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AN EVALUATION OF UNMANNED AERIAL SYSTEMS AND STRUCTURE-FROM-MOTION FOR FLUVIAL LARGE WOOD SENSING AND RISK ASSESSMENT

by

Daniel Gerke

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science
Geography
Western Michigan University
December 2019

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Daniel Gerke

AN EVALUATION OF UNMANNED AERIAL SYSTEMS AND STRUCTURE-FROM-MOTION FOR FLUVIAL LARGE WOOD SENSING AND RISK ASSESSMENT

Daniel Gerke, M.S.

Western Michigan University, 2019

This research aims to show Unmanned Aerial System (UAS) and Structure-from-Motion (SfM) technology can, in combination, improve on traditional large wood (LW) monitoring techniques. More temporally and economically efficient data collected at a finer spatial resolution and greater spatial extent will increase the effectiveness of management plans and risk assessment for LW by providing decision-makers with a complete picture of the river.

Contemporary practices are too inefficient in time and labor for large-scale monitoring of fluvial LW with anything more than the most general management or risk assessment in mind. The paradigm of river research, the river continuum concept (RCC), where a river's traits are interpolated between discrete study areas, has shifted to a nested hierarchical structure (Woodget et al., 2017). The nested hierarchical structure paradigm demands higher temporal and spatial resolution combined with greater spatial extent for LW data, as called for in Zorn et al. (2018).

This study revealed UAS-SfM as a plausible option for creating data products capable of enhancing LW monitoring and risk assessment. Orthomosaics of a higher resolution (2.34cm/pixel) than those available via commercially available imagery and a 3D point cloud were both useful for general identification of LW, but both were subject to noise and errors. The sources of the noise and errors were the camera angles used during image collection, overhanging vegetation, and deep water. Changes to data collection techniques can alleviate these issues.

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CHAPTER 1

INTRODUCTION

In streams, large wood (LW) is an essential component for a healthy ecosystem. (Murphy, 1989) defines LW as wood greater than ten centimeters in diameter by one meter in length. According to Gurnell, Gregory, and Petts (1995) large wood benefits streams hydrologically by influencing the water table in the riparian area; hydraulically by modifying flood characteristics; geomorphologically by regulating sedimentation and erosion; and ecologically via storage, retention, and use of organic matter, habitat formation, and as a food source for life in the stream. The importance of these factors was not recognized until after the 1950's (Ruiz-Villanueva & Stoffel, 2017).

A meta-analysis by Miller (2010) showed LW to be the most effective means of increasing macroinvertebrate richness and density among instream cover additions. Salmonids are the focus of management actions in the river in this study and macroinvertebrates make up much of their diet (Zorn, Cwalinski, Godby, Gunderman, & Tonello, 2018). The salmonids also directly benefit from LW due to increased cover from predation, visual isolation, and the variety of habitats available for all life stages (Hunter, 1991; Crisp, 2000; Johnsson, 2004). These factors can lead to higher survival rates for young fish, greater density of all ages, and increased longevity for mature trout. Based on these benefits, LW should be a major focus for ecological planning.

Since recognition of LW's role in fluvial ecology, management plans for streams routinely include provisions for LW. Managing LW in streams has many complicating factors,

including the accepted nomenclature. In some studies, researchers refer to LW as large woody debris (LWD), which has a negative connotation and implies it is not natural, but a result of catastrophe. Wohl et al. (2016) proposed using LW instead of LWD and this paper will follow their recommendation.

Naming is not the only difficulty in managing LW. Accurate measurements of LW in fluvial environments are difficult due to accessibility in many streams. The lack of easy access for assessment of LW leads to low levels of monitoring both temporally and spatially. As an example, the Pine River in Michigan's northwest Lower Peninsula is visited by USDA Forest Service personnel for a once yearly float to assess LW (Pine River Association, 2017). The daily management of LW in Michigan rivers is often carried out by private citizens, specifically canoe liveries and fishing guides. These two river uses require a navigable waterway to provide safe transportation, which better assessment and management could provide.

The spatial extent of monitoring is also less than desirable when using traditional means of survey, including transects and discrete point sampling and the broad scale mapping from the data gathered by these two techniques (Woodget, Austrums, Maddock, & Habit, 2017). The diversity of habitat and the dynamic nature of the fluvial environment demand a more detailed and timely technique for study. Woodget et al. (2017) quote Newsom and Newson (p. 199, 2000), "Real contributions from research to sustainable management of river systems... need to match a sophistication of concepts with a direct practicality (without which applications are unlikely)."

Compromise between safe navigation and trout habitat is the crux of the issue regarding large wood on many Michigan rivers. Increased data on the amount and location of large wood

in a river will help decision-makers more equitably solve this dispute. Current methods for large wood inventory involve manual field methods. Recent literature considers these methods too time-consuming and expensive (Hubbart, Kellner, Kinder, & Stephan, 2017; Knehtl, Petkovska, & Urbanič, 2018). The expense and time rule out traditional field studies for temporally sensitive large wood management, such as when a storm increases LW loading rapidly. Researchers and other stakeholders need another way to inventory LW in rivers.

The use of unmanned aerial systems (UAS) has blossomed in the past decade to enhance data collection in many fields, including fluvial research. Data collected by UAS varies from crop growth to river ice cover to coral reef health (Alfredsen, Haas, Tuhtan, & Zinke, 2018; Casella et al., 2017; Hunt & Daughtry, 2018). The ability of UAS to cover difficult terrain and capture high resolution imagery at a variety of heights and angles in a timely and cost-effective manner lends itself well to this study. Research using commercial-grade UAS and digital photography to gather imagery for constructing spatially accurate and precise 3D maps of fluvial features using Structure-from-Motion (SfM) technology has been explored extensively in recent years (Dietrich, 2017; Jugie et al., 2018; Marteau, Vericat, Gibbins, Batalla, & Green, 2017; Rusnák, Sládek, Kidová, & Lehotský, 2018; Woodget et al., 2017).

The hypothesis of the research to follow is that UAS and SfM algorithm can improve fluvial management by quickly supplying accurate and precise data on the volume, location, and orientation of large wood in streams. The hypothesis will be tested on a low-gradient Lower Michigan stream, the Pere Marquette River (PM). The location, orientation, and volume of large wood in a river is of interest to many parties, including recreational users, biologists, and governments. In terms of this study, large wood can affect safety for recreational users, habitat

quality for trout and other animals, riparian erosion, and the risk or mitigation of peak flow events (Bilby, 1984; Bryant, 1983; Wohl et al., 2016). More informed management decisions will result in a better recreation experience for all river users and help maintain the ecological integrity of the river, a priority unknown in the past.

The *Management plan for inland trout in Michigan* (Zorn et al., 2018) states,

“Additional data are needed for characterizing instream fish habitat on trout streams throughout Michigan. Guidance is needed to determine if and what types of trout habitat is lacking on individual stream reaches.”

(p. 3)

and

“Some Michigan trout streams lack adequate instream cover to promote and maximize healthy fish and aquatic organism populations. Adequate instream cover is needed for trout streams to achieve their trout-holding potential. Fisheries Division, other government agencies, NGOs, and citizen scientists should identify trout streams where instream habitat is inadequate.”

(pp. 4,5)

and

“Human development and changes in land use typically have negative effects on trout populations through their influence on the hydrology and instream habitat. Michigan trout populations rely on high quality instream habitat and watersheds with minimal human effects.

(p. 8)

and

“Changing climate and habitat conditions require continued assessment of the suitability of habitats for wild and stocked trout... Continue to refine and implement the Status and Trends Program to assess coldwater systems... Explore additional methods to supplement standard fisheries techniques (e.g., **remote sensing**, citizen scientist, and eDNA).

(p. 8)

and

“Limited MDNR Fisheries Division Research Section staff time is available for investigating and providing science-based input on issues pertaining to inland trout management. Adequate Research Section staffing is needed to provide thoughtful, science-based input on inland trout management issues.”

(p. 6)

LW is a major contributor to habitat and cover for trout. Combining the preceding quotes from the *Management plan for inland trout in Michigan* with this knowledge leads logically to a

call for action. Management personnel need more data on LW in Michigan streams to ensure a maximized and healthy trout population. The need for better information will only increase with the effects of climate change and the MDNR needs more efficient ways to gather that information. This thesis can be one step towards that goal.

The use of UAS and digital photography to gather imagery for SfM 3D mapping is superior in many ways to traditional field surveys. One licensed Remote Pilot in Command (RPIC) can gather data with a UAS, while the visual observers (VO) can be effective with minimal instruction. Emerging research considers traditional LW surveys in reaches more than a few hundred meters in length impractical (Knehtl, Petkovska, & Urbanic 2018) A single RPIC with multiple unskilled VO's can cover miles of river in a day and the data obtained will be useful for fluvial studies besides LW. Imagery gathered in pursuit of LW data also provides opportunity to study flow, riparian vegetation, erosion, and substrate type. The UAS gathered data will be continuous, rather than discrete points, and will allow for volume and location to be accurately and precisely measured over the entire length of rivers, given sufficient battery availability for the UAS. Knowledge of the total volume of LW in the river will enable decision-makers to better judge the importance of individual pieces in the context of overall habitat. The map created via SfM will also allow management personnel to evaluate the hazards of large wood in three-dimensional space.

The research objectives of this study are as follows: (i) to demonstrate the ability of a commercial grade drone and digital camera to collect imagery which allows an SfM 3D point cloud to be constructed accurately and precisely showing the location, size, and orientation of large wood in a Lower Michigan river, (ii) to compare the current size and location of wood jams

in the study reach to the results of a traditional inventory of the reach in 2010, (iii) to explain the advantages and disadvantages of using this methodology for large wood monitoring in rivers.

The following sections will show how to use a commercial grade drone and digital camera to survey large wood in a river, using the Pere Marquette River as a test case. Background for the research will include history and ecology of the study area and the specific location, and context in the present. The literature review will explore the importance of large wood to the ecology of the river, past methods for gathering data on fluvial large wood, current practices using drones for data collection, and how this research fills the gap left in the literature. The methods section will show how the research was performed, from data collection to data processing, to accuracy assessments. The results will show the accuracy levels for supervised classification reached by the study and if these were expected. The usefulness of manual identification of LW and the efficacy of a 3D point cloud to inform management decisions will be discussed along with the change in LW size and location over time (2010-2019). If the results were not as expected, what changes are needed to improve them? The conclusion will explore how this methodology can enhance management of large wood in streams and better balance the recreational and ecological needs of the public and the river.

CHAPTER 2

BACKGROUND

Study area

The mainstream Pere Marquette River (PM) begins at the junction of the Middle and Little South Branches 0.5 miles east of Baldwin, MI (43.856°N, 85.841°W). The river then flows east to west 66.4 miles through Lake and Mason counties to Pere Marquette Lake and then Lake Michigan at Ludington, MI (43.932°N, 86.417°W) (Figure 1) (Bird 2008). The Little South, Middle, Big South Branches and the Baldwin River are the main tributaries of the Pere Marquette mainstream. The total watershed area is 755 square miles and includes portion of Lake, Mason, Oceana, and Newaygo counties (Fisheries Division, 2002; MDEQ Water Resources Division, 2017). The specific study reach is 2.41 river miles and begins downstream of McDougall's Resort (43.900°N, 85.958°W) and ends upstream of the Rainbow Rapids access site (43.911°N, 85.969°W) (Figure 2). The study area flows through the Huron-Manistee National Forest and private land.

Pere Marquette River

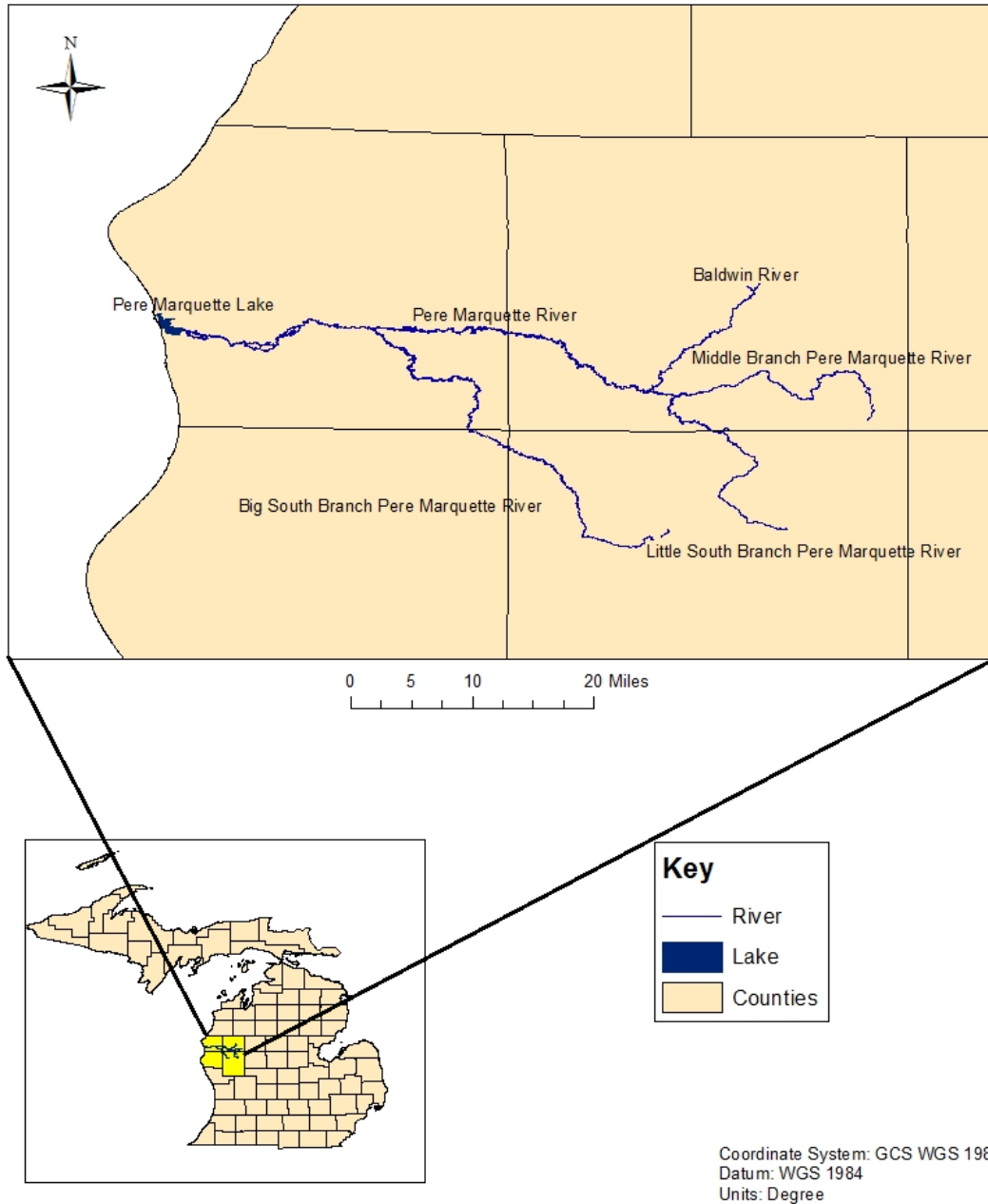


Figure 1: Pere Marquette River watershed, MI

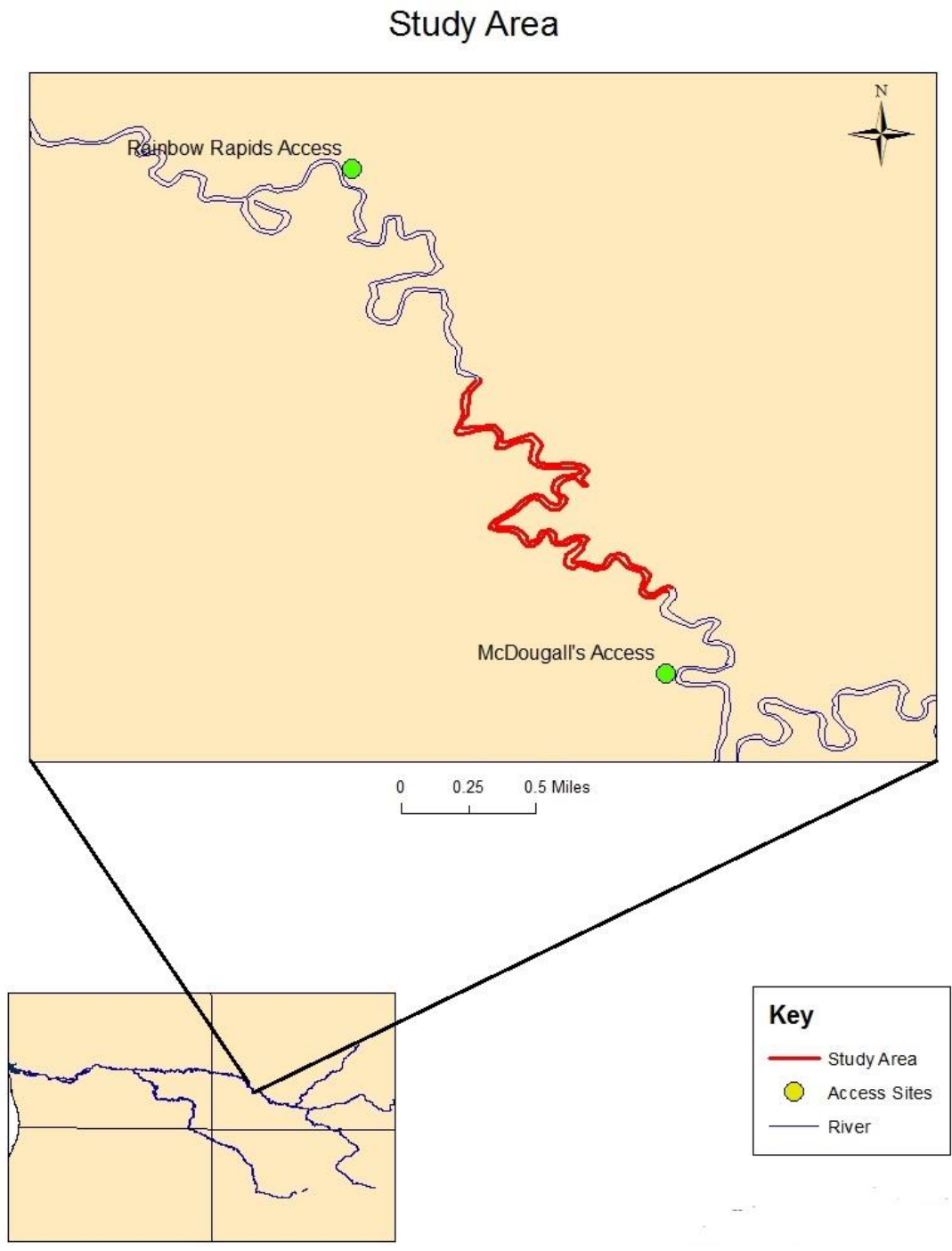


Figure 2: Study area on Pere Marquette River, MI

The PM flows through the Southern Michigan Northern Indiana Till Plain, which consists of coarse sandy plains and hills (Fisheries Division, 2002; MDEQ Water Resources Division, 2017). The agricultural potential of the area is low due to the easily eroded and nutrient-poor nature of this soil. However, the amount of land used for agriculture or human development increases in a downstream direction, increasing from 5% in HUC040601010505 (Tank Creek – Pere Marquette River) to 60% in HUC040601010509 (Pere Marquette River – mouth) (MDEQ Water Resources Division 2017). The well-drained soils predominant in the region lead to a stable flow regime due to low run off potential (Fisheries Division, 2002).

According to Omernik and Gallant (2010) the watershed is in the Northern Lakes and Forests ecoregion. This ecoregion is characterized by mixed northern hardwoods interspersed with coniferous trees. Trees found in the area include red pine (*Pinus resinosa*), white pine (*Pinus strobus*), jack pine (*Pinus banksiana*), aspen (*Populus tremuloides*), sugar maple (*Acer saccharum*), American beech (*Fagus grandifolia*), yellow birch (*Betula alleghaniensis*), tamarack (*Larix laricina*), black spruce (*Picea mariana*), northern white cedar (*Thuja occidentalis*), with white oak (*Quercus alba*) and black oak (*Quercus velutina*) being most common (Fisheries Division, 2002; MDEQ Water Resources Division, 2017; Omernik & Gallant, 2010). Most of the forest cover in the watershed is second or third growth (Fisheries Division 2002). The Michigan Department of Environmental Quality (2017) found the amount of natural cover in the 30-meter riparian zone surrounding the river to range from 54 – 90%. The amount of forested area ranged from 14 – 83%. An increase in agriculture and human development downstream led to the lower forested and natural land cover in this area.

Wildlife

Many species of terrestrial and aquatic animals make their home in and around the PM. Mammals using the watershed include white-tail deer (*Odocoileus virginianus*), beaver (*Castor castor*), gray squirrel (*Sciurus carolinensis*), red fox (*Vulpes vulpes*), cottontail rabbit (*Sylvilagus floridanus*), snowshoe hare (*Lepus americanus*), black bear (*Ursus americanus*), coyote (*Canis latrans*), raccoon (*Procyon lotor*), skunk (*Mephitis mephitis*), mink (*Neovison vison*), muskrat (*Ondatra zibethicus*), and otter (*Lotra canadensis*). Birds living in or migrating through the watershed include bald eagles (*Haliaeetus leucocephalus*) and other raptors, turkey (*Meleagris gallopavo*), many types of waterfowl, upland game birds, and songbirds (Fisheries Division 2002). Of the terrestrial animals, the beaver has the greatest impact on LW in the PM, due to its felling of trees, in the riparian area.

The Michigan Department of Environmental Quality - Water Resources Division conducted a biological assessment of the PM watershed in 2017. Macroinvertebrates found inhabiting the Pere Marquette include families traditionally mimicked by fly anglers, mayflies (*Ephemeroptera*), caddisflies (*Trichoptera*), and stoneflies (*Plecoptera*), as well as leeches (*Hirudinea*), worms (*Oligochaeta*), scuds (*Crustacea amphipoda*), crayfish (*Crustacea decapoda*), dragonflies (*Anisoptera*), damselflies (*Zygoptera*), true bugs (*Hemiptera*), dobsonflies (*Corydalidae*), alder flies (*Sialidae*), beetles (*Coleoptera*), flies (*Diptera*), snails (*Gastropoda*), and clams (*Pelecypoda sphariidae*). Many of these macroinvertebrates use LW as a shelter or food source and many of the terrestrial and aquatic vertebrates of the PM watershed use the macroinvertebrates as a food source.

The PM hosts 66 species of fish. The most sought after of these are all introduced, non-native species: chinook (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*), rainbow (steelhead) trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*). The brook trout (*Salvelinus fontinalis*) was native to some Lower Peninsula streams but it is not known with certainty if this includes the PM (Zorn et al. 2018). Other fish species present include native pike (*Esox lucius*), various suckers, and diverse minnow species. Other introduced or invasive species of note are sea lamprey (*Petromyzon marinus*) and common carp (*Cyprinus carpio*). Arctic grayling (*Thymallus arcticus*) are conspicuously absent from this list due to extirpation. A combination of habitat loss, overharvest, and competition from introduced trout species led to the grayling's downfall (Mershon, 1923; Zorn et al., 2018).

In 1884, the Baldwin River received the first recorded public water stocking of brown trout in the United States. Unrecorded stocking of rainbow and brook trout may have occurred on the PM prior to this (Zorn et al., 2018). Fisheries management on the PM from the late 1800's to the mid 1950's concentrated on brown trout. Stocking of brown trout in the PM continues today, with 26,950 6-7-inch fish planted in 2018 (MDNR Stocking Database, 2019). However, the potadromous fish runs (steelhead, coho, chinook) are now the focus of the fishery. A recent survey by the O'Neal and Kolb (2015) found 70% of angler effort targeted salmon during the period from April – September 2011.

Coho and chinook salmon both migrate up the PM each fall to spawn and steelhead follow, spawning in the spring. Natural reproduction and stray fish from stocked rivers completely support this potadromous run (Cassuto, 1994; MDNR Stocking Database, 2019). In fact, the PM system never received a plant of Chinook salmon and coho were only stocked in

Ruby Creek, a tributary to the Big South Branch (Cassuto, 1994). The last steelhead plant in the mainstream PM was in 1994, however, stocking does continue in the Big South Branch (MDNR Stocking Database, 2019).

History

Human occupation of the Pere Marquette watershed goes back 12,000 years to a time before the last glaciers covered Michigan. The final glacier, the Valdres substage, retreated around 5,000 years ago, and Lake Michigan came to resemble its current state 3,200 years ago (Cassuto, 1994). Glacial till is the remnants of rocks crushed and deposited by the advancing glaciers; this forms the basis of the soil. Outwash is crushed rock deposited by glacial meltwater and forms the remainder of the soil with organic material from plants. Glacial meltwater carved a path through the newly ice-free land to Lake Michigan, creating the general path the PM now follows.

Paleo-Indians colonized the area, living a hunting and gathering lifestyle from 10,000 B.C.E. until about 1000 B.C.E. when the Woodland culture emerged (Cassuto, 1994). The cultural change resulted in an increase in agriculture, using fire to clear areas for crops (Wohl, Lininger, & Baron, 2017). The Ojibway, Ottawa, and Potawatomi peoples rose to prominence in the area by 1000 C.E. and contacted Europeans starting with Etienne Brule in 1622 (Cassuto, 1994).

