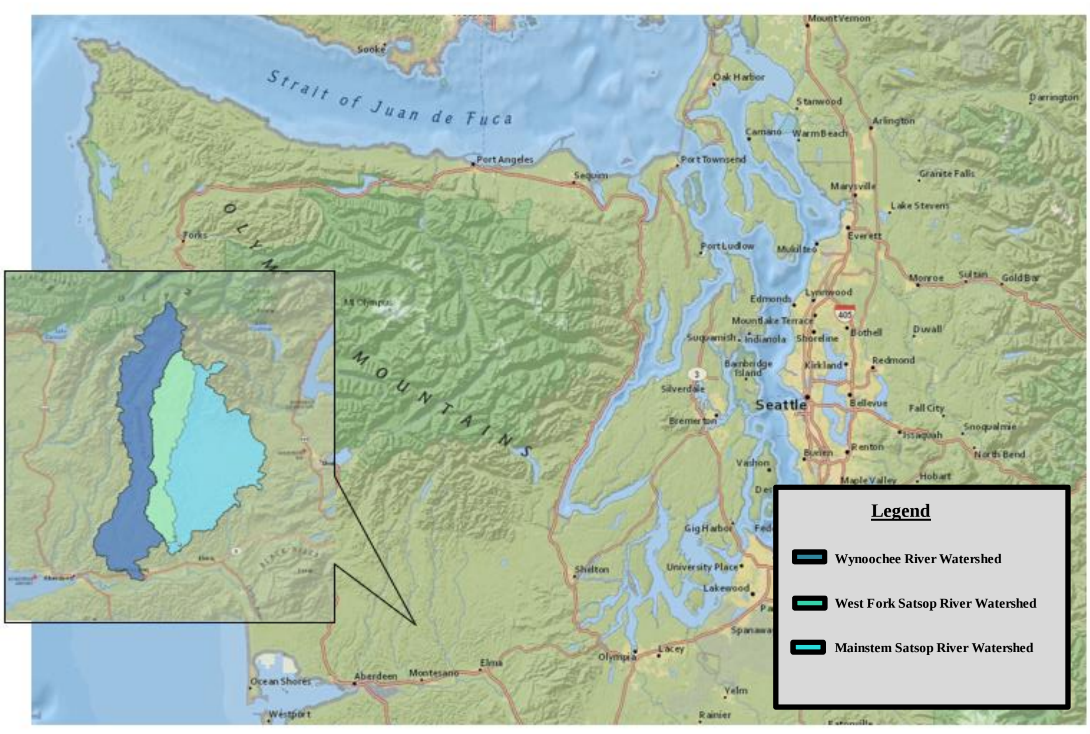


Figure 1 shows the research location proximity in Western Washington and a close look at the regional watersheds that were part of this research.

2.1 Wynoochee River Site (WYN-SR12)

Location

The Wynoochee River is located in Grays Harbor County between Central Park and Montesano Washington. With a total basin area of 187.07 mi^2, the Wynoochee River's headwaters are situated at the southern edge of the Olympic National Park. The Wynoochee River is confined in its upper reach by a dam that was constructed by the Army Corps of Engineers in 1972. The regulated flow on the Wynoochee River is to provide drinking water to Grays Harbor County and can also function as a hydroelectric facility although it currently does not. Due to the more restrictive hydrological function, the channel meander pattern is lesser in the upper reaches. Near the mouth of the river where the channel is influenced by many additional tributaries and small creeks, the channel migration pattern increases due to a more irregular flow pattern from increased hydraulic input. The site for this research was located in the lower reach of the river near its mouth that feeds the Chehalis River.

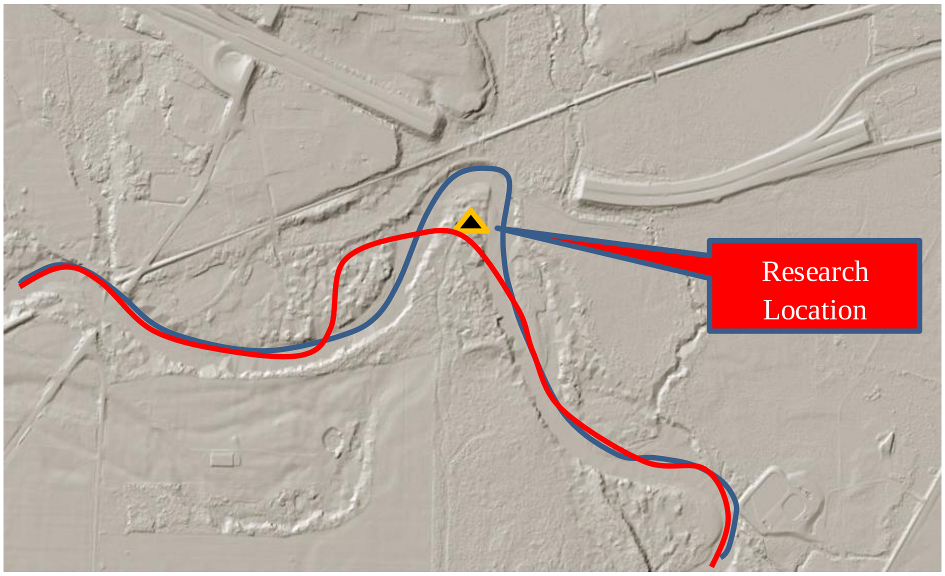


Figure 2 represents the historic 1996 channel (shown in red) and the post 100 year flood channel newly formed in 1997 (shown in blue) This figure also represents the Wynoochee River research location. Just south of the research location is the Chehalis River.

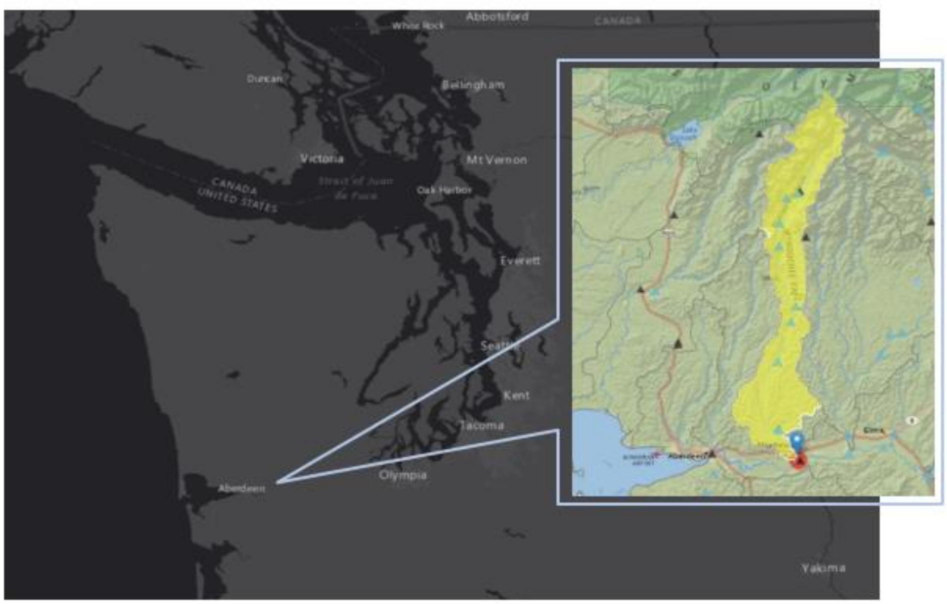


Figure 3 represents the location of the research location in addition to the entirety of the Wynoochee River Watershed. Basemap Dark Gray data provided by Esri, DeLorme, HERE, MapmyIndia.

Precipitation and Flow Deliverance

The Wynoochee River is fed by rain on snow events in addition to the mean annual precipitation events reaching 133in. The Wynoochee River watershed surrounding landscape and forests have been highly modified due to timber harvest. The watershed has historically provided Grays Harbor County with a primary source of income through timber sales and harvest. Forestry harvest as a land use change alters flow regime entering the river and can directly correlate to the increase of runoff adding to high regime flow events during hydraulic cycles. Flow patterns in the Wynoochee River are often flashy or high variance in the lower reaches influenced by the increased amount of storm water runoff entering the system. As seen in the hydrograph (Figure 4). peak flow season is from October through the middle of April. The spikes in the hydrograph show the large storm events that were captured using flow meters in the stream to measure cubic feet per second or cfs shown in the hydrograph below.

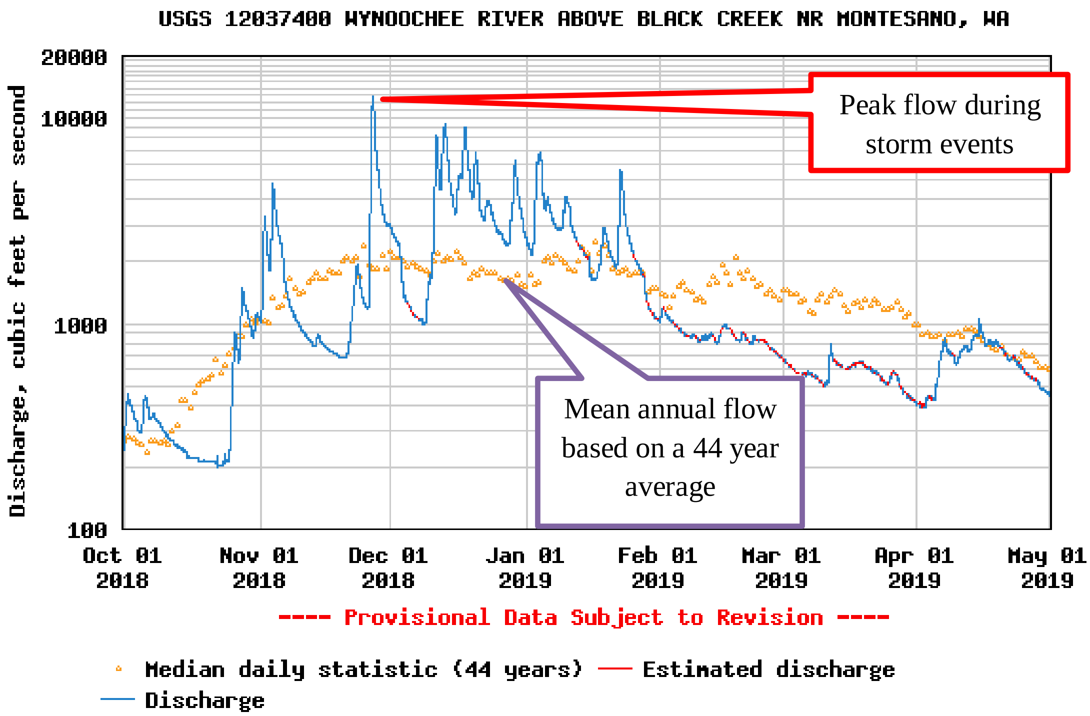


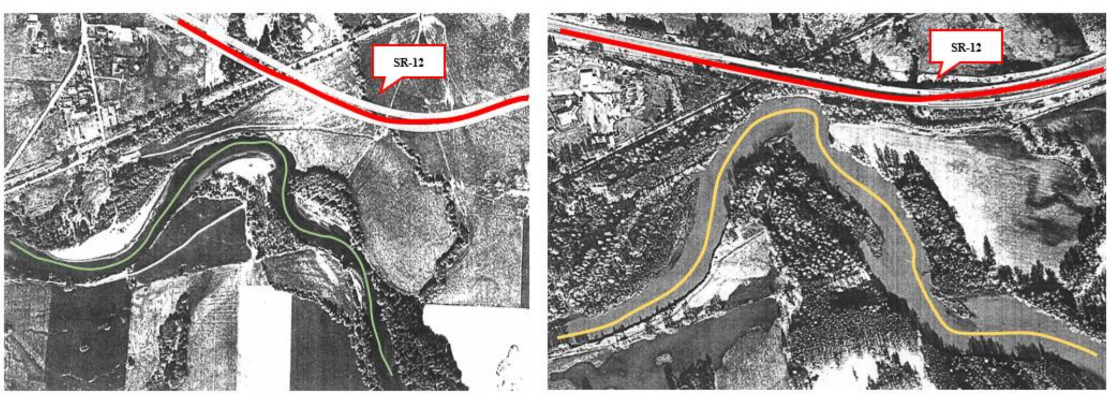
Figure 4 represents the temporal timing of flood season on the Wynoochee River and the storm events for 2019. USGS stream stats data link:https://nwis.waterdata.usgs.gov/usa/nwis/uv/?cb_00060=on&cb_00065=on&cb_63680=on&format=gif_default&site_no=12037400&period=&begin_date=2018-10-1&end_date=2019-05-01

Morphology of the Site

The WYN-SR12 site exhibits gravel bars and point bar morphology consisting of larger cobbles with a low mixture of fine gravel. The south point bar displayed annual growth recruitment patterns of alders (*Alnus incana)*, willows including Clatsop hooker willow *(Salix hookeriana)* and Placer willow *(Salix ligulifolia)*, as well as a strong presence of dogwood *(Cornus sericea.)* During the pre-site visit and the aerial survey, I observed a healthy recruitment of invasive species such as reed canary grass *(Phalaris arundinacea)* and knot weed (*Fallopia japonica*.) The north bend of the oxbow primarily consisted of the rip rap material used to armor the bank in 1997 and well-established alder and dogwood from the implementation plantings. The channel morphology appeared to have a mixture of fine gravels and fine sediment that had been deposited from last year's storm events (January 2018.)

Engineering Goals for Armoring Implementation

This reach was chosen for a bank armoring implementation project in 1997 due to a high scour from a 100-year storm the hydraulic season of 1996-1997. The storm put State Route 12 in jeopardy of imminent failure due to the erosion of nearby bridge piers. The SR-12 bridge was constructed in 1967 and the Wynoochee River channel was over 100m south of its current location (Figure 5 *a* & *b*). The location of the bridge was based on previous meander patterns and the knowledge of the rivers previous migration rate of less than two feet per year. The oxbow of the channel was fast approaching the bridge piers. The bank armoring installation was necessary to prevent critical scour and failure of the bridge piers. Washington Department of Transportation and Washington State Department of Fish and Wildlife developed an engineering goal to prevent further encroachment of the channel towards the piers.



(a) (b)

Figure 5 (a) represents the channel migration shown in green and structure prior to the 1996 one-hundred-year flow event while (b) represents the newly formed channel shown in yellow encroaching northward towards State Route -12 near the mouth of Sylvia Creek..

Type of Implementation

The structure implementation was a riprap rock drop graded back at a near 45◦angle shoring up the left bank side nearest to the SR 12 bridge. The purpose of the armoring structure was to span the entirety of the oxbow completely armoring the bank to prevent further migration (Figure 6). The structure also had vegetation integrated into the riprap to create deposition or sediment drop zones. The large woody material and angular rock can be seen in the raw image flight captured by the sUAV in Figure 7. The intention of this method called “key logging” or “stacked log cabling” was used to increase the fluvial roughness in unison with decreasing the hydraulic approach velocity creating a space for sediment to drop. In addition, the sediment build behind these structures is meant to redirect the channel back towards the more southerly historic channel paths or the 1997channel.

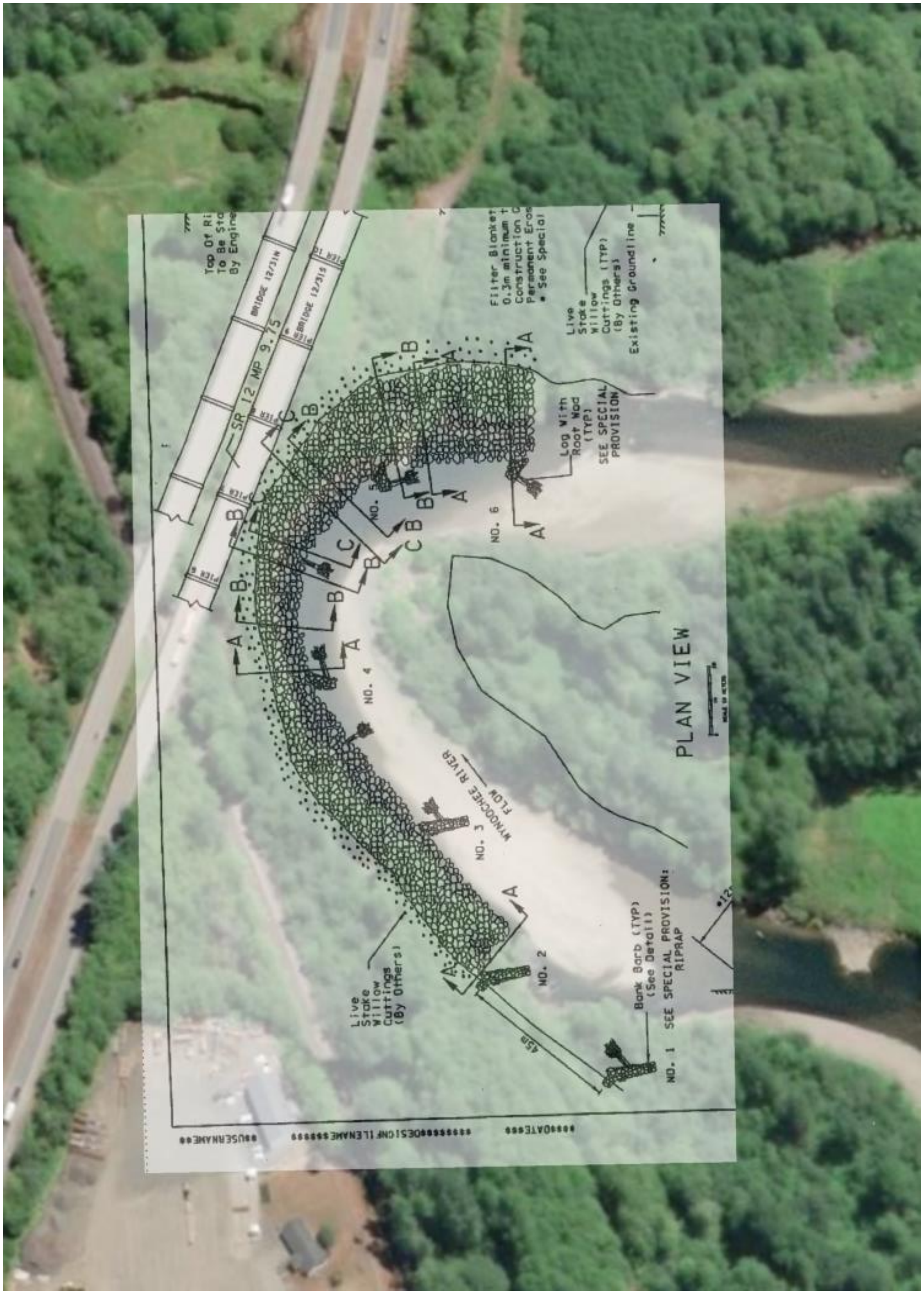


Figure 6 is an engineering plan created by the department of fish and wildlife engineering team with the help of the Department of Transportation design team. The overlay is the design used to heavily armor the north bank of the Wynoochee River to detour further scour from decreasing the integrity of the bridge pillars. The engineering design overlay was manually georeferenced to conform to the location of the imagery, using ArcGIS Pro software tools.

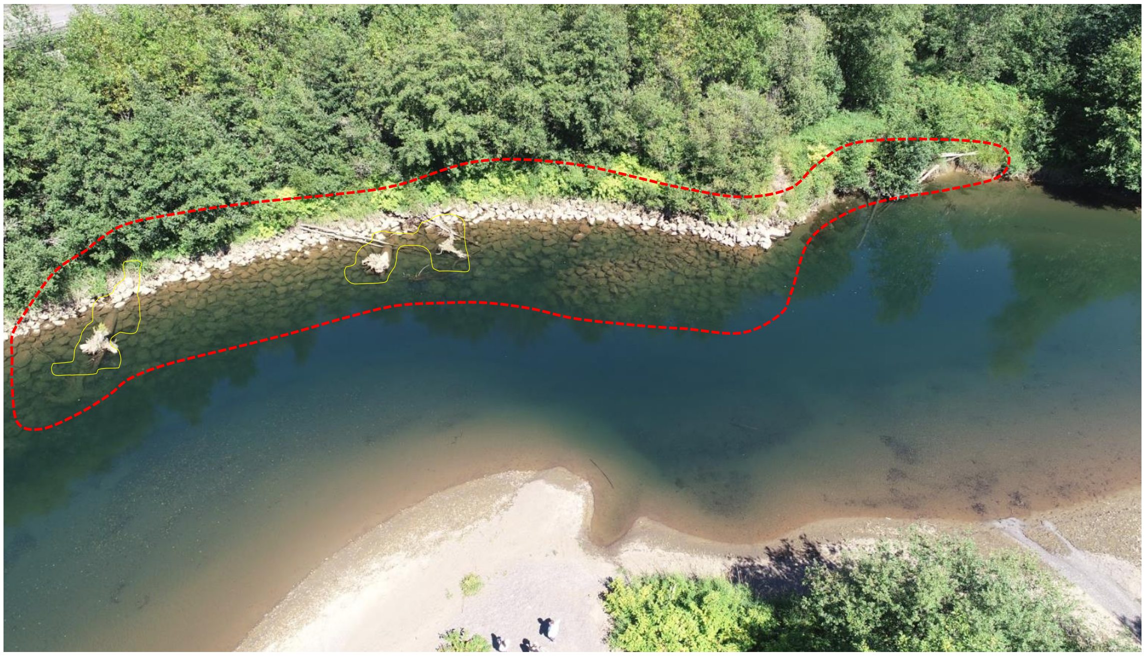


Figure 7 shows the rock dropped during the armoring implementation of 1997 shown in red and several of the remaining logs cabled into the structure (shown in yellow).

This integrated proposal also included softer or “green” methods to ensure the bank stability behind the implemented rip rap. The engineering team from WDFW proposed a mixture of dogwood, alder, and live willows be staked behind the structure to increase bank complexity as well as increase root mosaic in the fine alluvial deposit from the years prior flood (November1996 through January of 1997) (Figure 8).

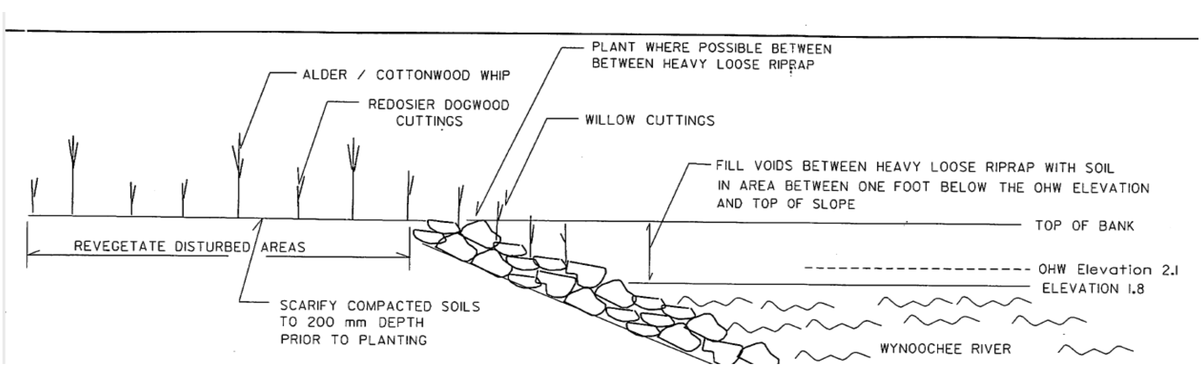


Figure 8 is an AutoCAD generated diagram of the initial engineering plans to integrate vegetation stakes into the bank armoring methodology. This diagram depicts the engineered slope of the rock placement up to the top of bank above water level where the plant stakes were placed.

2.2 Main Stem Satsop River Site (MS-SAT-GLICK)

Location

The main stem Satsop River is located in Grays Harbor County with its headwaters just south of the Olympic Range. This research location is located just north of the town of Satsop and north east of Montesano Washington. The main stem of the Satsop River has been notorious for its meandering behavior due to its low gradient channels and the land use practices in the area reducing bank complexity. Bank complexity is defined by an elaborate vegetation mosaic and multiple soil types. Vegetation on the banks reduces fluvial approach velocity and therefore erosive tendencies. The MS-SAT-GLICK site is located on a meander path in a floodplain. The current path the channel maintains would have eliminated the landowner's home during the winter high flow event of 2013 if it had not been for the bank armoring intervention that took place the winter of 2015.

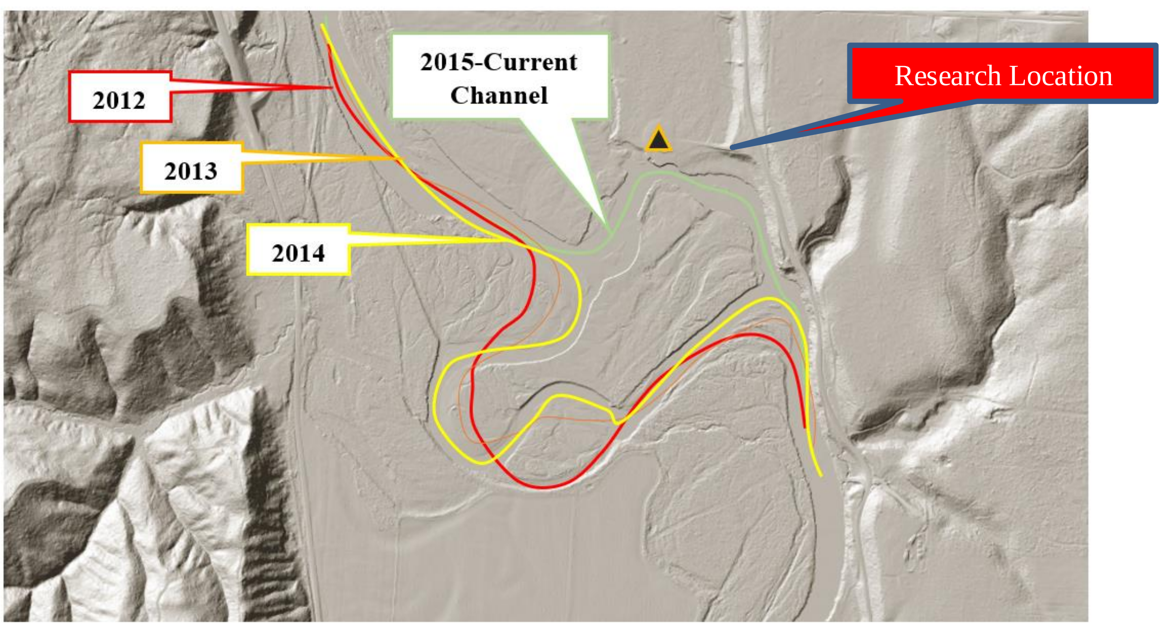


Figure 9 represents the Mainstem Satsop River research location. The present-day channel (shown in green) continues to threaten the landowner's home.

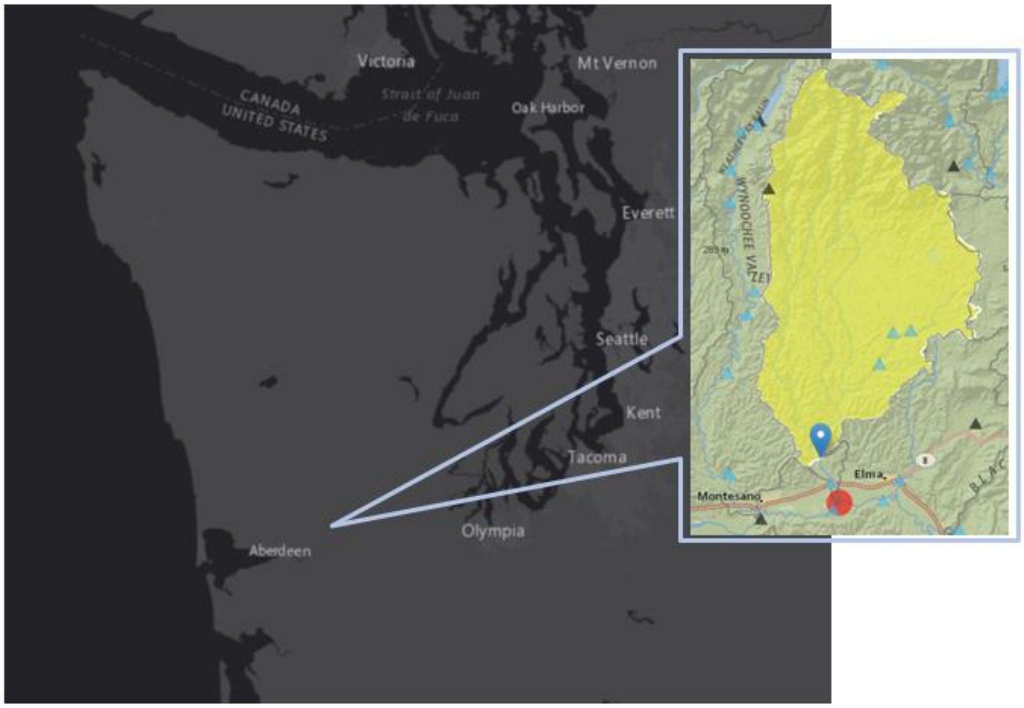


Figure 10 represents the watershed of the main stem Satsop River location. Basemap Dark Gray data provided by Esri, DeLorme, HERE, MapmyIndia.

The historic channel meander in this area has been primarily to the south of the present channel location (Figure 9). The research location is also influenced by a small tributary that is a main spawning stream for Chum salmon *Oncorhynchus keta* and Coho salmon *Oncorhynchus kisutch.* The location is heavily influenced by large woody material or LWM and continues to change consistently in a meander pattern each year. The initial avulsion of the channel into its now current channel was due to a LWM structure naturally occurring upriver from the landowner's home (Figure 12). The log jam redirected the flow from its southern location to a more easterly flow directly towards the landowner's home.

Precipitation and Flow Deliverance

The main stem Satsop River receives over117 inches in precipitation and the basin drainage area influencing the target site is 295.31 mi² fed by many tributaries including the East and West Forks of the river (Figure 11). The target location is a low gradient reach of the river with a significant percentage of channel avulsions and past meandering scarification. The hydraulic cycles in the mainstem Satsop River have continued to exceed the mean annual flow patterns over the past 80 years as seen in the hydrograph in Figure 11.