The Pere Marquette received its European name from Father Jacques Marquette, a French Jesuit missionary who died at the mouth in 1675 while returning from a journey exploring the Mississippi River. The Native Americans began calling the PM “River of the Black Robe” after the Jesuits customary clothing (Cassuto, 1994). As intertribal warfare increased because of

competition in the beaver pelt trade, Potawatomes made an attack on Ottawas in the area, with the loser's heads being stuck on spikes at the river mouth (Cassuto, 1994; Fisheries Division, 2002). The river became known as Not-a-pe-ka-gon, River with Heads on Sticks, until cartographers chose the French nomenclature, which is still in use today (Fisheries Division, 2002; Page, 1882).

Exploitation of beavers for their pelts immediately followed European contact. The removal of the beaver from the waterways reduced the addition of new large wood and affected the function of the ecosystem. According to Wohl, Lininger, and Baron (2017) removing beaver from a stream ecosystem reduces habitat, biodiversity, water retention, and sediment storage. Virtual extermination of the beaver was complete by around 1840, beginning the process of habitat degradation, which logging continued on an even larger scale (Cassuto, 1994)

Permanent European settlement of the area did not occur until 1847. Prior to this, settlers hunted, fished, and traded with the indigenous people of the area. Burr Caswell, the first permanent European settler, worked a farm during the spring, summer, and fall, and fished during the winter (Page, 1882). The first lumber mill was erected on Pere Marquette Lake in 1849, setting the stage for the lumber frenzy to come (Page, 1882). When A.S. Wordsworth explored the area in 1869 for the Michigan Geological Survey he wrote:

“...covering an area of 576 square miles, and drained by the Pere Marquette River, is a region unsurpassed by any portion of the state, in quality of soil, timber and climate...When our estimates are safe at one and one-half millions feet per forty-acre lot, it means pine...with a large per cent of upper qualities. Trees tall to first limbs, large girth, free from punk knots, few shaky or hollow butts, or black knots, prime as to age, and much of it growing in hard wood land, where there is little danger from fires; easy down grades and short hauling to Pere Marquette River, either branch of which above the forks is a spring brook stream but little affected by drouth, freshet or frost; the north fork floatable for saw logs eighteen miles above the forks, the south branch for twelve miles, airline; some flat rollways, but generally precipitous. There is but little swampy land in this district... affording abundance of rail timber, and ultimately meadow lands inexhaustible in richness for generations...”

(Page 1882, pg. 11)

Massive log jams, extending for several miles at a time, often completely blocked many rivers in the U.S. (Cassuto, 1994; Wohl, 2014; Wohl, Lininger, & Baron, 2017). In 1869 A.S. Wordsworth, now working for the River Improvement Company, reported multiple jams on the Manistee River, MI greater than 330 feet in length, and, “Cutting to the heart of a cedar twenty inches in diameter, growing over the center, I counted 160 years' growth. This must have been a respectable sapling when King George the Third claimed it as his own” (Page, 1882). Wordsworth estimated around \$40,000 would clear these jams to give passage for log floating. The clearance of natural jams and snags to ease general navigation and log transport occurred on many rivers (Wohl, Lininger, & Baron, 2017). The techniques included snagging from river boats, using dynamite to blow the jams up, dredging, and canalization (Wohl, 2014).

As the United States grew and the demand for lumber with it, the forests surrounding the PM heard the steady approach of the lumberjacks crosscut saw and axe; the river should have feared it too. The watershed would eventually yield over 3.25 billion board feet of lumber, enough to build 312,000 3-bedroom houses today (Fisheries Division, 2002). After the necessary preparation of removing natural log jams, boom companies drove much of this cut timber down the river to Pere Marquette Lake. The log drives scoured the stream bed, ripped up the riparian vegetation and left so much bark behind to it poisoned the water by producing ammonia and hydrogen sulfide and depleting oxygen during decomposition (Wohl, 2014).

As Europeans settled in Michigan and the territory passed from French, to British, and finally American hands, indigenous people still inhabited the land surrounding the PM. The Ottawa and Ojibway formally ceded the land encompassing the PM in the 1836 Treaty of Washington (Blackbird, 1887; Powers, 1912). Michigan became a state in 1837 and settlers

began farming and logging in the vicinity of the PM around this time (Page, 1882). For over 100 years after this, people used the river and the surrounding area as a vehicle and engine for commerce, with no attention paid to its ecology other than fish stocking. The land was denuded of vegetation and wildlife, as Herman Stephenson, quoted in Cassuto (1994, p. 22) illustrates,

“...back in 1913, I was walking through the woods with my father, and he took me over to the side of the road and showed me a deer track – something I had never seen before in my life – it was that rare.”

In 1938, the PM became part of the Manistee National Forest. The Civilian Conservation Corps (CCC) then planted the still scarred land with trees (Cassuto, 1994). The following 20 years saw no change in management of the PM. Change was on the horizon, as better access allowed the growing population within driving distance of the PM to tap its newly refurbished potential. While the wild appearance of the river drew growing crowds of canoeists, the emphasis on stocking non-native anadromous species in Lake Michigan to combat the alewife and sea lamprey problem changed the focus and pressure on the fishery on the PM. The anadromous fish attracted hordes of anglers during the spring and fall runs. The increased use of the river began to degrade the “north country appeal” and “Blue Ribbon” angling quality river users associated with the PM (Cassuto, 1994; Bird, 2008 p. 11, 15). The era of hands off “benign neglect” was about to morph into the era of hands on “benign neglect” (Cassuto, 1994).

River protection

Instead of logs bound for the sawmill the present day finds different commercial products floating downstream: canoes, kayaks, and driftboats. All want safe and easy passage on the “natural” river. Wood jams or single pieces can pose a safety risk for river users (Ortega-Terol, Moreno, Hernández-López, & Rodríguez-Gonzálvez, 2014; Wohl et al., 2016). On some rivers

federal and state regulations are stricter than during the logging days and limit trimming of instream wood to an eight-foot gap for safe navigation (Fisheries Division, 2002; Bird, 2008). The trimming of wood in streams is a controversial topic in Michigan, as seen on the Pine River, a river 30 miles north of the PM. The Pine River Association raised concerns about bank to bank removal of large wood in a 2017 newsletter.

In 1978, the Natural River Act (Part 305, P.A. 451) and Wild and Scenic Rivers Act (PL 90-542) designated the PM a Michigan Natural River (MNR) and a National Scenic River (NSR), respectively. Both state and federal designations came with a management plan, most recently updated in 2002 (MNR) and 2008 (NSR). The management plans follow similar directions:

“Goal

To preserve, protect and enhance the river environment in a natural state for the use and enjoyment of present and future generations.

Objectives

1. To maintain water quality consistent with the designated classification of the river and adhere to the concept of non-degradation of water quality.
2. To prohibit development or activity which may damage the ecologic, aesthetic or historic values of the river and adjacent lands.
3. To ensure that any development which may occur shall be done in an orderly manner consistent with the natural environment and aesthetic qualities of the stream.
4. To ensure that recreational uses which occur, be done in an orderly manner consistent with the natural environment and aesthetic qualities of the stream, and that a quality recreation experience is maintained.”

(Fisheries Division, 2002, p. 22)

“The ORVs (outstanding remarkable values) and the management objectives for the Pere Marquette National Scenic River are:

- Outdoor recreation – Visitors to the river experience a predominantly natural environment with moderate evidence of the sights and sounds of humans. Visitors easily differentiate between public land and private land. Visitors have a positive experience without impacting river resources or private property.
- Fisheries – High quality fish habitat is maintained and improved upon, including protection of threatened, endangered, and special concern species.

- Visual and aesthetic attributes – The shoreline and riverbed is maintained and enhanced to reflect the landscape character of the river corridor.
- Historic or archeological resources – Areas of historic or archeological significance receive special management attention.”

(Bird, 2008, p. 2)

The state of Michigan and the USDA Forest Service are the entities responsible for administrating the PM under the MNR and NSR designations. The agencies have had a “memorandum of understanding” since 1980, which facilitates cooperation in management of the river and its surrounding area (Bird, 2008). The Forest Service acknowledges this but has “primary management responsibilities with Pere Marquette National Scenic River corridor” (Bird, 2008, p. 3). The Comprehensive River Management Plan (CRMP) for the PM is the guiding force for decisions regarding the river. If the CRMP does not cover a subject, the Forest Service follows the Huron-Manistee National Forests’ Plan of 2006. The state of Michigan, through the MDNR, MDEQ, and MSHPO (Michigan State Historic Preservation Office) is, “responsible for the enforcement of State laws and regulations in the river zone, including those related to water quality standards, water use, Natural River District land use and development, hunting, fishing, and boating.” (Bird, 2008, p. 4).

Increasing river use led to the adoption of these designations, which maintain use levels and attempt to limit human induced change in the riparian and fluvial ecosystems. The regulations amount to a hands-on form of neglect, where river processes are allowed to follow their own course, but only with government approval. The new regulations put limits on river use. The NSR designation capped daily watercraft use during the peak canoe season from Memorial Day to Labor Day (Bird, 2008). The MNR designation comes with a 400-foot zoning ordinance on both sides of the river. The ordinance restricts industrial and commercial

development within 400 feet of the river, with exceptions possible for some uses (Fisheries Division, 2002). Both the MNR and NSR designations stipulate large wood should remain in place unless it is a navigational hazard; that is, a watercraft cannot go over, under, or around it. In this case, trimming of LW to allow navigation is legal but the trimming should not exceed eight feet. These specific regulations limit human impact on the river.

Large wood and ecosystem degradation

Rivers and human history are intertwined. The river gives beauty, sustenance, and life. Historically, the human takes more than the river offers. Overharvesting riparian resources, reshaping the channel and trimming wood for easier transport or flood control, and damming for energy production are ways we take more than the river naturally gives. Appreciation for the beauty of a river makes it easy to condemn this exploitation. However, even well-intentioned use can cause changes to rivers.

Appreciation for the beauty and life-giving power of the river draws us to it like a brook trout to a caddis fly struggling through the surface film. The brook trout wants the calories in the fly, and we want connection with a natural, more primitive world. The two urges seem innate to our respective species. However, our attractions may turn out to be fatal to what drew us in.

Use degrades things from their natural state. The more people using a resource, the harder it is to maintain a semblance of the original. Too many brook trout result in too few caddis to go around. The story of rivers in Michigan is one of increasing human population leading to increased exploitation, first of the natural resources, now of recreational uses. The brook trout will continue to attack objects that resemble crippled caddis flies until there are no more to eat. Historically, humans also continue to use resources until they are extinct, extirpated, or

destroyed. Humans seem to learn from past mistakes, but only enough to blunder into different ones. The clearcut logging of Michigan above ground in the past gives way to the fracking of Michigan underground today. In terms of this study, clearance of large wood from Michigan rivers for log drives is now removal of large wood for recreational ease and safety. The steady advance of ecological study gives hope for breaking this cycle of missteps.

Anthropogenic influence on the river will not go away, we can only hope to contain it. If we approach the problem in a Utilitarian mind set the goal will be the greatest good for the greatest number. Who or what is included in the greatest number? The humans who want to recreate? The fish who want to procreate? The industry that wants to devastate? Or are all these interests part of the greatest number? The impossibility of balancing these divergent interests is obvious. David Cassuto (1994) states maximizing for all these wants is mathematically impossible, as Garrett Hardin points out in *Tragedy of the Commons*. Maximization of a resource is what led to clearcut logging or the brook trout eating all the caddis. Effective management needs a different thought process. Instead of taking everything we can, set limits and maximize the *efficiency* of resource use inside those limits.

Better tools for monitoring how the environment responds to human influences are one avenue to increased efficiency within limits. An example of inadequate monitoring resulting in drastic consequences is the Michigan grayling. The decline of the grayling population was noted from the 1870's and complete by 1905 in the Lower Peninsula (Mershon, 1923). As early as 1874 Mershon (1923) noted haphazard efforts to stem the annihilation of this native fish, to no avail. The Michigan Department of Conservation (MDOC), precursor to the MDNR, officially declared the fish extirpated from Michigan in 1936 (Goble, 2018). The factor traditionally

blamed for their demise is the logging industries overuse of the rivers, resulting in habitat destruction (Goble, 2018). Contributing factors include the planting of non-native trout species and increased fishing pressure (Mershon, 1923). Better monitoring techniques could have curtailed this decline and discovered what factors truly played the largest role.

We may think of ourselves as intellectually superior to the brook trout when that struggling caddis is actually an imitation concealing a sharp piece of steel, but are we? The river we perceive as natural is far from it, with human modification pre-dating even European settlement, and even more drastic changes since (Cassuto, 1994; Wohl & Merritts 2007; Wohl, Lininger, & Baron, 2017). A natural, or, anthropogenically unchanged, river is something no longer known in most of the world (Wohl & Merritts, 2007). The rivers protected under the Michigan Natural Rivers Act or the National Wild and Scenic Rivers Act are not truly natural or undisturbed. The amount of wood in U.S. rivers today is much less than prior to European settlement (Wohl, 2014).

The current low levels of fluvial wood may be influencing what is perceived as natural on a cultural scale. Education level affects our perception of what a natural river looks like (Chin et al., 2014). Even undergraduate geography or environmental studies students across much of the U.S. consider wood in a river to be unnatural or dangerous. Wyzga, Zawiejska, and Le Lay (2009) found that course of study and level of post-secondary education also influenced perception of wood in rivers. Engineering students perceived wood as a negative while biology and geography students changed from a negative to positive perception over their academic career. Both studies show a cultural bias against the natural river state.

The treatment of large wood as undesirable is one of the ties binding the past and present human use of Michigan rivers. From the 1850's to 1900, progress demanded all natural wood be removed from rivers to facilitate the floating of white or 'cork' pine logs to saw mills near the Great Lakes (Page, 1882; Wohl, 2014). Natural wood jams caused the cut logs to pile up, creating dangerous and costly delays in transport. Logging companies removed the wood jams with no regard for the ecology of the rivers (Wohl, 2014). Attitudes have changed somewhat since the days of the lumberjack, but wood is still removed as canoes and kayaks pile up behind it.

Modern status

As the lumber barons continued westward, they left a river devoid of its native salmonid, the grayling and non-native trout populations hanging on only due to stocking (Cassuto, 1994; Fisheries Division, 2002). The riparian area was devoid of trees large enough to provide shade, inhibit erosion, or provide a source of LW recruitment (Cassuto, 1994; Wohl, 2014). The river spent the next 70+ years reshaping itself into something worthy of the rapturous words of Robert Lowry by way of Edward Abbey,

“Yes, we'll gather at the river,
The beautiful, beautiful river;
Gather with the saints at the river
That flows by the throne of God.”

(Abbey, 1991, p. 242)

If we are all going to gather there without destroying it, we need to know more about the natural processes making it so beautiful in the first place. As Daniel Willard asks in David Cassuto's *Cold Running River* (1994, p. 129),

“How can we plan a natural resource use when we don’t know how much there is?”

Towards this end, Chris Riley conducted a USDA Forest Service survey of large wood in the current study reach in 2010. The survey found 55 log jams, defined as three logs with a diameter of 10 inches being in contact with each other (Riley, 2010). The survey categorized jams by location in relation to the riverbank and river bends, diameter of the largest log, and presence or absence of a rootwad. The present study will compare the locations and size of the wood jams in 2019 to those found in 2010.

The Pere Marquette River is not the same river Father Marquette died at the mouth of in 1675. It is not as healthy as around 1870 when a chimney sweep could catch “great baskets of trout from Danaher Creek (a tributary of the PM) and sell them.” (Mershon, 1923, p. 161) It is a healthier river than when Herman Stephenson was shocked to find a deer track near it in 1913 or when he recalled log jams so extensive people were able to “walk the river from Branch to Ludington (a distance of over 20 miles!) and never getting their feet wet” (Cassuto, 1994, p. 20). The new regulations seek to stop or reverse some of the changes in the ecosystem humans created since European discovery.

The current state of LW in Michigan rivers mirrors that of the rest of the U.S., with lower than historical levels. The amount of fluvial LW varies in Michigan, with areas in the northern Lower Peninsula having higher levels, while the Upper Peninsula and southern Lower Peninsula have lower levels (Wills, Zorn, Hayes, & Wehrly, 2015). Large wood is one of the critical components of a Michigan river ecosystem, especially in a river where brown trout and steelhead coexist, as in the PM (Nuhfer, Wills, & Zorn, 2017). The quality angling in the northern Lower Peninsula may be related to this higher amount of LW in the local rivers.

The amount of LW in the river has changed from its natural state of permanent jams hundreds of feet long, to temporary jams measured in miles, to comparatively none following the logging era (Page, 1882; Powers, 1912; Wohl, 2014). The middle ground between these extremes is best for human river use today. Canoes and drift boats need the river to be navigable and trout fishermen want trout habitat created by LW. The management of riparian habitat for old growth forest and limiting instream wood trimming are ways the NSR and MNR management plans hope to keep optimal levels of LW in the PM (Bird, 2008). Monitoring LW volume, size, and orientation with increasing time and cost efficiency will be more important than ever, with limited budgets handicapping conservation efforts at a time climate change is exacerbating habitat degradation.

CHAPTER 3

REVIEW OF LITERATURE

Heterogeneity of rivers and UAS-SfM

Woodget et al. (2017) provided a review which identifies why the UAS-SfM process is the future of LW survey and management in fluvial systems. The researchers presented the previous research involving UAS and the Structure-from-Motion process and included two case studies as examples. The review introduces how the paradigm of river research and management is changing from one of large-scale classification known as the river continuum concept (RCC) which considers rivers to be smoothly changing as they flow downstream, to a nested hierarchical structure which recognizes the spatial heterogeneity of rivers over scales smaller than previously considered. The use of field studies in which transects or small reaches were surveyed and used to interpolate the rest of the river environment are now recognized as too small in scale to truly understand how the river changes during its course.

The review also highlights the utility of UAS-SfM in creating mesoscale maps or orthoimages for use in understanding the complete river system. The researchers identify four steps in the use of UAS-SfM and how they have and continue to revolutionize fluvial research. The first step was the proof-of-concept studies, showing UAS-SfM could be used for research. Next, researchers focused on how to optimize the UAS-SfM process. Third, there must be continued work in varied environments to increase the knowledge base about basic river functions and structure to improve fluvial management. This thesis fits into this step by collecting data on the LW in a wooded, low-gradient Michigan river. The literature review to follow will show how LW is important to the fluvial ecosystem and why it should be studied,

how remote sensing and UAS-SfM have developed into a tool capable of LW survey, and what the implications for management of LW in rivers is.

Large wood in fluvial systems

LW provides fluvial ecosystems many benefits. Roni and Beechie (2013) consider it, along with riparian vegetation and sediment, an essential building block for a healthy stream. A review by Roni et al. (2015) found LW increases stream depth and habitat complexity, decreases channel width, increases spawning gravel, retains sediment and organic material, and increases available instream cover. The same review quantified the data of 122 studies on LW placement and found the overall effect of LW positive. Not all of these effects are universal and as the size and gradient of a stream varies, so does the function of the LW in it (Keller & Swanson, 1979). In general, the ways LW influences the channel morphology and ecology of a stream all relate to its alteration of stream depth, velocity, substrate, and cover (Zorn & Nuhfer, 2007).

The presence or absence of LW affects the channel morphology of streams. A greater percentage of the stream blocked by LW leads to a greater effect on channel morphology (Keller & Swanson, 1979). The amount of pools, pool area, and pool size all correlate to the amount of wood in a stream (Roni, Beechie, Pess, Hanson, & Jonsson, 2015). LW causes increased variability in current speed, leading to pool and bar formation and scour holes in the immediate area of the LW (Keller & Swanson, 1979). Depending on the gradient of the stream, plunge pools also develop because of LW jams. Mosley (1981) found 40% of stream features (riffles, pools, gravel bars) related to the presence of LW. Gurnell, Gregory, and Petts (1995) estimated 50-100% of pools in a California stream were the result of LW accumulations. Both studies show the significant effect of LW on stream morphology.

LW increases or decreases stream bank erosion, depending on placement. LW causes an increase in local flow turbulence, dissipates stream energy, leading to a loss of erosive power (Ruiz-Villanueva & Stoffel, 2017). Conversely, LW increases erosion if it directs the stream flow towards the bank. This can lead to lateral migration of the stream channel (Ruiz-Villanueva & Stoffel, 2017). The migration of the stream channel, the loss or variation of hydraulic energy, and the increase or decrease of bank erosion all lead to varying rates of sediment deposition.

The local rate of sediment deposition determines the substrate composition of the streambed. Higher energy flow transports coarse substrate while lower energy flow deposits finer particles (Burroughs, 2011). The increased variability of flow energy caused by LW leads to areas sorted between coarse and fine substrate scattered throughout a stream channel (Flannery, Stubblefield, Fiori, & Shea, 2017; Shields, Jr. & Smith, 1992). Thus, the low energy pool areas created by LW act as sand traps and gravel predominates in higher energy areas. Shields, Jr. and Smith (1992) found this effect more pronounced in stream reaches not cleared of LW.

LW reduces the overall transport of bed load sediment due to the creation of low current velocity areas. Research revealed each cubic meter of wood stores from 3.3 to 8.0 m³ of sediment (Davidson & Eaton, 2013). The LW stores sediment for long periods of time and only releases it when the LW feature is destroyed or damaged (Mosley, 1981). The destruction of LW features releases the sediment trapped there, and Mosley (1981) found the newly released sediment only moves a short distance before becoming trapped again in other low energy areas created by LW.

Marcarelli et al. (2015) and Atkinson et al. (2008) demonstrate how sediment, and sand specifically, degrades the food web of a stream. The small size of sand particles results in an instability of the substrate. This instability is detrimental to the biofilm (algae, bacteria, and fungi assemblages). This instability and lower levels of biofilm lead to lower levels of GPP (Gross Primary Production). This is the beginning of the food web in a stream and compromising it compromises every level of the food web.

LW helps retain organic material along with the sediment. The retention of organic material increases nutrient cycling through the ecosystem (Warren, Judd, & Kraft, 2013). The dead wood itself usually only provides 5-10% of the nitrogen supply, but up to 70% of the organic material (Gurnell et al., 1995). However, the trapping of non-woody organic material such as leaves allows the stream to gain access to the nutrition locked within the leaves (Gurnell et al., 1995). Fungi, bacteria, and macroinvertebrates process the stable organic material, whether dead wood or other detritus. In fact, a meta-analysis by Miller (2010), showed LW was the most effective means of increasing macroinvertebrate richness and density among instream cover additions. The nutrients contained in the organic material thus enter the stream's food web as food for macroinvertebrates such as caddisflies, mayflies, and stoneflies (Balke, 2013).

The longer a piece of LW remains in a stream, the more useable it becomes as a source of nutrients for the stream (Bilby & Likens, 1980; Warren et al., 2013). The breakdown of Coarse Particulate Organic Matter (CPOM) to Fine Particulate Organic Matter (FPOM) happens only if the CPOM stays in the stream long enough. Gurnell, Gregory, and Petts (1995) explained the cycle of wood in a stream. Initially, wood forms part of the physical habitat of the stream, with little biologic benefit. Fungi, algae, and other microbes eventually soften the wood enough for

other invertebrates to gain access to its nutrients. As these invertebrates burrow deeper in the wood, the fungi follow, softening deeper layers of wood and allowing oxygen to penetrate deeper. The gradual decomposition of the wood allows for a greater diversity of invertebrates to eat or live on it and for more nutrients to enter the stream's nutrient cycle.

Substrate composition, flow velocity, availability of food, appropriate cover and the morphology of the river channel forms the basis of habitat for salmonid species (Raleigh, Hickman, Solomon, & Nelson, 1984). A stream missing the correct balance of one of these elements will not reach its highest possible fish population. LW affects all these attributes, creating a more heterogenous environment, each conducive to a different age class of these fish (Crisp, 2000; Roni et al., 2015).

LW affects the substrate composition of streams, or size of the particles making up the streambed. Salmonids species are dependent on a certain type and size of substrate for spawning purposes (Raleigh et al., 1984). Raleigh states the optimal substrate diameter for stream trout spawning to be 0.3 to 10.0 cm. 0.1 to 6.4 cm gravel and small cobble substrate was used most extensively for spawning by rainbow trout on the PM in a study by Workman, Hayes, and Coon (2004) Too much substrate finer than 0.3 cm (>30%) leads to poor survival for the eggs (Raleigh et al., 1984). LW can change flow velocities such that more gravelly spawning area can be cleared for salmonids (Harvey, Henshaw, Parker, & Sayer, 2018). The removal of LW can have the opposite effect and cover gravel spawning areas (Smith, 1993).

Beyond spawning, exposing gravel substrate benefits the salmonid's diets. Many of the aquatic invertebrates and macroinvertebrates fish feed on live in gravel (Mistak, Hayes, & Bremigan, 2003). Mistak, Hayes, and Bremigan (2003) did not find an increase in aquatic

insects being eaten by salmonids in gravel areas of the Pine River, Michigan compared to sandy areas of the same stream, although previous studies by Hynes (1970) and Allan (1995) indicated greater macroinvertebrate production in gravelly areas. Many macroinvertebrates drift with the current when hatching or after getting dislodged from gravel areas, possibly accounting for the trout diet consistency between the different habitat areas. The gravel areas produce more macroinvertebrate food sources for salmonids, whether consumed in the immediate vicinity or not. Suttle et al. (2004) look at the effect of sedimentation on macroinvertebrates. In areas with elevated levels of sediment they found the macroinvertebrate community shifts towards burrowing species, which are not available for salmonids to eat during much of the year. LW causes a blend of sedimented areas and gravel areas, which increases the range of food available to the salmonids year-round.

After the salmonids hatch, they continue to benefit from the habitat heterogeneity LW creates. According to Raleigh (1984), the newly hatched salmonids move to areas with current velocities under 0.3 m/s and cover less than one meter away. LW creates these types of habitats for the fry, along with the deeper pools they move to as they grow larger (Raleigh et al., 1984). The ideal size of objects for salmonid fry cover ranges from 10 to 40cm in diameter, and this size class should cover at least 10% of the stream area to be considered adequate (Raleigh et al., 1984).

As a salmonid grows to juvenile and adult stages, the habitat requirements change (Raleigh et al., 1984). LW remains essential for salmonids in streams without the preferred rock rubble substrate to use for cover (Raleigh et al., 1984). The LW creates deeper pools juvenile and adult salmonids use as refuges to escape thermal extremes and as resting areas due to the

lower current velocities. LW provides cover for the older salmonids as well. The density of adult fish increases with higher levels of cover available (Raleigh et al., 1984) Cover also increases the growth rate of rainbow trout (Walker, 2015). The reason for this is the difference in energy requirements to maintain stream position due to the current breaking effect of the cover. If the cover is LW then it is also an energy source for the stream and trout due to the increased production of macroinvertebrates (Langford, 2012). So, more food plus less energy expenditure between meals equals faster growth.

LW cover provides physical safety from aerial predators. Bald eagles are prevalent in the PM area, causing overhead cover to be at a premium. Trout exhibit more territoriality regarding overhead cover when they have been subject to aerial attacks (Johnsson, 2004). The increased territoriality leads to higher rates of survival and reproduction among territory holders. Cover does more for trout than just provide physical safety. According to Hunter (1991) a concept called visual isolation leads to higher population densities. Visual isolation means a salmonid cannot see other salmonids. The salmonids feel less pressured, leading to more population density in an otherwise unchanged stream.

The size, shape, and gradient of a stream changes the effect LW has on it (Abbe & Montgomery, 2003; Marcus, Marston, Colvard Jr., & Gray, 2002). Conversely, the size, shape, tree species, orientation, and location of LW determines its effect on the stream (Davidson & Eaton, 2013; Lawrence, Resh, & Cover, 2013). However, of these factors, Davidson and Eaton (2013) found wood orientation and volume to be the best explanatory variable for the hydro- and morphological effects of LW in streams. LW oriented perpendicular to the stream flow stores

the most sediment due to its breaking effect on the current (Martin, Pavlowsky, & Harden, 2016).

The source and total supply of LW changes with stream size. Marcus et al (2002) found LW in 1st and 2nd order streams did not move, resulting in what Abbe and Montgomery (2003) called in situ or autochthonous LW. LW in 3rd and 4th order streams had an equilibrium of LW transported in and out of reaches, while larger streams were supply-limited. The type of LW accumulations also changes with stream size, with larger streams tending towards allochthonous (transport) jams, small streams towards autochthonous (locally recruited), and midsize streams a combination of the two.

Abbe and Montgomery (2003) defined nine types of wood accumulations in streams based on location, orientation, and stability (Table 1). The nine types of jams are subdivided into autochthonous, allochthonous, and combination jams. Regardless of the type of jam, a key member is necessary for its formation. A key member is a stable piece of LW, which was either transported or recruited locally. The three main and nine subtypes of jams found by Abbe and Montgomery are not all found in the study reach of the PM. The gradient of the PM is less than 0.001 while the reaches inventoried in Abbe and Montgomery (2003) did not fall below 0.013. The types of jams varied with stream gradient and channel size, thus the jam types found in the PM may not include all the subtypes. The types of jams found by Abbe and Montgomery (2003) in channels the size of the current study reach of the PM include flow deflection, bar-apex, and meander.

According to Abbe and Montgomery (2003), flow deflection jams are a combination type accumulation and result from an autochthonous key member collecting raked or loose pieces of

allochthonous LW (Figure 3). Bar apex jams are allochthonous and formed when a key piece of LW with an attached rootwad becomes fixed in the channel with its rootwad facing upstream, collecting further racked and loose members (Figure 4). The bar-apex jam can enlarge an existing bar or island or create an entirely new one. Meander jams are located on the outside of river bends or on the outside bank just downstream of the bend (Figure 5). They are similar in function to flow deflection jams, with both types creating scour holes and resisting erosion of the bank they are associated with, but possibly increasing erosion on the bank the current is deflected

Table 1

Basic LW accumulation typologies

Type	Distinguishing characteristics
In-situ (autochthonous)	Key member has not moved down channel.
Bank input	Some or all of key member in channel.
Log steps	Key member forming step in channel bed.
Combination	In-situ key members with additional racked LW.
Valley	Jam width exceeds channel width and influences valley bottom.
Flow deflection	Key members may be rotated, jam deflects channel course.
Transport (allochthonous)	Key members moved some distance downstream.

Debris flow/flood	Chaotic LW accumulation, key members uncommon or absent, catastrophically emplaced.
Bench	Key members along channel edge forming bench-like surface.
Bar apex	One or more distinct key members downstream of jam, often associated with development of bar and island.
Meander	Several key members buttressing large accumulation of racked LW upstream. Typically found along outside of meanders.
Raft	Large stable accumulation of LW capable of plugging even large channels and causing significant backwater.
Unstable	Unstable accumulations composed of racked LW upon bar tops or pre-existing banks.

Source: After Abbe and Montgomery, 2003, p. 85

to. The classification of LW jams based on their origin (autochthonous, allochthonous, combination) is irrelevant to this research, however, the current size, orientation, and location of jams is important to making the best management decisions relating to the navigability and ecology of the river.

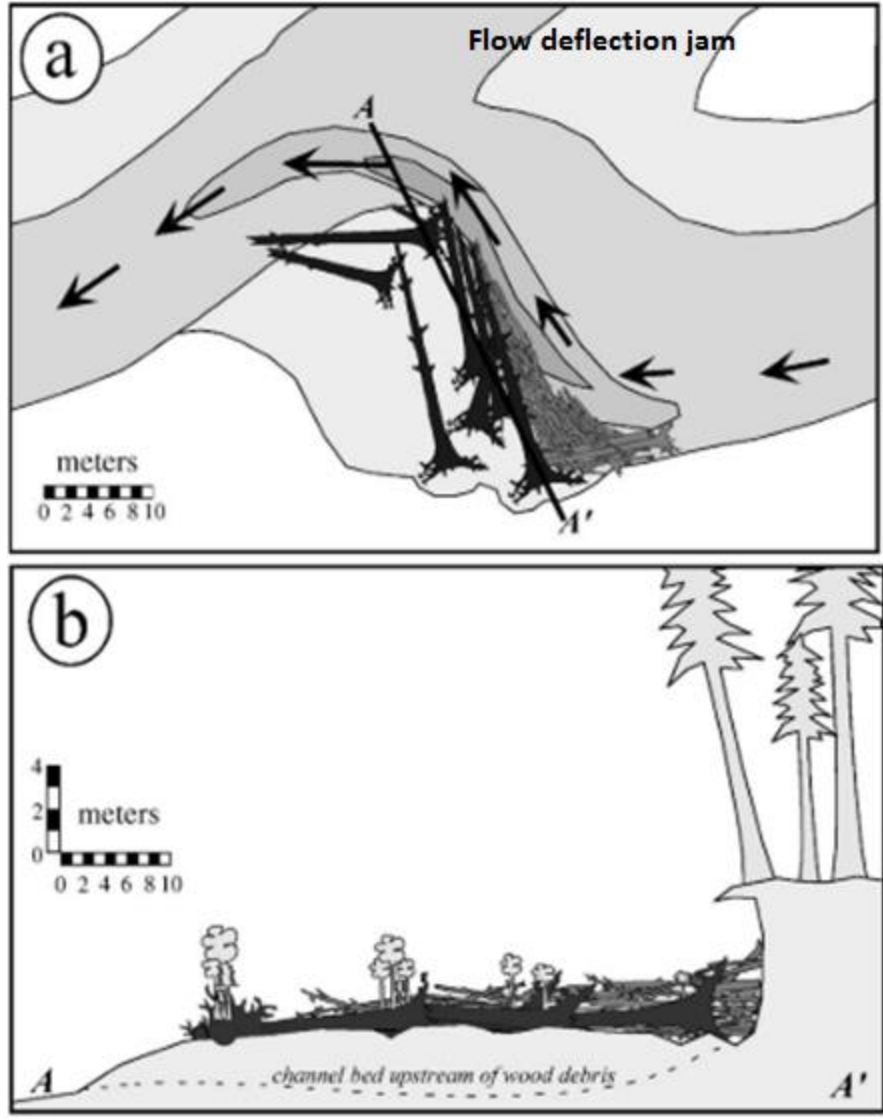


Figure 3: Flow deflection jam (a) planview, (b) channel cross-section view
Source: After Abbe and Montgomery, 2003, p. 89

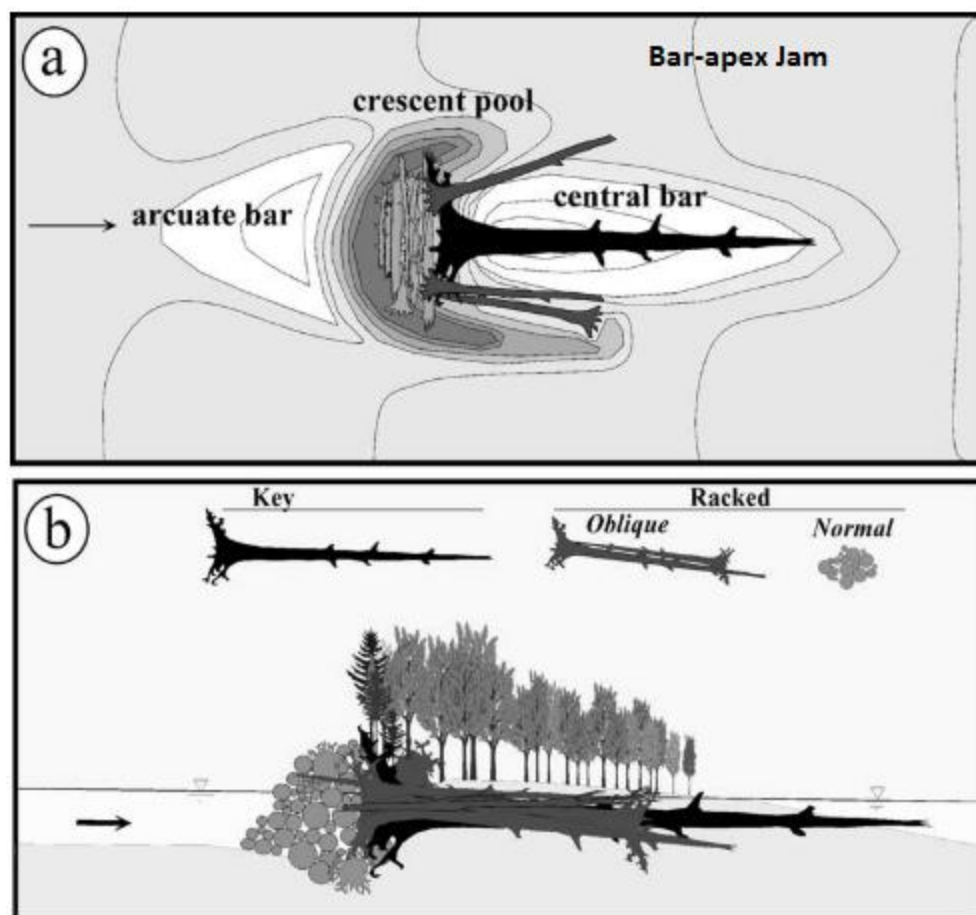


Figure 4: Bar-apex jam (a) planview, (b) channel cross-section view

Source: After Abbe and Montgomery, 2003, p. 93

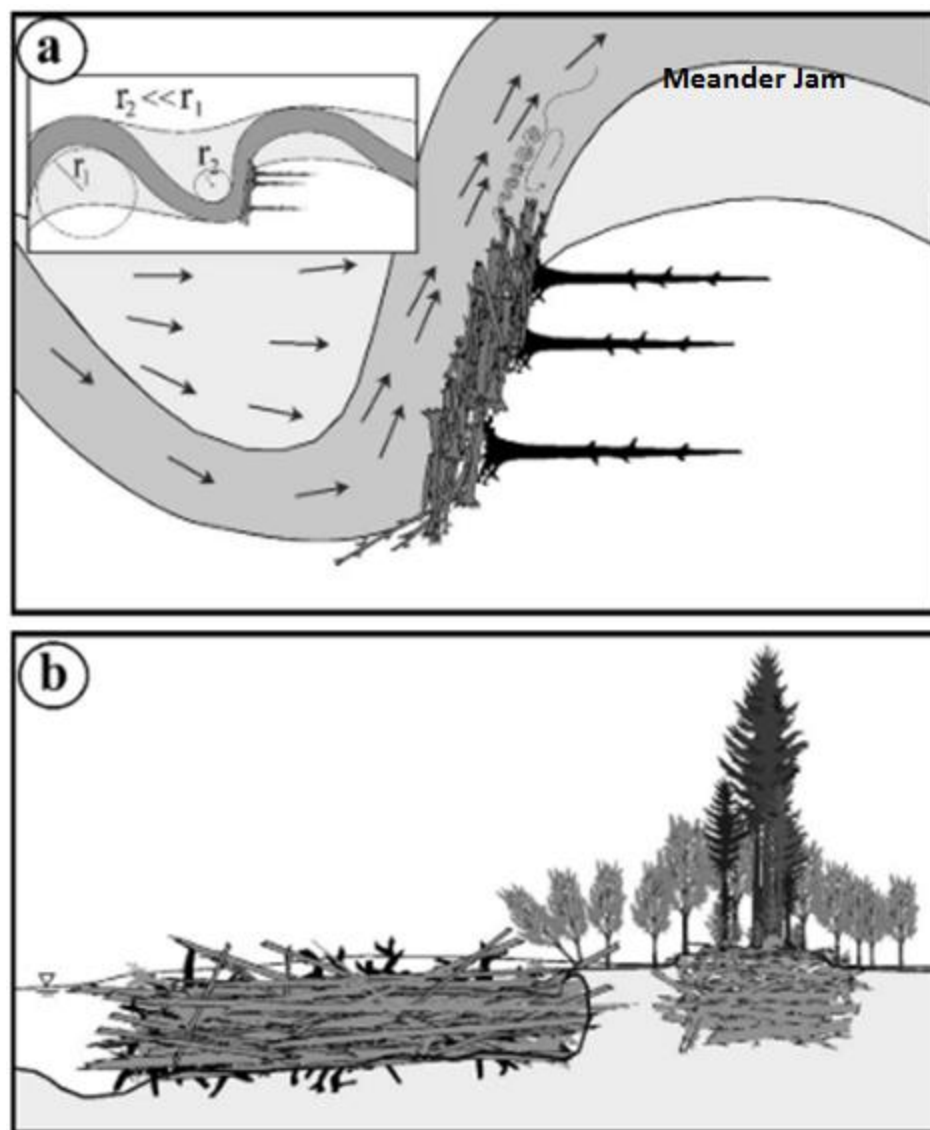


Figure 5: Meander jam (a) planview, (b) channel cross-section view

Source: After Abbe and Montgomery, 2003, p. 95

The definition of a wood jam varies in the study by Abbe and Montgomery (2003), but Wohl and Cadol (2011) and Costigan (2015) define a jam as three pieces of wood greater than 1 meter in length by 0.1 meters diameter closely associated with or touching each other. Riley (2010) used this definition in his inventory of wood jams in the current study reach on the PM.

This general definition of a wood jam will be used in this research, due to the focus on quick assessment of total LW.

The stability of a wood jam is related to the diameter and length of the bole and the presence or absence of a rootwad (Figure 6) (Abbe & Montgomery, 2003). A ratio of >0.5 for bole diameter to stream depth and bole length to stream width both indicate increased stability and the likelihood of a piece of LW serving as a key member in a log jam. Riley (2010) classified the wood jams in the study reach in three size classes, based on the diameter of the largest piece: $<24''$, $24-36''$, $>36''$. The inventory also noted whether any of the logs had an attached rootwad.

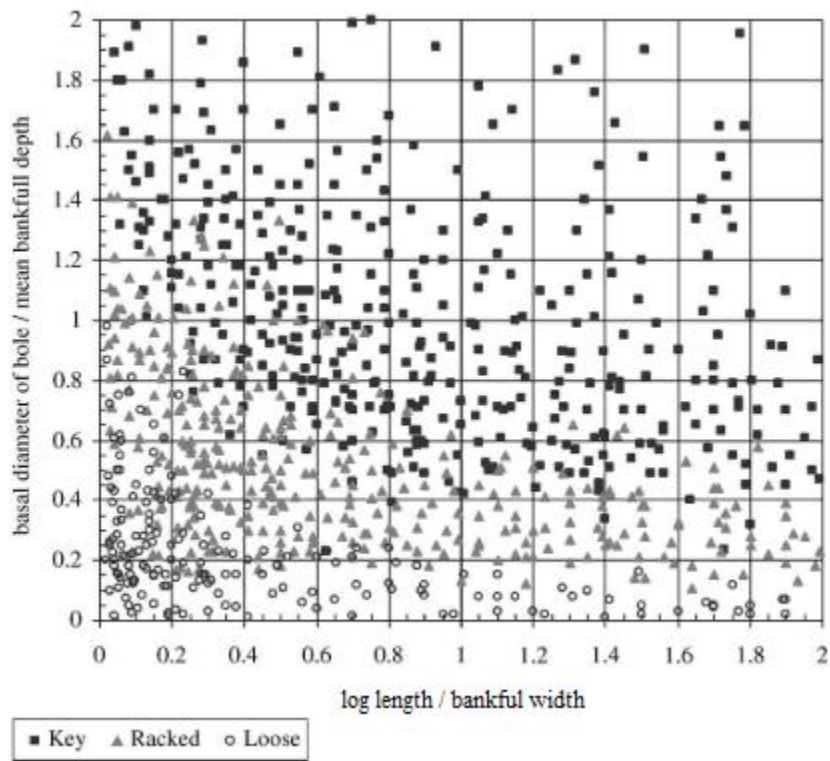


Figure 6: Dimensionless size plot of log stability threshold for key, racked, and loose LW in 32 jams on the Queets River, WA.

Source: After Abbe and Montgomery, 2003, p. 102

Management of large wood

Wohl, Bledsoe, and Fausch et al. (2016) published a review of LW management in the United States since nationhood. From 1776 to the 1950's, the country viewed LW as a hindrance to progress and a policy of removal reigned. Starting in the 1950's, academics such as Aldo Leopold began understanding the ecological value of LW to the nation's rivers. Since the 1970's, as the volume of research showing the benefits of LW increased, the national and state policies have shifted towards measured and ecologically responsible removal, especially on rivers protected by laws such as the National Wild and Scenic Rivers Act or the Michigan Natural Rivers Act. In fact, many rivers nationwide are the focus of "re-wilding" or artificial re-introduction of LW for ecological purposes (Harvey et al., 2018).

Rivers designated under the National Wild and Scenic River Act are managed to maintain or improve their current state (Bird, 2008). The Michigan Natural rivers Act also aims to maintain or improve the current state of rivers it governs (Fisheries Division, 2002). A major factor in the river state is LW. The benefits of LW were covered in the previous section of this research. The other side of the LW equation is the safety of humans using the river. Balancing the human and ecological needs is the current management problem.

Wohl et al. (2016) created an overview of a management plan for LW. They describe the risks associated with LW and a process for deciding if removal is justified. The study identifies the three ways LW increases risk for humans and infrastructure as 1) higher water levels, 2) changing where sediment is stored or moves, and 3) mobile wood. Specific to this thesis, there are eight risk factors influenced by LW for recreational users. Four of these factors are affected by the user themselves or the river. These factors are access, reach characteristics, ability to

avoid hazards, and prior knowledge. LW causes the other four factors. These factors are location, snagging potential, strainers, and anchoring. This thesis can lower risk for users by increasing prior knowledge and the ability to avoid and identifying LW likely to present one of the previously mentioned hazards.

Prior knowledge of a river environment forewarns recreational users of any hazards or possible trouble spots. Recreational users can better avoid obstacles if they know they are coming. The ability to avoid is impacted by visibility. If a river user encounters a hazardous piece of LW around a blind corner in the river the danger is much higher than if they saw LW was located with clear visibility from a distance. Detailed maps of the LW in a river environment will provide river users this knowledge, but only if the map is up to date. The changing nature of a fluvial environment means the users should be prepared to encounter unexpected LW, but the more knowledge of potential hazards, the safer the river.

LW hazards recreational users should have prior knowledge of are areas with snagging potential, strainers, or where the river is impassable due to blockage. The possibility of snagging increases with the number of branches on a piece of LW. The tree limbs can snag on a recreational user's clothing or watercraft, causing a tip or holding the user underwater. A strainer is a porous accumulation of LW. The openings between LW allow the river to flow through and potentially pin users with the force of the current against the solid pieces of the jam. A less porous jam creates slow water in front of it, lessening the pinning potential. The location of LW determines much of its danger to river users. Location refers to the position of the LW in the water column. The American Whitewater organization recommends a clearance of 3 feet for canoes and kayaks and 6 feet for rafts (Colburn, 2012). If the LW is lower than this, the

potential for tipping increases. Wood below the waterline is not as hazardous for watercraft, but wading users may have their foot trapped if there is space between the LW and riverbed.

The types of LW posing a hazard to human safety differ according to the accessibility of a river, the average skill level of the users and water level at time of use. A remote, difficult to access river could expect only highly skilled users, thus allowing more complex and hazardous LW to remain in place. A river with many access points and large human population nearby should expect a lower user skill level and the LW management should reflect this in its clearing practices. The difficulty, yet again, is determining the proper level of removal to facilitate both human and ecological needs.

The risk factors listed by Wohl et al. (2016) are the source of many recreational user injuries. Studies on user injuries during water-related recreation include Branche et al. (1991), Franklin and Leggat (2012), and Kane et al. (2015). Branche et al. (1991) reviews the case information for water-related spinal cord injuries. The chance of sustaining a spinal cord injury increased for individuals who used alcohol during water recreation or were unfamiliar with the body of water. The environmental factors influencing the chance of injury were diving from a dock or diving into less than five feet of water. The study did not consider LW a factor in spinal cord injuries. The use of alcohol and unfamiliarity with a waterbody could both impact users of the PM, influencing the ability to avoid obstacles and extricate oneself from them when not avoided. Enhancing river user's prior knowledge of the river via better monitoring could reduce the chance of spinal injuries.

Franklin and Leggat (2012) looked at water recreation injuries specifically involving canoes, kayaks, and rafts. The study found death rates for these paddling activities to be less

than 1 per 100,000. Drowning was the leading cause of death, especially in unfamiliar waters. The death rate did not include the numerous other injury risks associated with these activities. Paddlers most often suffered injuries to the face and appendages. The injuries sustained include bruises, scrapes, broken bones, sprains, pulled muscles, dislocation, and hypothermia. The risk factors observed for the cases in the study included alcohol use and overhanging vegetation, both of which are factors on the PM. The researchers provided a checklist for recreational watercraft users to reduce the chance of injury or death on a recreational float. The checklist includes assessing the current conditions of the river. LW locations are a factor in current river conditions and with an up to date model of the river paddlers can be made aware of dangerous areas to be cautious around.

Kane et al. (2015) examined severe trauma water recreation injuries in a coastal city. The researchers found alcohol to be a contributing factor due to its effect on the judgement and coordination of recreational watercraft users. The use of alcohol amplifies the danger of a hazard by making the subject less able to take quick and decisive action in the event of an unforeseen circumstance. The LW present in the PM could present an unwary paddler with just such a scenario. Franklin and Leggat (2012) cited the relaxed atmosphere of a paddling trip as the primary attraction for recreational users, and the three previous studies cite alcohol as increasing injury risk. The risk factors inherent to a paddler, the river, and LW cited by Wohl et al. (2016) could all increase with alcohol use degrading the perceptions and physical abilities of the river users. With more prior knowledge of the river, paddlers can better avoid the negative consequences of the impairments of alcohol.

Management of a river's LW is a balancing act between all these risk factors and leaving enough of the perceived natural environment to contribute to the relaxed atmosphere desired by users. To facilitate the decision-making process, Wohl et al. (2016) presented four tools and a decision band. Management could use part of this process or a similar logical progression in conjunction with the SfM model provided by this thesis to assess LW and make removal decisions (Appendix A). The hazards of all wood or other objects above the water surface could be assessed from a 3-dimensional perspective. The visibility of objects above the water could be assessed from the perspective of a river user coming downstream. The gradient of the stream in areas of potential hazards could also be assessed using the digital elevation model created from the point cloud in the SfM process.