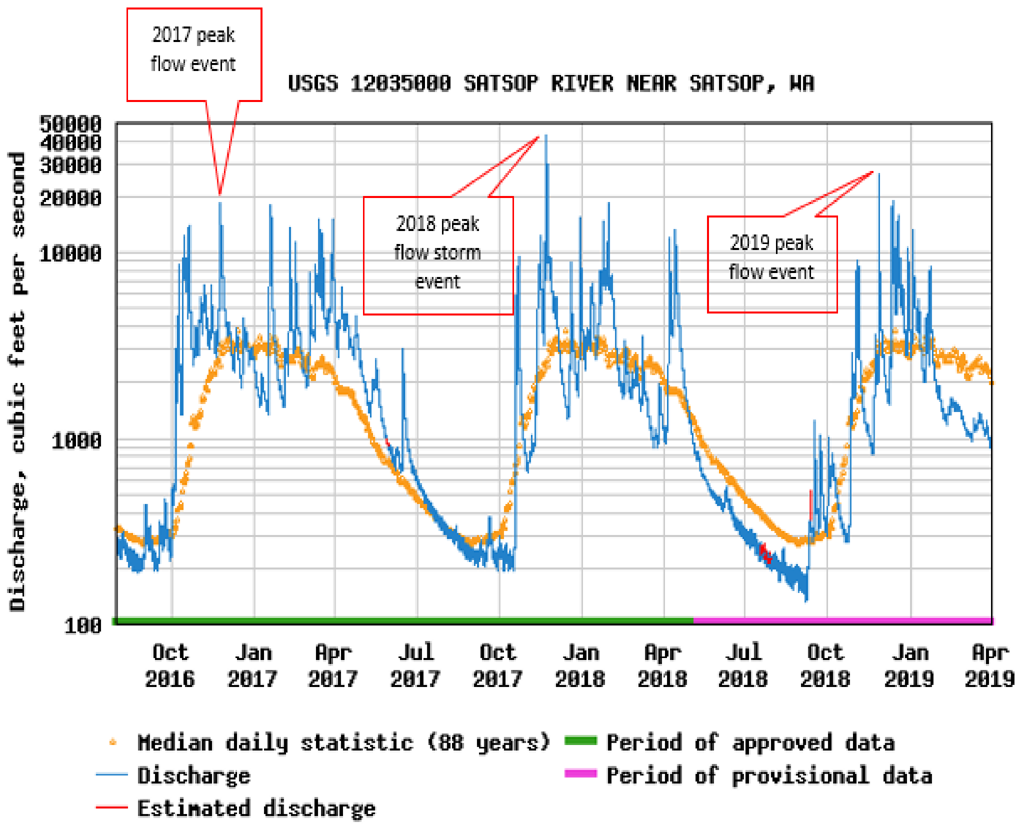


Figure 11 is a hydrograph showing the peak storm events in each water cycle during the years 2017-2019. The day to day data (show in blue) represents the daily discharge recorded at the stream gauge station, while the ,median daily statistics over an 88-year period (shown in orange) are representative of a more averaged flow pattern.

Morphology of the Site

The morphological landscape of this reach was particularly altered due to the land use practices. There is a heavy agricultural use as well as grazing livestock on the upper banks of this reach. Using aerials from 1991 through 2013 it was determined that the mainstem channel was about .3 miles south west of its current position (Figure 12). The winter of 2014 a significant storm event increased the amount of LWD entering the system. As seen in Figure 12 below, the logjam formed just to northwest of the historic channel of 2013 avulsed the river into another historic channel towards the landowners' home. Using LiDar imagery seen in Figure 9, it can be shown that there was once a historic meander path that the river once followed in its now current path. The channel returned to a path that it had previously occupied many years ago.

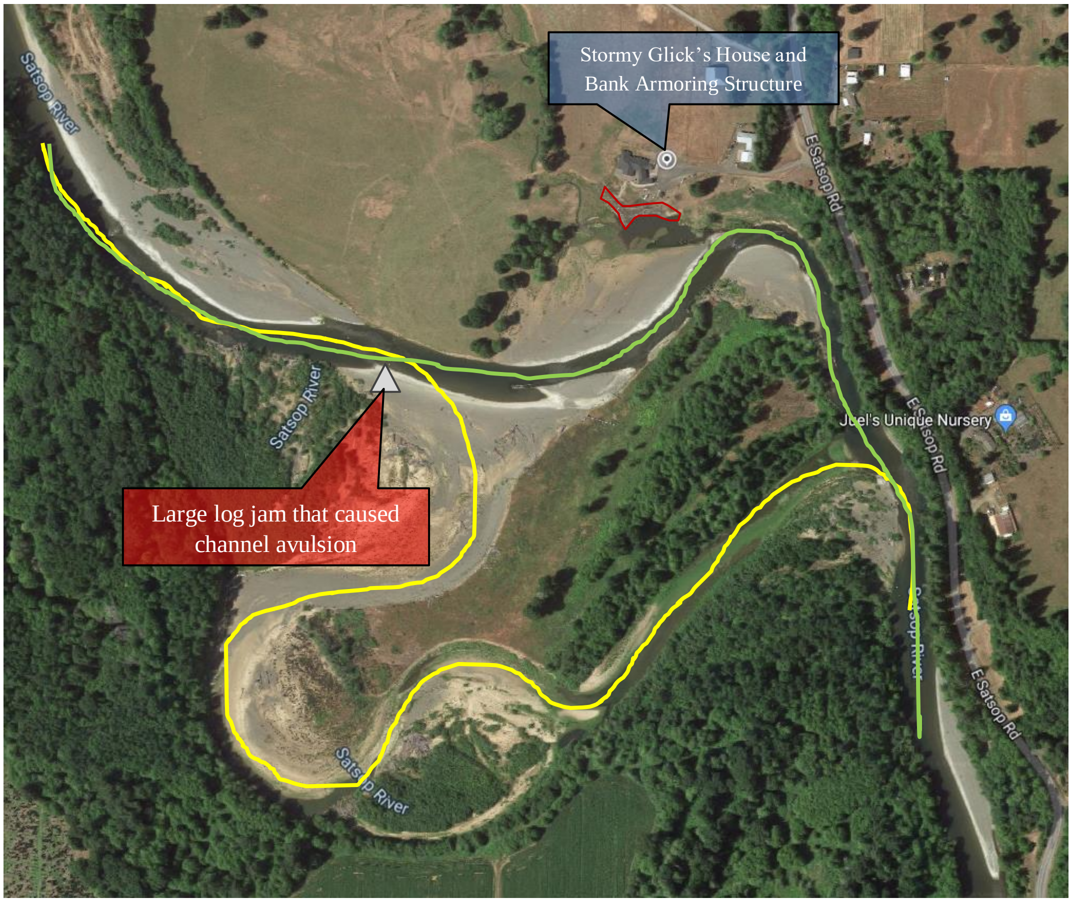


Figure 12 shows the scars of the historic channel (shown in yellow) on the Mainstem Satsop River that avulsed the winter of 2013 into its present channel path (shown in green) of 2019. Basemap World Imagery provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

The MS-SAT-GLICK site was chosen due to its engineering goals and the bank armoring methodology used. The intention of the project was to place angular rock on the banks to prevent further erosion and toe undercut of the bank (Figure 13). The thalweg of the flow was rushing directly into the point of the newly created rock barb developing a split flow. The channel composition in this reach was a mixture of sand, fines, and course cobble material with intermittent LWM. The bank morphology was a mixture of fines, sand and clay. The bank mosaic and lack of vegetation presence showed sign of further erosive behaviors due to the lack of stabilization downstream of the project.

Engineering Goals for Armoring Implementation

Site MS-SAT-GLICK was chosen for a bank protection structure due to potential loss of the landowner's home. The structure design was put on a rush schedule so that immediate action could take place to protect the home. Due to the decreased design window the complexity of the armoring structure was not as complex as others that have been implemented on the Satsop. The structures goal purpose was to generate a flow diversion to direct the flow away from the direction of the landowner's home. From the aerial diagram shown in Figure 24, it can be seen that the structure has created a large pool and is developing additional toe erosion on the east end of the rip rap. The structure has provided protection for the home in several high-water events that have surpassed the top of bank mark.

Type of Implementation

Implementation type for this location was a bank armoring protection method using angular rock otherwise known as riprap and one LWM feature with a large root wad to generate fluvial roughness and a sediment deposition zone. As seen in the plan schematics in Figure 2.14, it was planned that the barb be placed directly into the thalweg and the LWM structure be anchored downstream from the bank protection. At time of research the large barb and rock structure was fully present but appeared to be experiencing toe erosion at the point and about 15m downstream of the barb. The LWM structure was not present and the bank downstream of the site was displaying signs of annual destabilization. Using ground survey collected data it was calculated that the downstream cut bank reaches a height averaging ~3.5m (Figure 13).

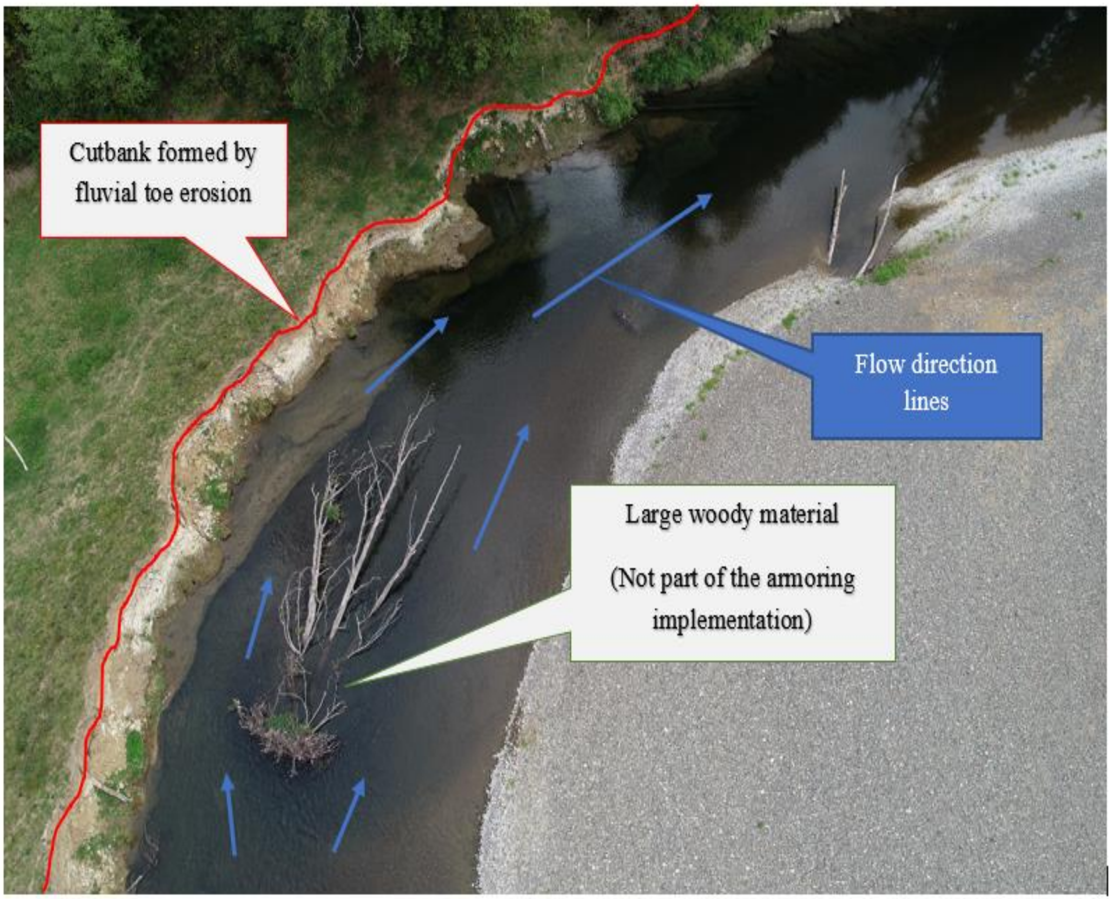


Figure 13 shows a raw sUAV image of the severe cutbank at site MS-SAT-GLICK. The length of this portion was measured at 68m with an average height of 3.2-3.5m in height.

This MS-SAT-GLICK research location has yet to be determined to be successful or not. Because the structure still resides in its currently intended location, it could be argued that this large riprap barb armoring configuration was successful. Downstream of the site, severe toe erosion has occurred developing incised banks and a severe cutbank (Figure 13).

The loss of annual mass due to fluvial erosion on the downstream banks may have been exacerbated by the riprap barb implementation. The meander in this location does not allow vertical hydraulic energy storage in the oxbow. Therefore, the energy from the increased approach velocity is continually scouring depth and width in this specific reach at the cut bank downstream of the armoring location. Due to the lack of complexity in bank vegetation or woody material there is nothing to create fluvial roughness to lessen the flow. This coupled with high water events leads to highly erosive behavior on cut banks with similar complexities.

Figure 14 depicts the plan sketch done by the permitting biologist at the Department of Fish and Wildlife to save the landowners home. The sketch was used and built upon by the engineering team due to the limited time the department had to help save this landowners home. The base imagery for this figure is generated from the aerial imagery collected during the 2018 research flight. The engineering design overlay was manually georeferenced to conform to the location of the imagery, using ArcGIS Pro software tools.

Figure 15 shows the MS-SAT-GLICK site and the armoring structure. The extreme toe erosion (shown in red) and the large scour pool (circled in blue) are potential effects of the armoring implementation and the fluvial interaction with flood waters each year.

2.3 Westfork Satsop River Site (WF-SAT-BRIDGE)

Location

The West Fork Satsop site is situated at the southern edge of the Olympic range just north of Montesano. Site WF-SAT-BRIDGE is in the northern part of Grays Harbor County between Montesano and Elma Washington. WF-SAT-BRIDGE is located on private land that has been used primarily for timber harvest and agricultural practice. The Watershed that influences this location spans a total of 93.91mi² and is in an unconfined reach of the upper river. The site also spans downstream to the Middle Satsop Road bridge that is just north of the East fork and West Fork Satsop River confluence. The Middle Satsop Road bridge spans directly over the West Fork of the Satsop River and has high potential to be influenced by any significant high-water event.

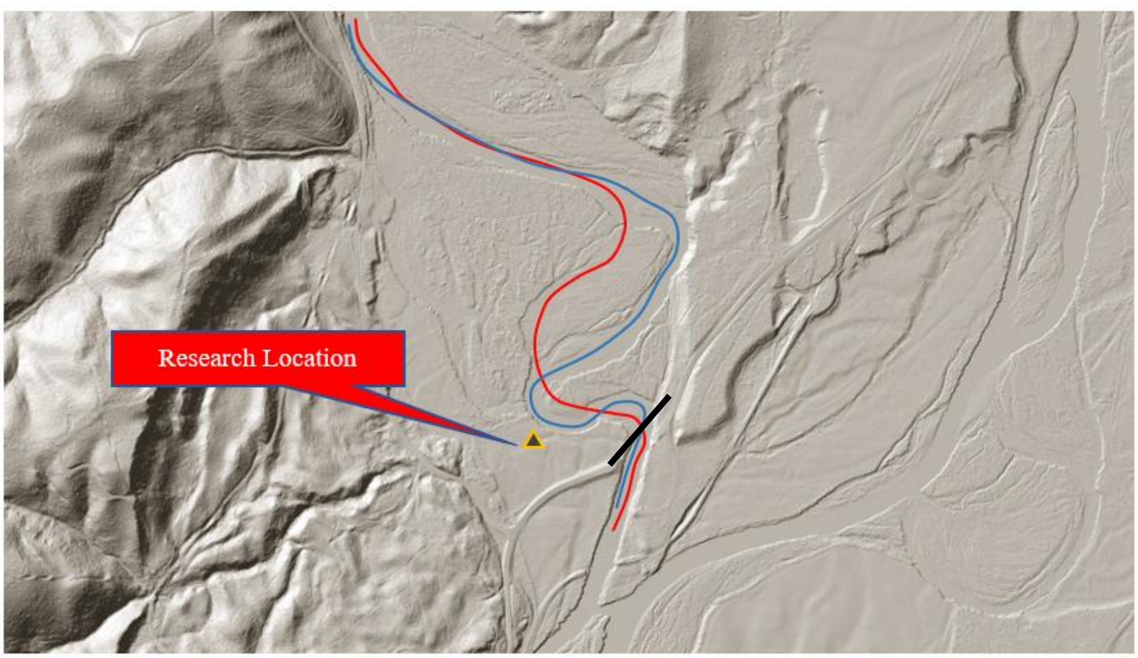


Figure 16 represents the research location on the West Fork Satsop River. The 1m LiDar basemap used for this figure was generated by the Department of Natural Resources in January of 2019. The red line depicts the 1996 river meander path while the blue line represents the meander path generated by the 1997 storms now endangering the bridge (shown in black)..