The current management of the PM is governed by the Michigan Natural River Act and the National Wild and Scenic River Act, both of which strive to maintain or improve the state of the river for its intended uses. Climate change is a factor in the state of the PM in the coming years. The MDNR's *Management plan for inland trout in Michigan* (Zorn et al., 2018) recognizes the threat of climate change and anticipates the need to modify the management of the fluvial environment of Michigan's trout streams to meet the challenge. The riparian and fluvial habitat must change with the climate to provide fish with refuges from extremes of heat or cold. The management of streams for ideal habitat (cover, flow, channel morphology) will be instrumental in keeping trout populations in streams which will become warmer over time (Carlson, 2015). Ideal stream characteristics other than temperature can allow trout to remain in suboptimal thermal conditions (Carlson, 2015). This shows the importance of continuing to improve the habitat available to salmonids in the PM.

Harvey et al. (2018) presented a review of artificial LW re-introduction. The widespread practice of placing single logs, or logs with no limbs attached in orientations designed to avoid river blockage rather than maximal fish habitat has been the predominant means of this re-introduction. The effectiveness of single logs is reduced compared to the introduction of whole complex logs from the riparian area. The artificial re-introduction works, but natural wood loading is a more sustainable and is preferred in the long run. LW is predicted to increase naturally in Midwest streams due to management practices resulting in more forested riparian areas (Martin, 2016). The management plans mentioned by Martin focus on long-lived riparian tree species which will be recruited to the river channel via erosion and provide key members to accumulate LW jams. The management of the riparian area of the PM is consistent with this focus (Bird, 2008; Fisheries Division, 2002)The jams created by large, complex, full trees will be more stable than single logs and provide more consistent ecological and morphological benefits to the river (Abbe & Montgomery, 2003)

The change in official policy towards LW demands a more nuanced approach to LW management. The blanket policy of removing everything was simple for management or civilian personnel to carry out, but the regulations governing rivers such as the PM mean factors such as human safety and environmental health must now inform the decisions on LW removal.

The stated policy on LW in the Pere Marquette National Scenic River in Bird (2008) allows clearance of LW for navigational purposes, but removal should be minimized when possible and in general clear a passage no more than eight feet wide. Consultation with the USFS and MDNR is advised for any clearance operations (Bird, 2008; Fisheries Division, 2002). The remote nature of some river segments and the immediate need for watercraft passage renders

this advisory impractical in many cases. To manage the LW in a river effectively, timely and accurate data are necessary. In the past, the nature of data collection on LW has been time consuming, labor intensive, and focused on the ecological or morphological consequences rather than on overall management of river systems.

Better management of LW can improve the health of the river. This affects the fishery resource, which is a source of income for the local economy (Cassuto, 1994). Melstrom et al. (2015) studied the value of recreational fishing on rivers and streams in Michigan. The study used fish biomass as obtained by biological assessments as a proxy for fishing quality because biomass has been correlated with angler catch rates. The study surveyed Michigan fishing license holders during the open water season from March - November and found the willingness of anglers to travel for greater biomass of different fish species. Anglers traveled and incurred the highest cost for brook trout and walleye, with brown trout placing third. The average cost per trip for all species was \$19 - \$23.

The study did not include steelhead or salmon in the fish species considered, which is a limitation in Michigan, as the potamodorous runs of these fish draws crowds of anglers. O'Neal and Kolb (2015) found 70% of anglers targeted salmon from April – September 2011 and the total annual harvest for salmon, steelhead, and brown trout was (75, 19, and 6)% respectively. The importance of these fish to the PM is obvious, so the valuation by Melstrom et al. (2015) is not accurate regarding angler attention on the PM. O'Neal and Kolb (2015) estimated the value to the local economy of an angler trip to the PM as \$39 day⁻¹ with a total value of \$1.5 million for the year 2011. The difference in the values found by Melstrom et al. (2015) and O'Neal and Kolb (2015) may be related to the absence of migratory fish from Melstrom's analysis. In either

case, a healthy fish population stimulates the local economy and a healthy fish population needs appropriate fish habitat, of which LW is an integral part.

The value a fishery provides is only one of the benefits LW helps add to the ecosystem services equation. The value of flood prevention, nutrient retention, water purification, and recreational opportunities are all benefits with a monetary or sociocultural value affected by LW (Acuña, Díez, Flores, Meleason, & Elosegí, 2013; Vermaat et al., 2016). The current understanding of how ecosystem services benefit humans is limited by a lack of data, according to Van Looy et al. (2017). The researchers believe finer grained data will improve the accuracy of ecosystem service calculations, especially for specific locations.

The data on LW is often coarse or interpolated from transects or small areas to provide estimates for entire river corridors, with no consistency in methods from study to study (Máčka et al. 2011). Máčka et al. (2011) and Van Looy et al. (2017) consider these methods problematic due to the heterogenous nature of fluvial systems. A faster, cheaper, more complete system for gathering data at the scale needed to accurately assess LW over entire river systems is needed.

Gathering data on large wood

The methods for gathering data on LW in fluvial systems are as heterogenous as the river ecosystems they attempt to quantify. A review by Máčka et al. (2011) randomly selected 100 studies focusing on LW and found different methods for every one. The studies identified 29 different variables for LW and 15 for LW accumulations. The review focused on field survey methods, which may be becoming obsolete, as Knehtl, Petkovska, and Urbanič (2018) explored.

As of 2016, Ruiz-Villanueva et al. (2016) found approximately 3000 scientific articles advancing the literature on fluvial wood. An exhaustive review of these papers would be excessive, so an overview on the state of LW field survey methods by Máčka et al. (2011) will provide a snapshot of a typical LW field study. The use of remote sensing for LW data collection will be covered in more detail in the Remote Sensing of LW section of this paper.

In the review of LW data gathering techniques by Máčka et al. (2011) the researchers found the scientific community lacking in common nomenclature and methods. The lack of standard procedures led the researchers to develop a comprehensive plan for LW data collection. A researcher can modify the plan to focus on the core principles they are interested in. The plan was based on the most common methods and variables from past studies. The plan distills the essence of the past 100 years of LW field studies.

The comprehensive plan includes 20 variables. The variables, units used, and methods for collection are included in the Appendix B. Via literature review, the researchers identified five core components of LW data. The core components are: 1) basic identification, location, and orientation 2) recording the dimensions of the LW including diameter, length, and rootwad diameter 3) assessing the decay status of the LW 4) noting if the LW causes geomorphological or ecological effects 5) assess stability of the wood via its place in the channel, orientation, or accumulation. The researchers assert these variables provide enough context for management.

The methods the researchers recommend using to collect data on these variables include visual inspection and the use of tools. GPS, electric distance meters (EDM), and tapes, and compasses are used to determine the location, size, and orientation of the LW. Visual inspection using predefined classes assesses the decay, position in the channel, and ecological and

morphological function of the LW. The research team must be physically present at the study site to gather the data. River conditions may be dangerous for wading or too small for a boat. The time spent on gathering data using the field survey methods could be prohibitive.

The study estimated a crew of two could assess 80-140 pieces of LW per eight hour day (Máčka et al., 2011) and they found an average of 580 pieces of measurable LW on the three rivers they studied. The average length of river surveyed in the study was 2.74 km. Using these figures, the average survey took from 4.14 - 7.25 days. The hours worked for the two-person team ranged from 33.12 – 58 per crewmember for a man-hour total of 66.24 – 116.

With manpower requirements of this level, it should not be surprising field methods are becoming obsolete as remote sensing capabilities improve (Knehtl et al., 2018). Remote sensing can reduce time, cost, and danger in LW data collection compared to traditional field studies. The data obtained via remote sensing can also cover a larger study area, even whole watersheds, whereas traditional field methods were limited in their sampling capability. Line-intersect, transect, and reach sampling were used by researchers to statistically control for the heterogenous nature river corridors (Ruiz-Villanueva et al., 2016). With RS, the entirety of a watershed can be assessed, albeit with some current limitations (Knehtl et al., 2018).

Remote sensing of LW

Prior to the development of remote sensing (RS) platforms for LW data acquisition the only way for researchers to collect the data was getting into the field and interacting personally with the LW. The time, labor and expense of these methods make remote sensing an attractive alternative for LW surveys (Knehtl et al., 2018). The use of RS in fluvial LW study is growing,

especially in recent years as calls for better methods of data collection to facilitate understanding of LW dynamics grow (MacVicar et al., 2009; Wohl & Scott, 2017).

Remote sensing is the collection of data on a subject without coming in physical contact with it (Lillesand, Kiefer, & Chipman, 2015). Platforms used in remote sensing include satellites, airplanes, helicopters, balloons, kites, ultralights, and UAS. The different systems operate at different altitudes, influencing the spatial resolution and field of view of images (Ortega-Terol et al., 2014). Remote sensing of LW involves mounting a camera or lidar on one of these platforms and collecting images of the river under study. The imagery used in studies of LW range from historical aerial photos, to low (1 meter) resolution satellite images, to high (< 1 cm) resolution helicopter and UAS images, lidar point clouds, and hyperspectral images (Marcus et al., 2003; Bakker and Lane, 2017; Dauwalter et al., 2017; Atha and Dietrich, 2016; Atha, 2014; Dietrich, 2016; Woodget et al., 2017).

Limitations inherent to RS in any environment can include temporal, radiometric, and spatial resolution and cost (Lillesand et al., 2015). Different platforms for RS have their own limitations. Satellite imagery can be expensive and low in temporal and spatial resolution. The various manned aircraft have limitations in cost, and temporal resolution. UAS limitations include spatial coverage due to line-of-sight regulations and battery life (Federal Aviation Administration, 2015; Woodget et al., 2017). The difference between different remote sensing platforms often involves the tradeoff of spatial resolution and spatial extent (Woodget et al., 2017). As an example, satellite imagery can cover the entire globe at lower resolution, while a UAS can obtain high resolution imagery of local areas.

There are many limitations specific to using remote sensing to survey LW in fluvial environments. Vegetation may block the camera, or the water may be turbid or rough, resulting in an inability to see LW behind the vegetation or under the water (Carrivick & Smith, 2018; Ruiz-Villanueva et al., 2016). Even if the water is clear, sun glint, surface reflection, or refraction can render images unusable (Dietrich, 2017; Woodget et al., 2015).

Advantages of remote sensing are numerous. A researcher can collect data without being in physical proximity to the object or phenomena being observed. This increases user safety and ease of data collection and decreases time spent covering an area. The use of RS gives a researcher a tool to observe and record data on a large area or in places not suitable for human travel. Examples of this include river areas with deep or fast water, and eroding cliffs (Máčka et al., 2011; Westoby et al., 2018). RS can also reduce field time, cost, and manpower necessary compared to traditional field surveys (Ortega-Terol et al., 2014).

The limitations of satellite and manned aircraft remote sensing in spatial and temporal resolution limit their effectiveness or practicality for fluvial LW data collection. The spatial and temporal resolutions are inadequate due to the time sensitive nature of LW monitoring and the small diameter (10 cm) of some LW. Dauwalter et al. (2017) believe the relative lack of temporal change analysis on streams is due to the low availability of high temporal resolution data. Ruiz-Villanueva et al. (2016) recommend the ground sample distance (GSD) for a pixel of imagery intended to identify LW be no more than 5 cm, and smaller if possible. The UAS can be cheaper, have better temporal resolution, higher spatial resolution, and comparable radiometric resolution, depending on the file format (JPEG vs. RAW) of the images used (Dietrich, 2016;

Detert, Johnson, and Weitbrecht, 2017; Westoby et al., 2018; Westoby et al., 2012; Carrivick et al., 2013).

Advantages to UAS remote sensing for fluvial LW research start with the spatial and temporal resolution achievable (Hamshaw et al., 2017). In UAS data collection temporal resolution is not limited by satellite orbits and swaths, or by the cost of manned aircraft flights. UAS flight regulations under FAA 14 CFR Part 107 prohibit flying a UAS in many areas without permission or during adverse weather and visibility conditions. These limitations are the only hindrances to the temporal resolutions possible with UAS (Ruiz-Villanueva et al., 2016).

The spatial resolution achievable with UAS is a product of the camera used and flight heights (Ruiz-Villanueva et al., 2016). To achieve the spatial resolutions of < 5cm necessary for LW inventory with cameras light enough not to compromise UAS flight times, flight heights must be low altitude, thus limiting the spatial extent of the imagery collected by each flight (Gabrlík, Cour-Harbo, Kalvodova, Zalud, & Janata, 2018; Ruiz-Villanueva et al., 2016). In any case, FAA 14 CFR Part 107 restricts UAS to flight altitudes of under 400 feet above ground level (AGL) unless in close proximity to a structure.

UAS can solve some of the major problems with RS of fluvial LW. Obtaining a view of the whole river channel is necessary to identify as much LW as possible. Riparian vegetation, landforms, and shadows often block or obscure satellite imagery of the stream (Hamshaw et al., 2017). UAS can mitigate these issues because of the flexibility in flight times and camera angles (Overstreet & Legleiter, 2017). Cloudy days minimize shadow effects, while multiple viewing angles (oblique, nadir, off-nadir) can see around or underneath obstructions. Flying on cloudy days and taking images from multiple angles can also minimize sun glint, which occurs when

the camera's viewing angle is the same as the specular reflection angle, allowing better penetration into water (Figure 7) (Overstreet & Legleiter, 2017).

UAS fluvial LW surveys are limited in spatial extent by three factors. FAA 14 CFR Part 107 stipulates the Remote Pilot in Command (RPIC) or a visual observer (VO) must keep the aircraft in line-of-sight at all times. Combined with the need to keep the altitude low for high spatial resolution (<5cm / pixel), this results in a limited flight distance in wooded fluvial environments (Hamshaw et al., 2017). The battery life of UAS varies with the model, payload, and flight conditions (wind, height, speed) (Woodget et al., 2017). Between these three factors, in wooded fluvial environments, UAS are restricted to local data acquisition on a per flight basis.

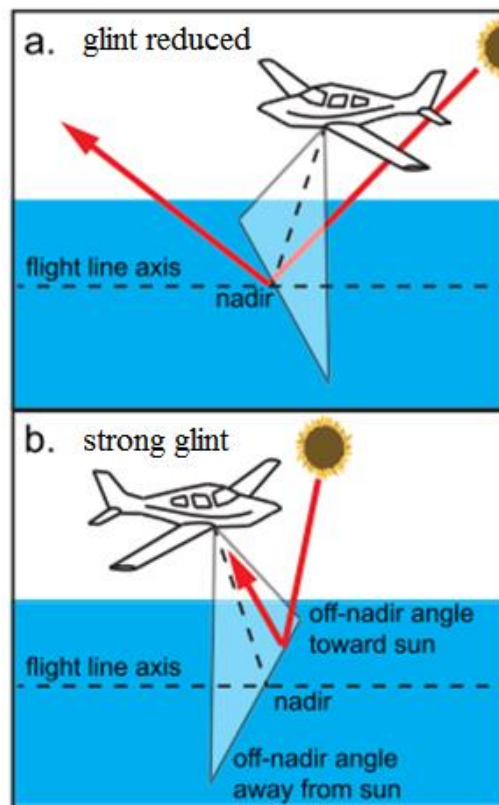


Figure 7: Illustration of (a) ideal and (b) non-ideal image collection geometry

Source: After Overstreet and Legleiter, 2017, p. 320

The scale of UAS collected data cannot be known unless the imagery is georeferenced either directly or indirectly (Westoby et al., 2012). The accuracy of the georeferencing depends on the accuracy of the UAS GPS or the GPS used to collect the GCP. Direct georeferencing uses the 3-dimensional position and pose of the camera at the time of image collection, while indirect georeferencing uses the position of ground control points (GCPs) to triangulate the images.

The process for reconstructing a scene in traditional photogrammetry involves knowing the 3D location and pose of the camera at the time of image capture or multiple GCPs visible in the image (Westoby et al., 2012). The photogrammetrist uses these known locations to triangulate the position of items in the image. Georeferencing and scale are inherent to the process.

The process of Structure-from-Motion (SfM) uses automatic feature matching between images to reconstruct the camera position and poses (Westoby et al., 2012). The feature matching or extraction process is known as scale invariant feature transform (SIFT). The SIFT process provides matching keypoints between images to the SfM algorithm, which then reconstructs the scene via the Bundler algorithm . The point cloud generated by this process is without scale until georeferenced via known camera positions or GCPs. The next section of this thesis will elaborate on SIFT, bundle adjustments, SfM and their development and applications.

From satellites to UAS

Field surveys were the only source used for LW data collection until 2002, when Marcus et al. attempted to map LW in the Greater Yellowstone Ecosystem using 4-band digital airborne imagery with 1-meter resolution. The attempt was unsuccessful due to the inability to

differentiate logs from sand and gravel within a pixel. Marcus et al. (2003) obtained better results using hyperspectral 128-band 1-meter resolution digital imagery. The hyperspectral imagery was able to detect LW below the size of the pixel. However, the accuracy of the LW classification was still only 83% after field validation tests. Higher spatial resolution imagery was needed to make remote sensing of LW practical as an alternative to field surveys.

Carbonneau, Lane, and Bergeron (2004) applied aerial imagery to a fluvial environment in their study *Catchment-scale mapping of surface grain size in gravel bed rivers using airborne digital imagery*. The study used a helicopter to cover 80 km of river. The images were taken at heights of 450 and 155 meters for resolutions of 10 and 3 centimeters, respectively. The flights took three work days. Compared to the work by Marcus et al. (2002; 2003), the GSD was 10 to 33 times smaller, and individual grains of gravel were identified. The researchers found using the smaller pixel size better identified gravel and had an overall precision of +/- 15.4 %. Manual methods in grain size estimation are around +/- 10% precision. The researchers attributed the lower precision to the pixel size being larger than clay, silt, sand, and small gravel. The use of aerial imagery in this study greatly expanded the area the researchers were able to estimate, enough that the lower precision was deemed acceptable.

The implications for LW survey using an aerial platform and high resolution imagery were positive, especially since the pixel size of 3 cm in this study was well below the 5 cm minimum requirement for LW identification cited by (Ruiz-Villanueva et al., 2016). The spatial resolution was adequate to detect LW, but without a more cost and time effective way to obtain imagery, the use of aerial imagery obtained by manned aircraft was still impractical on a large scale. Unmanned flight was the next step in the evolution of RS in fluvial data collection.

Jones, Pearlstine, and Percival (2006) presented their findings on the use of UAS in wildlife surveys. The study took place in 2002-3 following the introduction of UAS outside of military use. The platform was a fixed-wing nitromethane powered drone called the FoldBat. The study was conceived to obtain high quality, georeferenced aerial imagery of landscape and wildlife on a scale beyond the reach of traditional field surveys without the obstacles such as cost, safety, and logistics involved with manned flights.

The UAS was remotely piloted during landing and takeoff, while the flight missions were carried out on autopilot via the onboard computer. The onboard flight computer was essential to the success of the UAS in carrying out its mission because the lack of drone regulations at the time allowed flights beyond line-of-sight. If the UAS lost communication beyond line-of-sight it needed a way to complete its mission and return safely. The UAS was equipped with a consumer-grade GPS and two video cameras. One camera was used for manual flight and the other, a Canon Elura 2 progressive-scan model, for data collection. The researchers were able to extract quality stills from the video but were unable to link images to locations because of the time lag in the radio transmission from the UAS to the control station.

Overall, the use of FoldBat was a learning experience for the UAS data collection community. The importance of linking GPS positions to the images instantly and storing all data onboard the aircraft to avoid data corruption during transmission to a ground station were two lessons learned in this study. The researchers also recommended using a different style of aircraft, specifically battery powered with a shallower learning curve for users unfamiliar with flying UAS. The use of a combustion engine was not ideal for people unfamiliar working with one, and the difficulty of taking off and landing was high, especially in areas without clear

runways. The inability to take off and land vertically or on uncleared areas critically hampered the utility of Foldbat for collecting data in remote areas with no clear site for launch and retrieval. New UAS technology using lightweight, battery powered aircraft would soon consign these limitations to the past.

Watts et al. (2010) presented a solution to many of these issues with their paper *Small unmanned aircraft systems for low-altitude aerial surveys*. In this study, the researchers demonstrated the usage of the Nova 2; a small, battery-powered, fixed-wing UAS capable of taking off with no runway or catapult and landing on water or rough surfaces. The UAS was equipped with a differential GPS and a digital camera, linked together and calibrated to record the position of images with an accuracy of 2 microseconds.

The study was able to successfully use photogrammetric techniques to produce orthomosaics with an error of 0.50 m and SD of 0.31. This level of precision was aided by the use of more accurate differential GPS to guide the autopilot system than that used by Jones, Pearlstine, and Percival (2006) and the use of a still camera for recording the imagery. Image georeferencing was found to be more accurate than using video stills and calibrating the GPS and camera was easier than with video. Using still imagery also improved the images by providing higher spatial resolution and limiting blur by increasing the lens shutter speed.

The use of a battery-powered UAS for data collection was another step forward for ecological research. The researchers here used traditional photogrammetric techniques to orthomosaic the images. The traditional techniques were based on knowing the position of items in the images (indirect georeferencing) or the location and orientation of the camera (direct georeferencing) to reconstruct a 3D scene. The expense of the sensors necessary to know the

precise position of the UAS were prohibitive for extensive public use (IMU approximately \$10,000). Airframe costs of \$5,000 minus the camera, GPS, and IMU also restricted the common use of UAS at the time. The photogrammetric techniques used to create useful, georeferenced maps from the images more cheaply, quickly, and precisely were already in use in the field of computer vision and would be breaking through into the world of ecological data collection soon.

At this point in the evolution of remote sensing towards the subject of this thesis, the photogrammetric techniques and the data collection platforms become intertwined (Carrivick & Smith, 2018). A new technology called SfM would begin to accentuate the best traits (adaptability, spatial and temporal resolution) of UAS-based data collection. The days of traditional photogrammetry or 2D orthophotos were about to become obsolete when studying the fluvial environment. A review of the beginnings of Structure-from-Motion as a photogrammetric technique is necessary before addressing the advances of the last 9 years of fluvial remote sensing with respect to LW.

Structure-from-Motion

Traditional photogrammetry, as outlined by Bakker and Lane (2017), followed a protocol to reconstruct a 3D scene from 2D images. The protocol started by defining the areas of images and the properties of the camera lens used. The photogrammetrist would then use GCP's, tiepoints, and approximate camera positions to develop a conceptualization of the location each image was taken, apply the bundle adjustment, and then use stereo-matching to create the 3D

point cloud. The process was dependent on knowing the precise GPS coordinates of GCP's, features in the image, or the camera location to create the model.

SfM automates the first two steps of this process (Bakker & Lane, 2017). Seitz et al. (2018) provide a summary of the techniques involved in using SfM to create georeferenced 3D models from images. The first step is to collect overlapping images to use in the process. Second, algorithms detect areas with no variance from scale or rotation in images that overlap, then scale invariant feature transform (SIFT) is applied to match keypoints (now tiepoints) among all the photos and establish their positions in a 3-dimensional space. From this, the position of the camera at the time it took each photo can be determined and a sparse point cloud developed and refined via bundle adjustment. Third, the sparse point cloud is enhanced by a multi-view stereo (MVS) technique which looks at every pixel in all the images to produce a dense point cloud. The dense point cloud is then triangulated to form a 3D model, which is given a scale and georeferenced using ground control points or the camera locations at the time an image was taken. Without GCP's or camera locations SfM can only create a dimensionless model. Georeferencing to a known coordinate system and scale require a minimum of three known points among the images (Javernick, Brasington, & Caruso, 2014)

The process of SfM for LW survey, then, relies on effective image collection, keypoint detection, SIFT, bundle adjustments, and georeferencing for scale. Keypoint detection, SIFT, and bundle adjustments are the domain of SfM, while image collection and georeferencing rely on the platform and sensors used. The progression of SfM from keypoint detection and matching in traditional photogrammetry, to the development of SIFT, to the combination of SIFT with bundle adjustments will be covered in this section.

Snavely, Seitz, and Szeliski (2008) provide an overview of prior research in computer vision leading to SfM. The process of using algorithms to find keypoints and match them to create tiepoints between images of one scale and in 2D began with the work of Kanade (1981) and continued through Harris and Stephens (1988). These early works on keypoint identification and matching only worked if the images were from the same perspective and in order. The keypoints were tracked from image to image.

Szeliski and Kang (1994) referenced the work of Tomasi and Kanade (1991), and Taylor et al. (1991) both of which used multiple frames and points to reconstruct the 2D geometry of images, with a method to reconstruct images in 3D without complete point tracks. This was still based on images from the same perspective, however.

Szeliski and Kang's study used a nonlinear least squares statistical approach to simultaneously solve for structure and motion, or the 3D location of items in an image and the camera position where images were taken. The study was a breakthrough due to its ability to recover 3D structure and camera motion without initial algebraic steps to start the process and the use of a sparse matrix of points to limit the computing power needed to process the data. The algorithm creates models without complete point tracks, meaning the stream of images does not need to be in order. This development will be further advanced by Snavely, Seitz, and Szeliski (2006).