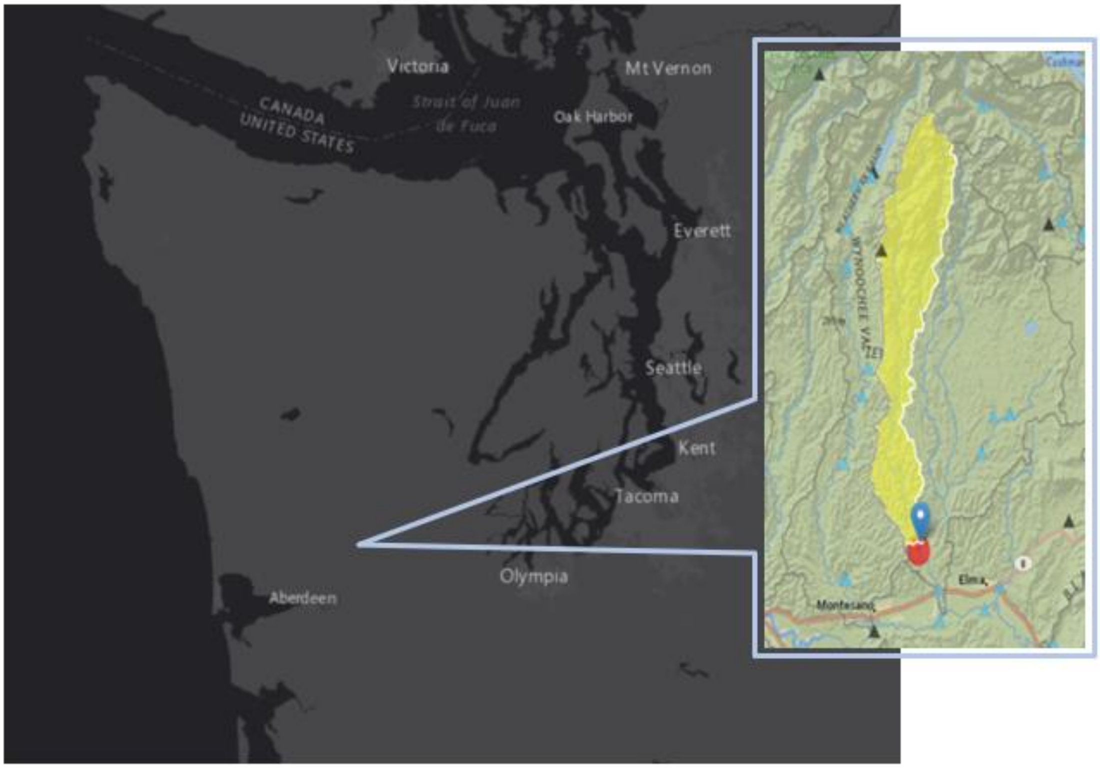


Figure 17 outlines the entire watershed of the West Fork of the Satsop River. The red marker on the map represents the location of research location WF-SAT-BRIDGE. Basemap Dark Gray data provided by Esri, DeLorme, HERE, MapmyIndia.

Precipitation and Flow Deliverance

The primary water deliverance to this watershed is from rain-on-snow events and standard annual precipitation runoff from surrounding forest land. Because this area is highly influenced by land use changes, it presented an optimal location to research a failed project that was implemented over ten years ago.

The research location is a feed to the mainstem of the Satsop river and is just upstream of the East and West Fork confluence. Local biologists and engineers refer to site WF-SAT-BIDGE as the “forks.” The site experiences severe hydraulic events due to the steep nature of the hillsides upriver and relative scarcity of forested vegetation. The increased woody material deliverance from logging practice and a series of high intensity storms lead to a scenario that resulted in structural failure of the implemented armoring method used for WF-SAT-BRIDGE.

Morphology of the Site

The substrate composition and morphology of the site is a compilation of fine and course sediment with a high LWM count. The cut banks are a silt, sand, and clay mix experiencing extreme toe erosion. The historic channel had less of a meander and cut diagonally through what is now a substantial point bar (Figure 18). The site is complex in its historic meander and present platform dynamics from high flow events interacting with the remaining portions of the structure. The site is forming an immense oxbow with a max depth at time of survey reaching 4.2m (Figure 19). The site has complex LWM structures throughout and carries a 2:1 pool to riffle ratio resulting in prime habitat for adult and juvenile salmonids. This site is surveyed annually by the Department of Fish and Wildlife's Fish Program for spawning steelhead *Oncorhynchus mykiss* and Coho salmonids *Oncorhynchus kisutch.*

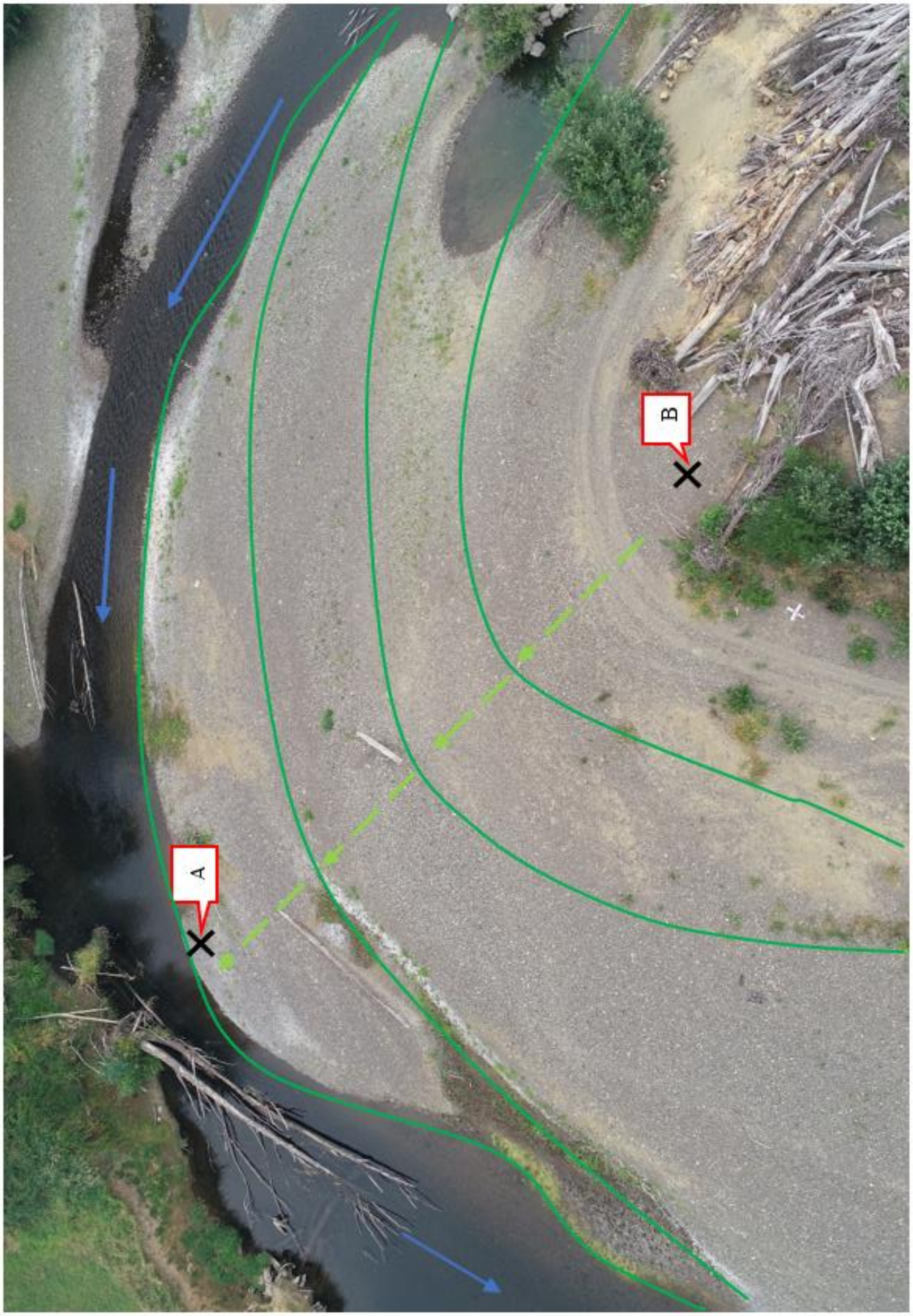


Figure 18 Shows the continually growing pointbar on the West Fork Satsop River. The flow (shown in blue) and channel of the river is pushed away from the pointbar continuing the erosion of the downstream bank due to the pointbars' gain in elevation or growth(shown in green). From point (A) to point (B) is a difference of 1.26m in elevation. Imagery captured during 2018 sUAV research flight.

Figure 19 is the full surface orthomosaic of the WF-SAT-BRIDGE location with generated during the 2018 research flights. The immense oxbow (shown in blue) formation continues to grow due to the bank erosion and lack of vegetative complexity. Underlay basemap World Imagery provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

The WF-SAT-BRIDGE location was experiencing toe erosion and scour from a 100-year flood event the winter of 1995. The channel began to cut into the property owners hay field. Due to the lack of vegetative complexity from agricultural practice, the bank erosion increased during periods of the floodwater. The downstream effects were also threatening the Middle Fork Satsop Road Bridge.

Engineering Goals for Armoring Implementation

The project goal for this site was to implement a hard-armoring structure on the oxbow of the channel to protect the landowners' field. This implementation goal was designed to re-channelize the river back towards its historic channel (Figure 15) away from the course it was currently taking. The structure implementation was intended as a bank stabilization method using angular rock and large woody debris cabled into place to create rock barbs or groins (Figure 19).

The Middle Satsop Road bridge was also of concern during the design phase of this project. The footings of the bridge are placed outside of the bankfull span of the channel. However, the bridge has been jeopardized during the high flow events of the past three winters. A storm surge in the winter of 2017 breached the south east bank of the oxbow and carried wood 15m in length and 1m in diameter up onto the field. As seen in Figure 23, there is a high flow channel forming in the upper extent of the field behind the stand of alder just upstream of the bridge, presenting risk of future failure.

Type of Implementation

The bank armoring methodology used to protect the Middle Satsop Road Bridge and the landowner's property was a rip rap rock drop with protruding groins and LWM integration in the design. The structure implementation was intended as a bank stabilization method using the angular rock and large woody material cabled into place (Figure 19). The engineering goal of this project was to create deposition zones behind the groins for sediment to build and later protect the bank. The implementation of the groins and the cabled woody debris did not prevent the river from continuing its intended path. Figure 20 depicts the overlay of the engineering plans developed in 1995 before construction in 1996.

The structure was designed to redirect the flow of the channel away from the armoring structures and develop a deposition zone for sediment to drop behind the large structures in the channel. The sediment deposit in these locations would then theoretically generate a new pointbar, thus redirecting the channel in an opposing path.

(a)

(b)

Figure 20 (a) Large woody material cabled into a rock groin or barb in 1996 to redirect flow from a landowners' property and confine the channel from potentially destroying the Middle Satsop Road bridge. (b) Shows a more downstream angle of the rock groin and two more structures as well as LWM that was part of the implementation.

Figure 21 shows the engineering plans for the bank armoring structure developed and implemented on the West Fork Satsop River in 1995 and 1996. . The engineering design overlay was manually georeferenced to conform to the location of the imagery, using ArcGIS Pro software tools. Underlay basemap World Imagery provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 22 depicts the aftermath of the debris pile up downstream of the structure implementation near the Middle Satsop Road bridge the after the winter storm surge of 1996. The LWM (circled in red) used for the armoring structure has been uplifted by the floodwaters and is stacked under one of the bridge footings.

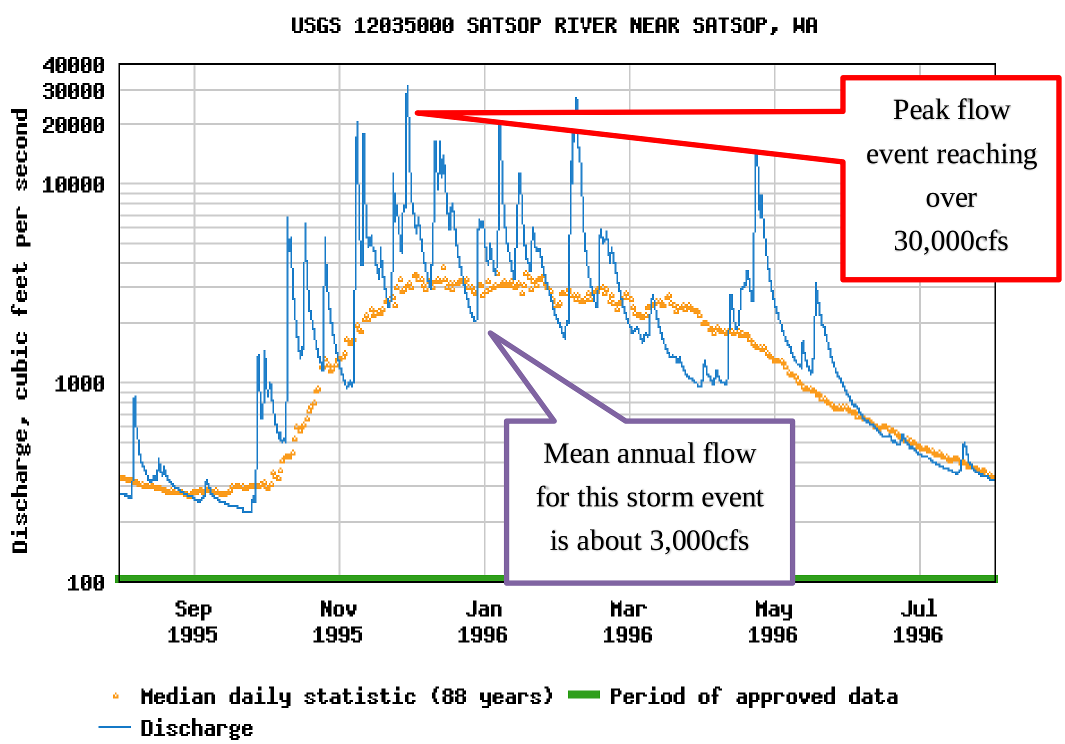


Figure 23 is a hydrograph generated using the historical hydraulic data provided by USGS to show the high flow event that the Westfork Satsop river experienced the year after implementation in 1995.

Two and a half of the remaining rock groins were captured in the sUAV flight pattern for this research. The most pronounced of the two remaining groin structures is surrounded by more complex bank structure. Embedded into the bank behind the structure there is a cottonwood and alder stand. The vegetative stand is also inhabited by blackberry, common grasses and other low-profile vegetation. Where the previous rock groins were placed, the vegetative structure on the bank was less complex consisting of only grasses such as fescue and rye that are grown by the landowner for agricultural purposes.