The use of bundle adjustments to refine the camera positions and keypoint matches found via SfM was introduced to computer vision from photogrammetry by Triggs et al. (1999) (Snavely et al., 2008). The use of bundle adjustments simultaneously calculates the camera parameters and the position of keypoints found during the keypoint detection and matching

process. The use of the sparse point cloud created via bundle adjustments to create a precise 3D model from images remains in use to this day.

The work of Pollefeys and VanGool (2002) allowed bundle adjustments to be made without prior knowledge of camera calibration or GCP's. The researchers set out to create a process to extract the camera properties and motion and the location of points in the images. The process of camera self-calibration was automated with an algorithm developed in Pollefeys et al. (1999). The algorithm was created to remove the skew created in images by projection, in which angles and distances are not correct. The initial projection is corrected this algorithm and the result is a sparse point cloud with much higher precision than otherwise possible without camera calibration. Pollefeys and Van Gool then provide a very clear explanation of how the sparse point cloud is densified. Each pixel in an image corresponds to a ray in space. Since the position from where the image was taken is known, the rays corresponding to pixels in different images can be matched. Combining the location of different points and the camera, the distance from the camera to the points and from points to other points can be triangulated. While the densification of the point cloud was not a breakthrough in the field, the explanation is enlightening, and along with making camera calibration unnecessary, thus reducing the complexity of image collecting for SfM, was a major contribution of this study.

Lowe (2004) developed SIFT, a feature detection and matching algorithm which remains in use today for SfM, with minor modifications depending on the SfM algorithm in use (Javernick et al., 2014). SIFT was introduced by Lowe (1999), in which the author extended the work of Schmid and Mohr (1997) on rotational invariance. Rotational invariance in an image allows pixels or features to be matched from various orientations and even if they are blocked in

some of the images. The scale of the images, however, must be constant for keypoint matching between them to work. Local maximum and minimum value pixels are considered keypoints. The local extremes are found by comparing each pixel to its eight neighbors and the nine pixels nearest it in the scale. Low contrast and unstable keypoints below a threshold are filtered out.

The utility of SIFT is found in its ability to equalize the differing scales of images due to various distances from the camera to pixels at the time of image capture. Affine (3D camera viewpoint) or homographic images can cause distortions in traditional photogrammetric techniques, but are protected against in SIFT (Lingua, Marenchino, & Nex, 2009). SIFT equalizes the scale of keypoints by assigning a vector to each keypoint. The vector allows matching of keypoints that can undergo scalar and rotational transformations and some affine or illumination transformations without being distorted.

Lowe tested SIFT using 32 images ranging from human faces to outdoor scenes and found his results similar for each. The strengths of the SIFT tool include the distinctness and large number of keypoints (1000's) found over a variety of scales in most images, which increase total matching and locational precision. In SIFT, the percentage of correct matches is less important than the total number of matches. The work was only tested with monochrome lighting intensity and Lowe recommended future work to solve the problem of illumination variation especially in 3D objects. The robust quality of the feature matching in SIFT resulting from the large number of keypoints found in each image makes it ideal for use in SfM, as Snavely, Seitz, and Szeliski (2006;2008) were about to show.

Snavely, Seitz, and Szeliski (2006;2008) built on Pollefeys and Van Gool's work by using images from completely unknown sources to construct SfM point clouds and the resulting

photomosaics. Their research looked at using public images from searches on Google to reconstruct landmarks around the world via SfM. The importance of camera calibration was reduced further, thousands of different cameras and no information on camera type or attributes available for many of the images used. The quality and conditions of the images varied greatly, with changes in illumination, orientation, distance, and spatial scale.

SIFT was used for keypoint detection and matching, followed by a bundle adjustment using the features detected and catalogued by SIFT. Prior to the bundle adjustment the researchers selected two frames with the lowest amount of homogeneity and at least 100 keypoint matches. This avoids using cameras from the same location, where there would be no ability to triangulate, but assures a large amount of overlap in the images. The camera properties were estimated using these two images, and the resulting tracks found between the images are bundle adjusted. The bundle adjustment used in this study was iterative, adding an image at a time to the existing model, while only allowing points under observation by that camera to change. The images added were selected by first finding the image with the most matches to the existing model and adding any image with at least 75% of that number. Once reliable new matching points were found, they were added to the estimates of all points and underwent a global bundle adjustment. Following the global bundle adjustment outlier tracks were removed and the bundle adjustment rerun. This procedure was repeated for all images until less than 20 matching points could be found in a new image.

Lingua, Marenchino, and Nex (2009) validated the use of SIFT for images obtained via UAS which do not fit the traditional photogrammetric standards for taking geometry, especially convergent angles, affine transformations, and poor texture (low range of pixel values). The

UAS imagery was detected and matched using SIFT and three traditional photogrammetric techniques: the Cross Correlation, Least Square Matching, and the Forstner operator.

The researchers found SIFT to generate a far higher number of keypoints and matches than the traditional techniques, especially for imagery with bad geometry or texture. SIFT was able to withstand high levels of distortion and rotation and matches could be made without any initial estimated solutions. The tradeoff of this increased number of keypoints and matches was a greater computational load. The researchers found low texture areas of images to lack matches in proportion to high textured areas. The texture problem can be manually solved with threshold manipulation, but the researchers adjusted the contrast threshold for areas detected to have low texture. This resulted in higher point detection and matching in these areas compared with the stock threshold suggested by Lowe. This adjustment is not present in any of the other literature reviewed here, but is possibly the modification to SIFT present in Photoscan SfM algorithm mentioned in Javernick, Brasington, and Caruso (2014).

The methods followed in Snavely, Seitz, and Szeliski (2006;2008) formed the nucleus leading to the use of SfM-MVS for ecological and geoscience work in the future (Bakker and Lane 2017; Westoby et al. 2012). Their work owed much to Pollefeys and Van Gool (2002) who were showed it was possible to reconstruct 3D space from with 2D images from uncalibrated cameras. Szeliski and Kang (1994) had previously developed a method to extract 3D points with images from calibrated cameras but incomplete spatial location information. The combination of images without spatial metadata from uncalibrated cameras was then combined with SIFT by Snavely, Seitz, and Szeliski (2006;2008) to reconstruct world landmarks. Lingua, Marenchino, and Nex (2009) tested SIFT's keypoint detection and matching against traditional

photogrammetric techniques for UAS-gathered imagery. The results showed the superiority of SIFT for images exhibiting bad taking geometry or texture (convergent angles, affine transformations, low contrast).

The development from satellite and manned aircraft airborne imagery to combustion-powered UAS to lightweight, battery-powered UAS with internal memory capacity and easy pilot learning curves would combine with SIFT and SfM-MVS in 2010 to provide a remote sensing option with lower costs and higher spatial and temporal resolution than anything before.

The marriage of SfM and UAS

Carrivick and Smith (2018) provide an overview of the co-development of UAS and SfM technologies and their application to fluvial research over the last decade. The review begins with a summary of the relative performance among SfM and other fluvial survey methods regarding spatial extent and point density, acquisition rate, and accuracy. The table included in Appendix C shows UAS-based SfM surveying increases the spatial extent compared to traditional field surveys by a factor of 5, can create similar point densities at a similar rate to aerial or ground based lidar, and has point locational accuracy within an order of magnitude of Total station-based surveys. The combination of these four factors plus the increased safety for users and low costs of operation and data processing make UAS-based SfM an attractive option for data collection in many fields, but especially for fluvial environments.

The beginning of the UAS-SfM marriage did not involve the fluvial environment. Dandois and Ellis (2010) used the foundation laid by the work of Snavely, Seitz, and Szeliski (2006;2008) to use SfM to reconstruct 3D vegetation structure. The researchers wanted to create a low-cost alternative to lidar for vegetation structure analysis used in forestry, firefighting, and

ecology. The study collected the imagery using a kite fitted with a Canon A470 digital camera with a 5.0-megapixel resolution. The researchers then processed the images using the Bundler SfM algorithm developed by Snavely (2010), which combined SIFT and a bundle adjustment, before analyzing the point cloud in Ecosynth.

The study compared the precision of lidar and SfM generated digital terrain models (DTMs), tree canopy heights, above ground biomass (AGB). The precision of SfM was lower than lidar in the DTMs, partly because the lidar data was collected during leaf-off conditions and the SfM during leaf-on. Performance was equal in areas of uniform tree canopy heights, but lidar was superior where there were extreme variations. The performance of SfM for measuring AGB was within the acceptable range for lidar, although lower than the lidar in this study.

The limitations of UAS-SfM at this stage were numerous. The researchers included a table of the challenges and possible solutions, shown in Appendix D. Some of the issues were due to technology, such as the poor image overlap caused by strong winds rendering the kite uncontrollable. The low performance of the generated DTM and AGB measures could have been corrected by flying during leaf-off conditions and by placing GCPs in the images rather than using publicly available DTMs and orthophotos for georeferencing. The poor distribution of points in low texture areas was also observed by Lingua, Marenchino, and Nex (2009) and corrected for by changing the contrast threshold in SIFT. The researchers may not have been aware of this research. The point cloud densities obtained for areas of coarse (high texture) vegetation indicated that surveying features such as LW with UAS-SfM would be possible. Much research would attempt to rectify the issues raised by Dandois and Ellis over the next nine years.

Carrivick and Smith (2018) break down the next steps taken in UAS-SfM development into two types. James and Robson (2012) and Fonstad et al. (2013) both approached UAS-SfM similarly to Dandois and Ellis (2010), intending to show it was a viable alternative to lidar for DEM and DTM generation. Jensen and Mathews (2016) demonstrated the use of UAS-SfM to assess canopy heights with UAS-SfM generated DTMs, which showed UAS-SfM capable of both terrain and vegetation modeling. These proof-of-concept studies gave way to studies attempting to codify the best practices for UAS-SfM, including James and Robson (2012), James and Robson (2014), James et al. (2017) O'Connor, Smith, and James (2017), Carbonneau and Dietrich (2017), and Mesas-Carrascosa et al. (2016).

Studies proceeding from the basic templates of the two types above include those specifically answering the question of direct and indirect georeferencing for UAS-SfM point clouds: Gabrlik et al. (2018); Masiero, Fissore, and Vettore (2017); and Turner, Lucieer, and Wallace (2014). The use of UAS-SfM for mapping fluvial environments was explored by Javernick, Brasington, and Caruso (2014), Rusnák et al. (2018), Seitz et al. (2018), and Tamminga et al. (2015). The use of UAS-SfM being well established for precision and for use in fluvial environments, the stage was set for comparison between traditional LW field surveys and UAS-SfM techniques. Bojakowski, Bojakowski, and Naughton (2015) and Knehtl, Petkovska, and Urbanič (2018) explored the possibilities in this line of thinking.

In 2012, James and Robson brought SfM to the geosciences with their comparison of SfM to traditional photogrammetry and lidar based 3D models. The different techniques were compared via three case studies, with a final proof-of-concept done on a cliff erosion site to quantify the soil loss over a year. The study used a consumer-grade camera to collect images of

cliff erosion and processed them using Bundler and an MVS densifier. The initial sparse point cloud created by Bundler was used to create a framework for the densified point cloud created by the MVS process, which was then used in the subsequent analysis. Bundler considered each image added to the model to be from a different camera, with no ability to specify a consistent internal geometry. This was purposeful for the original work from Snavely, Seitz, and Szeliski (2006) because their purpose was using images from unknown sources. The inability to set a consistent internal geometry degraded the precision of the resulting models.

The case studies spanned scales from centimeters to kilometers and the results were reported by a relative precision measure which compares the precision to the average distance from the camera to the surface being imaged. The precision achieved in the study was 1:1000 over a variety of spatial scales. The case study surveying the volcano crater expanded the spatial extent of SfM compared to Dandois and Ellis (2010). The crater was a kilometer wide and was surveyed with a UAS and consumer-grade camera. The results showed a longer camera focal length (28mm for the coastal erosion site to 20mm for the volcano) produced higher precision between the SfM models. Clustering of GCPs reduced the precision of the coastal erosion site model. The researchers recommend scattering GCPs throughout the images and near the edges to better reduce distortions.

The increased spatial extent without loss of precision for this survey was a step towards using UAS to expand the reach of fluvial LW surveys. Compared to terrestrial laser scanning, SfM-MVS reduced field time by 80% with similar precision. The SfM process increased the spatial density of points by two to three orders of magnitude over the traditional field methods

and would benefit LW surveys, which often only record one point for location and one measurement for length and width.

Westoby et al. (2012) provided a similar proof-of-concept study to James and Robson (2012), comparing the performance of SfM creating a digital elevation model (DEM) of three types of terrain to a terrestrial laser scanner. As in James and Robson, indirect georeferencing via GCPs was used for transforming the point cloud to an absolute coordinate system. The point cloud was again generated with open-source software using SIFT, Bundler, and MVS. After MVS, the researchers reduced the points to decrease the computational load because the DEM did not require a point cloud with extremely high densities.

Actions such as the reduction of points and subsequent loss of information due to limitations on computer memory and processing power are diminishing with time. However, researcher need to be cognizant of oversampling; as data collection becomes easier with UAS, the volume of imagery also increases, potentially beyond the capabilities of current computing to handle. The researchers found areas of difference between the terrestrial laser scanner and SfM models corresponded to areas of dense shrub cover. Dandois and Ellis found similar issues in 2010. SfM's low performance in areas with dense vegetation would be a limiting factor in LW inventory in forested fluvial areas. The use of SfM for remote sensing of the environment was gaining acceptance, but would the limitations imposed by dense vegetation impede it from use in fluvial settings?

Javernick, Brasington, and Caruso (2014) delved into this question in their study *Modeling the topography of shallow braided rivers using Structure-from-Motion photogrammetry*. The study brought SfM into a different environment than James and Robson,

Dandois and Ellis, and Westoby et al., by comparing aerial lidar to SfM for mapping the topography of a fluvial environment. The study covered a total of 3.3 river kilometers of the Ahuriri River in New Zealand, used indirect georeferencing via GCPs with imagery captured from a manned aircraft and a high-grade digital camera. The SfM process used Photoscan, which includes proprietary versions of SIFT, bundle adjustments, and MVS. The resulting dense point cloud was again filtered to reduce computational need, but also to filter vegetation for more accurate DEMs.

The filtering of the point cloud to reduce clutter from vegetation used raster differencing in ArcGIS to difference point clouds filtered for 0.75, 1, and 3-meter point spacing. Any differences of ≥ 0.4 meters were assumed to be vegetation and filtered out. The use of filtering to eliminate standing trees or shrubs in the fluvial environment may be useful in LW UAS-SfM surveys. The research was the first to specify image overlap parameters other than “high”. The researchers recommend 60% side and 70% forward overlap for adequate point cloud construction.

The researchers noted the difficulty of GCP placement for georeferencing. The image acquisition took four hours, while GCP placement took a team of three people ten hours. The need for direct georeferencing cannot be more apparent. Image altitudes of 600-800 meters high and near-nadir viewing angles in this study work for generating a DEM but would result in severe blind spots in a riparian area with overhanging vegetation. The use of UAS flying at low (<100 meter) altitudes and using oblique viewing angles for image taking would resolve many of the blind spot issues in the river channel itself. The advantages to directly georeferencing UAS-SfM point clouds was obvious and research was already being done to make it possible.

Turner, Lucieer, and Wallace (2014) presented their findings on the use of a direct georeferencing system to eliminate the need for field placement of GCPs and to fully automate the SfM process by removing the need for human identification of GCPs in images. The study used a multicopter UAS equipped with differential GPS and a consumer grade digital camera synchronized to the GPS to record the location each image was taken from. The images were also corrected for the distance between the GPS antenna and the center of the camera. The images collected were processed with Photoscan, Pix4D, and Bundler to determine the highest point precision when used with directly georeferenced images.

The researchers reference prior work to directly georeference aerial imagery by Turner et al., Chiang et al. and Eugster and Nebiker. The navigation grade GPS systems used in prior studies limited the planimetric accuracy levels to between 0.65 and 5 meters, depending on flight altitude. Turner, Lucieer, and Wallace compared the offset between the SfM created photomosaic and the GCP from each algorithm. The overall accuracy for the study was approximately 0.11 meters using the differential GPS, with Photoscan and Pix4D outperforming Bundler. The researchers also ran the SfM with navigation grade GPS data and the accuracy was approximately 2.3 meters, thus showing the GPS as the controlling factor in point cloud accuracy.

The issues with Bundler's spatial accuracy are attributed to the inability of the algorithm to use the same camera parameters for all images. This issue was previously raised in James and Robson (2012). The emergence of more spatially precise commercial software like Photoscan and Pix4D seem to have usurped Bundler's place as the SfM tool of choice for geoscience applications. The results of this study showed direct georeferencing of UAS-SfM imagery was

possible if the images are synched to the GPS and the lever arm distance between the GPS antenna and the center of the camera are accounted for. The only limiting factor was the accuracy of the GPS.

A study on a subject altogether different from LW surveying presented a compelling argument for the efficacy of SfM in quantifying objects in 3D. Bojakowski, Bojakowski, and Naughton (2015) explored the use of SfM to map a shipwreck in Bermuda more precisely than divers could with the traditional hand held tape measure, which was incidentally the same tool used by LW surveyors in the field.

The use of SfM to build 3D models of shipwrecks from images each showing a small part of the greater whole was the same concept as mapping a river of LW with many overlapping photos. In this study, the researchers did not specify an amount of overlap between images, other than “more is better”. The process of SfM underwater presented many of the same problems as terrestrially, with the added difficulties of waterproofing the camera with a lens that will not distort images, and the different rates of light wavelength absorption underwater, causing images to appear green or blue.

The accuracy achieved by SfM in this study was low compared to the traditional method, a few factors probably caused this. First, the images were not taken with SfM in mind, leading to low overlap. Second, the images were not corrected for the waterproofing lens or the underwater color absorption. The use of SfM was much quicker in this study, for the same reasons LW surveys via SfM could be faster. The researcher only needs to gather overlapping images of the ship or stream, and record at least three GCPs for triangulation, rather than measuring a ship’s hull by hand or each log in a jam individually.

Another study in archaeology, terrestrial in this case, was provided by Mesas-Carrascosa et al. (2016) and examined the differences in spatial accuracy of a SfM-generated orthomosaic for different UAS flight altitudes and image overlaps. The study was done on an archaeological site in Torreparedones, Spain. The researchers used a consumer-grade UAS and camera, with a navigational level GPS and GCPs registered with topography techniques rather than a GPS. The UAS flights were at altitudes of 30 – 80 meters in 10-meter increments. Flights at these altitudes were done with 70% front-lap and 40% side-lap, and again with 80% / 50%.

The results of the study showed flight altitude above ground level (AGL) was the dominant factor in error for both absolute and relative spatial accuracy, as shown by the graph in Appendix E. Increased overlap improved accuracy slightly, but only incrementally. The researchers concluded the root mean square error (RMSE) of an orthomosaic created with a GCP referenced UAS-SfM process could be predicted as 5 times the ground sample distance GSD of the images. The ground sample distance is directly related to the flight altitude AGL. More flights with progressively lower overlap could have identified the point at which overlap was insufficient to create an orthomosaic which could serve the purpose of the archaeologists. The ramifications for LW survey were the continued mantra that “more overlap is better” and higher flight altitudes reduce flight time for the same amount of overlap but increase GSD, thus decreasing spatial resolution and accuracy.

Continuing to refine the standards for effective UAS-SfM data collection, James et al. (2017) questioned the practices leading to large errors in UAS-SfM topographical studies. The researchers hypothesized that although SfM could create spatially accurate maps, using it with no understanding of photogrammetric principles was leading to widely divergent accuracy

outcomes. The researchers provide two case studies, one a gulley erosion site in Morocco and the other an active landslide in France. The survey used fixed-wing and quadcopter UAS, respectively, with the first flight piloted autonomously and the second manually. The imagery was processed using Photoscan.

The resulting orthomosaic of the study sites was checked for accuracy by numerous iterations of the Monte Carlo statistical analysis method, in which the photomosaic accuracy was checked against itself with a random selection of GCPs providing the georeferencing in each iteration. The study found that with strong image geometry (convergent images, high overlap), the amount of GCPs needed for subcentimeter level accuracy with cameras self-calibrated through bundle adjustments could be reduced by 50%. However, high quality cameras with consistent internal geometry were necessary for the consistent, clear, undistorted images needed for effective self-calibration. Image geometry improvements were possible through using a variety of oblique and near-nadir viewing angles. GCPs could also be reduced by 50% for studies using precisely pre-calibrated cameras, even with weak image geometry.

The researchers reiterated the position of Mesas-Carrascosa et al. (2016) in that GCP accuracy should exceed the survey precision or GSD of the images. This requirement could be bypassed in situations where only the GCPs are only used to provide orientation and scale to the model. The researchers conclude that GCPs should be distributed throughout the study site and their density depends on the accuracy desired in the survey. Strong image geometry and quality were essential to accurate results and the results should be checked for distortions or error, with all processes used in the check reported so others can reproduce the results.

The reduction of systematic errors and minimization of spatial variability is not as critical a concern for LW studies, but better procedures leading to more accurate results should not be ignored. The resolution defined by Ruiz-Villanueva et al. (2016) as necessary for fluvial LW inventory was 5 cm, which is an order of magnitude higher than the precision levels used in James et al. (2017). The use of UAS-SfM for management purposes could benefit from greater precision if the model was used for LW volumes, but orientation and scale would provide the necessary context for LW management. The recommendation to document the process of error detection and minimization would help others replicate the work and should be followed.

Carbonneau and Dietrich (2017) demonstrated the ability to use camera pre-calibration in the UAS-SfM process to obtain topographies with errors of 1:1000 of UAS flight height, comparable to the work previously referenced by James and Robson (2012). The difference was that James and Robson used GCPs obtained with RTK GPS, while Carbonneau and Dietrich used a consumer grade UAS equipped with navigational GPS and no GCPs.

The study created topographical maps of two fields in Durham, England. The cameras of the UAS were calibrated using a flat wall to detect any doming or dishing of the point cloud from lens distortion. The fields were surveyed with RTK GPS and then imaged with the UAS. The topography created with SfM was compared to the topography created by the GPS to check for error. The researchers found that camera pre-calibration reduced error to 0.1% of flying height, even with consumer-grade GPS recording imaging locations. Applications of direct georeferencing for LW survey would likely take the form of change detection, and therefore the authors recommend scaling corrections, which could be manmade objects of known length visible in the study images. The use of lidar datasets could be used to correct for elevation errors

if known points were visible in both the imagery and the lidar data. Limited numbers (three or four) GCP's were found to reduce error in the point cloud from 1.190 meters to 0.006 meters. The GCP relative locations (colinear or coplanar) and spacing were not found to affect the SfM model if used for georeferencing following point cloud formation. This has implications for fluvial LW surveys because of the narrow nature of river corridors dictating GCP placement in non-traditional locations (not well spaced and near the edges) of the study area.

The use of UAS-SfM, up to this point, mostly focused on topographical products such as DEMs or DTMs. The use of UAS-SfM to identify specific objects like LW was the next step. The lessons learned about flight characteristics and image collection during topographical surveys could be applied to the field of LW identification and management.

Recent work in remote sensing of LW in fluvial environments

Tamminga et al. (2015) demonstrated the ability of a small UAS to obtain imagery suitable to identify fish habitat, including LW in a 1km reach of the Elbow River, Alberta, Canada. The study used a consumer grade camera and UAS with an IMU and differential GPS with indirect georeferencing via GCPs. The flight paths and ratio of image overlap were not stated, but the UAS flew at a 100-meter altitude and stayed within line-of-sight (approximately 800 meters). The image processing was done in the ENSOMosaic UAV Package. This software used traditional photogrammetric techniques to create a georeferenced orthomosaic with a resolution of 5 cm in 2D.

The researchers used the imagery to create a DEM and map of the channel reach morphology. Of interest to the present research, they mapped the LW and other objects used for fish cover in the study reach. This was the first use of UAS imagery to inventory fluvial LW. The research did not attempt to directly georeference the imagery, as Turner, Lucieer, and Wallace (2014) showed was possible with a differential GPS equipped UAS. The opportunity to compare the accuracy of direct and indirect georeferencing in fluvial environments was lost, but this study opened the door for the use of UAS-SfM as a management tool to inventory LW in fluvial environments.

The use of UAS-SfM to inventory fluvial LW in 3D would wait, but a study using a helicopter to gather images for SfM would provide insight to how it might be done. 32 kilometers of the Middle Fork of the John Day River in Oregon were the subject of the study by Dietrich (2016). The author used a helicopter flying at 200 meters AGL and a consumer grade camera, for a planned spatial resolution of 5 cm. The images were overlapped by at least 60% and 66 GCPs recorded using differential GPS. Photoscan was used for the SfM process and Dietrich used a previously surveyed lidar DEM for elevation and horizontal accuracy checking following the creation of the point cloud and orthoimage.

While the study focused on large scale trends in stream width, depth, and gradient there were many aspects helpful for LW surveying and analysis. The author was able to identify individual LW in the orthoimage, which confirms 5 cm as acceptable resolution. The accuracy of the GCP locations was directly reflected in the accuracy of the georeferenced orthoimage, which confirms the work of Mestas-Carrascosa et al. (2016) in that the accuracy of the GPS used for GCP locations should be greater than the GSD (in this case 5 cm) or it would cause error.