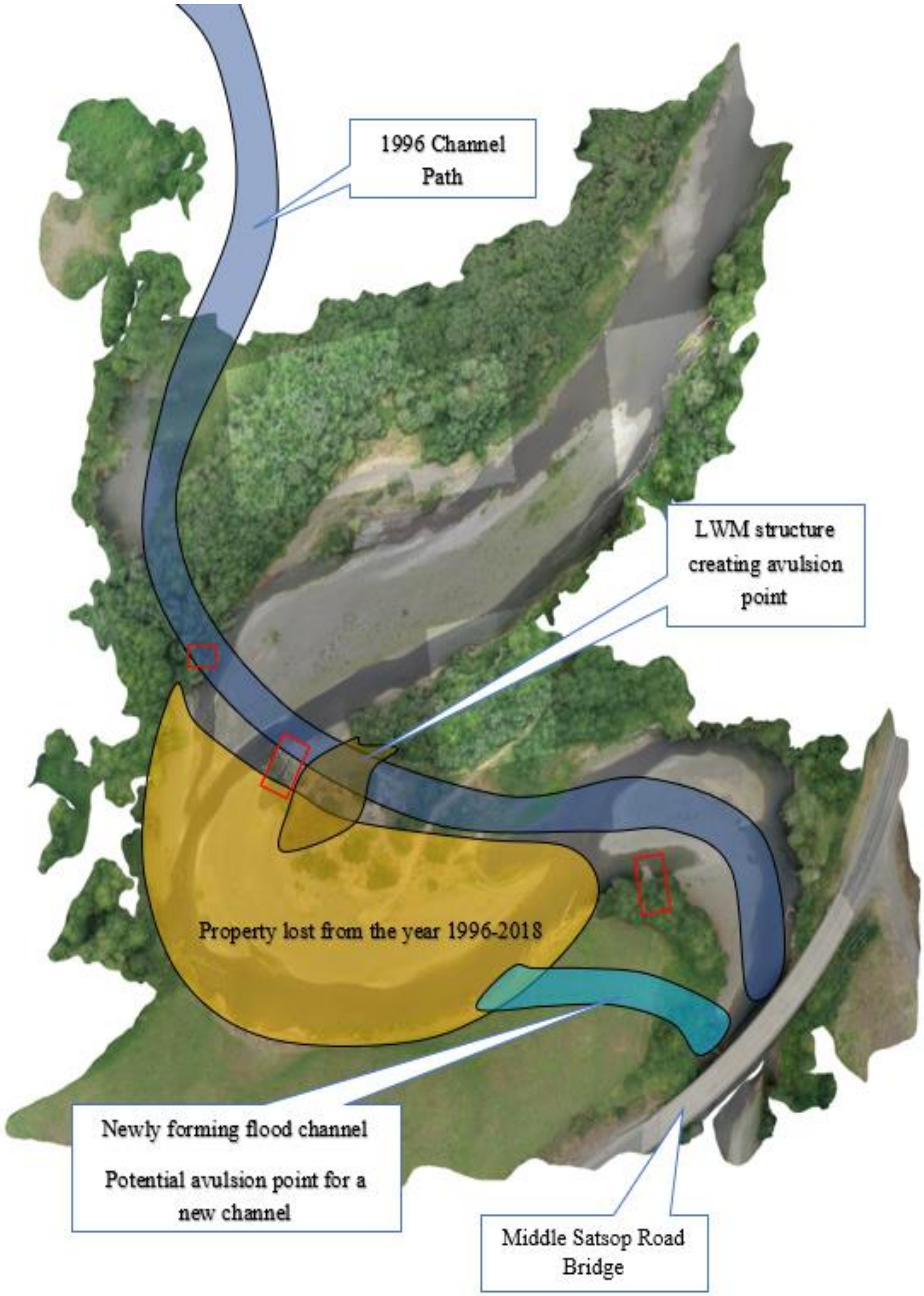


Figure 24 shows the captured features with call outs for each feature discussed in the site description. The orthomosaic used for the basemap in this imagery is generated from the 2018 research flight. The remaining rock groins observed during the research flight are depicted in red, and the 1996 channel path is depicted in dark blue

3. Methods

The methodology used to assess sUAV based photogrammetry of the armoring structures is based on a preset grid pattern flight using Pix4DCapture software, an array of GCP’s throughout the research location, and a DJI Phantom Pro 4 for image acquisition. A flowchart of the data collection methodology is summarized in Figure 25.

Figure 24 A store bought DJI Phantom Pro 4 equipped with a 20-megapixel camera and a 3 axis (pitch, roll and yaw) gimble. This unit is also equipped with 5 obstacle sensors on the sides and top of the machine. The sUAV was controlled by an iPad mini 4 using PixCapture4D for grid pattern flights.

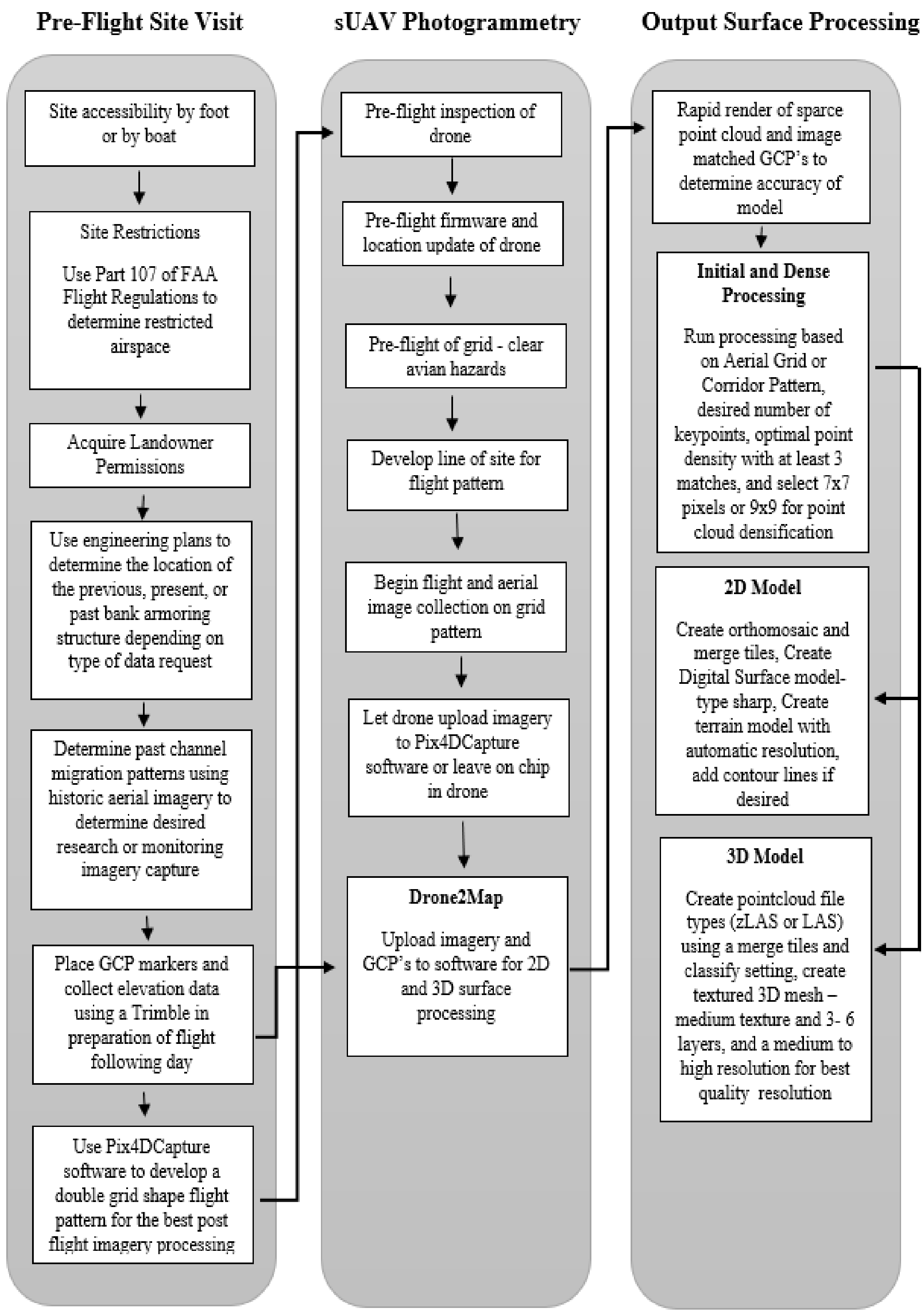


Figure 25 is a flow chart of the methodology developed for this research to determine pre-site accessibility and research viability, imagery acquisition, and post flight data processing. See Appendix I for additional details.

3.1 Materials

Aerial Imagery was acquired using the following sUAV Equipment

- DJI Phantom Pro 4
  - Using a pre-set flight plan generated in Pix4DCapture

The Ground control points were collected using the following field equipment systems.

- Trimble GPS System
  - Equipped with TerraSync Version 5.86

Ground control markers were constructed using the following materials.

- Vinyl ground control markers
  - 4ft x 4ft black and white strips
    - numbered for referencing in post flight data processing
- Surveyor stakes
  - 2"W x 3'H
    - Used to mark GCP locations in case of a secondary flight or if the site was not completed on the first day
- Construction flagging
  - High visibility orange used to mark the stakes
    - Was used to mark stakes and used as markers for additional GCP locations
- Hammer

The following materials and software were used to for post-flight data processing.

- Dell laptop computer
    - Intel CORE i7 7th generation processor
- Esri Drone2Map image processing software
    - Version 1.3.2
- ArcGIS Pro
    - Version 2.2.3

3.2 Image Acquisition

The images for this research were captured using a DJI Phantom Pro 4 sUAV with a quad propeller system. The sUAV was equipped with a standard factory issued 3-axis (pitch, roll, yaw) gimble, and a one inch 20-megapixel sensor with aperture capabilities from F2.8-F11. Figure 24 shows the above described system.

Each flight altitude was normally 50m above ground level which equaled a surface coverage of 70-80% surface overlap by every photo captured. The flight plan was executed using a preset capture grid using the software Pix4DCapture (Figure 26 *a, b, & c)*. The imagery capture rate was predetermined using Pix4DCapture using three captures per second at a 30◦ angle cant. The double grid quadrant over the study reach was used to increase variability in spatial analysis for post flight data analysis.

One of the factors influencing the flight pattern and imagery acquisition, was the outdated aerial imagery basemaps used by the Pix4DCapture software. I often found that the grid pattern needed alteration to capture the present-day channel location for each site. Due to the high variance in channel migration in the research locations, the grid developed was often updated upon arrival to the site. This was also the case at WYN-SR12 site where the channel had not changed its path dramatically in recent years. It was determined on the pre-flight visit that at least one GCP's be placed on a surface that had low probability of changing in the next 10-20 years. Establishing a reputable long duration GCP would allow for potential replication of the monitoring practices used in the ongoing future research. Unfortunately, setting a GCP on State Route 12 was not viable in the Wynoochee River location as the adjacent highway was far too dangerous.

For additional detail and summary see ***Appendix I***

3.3 Pre-Site Visit

For the pre-site visit the primary objective was to assess the accessibility of the desired location. I observed aerial imagery on google earth and on LiDar layers in ArcGIS Pro from WADNR. I then worked to gain the permission of the landowner and ensured safe entry points to the research locations. Using the FAA guidelines and regulations I then determined whether or not the research location was within compliant airspace and would be safe to fly with the sUAV. To generate the flight plan I developed a double grid flight pattern over the desired river reach I wanted to capture and model. I used the software Pix4DCapture to develop this grid pattern for each flight, guide the drone at the appropriate speed, flight height, and image capture rate.

For additional detail and summary see ***Appendix I***

3.4 Site Visit Part I

During the primary site visit the main directive was to analyze the sorroundings of the site, ensure tha the flight pattern would be over the correct portion of landmass. During the pre- sitevisit I collected the high accuracy elevational data using a Trimble GPS system. The Trimble data aided the elevational data capture by locking onto at least 10 satelites and concluded that a minimum of five ground control points or GCP’s was the an optimal amount of elevational points for post processing. The GCP’s were then corrected in the post processing stage using differential correction to reduce their erros to a minimum of 5cm of accuracy. See Table 2.3 for the number of GCP’s used for each site.

(a) (b)

Figure 25 (a) *A Trimble equipped with TerraSync Version 5.86 used to collect the elevation data at each research location for all ground control points or GCP’s for each location. Figure 25* (b) *is a ground control point that has been staked to the ground. This method along with high visibility flagging tape was used to correlate flight data to aerial imagery.*

Table 3 represents the number of ground control points captured in the field compared to the number used in post image capture processing using the software Drone2Map.

Site ID	Number of GCP's Captured in the Field	Number of GCP's Used for Post Capture Processing
WYN-SR12	10	5
MS-SAT-GLICK	23	5
WF-SAT-BRIDGE	12	5

In addition to capturing elevation data, it was essential to identify the condition and current location of the bank armoring structures. By doing so I was able note the location of the remaining structure for site WF-SAT-BRIDGE and identify whether or not I needed to extend my grid pattern. For site MS-SAT-GLICK and site WYN-SR12 I was able to reduce my predetermined flight grid and flight time significantly. Because the sUAV's are heavily battery dependent and you only get about a half hour of flight time for each battery, it is essential to plan accordingly. For each Flight I had a total of three batteries each with a flight time capability averaging one half hour. I used that calculation of timing coupled with Pix4DCapture to determine the size of my research grid patterns.

The MS-SAT-GLICK flight pattern was most challenging to develop due to the outdated basemap used by Pix4DCapture. Figure 26 *(b)* shows the channel much further south than it was located during the research flight in 2018. I had to use my pre-flight traditional ground survey data collection to determine what size and the location of grid I wanted to use.


END
START
GSD
0.61
in/px
169
168
167
ft
75%
597 x 780 ft
18 min : 42 s
START
(a)


START
END
GSD
0.61
in/px
169
168
167
ft
75%
925 x 1302 ft
41 min : 33 s
START
(b)

(c)

Figure 26 represents the predetermined gird patterns used for each sites flight pattern. The sites in order are as follows (a) *WYN-SR12* (b) *MS-SAT-GLICK* (c)*WF-SAT-BRIDGE.*

For additional detail and summary see ***Appendix I***

3.5 Site Visit Part II

During the secondary site visit I would begin the flights to capture the aerial based imagery for my research using the sUAV. To begin the process, I walked each site to ensure that there was not any potential danger for both the sUAV and wildlife or livestock in the area. In doing so I also determined where I would launch the sUAV and maintain a clear line of site on the unit to ensure clear airspace and lack of potential conflict with other aircrafts. I then launched the sUAV and began the grid pattern flight. If necessary, I would switch the battery in the unit, and the sUAV would return a battery change to its prior location in the pattern.

After the sUAV completed its flight pattern I then previewed the imagery captured to determine the quality and the coverage of the grid pattern. I chose not to upload any of the imagery from the sUAV's memory storage chip to the iPad on site due to the lack reliable cellphone signal bandwidth in the research locations. I removed the chip from the sUAV each time and uploaded the imagery to my home device and stored the imagery in a cloud-based file server for future processing.

*For additional detail and summary see **Appendix I***

4. Photogrammetric Processing

The post flight photogrammetric processing was carried out using the software Drone2Map for ArcGIS version 1.3.2.232 also compatible with ArcGIS Pro version 2.2.3. The licensing for the Drone2Map software was granted for this research from the Esri Conservation Program. The workflow for post imagery processing was a four-step process to generate the output of 2D orthomosaics and 3D textured mesh outputs seen in the results section.

To begin the process the raw flight images like those seen in Figure 27, are uploaded from the sUAV memory card to a file and then uploaded to ArcGIS Pro after setting the location of the source imagery. Because Pix4DCapture uses the coordinate system GCS WGS 1984 it is imperative that the image coordinate system be set to a matching coordinate projection as well in the initial *project build* options. The results from this image acquisition resulted in the best modeling with a minimum of 800 photos per location. To ensure an adequate number of photos, I checked the capture settings in Pix4dCapture before carrying out the flight of the grid pattern.

Figure 27 represents a raw image file from the flight over site MS-SAT-GLICK. It shows the east half of the bank armoring structure and the large cutbank (shown in red) developing where the rock structure ends.

After the image import process, the ground control points need to be referenced and matched to a minimum of three images to increase accuracy of the final projection. The GCP’s for this research were imported from the Trimble to be corrected using Differential Correction Wizard to then have an accuracy of 86% within 5 cm (Figure 28). The correction of the GCP’s resulted in a more accurate 3D model and less distortion in the modeling outputs for the orthomosaics.