The author identified the radiometric resolution (8 bit) and lack of a near infrared band in the JPEG imagery as limiting the ability of the imagery to find river depths and making image classification processes less efficient, respectively. The author found the geometric centerline of the river and created three-meter segments which intersected the centerline. Categorical variables, including LW were manually assigned to each segment. The segments were used to analyze channel width along the stream but could be used to analyze LW distribution.

While the scale of this study was greater than that usually done with UAS, the use of SfM to map a riverscape, and in the process identify LW, was now a part of the scientific literature. The lessons pertaining to LW survey in fluvial environments resulting from this study were that SfM could create an orthoimage capable of identifying LW and other habitat features, as well as allowing for analysis of changes along the stream length. The use of convergent imagery to increase spatial accuracy, using the highest radiometric images possible, and ensuring image overlap via better flight planning or image frequency all apply to LW surveys.

The use of UAS-SfM to identify and quantify LW in a river had not yet been studied. The work of Rusnák et al. (2018) would change this. Their study focused on identifying objects, rather than topography, in a 1.6km reach of the Bela River, Slovakia. The objects for identification and quantification included LW. The researchers outlined a workflow for object identification in a riparian environment using a consumer-grade UAS and camera with a resolution of 5 cm. GCPs were located using an RTK GPS and images were acquired at nadir, oblique and horizontal angles. The SfM processing used Photoscan to create the point cloud and orthomosaic of the images, with an example included in Appendix F. Accuracy of the model was on the decimeter scale.

ArcGIS was then used to manually classify different features, including LW. The vegetation in the point cloud was classified via Terrasolid Terrascan into different classes based on height. The low vegetation class included LW, which was extracted using the features previously manually classified in ArcGIS. This was accomplished by combining the RGB data from the orthomosaic to the point cloud. The orthomosaic then underwent supervised Maximum Likelihood Classification (MLC). The manually identified LW was compared with the results of the MLC to create a confusion matrix accuracy assessment. The LW was identified with an accuracy of only 17.70%, but a precision of 75%. The LW was most commonly misidentified as vegetation. The low accuracy could be improved by using imagery with a near-infrared band and using object-based image analysis with a segment mean shift, as done by Gerke (2018, unpublished).

LW volume was calculated using the point cloud to provide length and elevation profiles to determine diameter. The cut method in the Topolyst software was used to derive the volume of single pieces and accumulations of LW. Knowledge of the volume, orientation and location of LW in a river is critical to understanding the habitat available for salmonids (Davidson & Eaton, 2013). The level of accuracy in identifying the LW automatically was disappointing, but manual identification and the knowledge gained on volume, orientation, and location are valuable, even though more work is required. The work of Rusnák et al. (2018) showed this level of quantification was possible on a river in a mountainous, lightly vegetated environment. The efficacy of this method in a more densely vegetated region remains to be seen.

UAS-SfM applications in management

Johnson, Smith, and Wescott (2015) review the use of UAS for natural resource management. They identify five advantages UAS hold over manned aircraft for natural resource management four of which apply to LW management. These four are reduced cost, reduced risk to pilots, increased temporal resolution, and lower altitude flights. The authors also identify 12 areas UAS had been proved capable in as of 2015. Three of these areas apply to LW management. They are vegetation assessments, habitat assessments, and high resolution DTMs. These three areas are all aspects involved with monitoring or surveying LW.

The researchers also identified difficulties in the use of UAS for natural resource management. Many of these difficulties are related to the variety of regulations governing UAS flight and the different rules by jurisdiction and governing agencies (i.e. USDA Forest Service, FAA, MDNR). This study came out prior to when the FAA 14 CFR Part 107 regulations were finalized, thus rendering the concerns of an immature regulatory landscape moot. Other concerns include public mistrust of UAS and privacy issues, liability and insurance, and a lack of set operating procedures due to variations in data collection techniques. Technical concerns include the sheer volume of data collected with UAS and if the management agency can manage such vast amounts of information. Another technical concern is the limits on flight times due to battery capabilities. Overall, the authors believe the management concerns will be solved, and UAS will continue to develop into better tools for natural resource management.

River restoration is an area of management which involves LW, either its placement or monitoring. Marteau et al. (2017) examined how UAS-SfM could be used during this process, albeit for morphological change detection. The same concepts could apply to LW change

detection. The study was done on the Ben Gill in England, a first order stream with a watershed only 0.54 km². Restoration work on Ben Gill started in 2014 and reconnected the stream with its old course. Periodic UAS flights were done and the resulting DEMs derived from the SfM point clouds were compared to assess morphological change. The usefulness of the study to LW management is illustrated by repeated flights to study change, thus potentially allowing prediction of future change. Repeated flights surveying LW in fluvial environments could result in better understanding of the trends in LW volume, orientation, and location.

Woodget et al. (2017) began this literature review declaring UAS-SfM a bright new tool which could shift the paradigm of fluvial research from the RCC to a higher spatial resolution nested hierarchical structure. Much river management ignores the spatial heterogeneity inherent to and critical for fluvial ecology. The evolution of the technology and methods to make this happen has continued since then, and this study hopes to use them to take LW survey a step further. The authors state, "...an ideal approach for quantifying physical habitat parameters should also be practical, logistically feasible, cost effective as well as objective and repeatable." (Woodget et al., 2017, p. 3). The past practices for river habitats and LW survey, could, according to the authors, "...be subjective, scale-dependent, nontransferable, nonquantitative, inconsistent, and/or based on inference." (Woodget et al., 2017, p. 6). The progression of error quantification and expanding the use of UAS-SfM into new environments can help solve these problems.

Research gap

The development of better UAS-SfM technology allows for greater coverage of fluvial environments in a small temporal window with high spatial resolution. No previous research has

looked at using a UAS to quickly survey large reaches of river and use the SfM model to inform management decisions on LW removal. Wohl (2017) suggests more information is needed to predict the effects of LW in rivers of differing characteristics worldwide. I believe these predictions could be enhanced and management improved with the data provided by UAS-SfM.

CHAPTER 4

METHODS

Rusnák et al. (2018) created a template for mapping fluvial environments using UAS-SfM. The template delineates the process necessary to collect, process, and analyze data in six steps. The outline begins with step 0: understanding and complying with legislation and regulations governing flight in the study area; step 1: checking the area for dangers or limitations to UAS flight and plotting possible takeoff and landing areas; step 2: placing GCPs in appropriate areas; step 3: data collection flight; step 4: checking images and products created during data processing for quality; and step 5: data analysis. The six steps apply to this research and the following sections will elaborate on what was done during each of them.

Step 0: Legislation and regulation

Prior to flight, a remote pilot license for small UAS was obtained from the FAA after successful completion of the Aeronautical Knowledge Exam (Appendix G). The license permits the pilot to fly the UAS for a commercial or educational purpose. The airspace over the river corridor was checked for restrictions and any Notices to Airmen (NOTAMs) that may have been applicable via the B4UFLY app. The study area was found to be in Class G airspace and more than five miles from any airport, allowing flight up to 400 feet AGL without any permission from a control tower. Next, permission from the landowner of the Huron-Manistee National Forest, in this case the USDA Forest Service, was required. The permission letter is attached in Appendix H. The remote pilot license for small UAS, checking flight restrictions, and landowner permission were all obtained prior to any flight.

Step 1: Reconnaissance of the field site

One week prior to the data collection the study site was examined by two crew members. The reconnaissance was carried out via canoe and looked for UAS launch and retrieval areas. Areas were noted as practicable for launch and retrieval if they were 1) flat 2) clear of vegetation 3) had adequate line-of-sight for manual launch and retrieval. The crew members also noted any hazards to flight, such as electrical wires or unusually tall vegetation. Unique to this study, the navigability of the river was also noted, as less LW or other obstacles in the river reduced the chance of tipping the canoe with the data collection equipment inside.

Following the reconnaissance and consultation with Dr. Emerson and Mathews, the study reach was deemed practicable for manually piloted UAS flight. Manual flight control was chosen due to two factors. Limitations in the Pix4Dcapture application's flight planning options meant imagery at multiple viewing angles (oblique, near-nadir) along the sinuous river channel would be most efficiently gathered in manual flight mode. The first-person view of the camera allowed the RPIC to assure the images were being collected appropriately. The LOS requirement for flight operations also contributed to the decision for manual flight mode, as there was no way of knowing where LOS would end for the RPIC and VOs in the densely vegetated field conditions. A pre-planned flight path could easily carry the UAS beyond LOS.

Training of the VO's was done prior to the data collection flights. Training was brief and simple. The VO's were coached to watch for any obstructions the UAS could encounter such as power lines, trees, or other aircraft. The VO's were also told to keep the RPIC informed on their LOS to the UAS at all times.

Step 2: Pre-flight field work

The pre-flight field work was done on a flight by flight basis. Prior to a flight from a new launch and retrieval site, one of the crew members would set up a GCP station in a highly visible area free of overhanging vegetation. The four GCPs were set using two canoe paddles and a bright yellow dry bag with this location recorded via GPS (Figure 8). Four GCPs were set following this process and spaced through the study area. A somewhat linear placement of the GCPs could not be avoided due to the shape of the study area. The GCPs were placed at the beginning, middle, and end of the study area to increase georeferencing accuracy over the entire SfM point cloud.



Figure 8: Typical GCP

The Zenmuse X3 digital camera was not pre-calibrated, as the SfM algorithm could self-calibrate using the camera geometry during point cloud creation.

Step 3: Flight mission

Conditions

UAS-based collection of field imagery was performed on April 1, 2019. The imagery was collected during leaf-off conditions, as suggested by Ortega-Terol et al. (2014). The river discharge was 1400 ft³ per second, 400 ft³ per second greater than the 79-year average for April 1 (Figure 9):

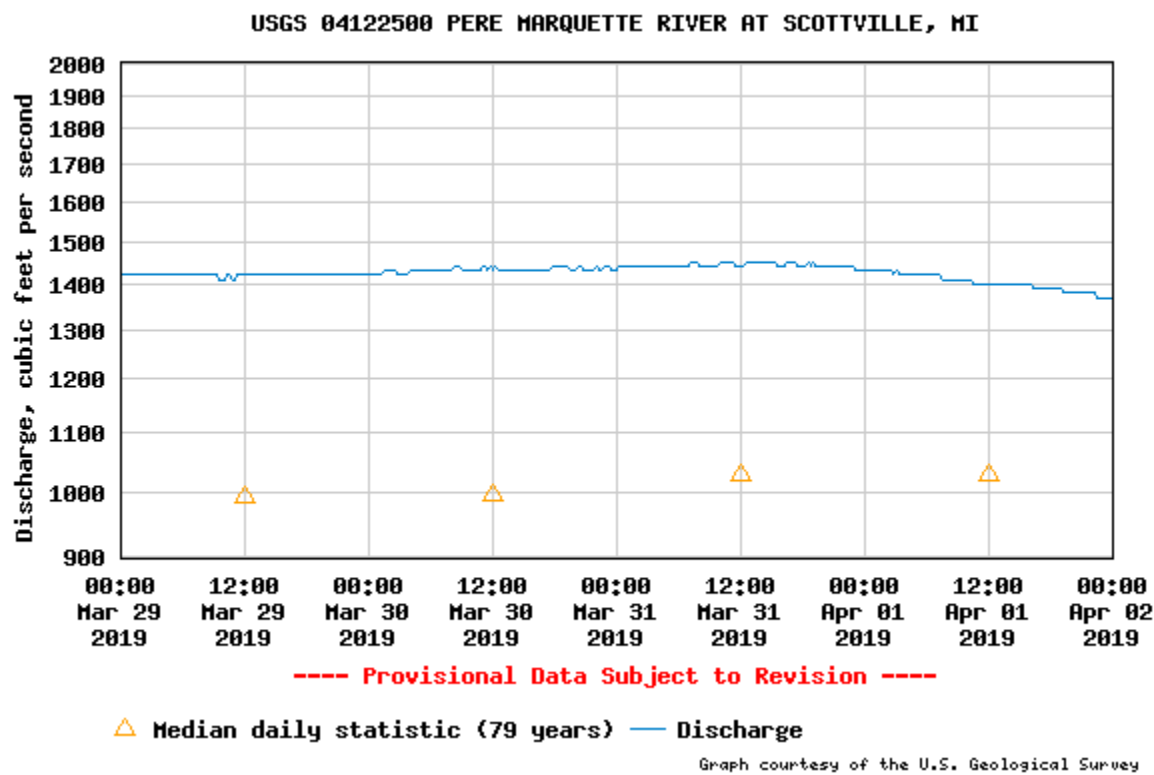


Figure 9: Flow data for Pere Marquette River for 5 days around field work

The conditions for UAS flight were cloudy, with visibility >3 mile and an approximate ceiling of 3,000 feet. Winds were steady from the southwest at 5 mph, with gusts to 10 mph. Air temperature was 42° F. Data collection was performed on this day due to the ideal lighting and wind conditions, with cloud cover reducing the risk of sun glint and shadows in the images, and low wind speed allowing better control during manual flight operations. However, the river was flowing above average with high turbidity, limiting the amount of water penetration possible in the images (Dietrich, 2016).

Materials

A combination of high and low-tech equipment was used to gather the data on the PM. The equipment and how it was used is illustrated in (Table 2).

Data collection

The data was collected by a DJI Inspire 1 equipped with navigational GPS and a Zenmuse X3 camera mounted on a 360° gimbal. The flight crew was one remote pilot in command (RPIC) and two visual observers (VOs). The UAS was within line-of-sight (LOS) of at least one of the VOs or the RPIC at all times. There were eight flights, due to the limitations imposed by battery life and line-of-sight requirements. Images with high amounts of overlap and varying view angles were needed for effective camera self-calibration and SfM point cloud precision; this was reflected in the flight paths, camera angles, and image frequency.

Table 2

Equipment and uses for Pere Marquette River field data collection

Equipment	Use
DJI Inspire 1 Quadcopter with 4 batteries	Carry camera in flight
Zenmuse X3 Digital Camera with 360° gimbal	Collect images
Sandisk 32gb microSD card	Store images
Pix4Dcapture	Flight and UAS monitoring
Canoe	Transport to and from flight areas
Canoe paddles and yellow dry bag	Create a highly visible GCP
GPS	Obtain GCP coordinates for georeferencing
ArcShell two-way radio	Communication between RPIC and VOs

The Pix4Dcapture application was used to set the frequency of image capture. An image was captured for every 9 feet of forward motion and 12 feet of horizontal motion to ensure high amounts of image overlap. The flight heights for the UAS ranged from 160- 180 feet AGL. The Zenmuse X3 camera had a sensor width of 6.17 mm, a focal length of 4 mm, and a pixel width and height of 4000x3000. These image attributes correspond to a GSD of around 2.75 cm/pixel, well below the maximum of 5 cm recommended by Ruiz-Villanueva et al. (2016).

The application provided a first-person view of the images being captured during flight as well as monitoring altitude, speed, and battery life. The flights were piloted manually due to the complex nature of the fluvial environment. Each flight was carried out in four segments, two flying away (down) from the RPIC and two flying towards (up) the RPIC. The down and up legs alternated between oblique and near-nadir viewing angles. Each launch and retrieval site was

used to conduct a flight upstream and a subsequent flight downstream. The VOs remained in contact with the RPIC via handheld two-way radios to report on LOS.

Data collection began at 1240 hours and concluded at 1500 hours, for a total time of 2 hours and 20 minutes. The four batteries provided enough flight time to image 2.41 miles of river.

Step 4: Data processing

Materials

The equipment for data processing and analysis and the use of each item is listed in Table 3.

Table 3

Equipment and uses for data processing and analysis

Equipment	Use
Intel Core i7-6700 CPU @ 3.40 GHz 32.0GB RAM 64-bit Windows 10 OS	Process data
Sandisk Extreme 1TB External hard drive	Store Images and Data Products
Pix4Dmapper V4.3.333	Generate SfM point cloud, orthomosaic, and DTM
ArcGIS10.6	Classify and analyze data products from Pix4Dmapper

1295 total images were collected during field work. The data was transferred from the 32GB microSD in the camera to the computer for processing. The data was manually checked for blur, images of the launching and retrieval sites, and other images deemed unsuitable for

photogrammetry, as suggested by Jensen and Mathews (2016). 46 images were rejected for these reasons, leaving 1249 for processing. The EXIF (exchangeable image file) data attached to each image loaded into Pix4Dmapper includes the pixel resolution and image bands as well as the camera parameters such as shutter speed, ISO, focal length, and data from the UAS GPS on the coordinates where each picture was taken. The next step of data processing utilized all of this information.

The remaining images were then loaded onto the Sandisk Extreme 1TB external hard drive, with all subsequent data products also saved to this disk. The SfM process began by loading the images into Pix4Dmapper, a black-box SfM-MVS program. The nature of a black-box program does not allow the user to know the exact algorithms used to create the data products, but some form of SIFT to generate and match keypoints, bundle adjustments to self-calibrate the cameras and reconstruct their positions, MVS to densify the point cloud, and georeferencing to give the image scale combine to create the sparse and dense point clouds, the 3D mesh, and their derivatives: the orthomosaic and DSM. The densified 3D point cloud was created for visualizing the location of possibly hazardous LW in 3D space, while the orthomosaics and DSM were used to develop a classification system to quickly identify LW over large study areas.

The initial dense point cloud created using all 1249 images was inspected visually. The point cloud was extremely “noisy” with many points clearly not representing actual vegetation or terrain features. The noise resulted from sky views in images, oblique images through the streamside vegetation, or problems viewing through water (Figure 10) The noise was reduced using two different methods. The first method involved removing oblique images from the

dataset where the nadir imagery overlap was sufficient for point cloud generation. This process reduced the images used during the SfM process and visual inspection revealed a marked decrease in noise. The second method was applied to both the original and majority nadir imagery sets. A defined processing area for point cloud generation was created, closely following the river channel horizontally and restricting the elevation from just above the highest trees and just below the lowest water surface. Combining the processing area with the majority nadir imagery resulted in a much cleaner point cloud (Figure 11).

Once these data products were created, Pix4Dmapper generated a quality report (Appendix I). The quality report details camera calibration, bundle adjustments, geolocation, and point cloud densification processes and quantifies their accuracy. After the quality report was reviewed and approved, the researcher exported the data products to ArcMap10.6 for further

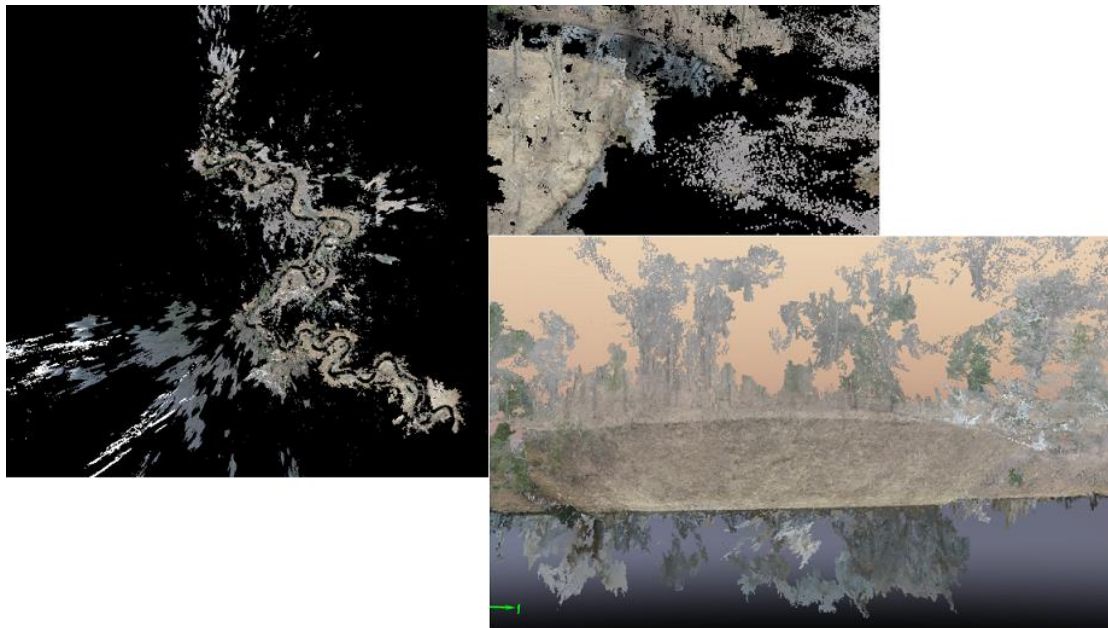


Figure 10: Examples of noise in the dense point cloud created using all images and no processing area.

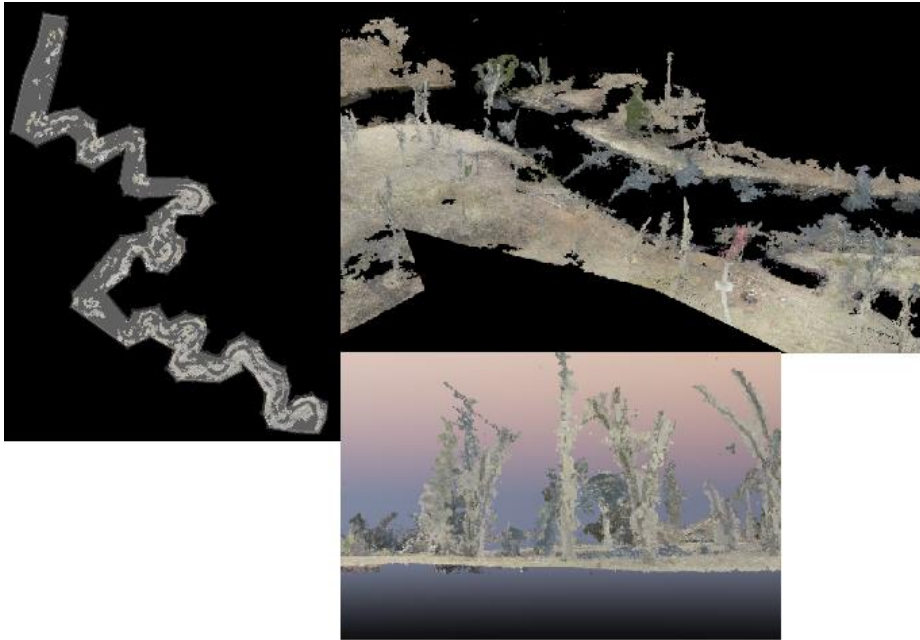


Figure 11: Examples of noise reduction following use of processing area and nadir-majority imagery.

analysis. The final orthomosaics exported from Pix4Dmapper was created using the majority nadir imagery set and a restricted processing area.

The LW jam data from Riley (2010) included a shapefile with point locations of LW accumulations. An Excel spreadsheet provided further information on where the accumulation was in relation to the stream bank, bend orientation, if there was an attached rootwad, and the diameter of the largest piece in the accumulation. The ArcGIS data was reprojected from NAD 1983 to WGS 1984 to match the data from the SfM process. The data from the Excel spreadsheet was added to individual points in the attribute table to facilitate further comparison with the data from 2019.

Step 5: Analysis of data products

Segment mean shift and supervised classification

The orthomosaic and point cloud were exported to ArcMap 10.6 as a raster TIF and three separate LAS datasets, respectively. The point cloud LAS contained elevation data. The LAS was mosaicked to a new raster containing this elevation data. The elevation raster was created in two versions, one a DSM with interpolation between LAS points and another elevation raster with no interpolation between points. The uninterpolated elevation raster was then given a false bottom to fill in the areas of no data. The relative merits of these rasters will be discussed in the results section. The elevation raster and the RGB orthomosaics raster were then combined using the Composite Band tool to create a 4-band orthomosaic. An Object Based Image Analysis tool called Segment Mean Shift (SMS) was then used in ArcGIS Pro on the composite band orthomosaic to group pixels into objects based on their spectral and spatial qualities. Although elevation was a spatial feature in the LAS, the nature of the SMS and the composite band tools resulted in it being considered a spectral characteristic, leaving only horizontal plane as a spatial determinant.

The SMS was done using multiple different parameters and band combinations. The tool parameters of spectral detail, spatial detail, and minimum segment size were modified until an ideal segmentation of LW was achieved. Higher spectral detail separates objects with more similar spectral characteristics, while higher spatial detail brings out small, or densely packed objects. Minimum segment size determines how many pixels were necessary to create each separate object, with a higher value resulting in a smoother appearance. The SMS could only consider three bands of the orthomosaic at a time. The original RGB orthomosaic was run first

using different parameters, the best results coming when spectral detail was 18, spatial detail 16, and minimum segment size 100.

The orthomosaics with the elevation band from the DSM or the non-interpolated raster added were most successful using the same SMS parameters. However, both of these SMS results were not useful for further analysis. The DSM band was hampered by the higher elevation of trees causing large areas of the river to appear elevated due to the interpolation. This caused any variation in the red or green bands to be overwhelmed by the false higher elevation (blue) band value. LW in these areas was unable to be segmented. The non-interpolated elevation raster caused issues with identifying LW as well. The LAS dataset did not have points for all the pieces of LW. These areas were then considered No Data. The false bottom was added to the raster to fill in the areas of No Data, which resulted in these pieces of LW having a consistent elevation (blue) band value with the surrounding water or ground pixels which had also originally been No Data areas. This caused the SMS to group LW more commonly with its surrounding areas than as a discrete object.