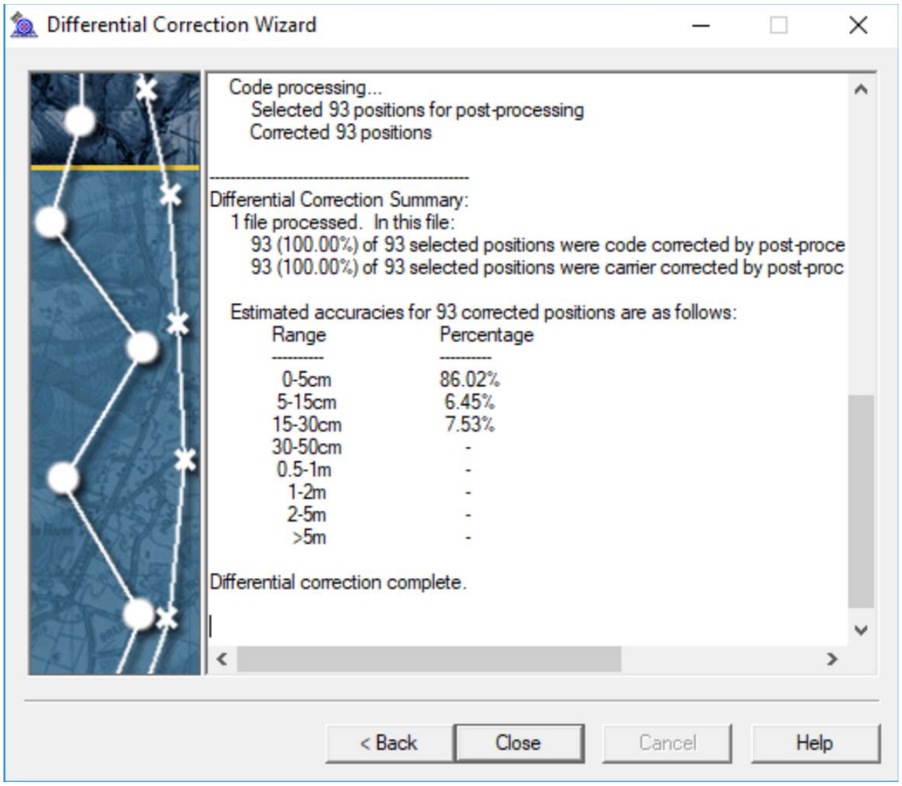


Figure 28 represents the ground control corrections using Trimble Differential Correction Wizard software to improve the elevational and spatial accuracy for the GCP data collected at each location. This specific correction achieved a 5cm accuracy for all points collected.

Once processed, the GCP's had to be uploaded to ArcGIS Pro to reclassify the coordinate system to WGS_1984_UTM_Zone_10N. This was the coordinate system that Drone2Map uses to generate the models and create the surface layer outputs. To reclassify the coordinate system in ArcGIS Pro, the points were stored in a file geodatabase and added to the workspace. After this step, I added two fields to the attribute table and field calculated for latitude and longitude in decimal degree units. The Lat and Lon fields were then added to the basemap projection due to reclassifying the spatial reference for the coordinate system in the layer properties (Figure 29).

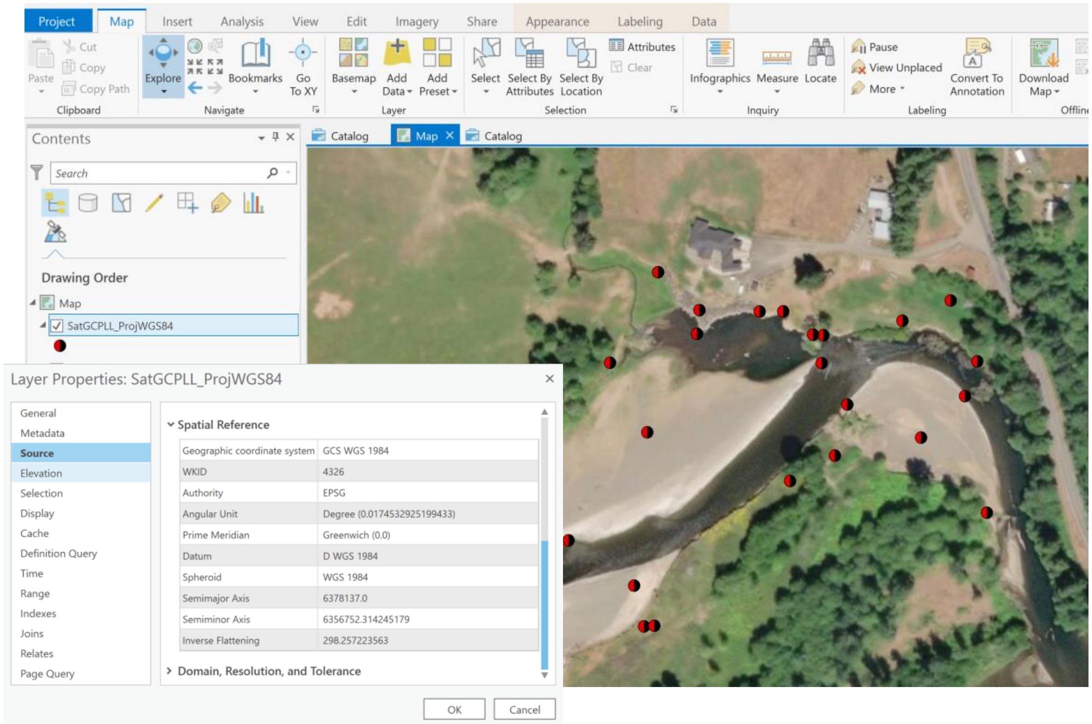


Figure 29 shows each of the GCPs collected and plotted after the spatial reference process. It also shows the layer properties from the MS-SAT-GLICK site ground control point layer file. Basemap- World Imagery provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Following the GCP coordinate reclassification, the GCP's must be manually matched to the flight images to correlate their spatial relationship in Drone2Map. Using the Manage GCP's icon the data can be imported from a Drone2Map GCP export, a file geodatabase, a CSV file, or a hosted feature layer. It is important to note that the *Use Feature Geometry* box be checked so that the data can be imported correctly seen circled in red in Figure 30. In the same *Import GCP's* window, the elevation for the GCP's will need to read as *GNSS_Heigh* to accurately project the data in the Drone2Map models.

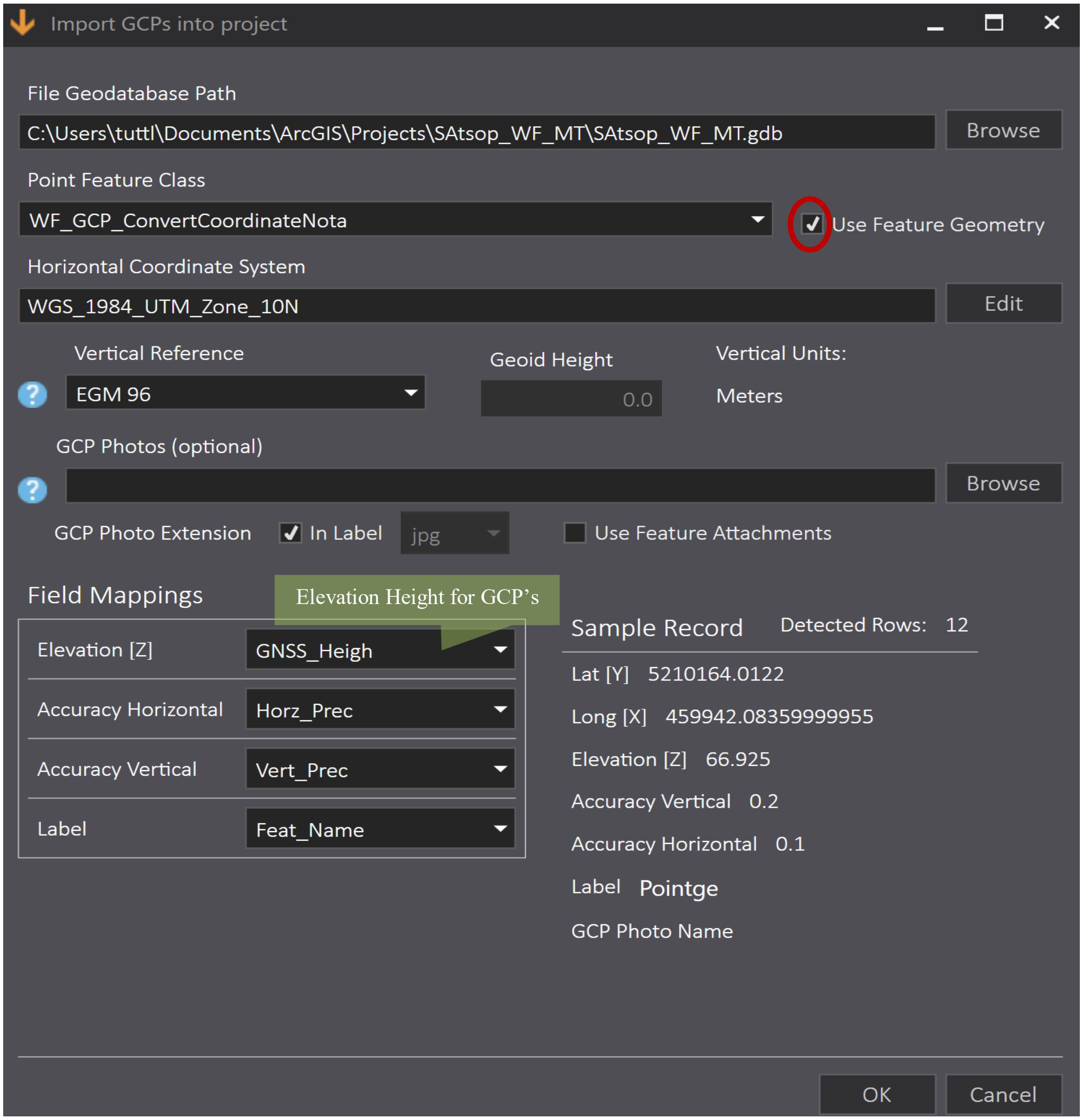


Figure 30 shows the Import GCP's window for Drone2Map software to accurately represent the elevation data collected in the field to correlate to the aerial imagery collected. This also shows the correct input for Elevation [Z] *as GNSS_Height.*

After the GCP's are linked to a minimum of at least three photos from the aerial imagery, the image icons will display as a green check mark rather than their initial symbology of a red X. Model processing can begin once there are at least three green checked symbols with sufficient GCP density. To have an accurate model that represents platform dynamics in a riverine system it is suggested to link at least four GCP's to the aerial imagery before processing can begin.

For desired capture of morphological platform complexity, a minimum of 5 GCP's were used to process the models seen in this research. Platform complexity defines the elevational characteristics of a river channel's elevational morphology. A step or a platform can be compared to a terrace like landform that becomes covered during high water events (Figure 31).

Figure 31 shows 3 GCP's at the WF-SAT-BRIDGE research site. The two GCP's circled in red show a complex platform change of 1.56m (measured during pre-site visit). Imagery captured during the 2018 research flights.

The next step is to develop the desired model type. For both a 2D and a 3D model the next steps are required. For the model processing to be succinct and high in accuracy it is suggested that the keypoint image scale be placed at full and the image pairs be set to the aerial grid or corridor setting. For this research a grid generated by the Pix4DCapture software is easily integrated into the algorithm used by Drone2Map to correlate image matches and positioning. Using the 2D product settings will aid in developing the orthomosaics of the site. The orthomosaics for this research were first run as a rapid half density point cloud models to determine the accuracy of the GCP's and imagery (Table 4). After that process had taken place, they were then run as high density full keypoint image scales using the aerial grid pattern imagery match settings. The same primary process was used to consider the accuracy of the models when considering the 3D models. To process the 3D models the point cloud settings were set to create zLAS and LAS files from merged tiles and classification settings. The 3D output was selected to be a scene layer package for presenting purposes at a medium quality with three number levels. The overall resolution of each 3D model was set to the default setting of medium resolution for imagery output.

Table 4 Shows the processing time for each point cloud model. These models were processed using a Dell laptop with a CORE i7 7th generation processor.

Processing Times for Orthomosaic Surface Layers

Site ID	Rapid Density Point Cloud Processing Time	Dense Point Cloud Processing Time
WYN-SR12	4 hours 37 min	18 hours 3 minutes
WF-SAT-BRIDGE	7 hours 45 min	32 hours 21 minutes
MS-SAT-GLICK	7 hours 23 min	25 hours 15 minutes

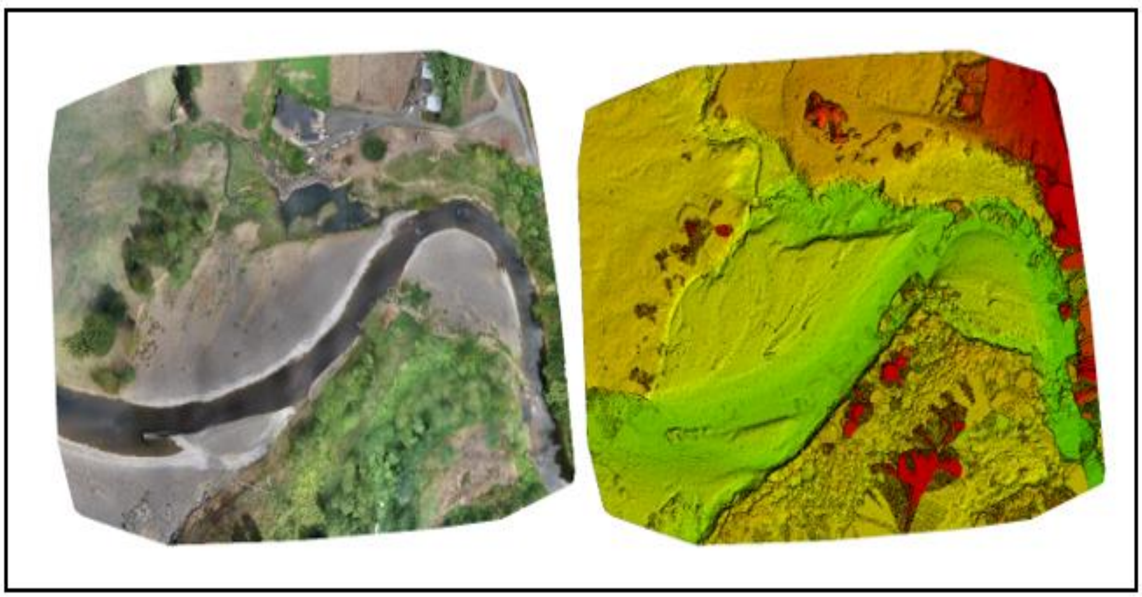


Figure 32 depicts two of the orthomosaics outputs of the mainstem Satsop River from the Processing Report in Drone2Map before densification. The ordinary colored surface layer on the left shows a stitched replica of the imagery collected during the flight, while the image on the right shows an elevation representation of the site with a color gradient to identify the low (green) and high (red) elevations of the site.

Processing times averaged 25-hours per dense model using a Dell laptop computer with a CORE i7 processor. The Drone2Map software generates a processing report which summarizes the following;

- The project specifications
  - Area covered by the sUAV
  - Processing time
  - Photos matches per point
- A set of orthomosaics pre-densification (Figure 32)
- A surface replica of the flight pattern and image captures from the imagery n progress.

Post processing surface layers can then be opened in ArcGIS Pro and manipulated for visualization. For the purpose of this research, the orthomosaics were used to show the entirety of the research location, a base for an overlay of the engineering design drawings of the implemented structure, as well as a representation of the current channel path. The 3D models were used to depict the platform dynamics, presence of large woody material, vegetative dynamics, structural presence, structural integrity, as well as other hydraulic interaction with the armoring structure. The 3D models also depict an interesting perspective of the flight pattern as well as any updraft that the done experienced during the gridded flight pattern (Figure 33).