The RGB-only orthomosaic was used for the next step in the analysis, which involved 1) supervised classification using Support Vector Machine (SVM) 2) manual attribute queries of the SMS results. Prior to using SVM training sites were selected following six classes: Water, Ground, Conifers, Shadow, Overhanging Trees, and LW. The training sites were selected carefully to only cover pixels of the selected class (Figure 12). Once the training samples were collected, they were used in the SVM process to train the classification.

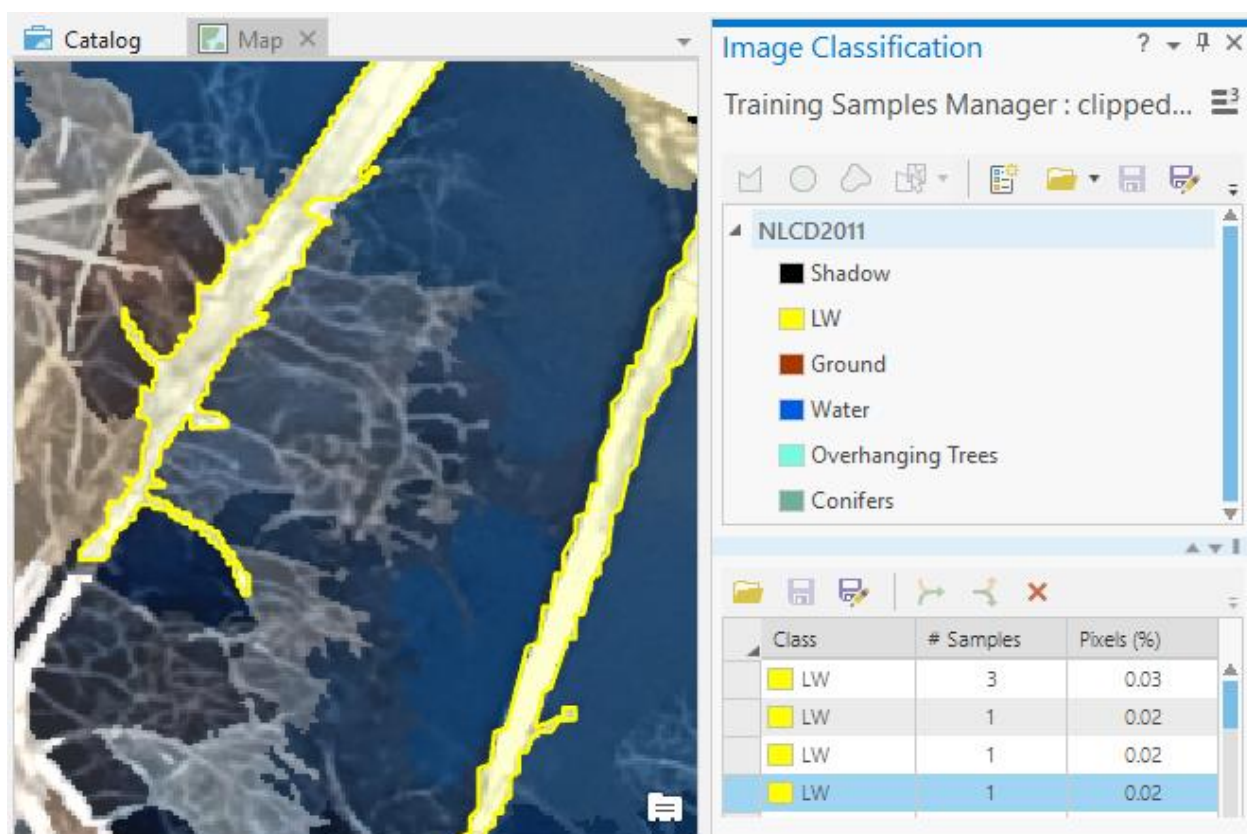


Figure 12: Example of training sample selection

SVM was used because of its ability to handle large images because the orthomosaic was 17.97 GB. SVM was also able to handle the wide variety of training area sizes in the classes. The LW training sites were very small compared to the rest of the classes, especially Water and Overhanging Trees. Following the SVM process, the classified orthomosaic was inspected and deemed acceptable to undergo Accuracy Assessment using a confusion matrix.

Prior to running the confusion matrix, accuracy assessment (AA) points were created. 360 AA points were seeded in an equalized stratified random distribution. An equal number of AA points were seeded in each of the 6 classes. This distribution was used to ensure adequate AA points in each class, although some classes occupied a much larger area. The AA points

were then manually ground-truthed using the RGB orthomosaic. Once the points were ground-truthed, they were input to the Compute Confusion Matrix tool in ArcMap10.6.

The confusion matrix results in a producer's error, a user's error, an overall accuracy, and a Kappa index of agreement. The producer's error is an error of omission, or a false negative. In this study, if a pixel of LW was classified as Overhanging Tree, it was an error of omission for the LW. The user's error is a false positive, or error of commission. The previous example would be an error of commission for the Overhanging Tree. These statistics allow a researcher to understand how accurate different classes are and if two classes are often confused with one another.

Segment mean shift and manual attribute query

The manual attribute queries were done in ArcMap 10.6. The SMS raster was converted to polygons. The polygons were given points using the Feature to Point tool, and then the values from the original SMS raster were added to the points using the Extract Multi Values to Points tool. The RGB data for each segment of the SMS was now associated with a point. The attribute table of the point data was then joined to the SMS polygons.

The geometry of the polygons was used to create new fields to help select the LW. The area and perimeter were calculated using Calculate Geometry in the attribute table. The Minimum Bounding Rectangle tool was used to get the maximum length and width of each polygon. Compactness and Elongation were derived from these four sources. Compactness was found using the Polsby-Popper formula: $(4\pi * \text{area}) / \text{perimeter}^2$. This measures how close a shape is to a circle, with one meaning complete compactness and zero meaning no compactness.

Elongation was measured with the formula: maximum width / maximum length. The closer the ratio is to zero the more elongated the shape, with one being approximately a square or circle.

The RGB fields, area, perimeter, max width, max length, elongation, and compactness were all used to select the SMS polygons by attributes. The variety of shapes and spectral qualities in the SMS polygons were difficult to account for. The use of manual selection by attributes was discontinued, and the analysis proceeded using the results of the SVM classification once the confusion matrix proved them acceptable.

Beyond the supervised classification and the manual attribute queries, the orthomosaics was used to manually identify the LW in the study reach. Each piece of LW was outlined with the Draw tool and these graphics then converted to polygons. The location and two-dimensional area of each polygon was then calculated. This data was also compared with the data on LW jams in 2010 provided by Chris Riley.

The data provided by Chris Riley of the USFS included information on the diameter of the largest log in the jam, and if a rootwad was attached (Table 4). These attributes were used to score the jams on an ordinal point scale. The three size intervals were scored from 10 (smallest) to 30 (largest). If a jam had a rootwad attached it received 9 points. The scores result in an approximation of overall jam size, due to the lack of any other size measurements in the Riley data. Larger logs and logs with rootwads tend to be more stable (Abbe and Montgomery 2003). Thus, the expectation would be for more wood accumulation to occur in jams with larger key members and rootwads attached, leading to a greater surface area for those jams. The scores were used as a way to generally compare the 2010 Riley data to the 2019 data gathered in this

study. The score of each jam and its location are shown in (Figure 13). The location of these jams relative to the jams found in 2019 will be discussed in the results section.

Table 4

LW jam data from Chris Riley, 2010

Number	Bank	orientation	Rootwad	Easting	Northing	< 24"	24-36"	> 36"
7	DL	NB	1	583,544.15	4,861,182.92		1	
8	DR	O	1	583,417.56	4,861,427.86		1	
9	DL	OD		583,326.99	4,861,339.35	1		
10	DL	NB	1	583,215.84	4,861,419.62		1	
11	DL	I	1	583,254.04	4,861,477.10	1		
12	DL	NB	1	583,147.36	4,861,462.09	1		
13	DL	I	1	583,116.65	4,861,513.04	1		
14	DL	NB	1	583,076.86	4,861,498.39	1		
15	DL	NB	1	582,884.20	4,861,613.56	1		
16	DL	NB	1	583,096.40	4,861,762.24	1		
17	DR	O	1	583,161.32	4,861,698.72	1		
18	DR	OD	1	583,175.28	4,861,776.20	1		
19	DR	NB	1	583,175.28	4,861,783.18	1		
20	DR	NB	1	583,185.05	4,861,869.04	1		
21	DL	NB	1	583,201.80	4,861,900.45	1		
22	DL	NB	1	583,215.07	4,861,906.03	1		
23	DL	NB		583,035.67	4,862,035.17	1		
24	DL	OD	1	582,888.39	4,862,116.84	1		
25	DL	NB	1	582,739.01	4,862,370.92		1	
26	DL	NB	1	582,771.82	4,862,437.93		1	

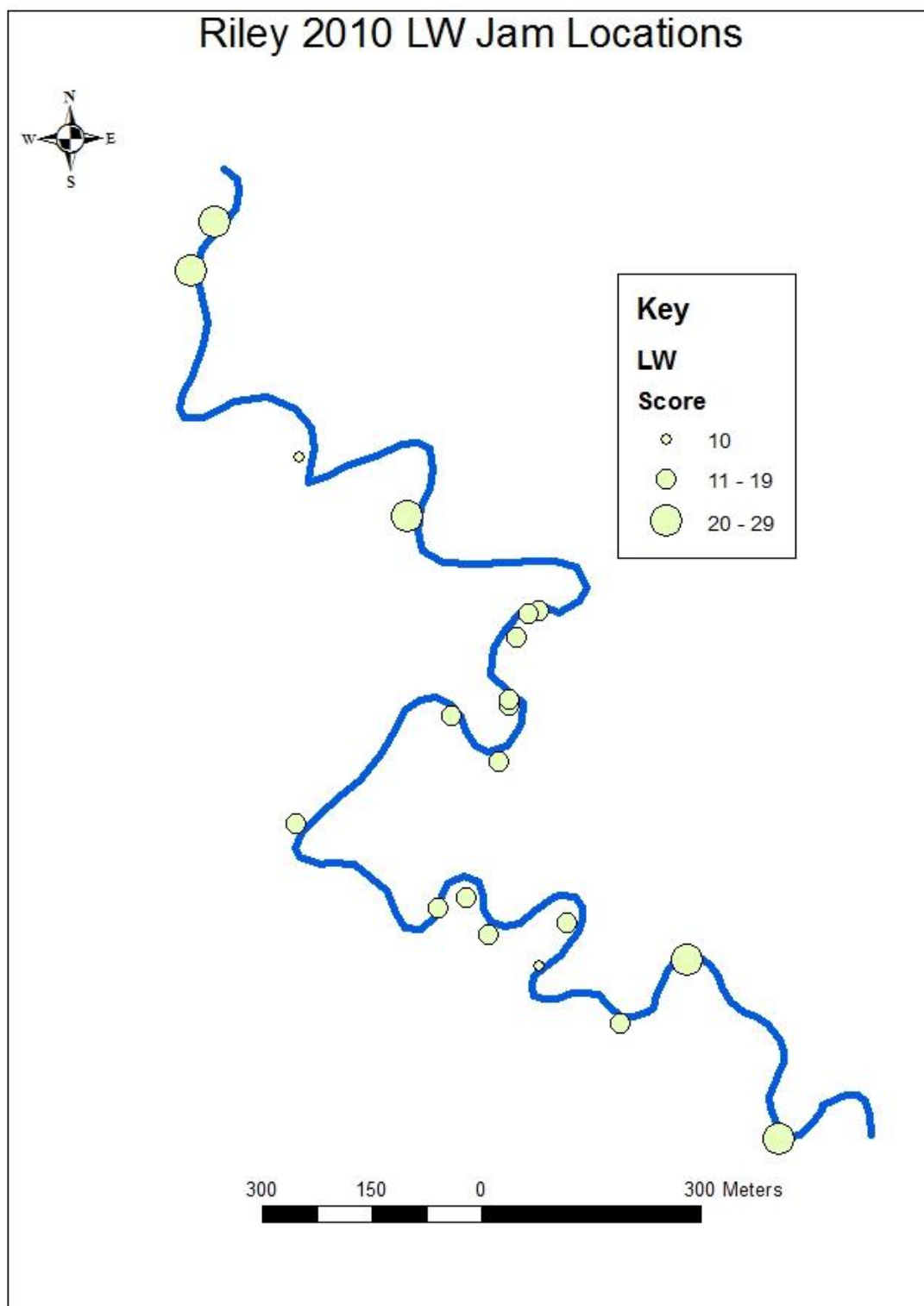


Figure 13: Location and score of LW jams from Chris Riley, 2010.

CHAPTER 5

RESULTS AND DISCUSSION

Results

Point cloud and orthomosaics assessment

The SfM process produced both a point cloud and an orthomosaic. Pix4D produced a quality report detailing the camera calibration, bundle block adjustment, geolocation variance, and processing options used (Appendix I). The GSD of the orthomosaic was 2.34 cm/pixel, rendering the GPS used for GCP locations moot. The error in the GPS locations was larger than the GSD and would increase error in the final products (Deitrich, 2016; Mesas-Carrascosa et al., 2016). The geolocational accuracy was still sufficient for the purpose of the study, as the mean camera position uncertainty was twice the GSD and the mean camera orientation uncertainty was less than 0.1. The relative geolocation variance was also acceptable, as all images were within the 5 meter horizontal and 10 meter vertical stated GPS accuracy.

The quality report produced an image showing the amount of overlapping images for the study area (Figure 14). The low level of overlapping images in two areas were the cause of some orthomosaic errors. The areas in Figure 14 colored green indicate where a pixel of the orthomosaic was visible in 5+ images. The overlap was better when using all the images gathered, including obliques, but the artifacts generated in the orthomosaic and point cloud made the oblique images problematic to include.

Orthomosaic errors also occurred due to relief displacement. Relief displacement occurs in nadir imagery when the image is not taken directly above a feature, causing it to appear to lean. The camera track for image collection was not perfectly aligned over the river course, causing relief displacement in some parts of the orthomosaics (Figure 15).

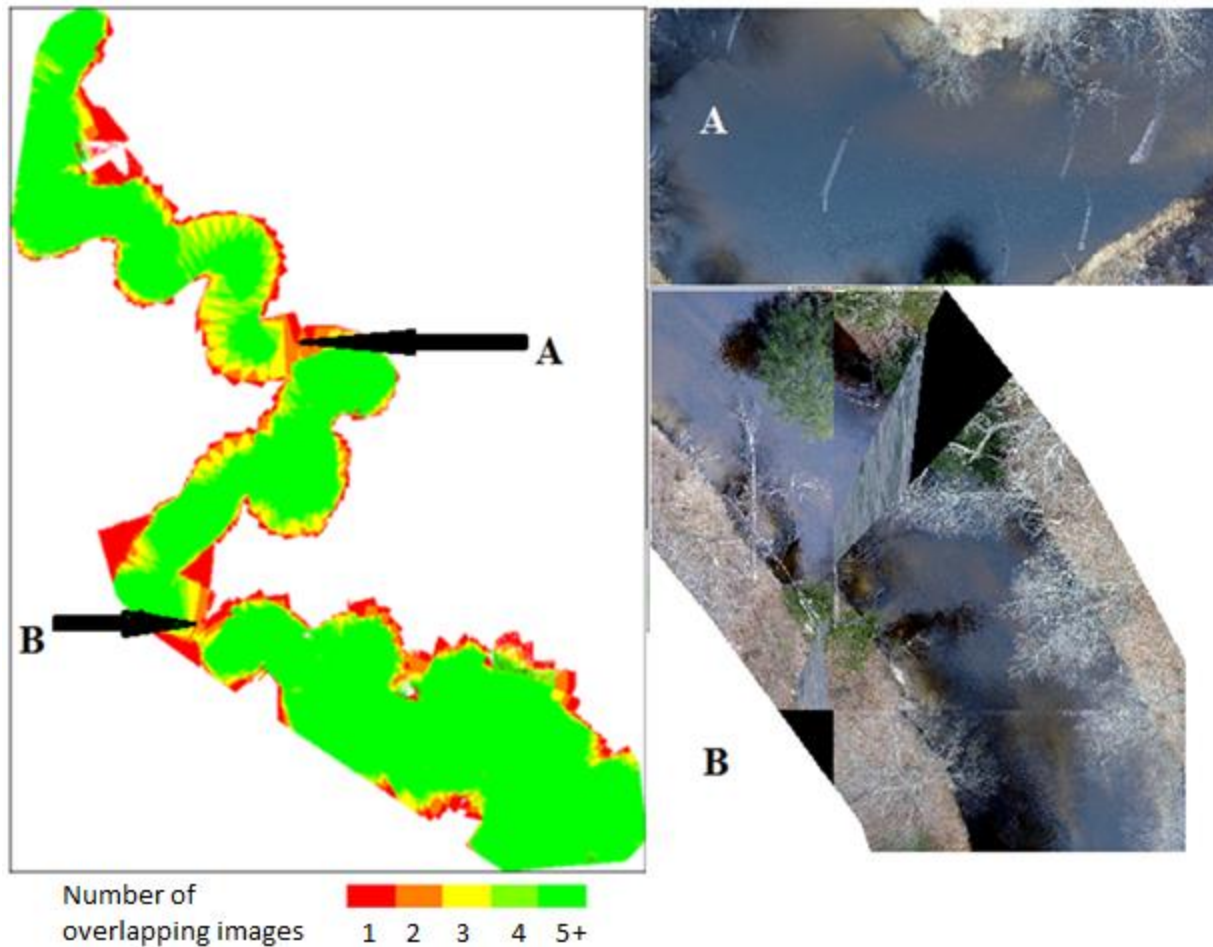


Figure 14: Overlapping images and examples of orthomosaic errors resulting from low overlap.

When manually identifying the LW, clues such as ripples in the water behind a tree helped to separate LW and trees that only appeared to be in the river (Figure 16). When this failed, the point cloud was consulted and the true angle of the tree to the water was found.

The point cloud, and subsequently, the elevation data derived from it were degraded by the inability of the camera to see river bottom in deep areas, reflections, and obscuring vegetation. Some parts of the study area were not covered by the point cloud, or appeared inverted due to these issues (Figure 17).



Figure 15: Examples of relief displacement. A) point cloud showing true verticality B) nadir image showing relief displacement C) oblique image showing true verticality D) orthomosaic showing relief displacement.

The areas of the river with no elevation data due to these issues and areas with overhanging vegetation obscuring the LW led to problems using the 3D nature of the SfM derived products to assist in LW identification. Some pieces of LW had no point data, while other pieces of LW were close to upright, living trees, which caused false elevation readings. An interpolated DSM and a non-interpolated rasterized point cloud were both added to the RGB



Figure 16: Example of riffle water downstream of LW.

orthomosaic as a 4th band for SMS. The DSM was ineffective due to the interpolation of tree elevations over areas of no data, while the rasterized point cloud was ineffective because of the false bottom's consistent value. The interpolation of the DSM obscured the small elevation changes necessary to pull out LW just above the water surface. The false bottom of the rasterized point cloud was a consistent value, causing the SMS to group pieces of LW with neighboring areas which shared the false bottom, whether they were ground, water, or overhanging trees in the RGB-only imagery. In both cases, the DSM and rasterized point cloud were rendered useless by areas lacking point data (Figure 18).

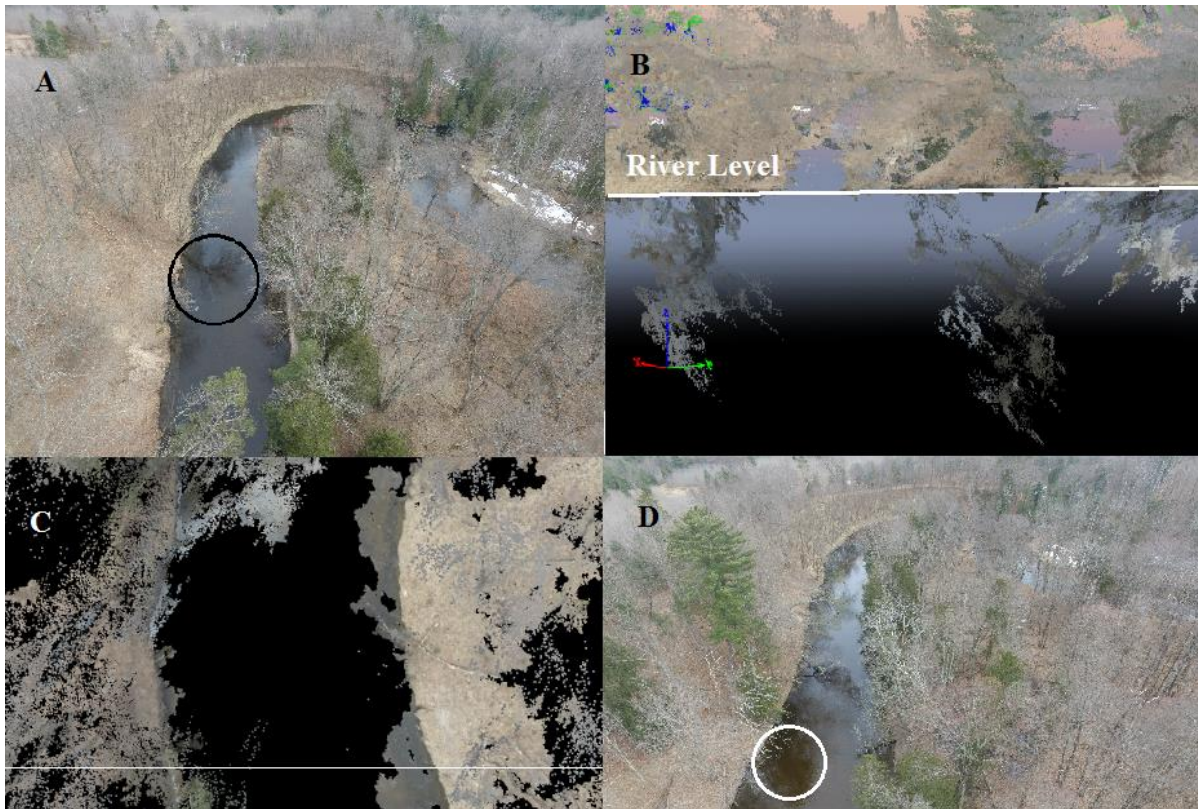


Figure 17: Examples of reflections and deep water compromising the point cloud. A) reflection and deep water B) inverted point cloud resulting from reflection, C) no points in river channel due to deep water, D) reflection and deep water.

LW identification and classification

Manual identification of LW using the RGB-only orthomosaic found 227 individual pieces and 26 jams in the study area. The total area of LW was 511.1m^2 , with 316.1m^2 occurring in the jams. The largest individual piece was 9.3m^2 and the largest jam was 33.1m^2 . The jams were classified by type using the classes found in Abbe and Montgomery (2003), with five types (bank input, flow deflection, bar apex, meander, and unstable) represented and located in Figure 19. The most common class was flow deflection (11) and least bar apex (1). The overall area of

each jam type is shown in Figure 20. The sizes of individual jams according to type are shown in Figure 21.

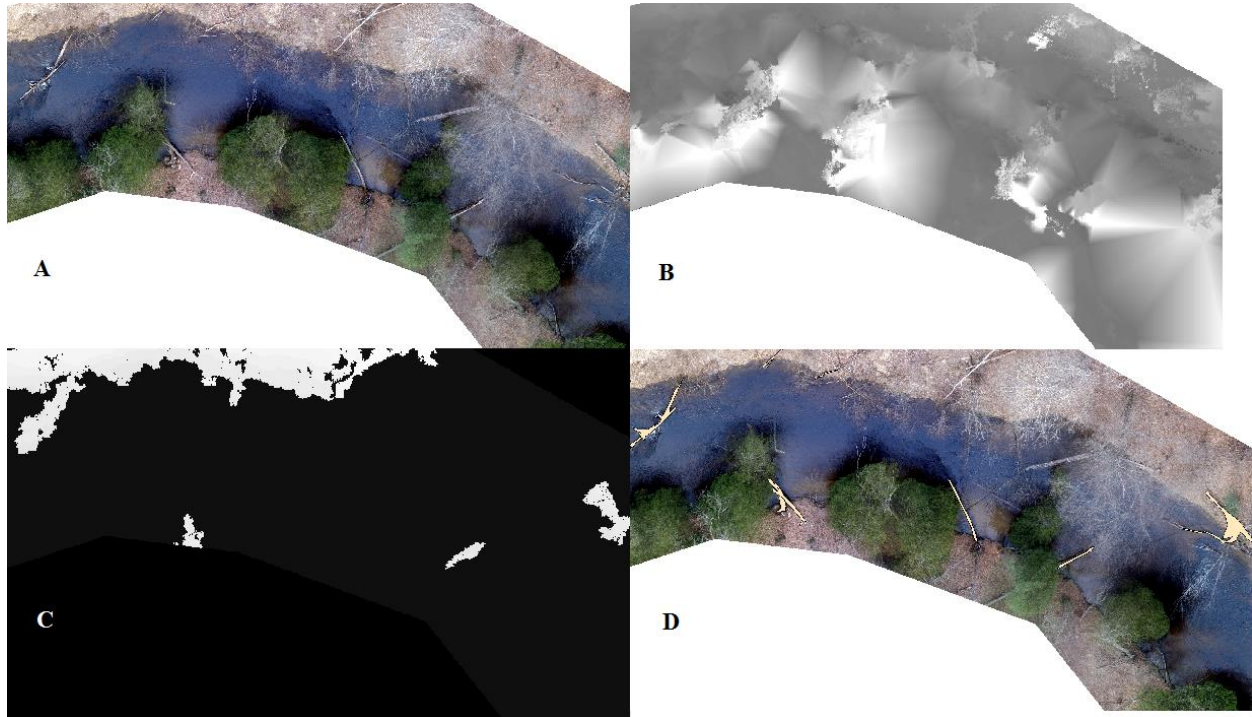


Figure 18: Examples of problems with elevation bands for identifying LW. A) RGB orthomosaic, B) interpolated DSM, C) non-interpolated point cloud, D) manually identified LW.