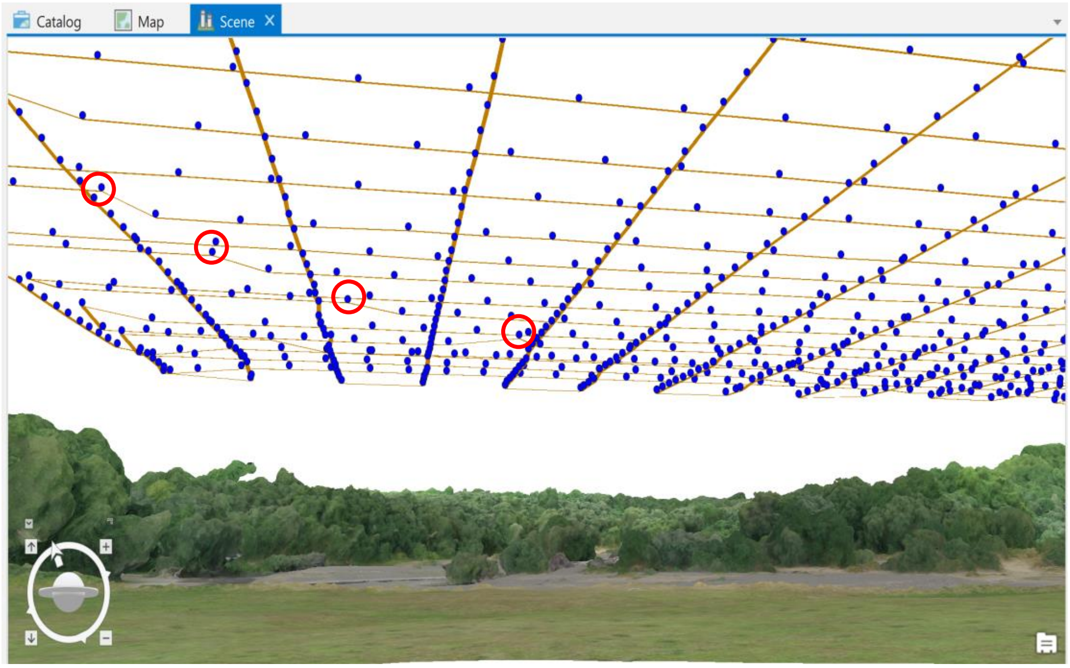


Figure 33 shows the modeled flight path in ArcGIS Pro after the 3D imagery has been processed in Drone2Map. Irregularities in the orange line represent wind uplift that the drone experienced during the gridded flight pattern. An uplift from wind (circled in red) can be seen in multiple areas of this flight pattern on the WF-SAT-BRIDGE flight.

5. Results

Using Pix4dCapture, Drone2Map, and ArcGIS Pro to digitize the aerial imagery of the structures chosen for this research, results show the ability to determine the accuracy and capability of using sUAV's as a conclusive methodology for riverine systems. Integrating historical aerial imagery and engineering plans to represent the intentions of the original structures and their initial protection goals has enhanced the results of this research. After post processing the 3D modeling results show the locations flown on days with dispersed lighting and low contrast were the highest in dense modeling output. The orthomosaics, elevational data, and 3D textured mesh models from the sUAV's photogrammetry resulted in high accuracy models used to determine structural success of the research locations. This analysis type provides an additional method to conduct terrestrial field surveys, and an insight into the future of riverine research. The capabilities of this methodology also highlight the ability analyze restricted or dangerous sites that require assessment.

Although there were a limited number of flights on each bank armoring structure, every site was thoroughly analyzed, and a highly accurate output was generated for each research location. The downside to the low numbers of flights was the output of data that was collected on days that were high contrast in light creating some distortions in the 3D modeling. The orthomosaic output data was unaffected by the light and processed to have minimal error in projection. Additional projection errors included reflective light on the water surface and days flown with high shadowing on surfaces. The geometric calculations in Drone2Map were unable to mask these defaults and detour the algorithm from distorting the imagery.

The results from each research location were dependent on the light and the weather conditions experienced during each flight. The WF-SAT-BRIDGE site resulted in the best imagery out of the three sites flown (Figure 39). The primary variable resulting in the most accurate imagery was the dispersed lighting form highly overcast and smoky skies during the 2018 summer wildfires in British Columbia Canada. The MS-SAT-GLICK site produced the second-best imagery due to the early morning flight time (Figure 41). The weather that day was predicted as sunny with high light intensity. The determination was made to start the flight early when the skies were still overcast with the marine layer that is present in Grays Harbor County on summer mornings.

In contrast, the diffused light during the WF-SAT-BRIDGE flight generated exceptionally clear data with minimal distortion in the 3D textured mesh layer (Figure 34). Weather conditions at the WYN-SR12 site and the WF-SAT-BRIDGE overflights showed uplift in the sUAV's flight pattern from wind influencing the elevation of the imagery capture flight grid (Figure 33). The WYN-SR12 site was highly contrasted in light and had severe reflections on the water surfaces due to an unexpected storm that came through during the flight. The timing of the flight was also early morning but due to the storm, there was clearing of clouds allowing high intensity light to project onto the water surface generating a highly reflective surface. The orthomosaic without GCP rectified data for this location was complete. The 3D textured mesh however, had several extreme distortions in the water layer resulting in large uplifts in the water (Figure 34).

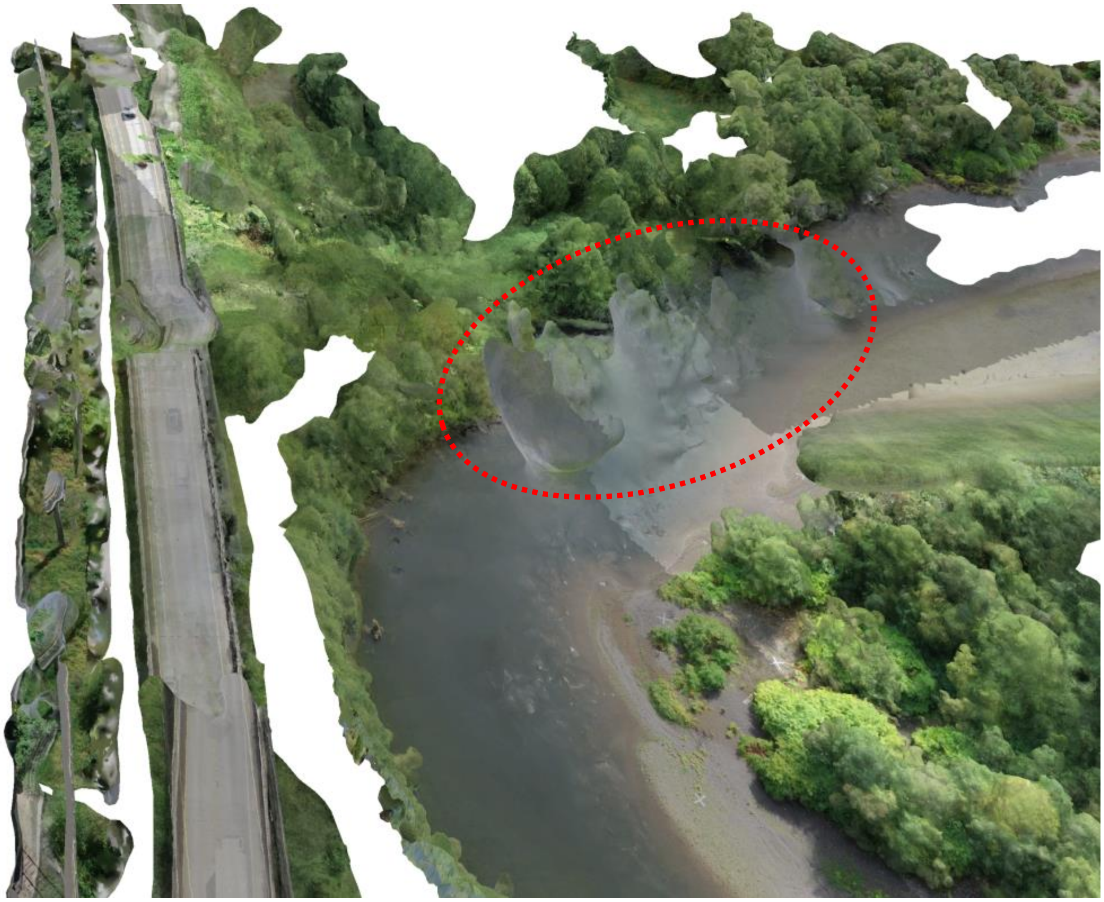


Figure 34 is a rendering of the WYN-SR12 research location. The image above shows the distortions (circled in red) in the output imagery that was created by highly reflective water due to weather conditions and high sunlight hitting the water surface. This image was from the primary processed data that was run prior to using ground control points.

From three separate flights in multiple locations this research represents over 300 hours of imagery acquisition and processing. Processing time for the sUAV based imagery, ground control points, orthomosaic products, and 3D textured mesh mosaic outputs account for over half of the hours spent due to methodology development. The processing of the orthomosaics and textured 3D mesh outputs was a labor-intensive process that was time consuming due to the high-density model outputs desired for this research. The processing on average for each 3D textured mesh required 25-30 hours for each project, and an average of 14-16 h for each orthomosaic surface layer output.

Each site possessed an engineering goal and part of the research was to determine the success or overall state of each structure through the imagery captured by the aerial survey. The 3D textured mesh mosaics generated in Drone2Map were able to accurately represent the current state of each bank armoring structure. Comparing the present channel path with the goal for each armoring structure in ArcGIS Pro in the *Scene* view, the presence or lack of presence of each armoring structure is clear and concise.

The following figures are from the 3D models generated from my research flight using Drone2Map then further manipulated using ArcGIS Pro. The models from this research conclude that by using sUAV base imagery, 3D models can generate high-quality photogrammetry to extensively assess bank armoring structures.

The main purpose of defining the structural integrity and success of bank armoring structures is to preserve a natural process that allows for habitat regeneration and stability. Riverine systems are stewards for regeneration and growth that are commonly unable to carry out their natural functional role due to anthropogenic encroachment. The models produced from my research have the potential to become a methodology for reliable and safe monitoring of bank armoring structures. In addition, the models produced from this research represented data collection that was not intended. The high-density point cloud data from the sUAV flight at each location generated habitat data, fluvial mechanic data, channel morphology data, and vegetation data.

5.1 Site Implementation Success or Failure, Observed by sUAV Imagery

The purpose of the research flights was to identify three different research locations and assess whether or not sUAV based imagery was capable of determining the success of bank armoring structures. Comparing each location with the preexisting knowledge of structure design derived from the engineering schematics set the basis for comparison for the three locations. Prior to the sUAV based overflights, I used satellite based aerial imagery to determine whether the structures were present or had been damaged or destroyed by historic high flow events. Knowing that some of the satellite imagery used to make this determination was dated, a field investigation followed. The goal was to identify a successful project, an active project, and an unsuccessful project implementation. Each of the sites reviewed for this research represented one of the three above mentioned categories.

Active Implementation

Seen in Figure 35, the MS-SAT-GLICK location was determined as active status due to its current structural status and how it is effecting the channel. The project met its designed engineering goals that were initially implemented, however the downstream effects to the landowner's property continue to display erosive behaviors. Reviewing the 3D model generated for the research in Figure 35, it is apparent that the bank armoring structure protected the landowner's home and kept the river from eroding away the bank. Based on this variable alone it could be argued that the structure could be categorized as successful.

Successful Implementation

The WYN-SR12 location was determined as a successful bank armoring structure based on several observed variables. The 3D textured mesh surface layers in Figure 36 show bank protection implementation as structurally viable and present. It has withstood near two decades of hydraulic cycles and remains structurally paralleled to its original implementation design. The LWM is angled in its original implementation design, the rip rap is present, and the vegetation stakes have grown into full sized trees increasing bank stability. In addition, the WYN-SR12 location continues to meet its engineering goals keeping the channel from threatening the bridge pillars of State Route 12.

Failed Implementation

The representation of an unsuccessful project was captured at the WF-SAT-BRIDGE location. The conclusion was based on both the aerial imagery captured with the sUAV during this research as well as multiple variables collected using traditional ground survey. With the aerial imagery from 3D textured mesh surface layers seen in Figures 37 and 38, it was determined that the remaining portions of the initial bank protection structure were no longer influencing channel direction as they were intended or designed. The upstream most remaining rock groin is influencing the channel by creating a large sediment deposition zone (Figure 37). The deposition zone is gathering gravels and ultimately redirecting the channel more aggressively into the bank downstream that it was initially implemented to protect (Figure 31).

The remaining rock groins represented in the sUAV based imagery of site WF-SAT-BRIDGE are the only structural representation of the initial implementation. The main variables used in this research to determine success of a bank armoring structures were the presence of the structure and the influence it had on the riverine system. The WF-SAT-BRIDGE armoring structure is no longer meeting its engineering goals and was therefore determined as an unsuccessful project.

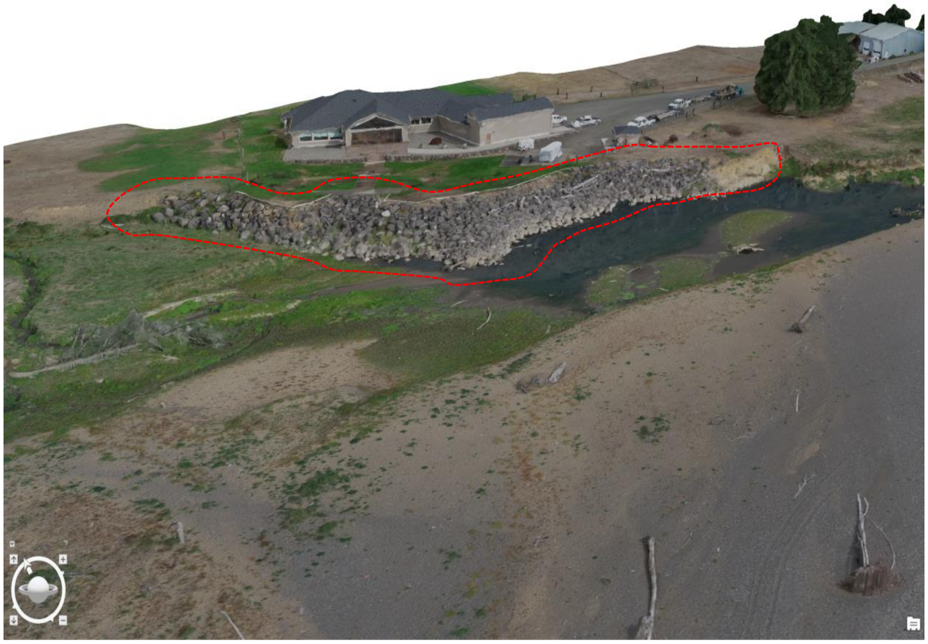


Figure 35 Active Site Status - The armoring structure at site MS-SAT-GLICK (circled in red) that has been captured from the 3D model created using Drone2Map and ArcGIS Pro.

Figure 36 Successful Site Status- The armoring structure at site WYN-SR12 (circled in red) captured from the 3D model created using Drone2Map and ArcGIS Pro.

Figure 37 Failed Site Status - One of the remaining rock groins that was part of the 1997 implemented armoring structure at site WF-SAT-BRIDGE (circled in red) captured from the 3D model created using Drone2Map and ArcGIS Pro.

Figure 38 Failed Site Status- An additional remaining rock groins that was part of the 1997 implemented armoring structure at site WF-SAT-BRIDGE (circled in red) captured from the 3D model created using Drone2Map and ArcGIS Pro.

Figure 39 Shows the collective flight and 3D textured mesh surface layer generated in Drone2Map of site WF-SAT-BRIDGE. Underlay Basemap World Imagery- transparency set to 45% provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 40 Shows the collective flight and 3D textured mesh surface layer generated in Drone2Map of site WYN-SR12. Underlay Basemap World Imagery- transparency set to 25% provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 41 Shows the collective flight and 3D textured mesh surface layer generated in Drone2Map of site WF-SAT-BRIDGE. Underlay Basemap World Imagery- transparency set to 35% provided by Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

6. Conclusion

Remote sensing methodologies have been demonstrated to be effective in many natural science applications. However, the use of such methodologies is on the brink of riverine research and restoration projects. A frequent use of sUAV imagery used to monitor fluvial response to geomorphic change from implemented bank protection structures can accurately model complex hydraulic interaction and habitat integrity. Using sUAV offers a comparable output that requires less time, cost, and terrestrial survey investment than the use of classic manned aerial imagery data acquisition. This research showed that using sUAV photogrammetry to assess riverine bank armoring structures provided dense modeling and alternate methods to riverine restoration modeling and monitoring practices.

While physical collection of data in the field is virtually essential, the use of topographic map review and aerial assessment data illuminated hidden characteristics of the riverine systems in this research. Bank armoring structures can create multiple downstream and upstream effects when encountering high-water events and are often not completely visible by traditional ground survey methods. Using sUAV's for this research deobfuscated potentially challenging landscape to access on foot, as well as aerial assessment of thick stand vegetation that would have otherwise been overlooked. The topography of the landscape is often challenging in natural riverine systems, so using sUAV's allowed for the imagery acquisition of areas that would not have been otherwise surveyed for this research.

The sUAV used in this research produced high quality imagery and facilitated rapid data collection in the field. This research successfully concluded that sUAV's can collect precise aerial imagery that can be used for extensive riverine research applications. Because the site locations were flown in the summer months, there was no present danger of flood waters or sediment and material transport. However, if the sites were to be surveyed in the winter months, the use of sUAV's as shown in this thesis represents a practice to enable safe data acquisition at a low cost. During the winter seasons high flows make the river channels dangerous or impossible to conduct monitoring using a terrestrial survey methodology. During these high flow events, monitoring data that cannot typically be collected by ground survey could be safely recorded from the study-area at a safe distance from danger. If the pilot can maintain a visual with the sUAV, data can be collected, and surveyors can remain clear of the channel while conducting an effective survey.

The research methodology of using sUAV's to monitor bank armoring structures has also shown to be an effective methodology for future monitoring. The sUAV based monitoring technique consisted of developing a flight plan, executing the flight, and processing the imagery collected from the flights. The data acquired by these flights and processed using a high-density point cloud process rendered high quality imagery that could be used in many different applications. In contrast to terrestrial methodologies which rely heavily on external data acquisition from external entities, using sUAV's in state agencies develops a constant and reliable source of data acquisition than can be replicated inexpensively.

Using sUAV's presents a new technological application of using aerial imagery in riverine science and structural monitoring. The major contribution of this work is to present a methodology to state agencies that is accessible in both cost and efficacy to increase monitoring efforts in the future. A long-term objective for using sUAV based imagery is to increase the temporal monitoring of structures in riverine systems to enhance the understanding of their effects on hydraulic habitat. In addition, using sUAV's has the potential to provide support to landowners and state agencies to increase understanding of bank armoring structures and the fluvial interactions in hydraulic systems.

References

Arif, M. S. M., Gülch, E., Tuhtan, J. A., Thumser, P., & Haas, C. (2017). An investigation of image processing techniques for substrate classification based on dominant grain size using RGB images from UAV. *International Journal of Remote Sensing*, *38*(8–10), 2639–2661. https://doi.org/10.1080/01431161.2016.1249309

Brooks, K. N., Ffolliott, P. F., & Magner, J. A. (2013). *Hydrology and the management of watersheds*. Ames, IA: Wiley-Blackwell.

Konsoer, K. M., Rhoads, B. L., Langendoen, E. J., Best, J. L., Ursic, M. E., Abad, J. D., & Garcia, M. H. (2016). Spatial variability in bank resistance to erosion on a large meandering, mixed bedrock-alluvial river. *Geomorphology,252*, 80-97. doi:10.1016/j.geomorph.2015.08.002

Li, M.-H., & Eddleman, K. E. (2002). *Biotechnical engineering as an alternative to traditional engineering methods A biotechnical streambank stabilization design approach*. *Landscape and Urban Planning* (Vol. 60).

Martínez-Carricondo, P., Agüera-Vega, F., Carvajal-Ramírez, F., Mesas-Carrascosa, F. J., García-Ferrer, A., & Pérez-Porras, F. J. (2018). Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points. *International Journal of Applied Earth Observation and Geoinformation*, *72*, 1–10. https://doi.org/10.1016/j.jag.2018.05.015

Polvi, L. E., Wohl, E., & Merritt, D. M. (2014). Modeling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms*, *39*(9), 1245–1258. https://doi.org/10.1002/esp.3577

Science, T. C. (2012). Dawn of drone ecology : low-cost autonomous aerial vehicles for conservation Dawn of drone ecology : low-cost autonomous aerial vehicles for conservation, (June 2014). https://doi.org/10.5167/uzh-72781

Schook, D. M., Rathburn, S. L., Friedman, J. M., & Wolf, J. M. (2017). A 184-year record of river meander migration from tree rings, aerial imagery, and cross sections. *Geomorphology,293*, 227-239. doi:10.1016/j.geomorph.2017.06.001

Thumser, P., Haas, C., Tuhtan, J. A., Fuentes-Pérez, J. F., & Toming, G. (2017). RAPTOR-UAV: Real-time particle tracking in rivers using an unmanned aerial vehicle. *Earth Surface Processes and Landforms*, *42*(14), 2439–2446. https://doi.org/10.1002/esp.4199

Bibliography

Alber, A., & Piégay, H. (2017). Characterizing and modelling river channel migration rates at a regional scale: Case study of south-east France. *Journal of Environmental Management*, *202*, 479–493. https://doi.org/10.1016/j.jenvman.2016.10.055

Arif, M. S. M., Gülch, E., Tuhtan, J. A., Thumser, P., & Haas, C. (2017). An investigation of image processing techniques for substrate classification based on dominant grain size using RGB images from UAV. *International Journal of Remote Sensing*, *38*(8–10), 2639–2661. https://doi.org/10.1080/01431161.2016.1249309

Benjankar, R., Burke, M., Yager, E., Tonina, D., Egger, G., Rood, S. B., & Merz, N. (2014). Development of a spatially-distributed hydroecological model to simulate cottonwood seedling recruitment along rivers. *Journal of Environmental Management*, *145*, 277–288. https://doi.org/10.1016/j.jenvman.2014.06.027

Capilleri, P. P., Motta, E., & Raciti, E. (2016). Experimental Study on Native Plant Root Tensile Strength for Slope Stabilization. In *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2016.08.415

Fernández-Guisuraga, J. M., Sanz-Ablanedo, E., Suárez-Seoane, S., & Calvo, L. (2018). Using unmanned aerial vehicles in postfire vegetation survey campaigns through large and heterogeneous areas: Opportunities and challenges. *Sensors (Switzerland)*, *18*(2). https://doi.org/10.3390/s18020586

Flow Velocity in Sarply curved river bends (Vriend) 1983. (n.d.).

Fraser, B. T., & Congalton, R. G. (2018). Issues in Unmanned Aerial Systems (UAS) data collection of complex forest environments. *Remote Sensing*, *10*(6). https://doi.org/10.3390/rs10060908

Frothingham, K. M. (2008). Evaluation of stability threshold analysis as a cursory method of screening potential streambank stabilization techniques. *Applied Geography*. https://doi.org/10.1016/j.apgeog.2007.07.006

Gafurov, A. M. (2018). Small catchments DEM creation using Unmanned Aerial Vehicles. *IOP Conference Series: Earth and Environmental Science*, *107*(1). https://doi.org/10.1088/1755-1315/107/1/012005

Haas, C., Thumser, P., Tuhtan, J. A., Thongkao, S., & Treitler, R. (2016). UAV based monitoring of a living weir in Thailand. *11th ISE 2016*, 2–6.

Iwasaki, T., Shimizu, Y., & Kimura, I. (2016). Numerical simulation of bar and bank erosion in a vegetated floodplain: A case study in the Otofuke River. *Advances in Water Resources*, *93*(Part A), 118–134. https://doi.org/10.1016/j.advwatres.2015.02.001

Knox, N. M., Strohbach, B. J., & De Cauwer, V. (2018). Potential use of 3D-derived products generated from unmanned aerial vehicle (UAV) imagery for monitoring forest degradation and woodland structure changes in the Namibian dry woodlands. *Biodiversity & Ecology*, *6*(April), 378–379. https://doi.org/10.7809/b-e.00349

Konsoer, K. M., Rhoads, B. L., Langendoen, E. J., Best, J. L., Ursic, M. E., Abad, J. D., & Garcia, M. H. (2016). Spatial variability in bank resistance to erosion on a large meandering, mixed bedrock-alluvial river. *Geomorphology*, *252*, 80–97. https://doi.org/10.1016/j.geomorph.2015.08.002

Milas, A. S., Arend, K., Mayer, C., Simonson, M. A., & Mackey, S. (2017). Different colours of shadows: classification of UAV images. *International Journal of Remote Sensing*, *38*(8–10), 3084–3100. https://doi.org/10.1080/01431161.2016.1274449

Polvi, L. E., Wohl, E., & Merritt, D. M. (2014). Modeling the functional influence of vegetation type on streambank cohesion. *Earth Surface Processes and Landforms*, *39*(9), 1245–1258. https://doi.org/10.1002/esp.3577

Priceputu, A., Bugea, A. L., Rosu, C. V., & Serbulea, M. S. (2014). Optimization of River Bank Protection Design By Discrete Element Method. *14th SGEM GeoConference on Science and Technologies In Geology, Exploration and Mining*, *2*(GEM2014 GeoConference Proceedings, ISBN 978-619-7105-08-7 / ISSN 1314-2704, June 19-25, 2014, Vol. 2), 683–690 pp. https://doi.org/10.5593/SGEM2014/B12/S2.087

Schuurman, F., Shimizu, Y., Iwasaki, T., & Kleinhans, M. G. (2016). Dynamic meandering in response to upstream perturbations and floodplain formation. *Geomorphology*, *253*, 94–109. https://doi.org/10.1016/j.geomorph.2015.05.039

Science, T. C. (2012). Dawn of drone ecology : low-cost autonomous aerial vehicles for conservation Dawn of drone ecology : low-cost autonomous aerial vehicles for conservation, (June 2014). https://doi.org/10.5167/uzh-72781

Smith, M. J., & Pain, C. F. (2009). Applications of remote sensing in geomorphology. *Progress in Physical Geography*, *33*(4), 568–582. https://doi.org/10.1177/0309133309346648

Thumser, P., Haas, C., Tuhtan, J. A., Fuentes-Pérez, J. F., & Toming, G. (2017). RAPTOR-UAV: Real-time particle tracking in rivers using an unmanned aerial vehicle. *Earth Surface Processes and Landforms*, *42*(14), 2439–2446. https://doi.org/10.1002/esp.4199

Zaid, B. (2018). Development of Design Guidelines for Shallow Groynes Development of Design Guidelines for Shallow Groynes, (April). https://doi.org/10.24355/dbbs.084-201804100941

Appendices

Appendix I

2.1 Pre-Site Visit

1. Determine whether the site is accessible by foot or boat. If the site is not accessible, then it is determined as non-viable. During this portion of site research, one must also decide the intended reach length desired for aerial survey. If not accessible by either landowner permission or by foot site viability should decrease. It is necessary to reach all locations of the desired reach if there were to be technical failure of your UAS.
    a. Locational airspace should also be a factor in this portion of site determination. The FAA has strict regulations that require a permitting process if flying in a restricted airspace as part of a public entity. The pilot must apply for a LAANC or Low Altitude Authorization Notification Capability Permit and receive approval to fly in the desired airspace. If the airspace is nonregulatory and is merely over private land, then the pilot must be willing and able to yield to all other aircraft that enter the proximity of the study reach.
2. Contact the landowner to determine permission to access the property. During this stage it is important to also inform the landowner that the imagery captured becomes public data if you are flying for a state agency or an institution.
    a. If permission is denied, move onto the next potential site location.
    b. If permission is granted, proceed to step three of the methods sections.

3. If available through a state agency or local government, review engineering plans to determine what structural methodology was used for the bank protection methodology of your desired site.
    a.
4. Research past aerial imagery to determine previous scour, previous channel migration patterns, and potential future avulsion sites that become part of the grid pattern you intend to set up for the aerial assessment of your intended research reach.
5. Develop a double grid flight pattern using the software Pix4Dcapture.
    a. Ensure that the flight covers the engineering plans radius
    b. Ensure that the flight covers enough of the reach to determine habitat influence from the structure
    c. Determine potential crossings for ground truth locations
6. Create a preflight map for ground truth locations
7. Preflight inspection and preflight of drone the evening before planned flight to determine any potential errors or faults with equipment
8. Prepare equipment for transport

2.2 Site Visit Part I

1. Landowner meeting and proposal of intended methodologies
2. Survey the reach to determine that aerial imagery used for grid mapping in Pix4DCapture is accurate
    a. Have an accurate representation of the ground data so that your grid pattern is not off
3. Implement ground truths

a. Using the Trimble seen in Figure 25 *(a)* generate at least 12-15 ground truths throughout your study reach to determine the morphological differences in platform dynamics of the reach.
b. TerraSync Version 5.86
c. Lock into satellites available
d. Begin point capture data collection process
    i. You want at least 5-16ft of stated accuracy on the Trimble display screen, for best results wait for 1” accuracy if available.
e. Stake, “X” using ground truth material, or flag each ground truth location so that it can be seen from the flight pattern seen in Figure 25 *(b)*
    i. This will be how we later render the imagery and analyze the elevation data captured

4. After each location desired has been marked return to a flat location in the study reach with a firm line of site for your flight pattern.

2.3 Site Visit Part II

1. Begin preflight- this flight is to test wind speeds, potential errors with the sUAV, as well as to detour any potential hazards in the area
2. Clear Hazards- Bird eradication of the intended flight path
    a. Often small birds will not attack the drone
        i. Large raptors and crows will flare the drone to establish dominance

        ii. Geese and ducks are faster mobile hazards that will clear the area with one pass of the sUAV

3. Develop a clear line of site for the first portion of the grid pattern
4. Set Pix4DCapture predetermined flight path into motion and begin flight pattern
    a. During the first several North South passes of the drone keep a keen eye on potential hazards such as birds and treetops
        i. Your flight height is a variable up to a maximum of 165ft
    b. During the first several East West passes of the drone keep a keen eye on potential hazards
5. If the flight pattern is larger than a 1 battery charge, pause the imagery capture and have the drone return to home to switch batteries
6. After drone has completed your flight pattern it will automatically return to home.
    a. Do not force the drone to return to home as it may skew some of your final imagery
7. Land the drone safely in a chosen location
8. If desired you can begin an upload to your flight directory device (iPhone, iPad, etc.)
9. If you do not wish to preview your images, you can simply complete the task on the flight directory device and end flight
10. The images are stored on the sUAV's chip and can later be transferred to a computer for rendering

Appendix II

Other Potential Applications for using sUAV's

Habitat Data Collection Applications

- Channel morphology
    - Upstream and downstream habitat categorization
        - Channel geometry
            - Height
            - Gradient
            - Pools/riffles
            - Meander patterns
        - Sediment composition

Biological Data Collection Applications

- Vegetation composition
    - Amount of large woody material
    - Vegetation abundance
        - Potentially species
    - Flow directionality
    - Sediment accumulation
    - Output of 3D model for each target site
- Fish presence
    - Spawning ground survey data review or physical survey
    - Areas of critical habitat for adult and juvenile salmonids
- Species modeling
    - Habitat monitoring
    - Herd, pack, or school interactions and dynamics

Fluvial Data Collection Applications

- Flow Pattern
    - Model flow dynamic based on 3D model created from aerial imagery
        - Applications for Hec-RAS or iRIC Modeling
    - Determination of thalwag directionality
- High water scarification patterns
- Indication of channel meander or historic channels
- Channel morphology
    - Geologic formation
    - Platform dynamics
    - Constrained or access to floodplain
        - Reach topography

Geological Data Collection Applications

- Monitoring of mass movement events and debris flows
    - Modeling the pre-slide and post slide debris movement
    - Determining the width, length, and severity of the slide
    - Model the debris movement impact
        - Structural impact
        - Mobilization into rivers
        - Categorization of vegetation loss
- Modeling landscape change and interaction
- Aerial assessment of dangerous landscapes
    - Erosion in flood zones
    - Volcanic activity
    - Active fault lines