The Support Vector Machine classification of the six land classes identified in the orthomosaic was checked with 360 accuracy assessment points. A confusion matrix run on the classified and ground-truthed points resulted in overall accuracy comparable to Rusnak et al. (2018) and slightly lower than Casado et al. (2015) for similar studies looking at fluvial features (Table 5). The overall accuracy of 0.675 was lower than both Rusnak (0.815) and Casado (0.81), however this was affected by the focus on identifying LW. LW was identified with 0.816 producer's accuracy and 0.67 user's accuracy. Casado et al. did not specifically look for LW, but overall vegetation accuracy was 0.81. Rusnak et al. included LW as a class and had a true

positive (producer's) accuracy rate of only 0.177%. The kappa index of 0.61 for the current study was on the low end of substantial agreement but high accuracy of LW identification was the goal, not an overall landscape classification.

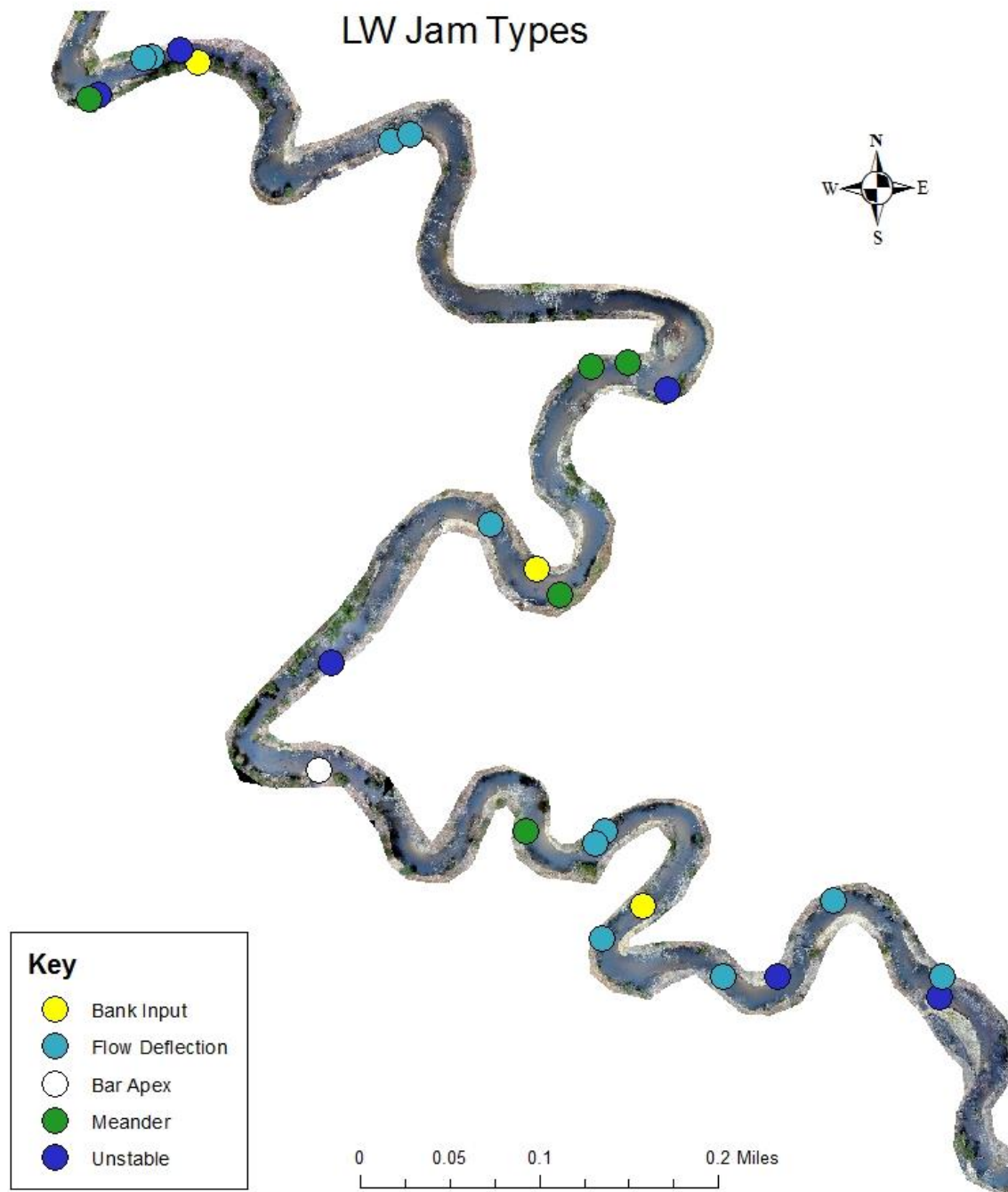


Figure 19: LW jam types and location within study area.

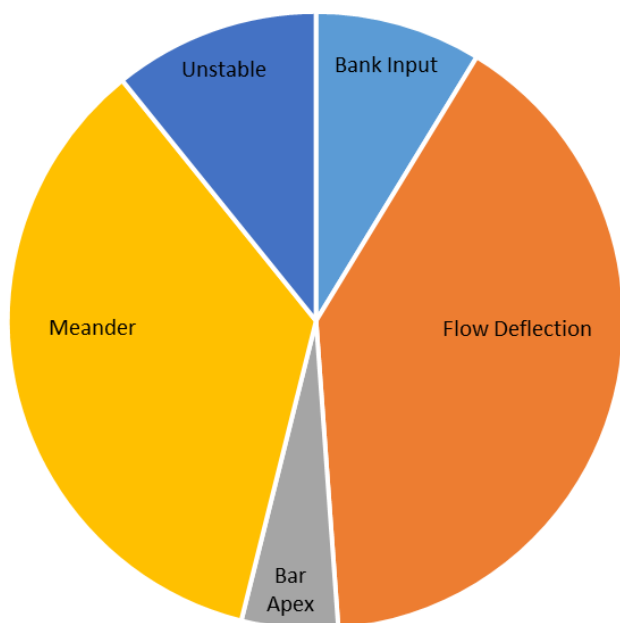


Figure 20: Relative area of different jam types.

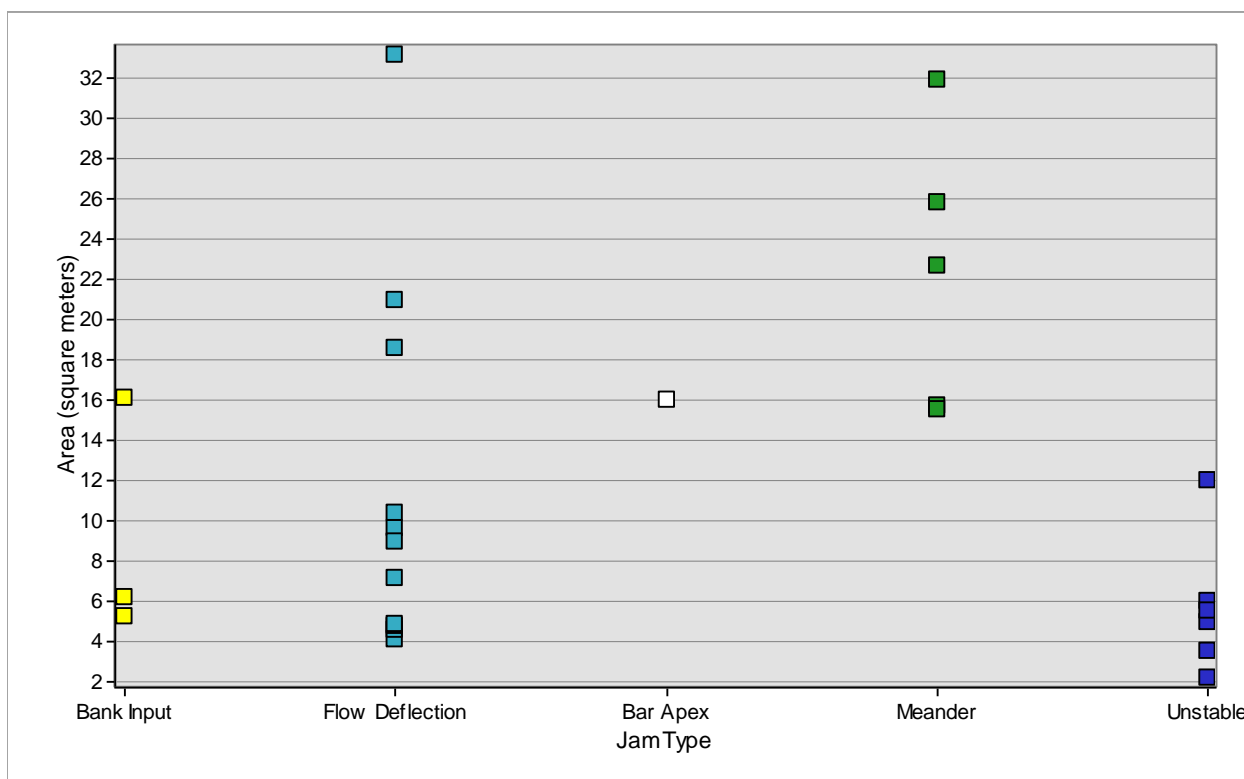


Figure 21: Individual LW jam type and area (m²)

Table 5

Confusion matrix for SVM classified RGB orthomosaic

ClassValue	Water	Shadow	Ground	OH Trees	Conifers	LW	Total	U_Accuracy	Kappa
Water	59	0	0	1	0	0	60	0.983333	0
Shadow	15	33	0	4	8	0	60	0.55	0
Ground	10	0	34	9	3	4	60	0.566667	0
OH Trees	2	0	0	54	0	4	60	0.9	0
Conifers	6	0	2	28	23	1	60	0.383333	0
LW	0	0	11	9	0	40	60	0.666667	0
Total	92	33	47	105	34	49	360	0	0
P_Accuracy	0.641304	1	0.723404	0.514286	0.676471	0.816327	0	0.675	0
Kappa	0	0	0	0	0	0	0	0	0.61

2010 to 2019 LW jam comparison

The 2010 LW jams were scored according to the diameter of the largest log and if there was an attached rootwad. The 2019 LW jams were scored based on area (m²). The comparison was not perfect, but in general, larger logs are more stable and result in larger jams (Abbe & Montgomery, 2003). The distribution of the jams from 2010 and 2019 are plotted in Figure 22. No jams remained in the exact location from 2010, however, the overall trend of the jams was similar between the two years.

The sinuosity of the river channel was measured using the Sinuosity plug-in on ArcMap10.6. The sinuosity measures how far the river deviates from a straight line and was measured in 250-meter segments. A sinuosity value of 1 is a straight line with lower numbers indicating higher sinuosity. Sinuosity was used as a proxy for flow velocity. In both 2010 and 2019, the LW jams were more common in areas with higher sinuosity.

LW Jam Distribution 2010 vs 2019

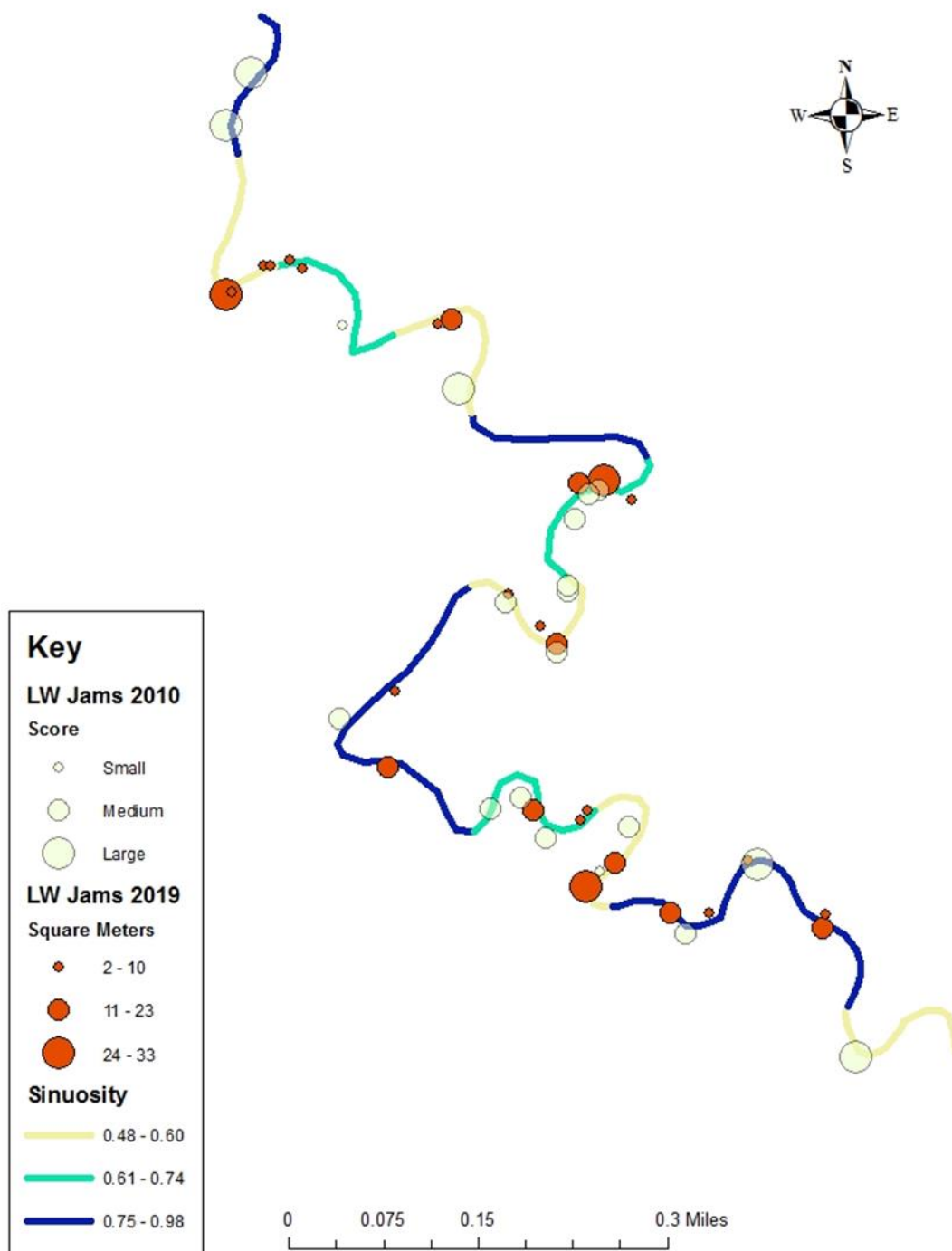


Figure 22: River sinuosity in 250-meter segments, LW jam location and score or area in 2010 and 2019

LW hazard to recreational users

The orthomosaic and point cloud were used to evaluate the hazard of LW pieces to river users. The quick assessment was done following the guidelines of the Michigan Natural River and National Scenic River Acts, where an eight foot gap can be cleared to allow for safe navigation. The initial assessment found four pieces of LW which could be trimmed under these ordinances (Figure 23). These pieces all extend across all or most of the channel and leave less than an eight foot gap for navigation and are identifiable using only the orthomosaic.

Investigation of other pieces or jams of LW as hazards involved using the point cloud to evaluate potential visibility issues during a video animation tour of the river. The video animation moved at 4 meters per second, which is about the maximum speed a recreational user would travel down the river. The video animation allows the hazard of obstacles to be assessed in approximately the amount of time a river user would have, especially as the user travels around bends in the stream. The video animation can be found at <https://youtu.be/PNJtjqrXyA4>. The quality of the point cloud was not high enough to critically examine LW for overhead clearance hazard or snagging and strainer potential, especially without a river surface in the point cloud (Figure 24).



Figure 23: Possible areas for LW trimming found in orthomosaics

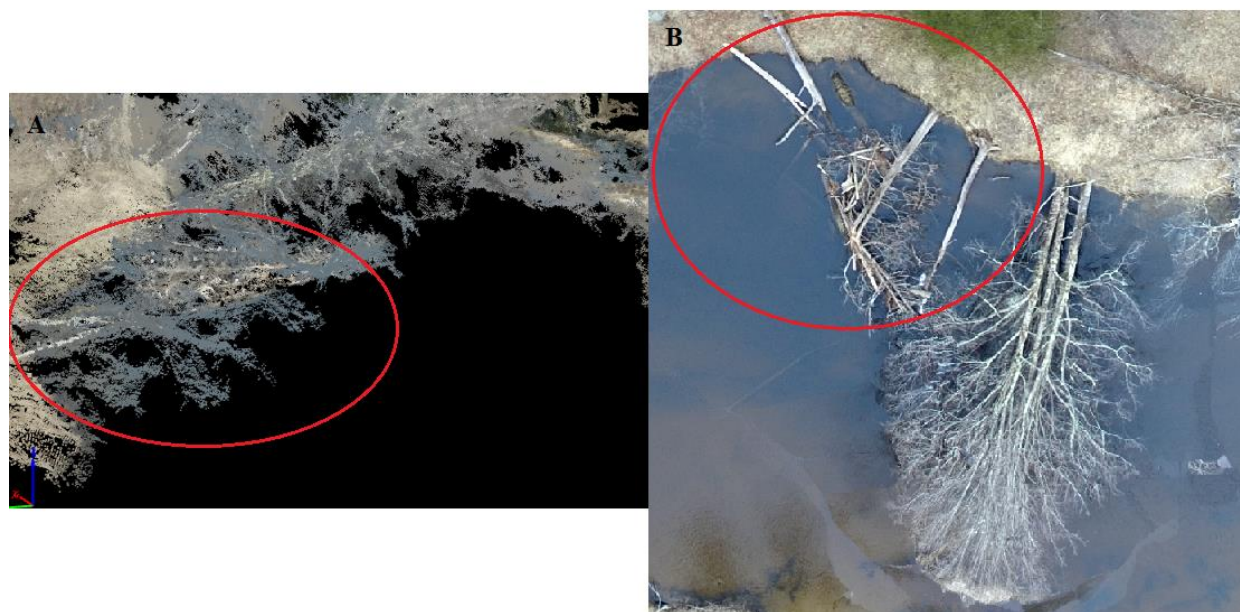


Figure 24: Example of point cloud and orthomosaic unable to discern snagging or strainer potential of LW jam A) point cloud, B) orthomosaic.

Strengths

Data collection

The first three strengths of this study relate to the paradigm presented by Woodget et al. (2017) of the river as a nested hierarchical structure as opposed to a smoothly changing continuum. Gathering the data using a UAV with a high resolution digital camera allows a researcher to obtain detailed information about large amounts of space in a much shorter time. The image resolution of 2.34 cm / pixel is more than adequate to identify LW as defined by Murphy (1989): 10cm diameter by 1m length. 2.41 miles of river were covered in 6.99 man-hours, a rate of 0.34 miles per hour, with 227 individual pieces of LW subsequently identified and geolocated, a rate of 32 pieces per hour. Compare this to the estimate of Máčka et al. (2011) of traditional LW surveying covering 1.7 miles and identifying an average of 580 pieces of LW in a range from 66.24 to 116 man-hours. The rates for the traditional methods are 0.01- 0.03 river miles per hour and 5.0 – 8.8 pieces per hour. The methods used in this study are up to 34 times faster than traditional LW surveying. The speed of this method also included placing and recording four GCP's, which did not get used in the final data products, meaning the process could be even quicker.

The three elements above: image resolution, efficiency of image collection, and no need for GCP's combine to greatly expand the amount of detailed data a researcher can gather on a river in a short amount of time. The increased efficiency allows a more thorough analysis of larger sections of river, enhancing the researcher's understanding of the river as a nested hierarchical structure. If a researcher using this method was given the same number of man-hours as the traditional LW surveys referenced by Máčka et al. (2011), 22.5 – 39.4 miles of river

could be completely surveyed. In the context of this study, the entire 66.4 mile main branch of the Pere Marquette River could be completely imaged by a crew of three in 8.1 8-hour work days.

The Pix4Dcapture app made setting the image collection parameters simple. The app allows the user to set when images are captured, either by time or distance traveled. To ensure sufficient overlap between consecutive images, the app was set to collect images every 9 feet of forward motion and 12 feet of horizontal motion. The combination of the Pix4Dcapture app and the DJI Inspire 1 UAS system also gave the RPIC a first-person view of the camera during flight operations. This was useful for maintaining alignment with the river course during the free flight manually piloted image collection. Each image was given an EXIF file with the image parameters and geolocation, which increased accuracy in the next step, data processing.

Data products

The data products (orthomosaic, point cloud, DSM) derived from the images collected during this study were created by Pix4D in 7.02 hours. The processing time for the data products was completely hands-off, the researcher only inputting the processing options to start. The entire process then ran automatically, freeing the researcher for other tasks.

The use of the high resolution orthomosaic for LW classification was highly successful, with a true positive accuracy of 81% and a true negative accuracy of 67%. Marcus et al. (2002) used RGB-NIR satellite imagery with a 1 meter resolution for a supervised classification and only achieved 17% and 45% true positive and negative accuracy. The increased spatial

resolution in the current study may have contributed to this increase in classification performance.

The spatial resolution was high enough to detect disturbances in the water from the current flowing around branches, which helped discern between true LW or upright trees which appeared to be LW due to relief displacement. The point cloud added to the effectiveness of manual LW identification by allowing the researcher to identify areas of relief displacement in the orthomosaic.

River research, education, and safety

Data collection speed, extent, and resolution were all increased compared to traditional methods with a fourth factor also improving: researcher safety. Increased safety for researchers was a driving factor for Jones, Pearlstine, and Percival (2006) to reduce dangerous manned flight practices by developing UAS data collection. Máčka et al. (2011) believed traditional LW survey techniques were dangerous, especially in deep or fast water. The polygons used to manually identify LW in ArcMap10.6 allowed the researcher to measure the surface area of jams and individual pieces of LW in the lab. The measurement of surface area by traditional methods could be dangerous or impractical for certain pieces of LW. Measuring the LW orientation to flow was another advantage for this method. The researcher need not physically measure the angle when the orientation is clear and can be measured using the angle of the polygon to the river line in the lab. Increased safety for researchers using UAS in fluvial environments is an advantage of this study.

The imagery and data products used in this study may also be useful for studying research questions other than recreational hazard and trout habitat. Obtaining the imagery during

leaf-on conditions would enable researchers to identify potential areas for LW recruitment (i.e. standing dead or dying trees, species susceptible to disease). Imagery obtained over time using these methods with the addition of high accuracy GCPs could identify erosion rates on river banks, a major problem in the sandy soils of northwest Michigan as noted by Hansen (1971).

The ability to image up to 8.16 miles (0.34 miles per man-hour * 24 hours) of river per day and process the data into a useable 3D point cloud in 7 hours means a turnaround time of about two working days. This speed makes the process feasible for studies with monthly or yearly temporal resolutions, if not daily, which will be explored in the next section. The point cloud and orthomosaic would allow people unfamiliar with the river to explore it virtually and understand the total system as it relates to recreational hazards, fish habitats, or other areas of interest. Using the point cloud, canoe liveries could show potentially hazardous areas to paddlers, satisfying the prior knowledge risk factor proposed by Wohl et al. (2016).

The logistics of taking an entire class of students on a field trip to a river are daunting, but with the point cloud and orthomosaics a teacher could take the class on a virtual tour of a river. Exposing students to natural river environments early in their education could help offset the cultural bias against LW shown by Chin et al. (2014) and Wyzga, Zawiejska, and Le Lay (2009). Showing students real-life 3D examples of the ecology of rivers would be much more stimulating than a two-dimensional picture in a book, possibly increasing interest in environmental fields among students.

River management

Revisiting the *Management plan for inland trout in Michigan* by Zorn et al. (2018) shows how management personnel are already calling for gathering more spatially continuous data on rivers more rapidly:

“Additional data are needed for characterizing instream fish habitat on trout streams throughout Michigan. Guidance is needed to determine if and what types of trout habitat is lacking on individual stream reaches.”

(p. 3)

and

“Some Michigan trout streams lack adequate instream cover to promote and maximize healthy fish and aquatic organism populations. Adequate instream cover is needed for trout streams to achieve their trout-holding potential. Fisheries Division, other government agencies, NGOs, and citizen scientists should identify trout streams where instream habitat is inadequate.”

(pp. 4,5)

and

“Human development and changes in land use typically have negative effects on trout populations through their influence on the hydrology and instream habitat. Michigan trout populations rely on high quality instream habitat and watersheds with minimal human effects.

(p. 8)

and

“Changing climate and habitat conditions require continued assessment of the suitability of habitats for wild and stocked trout... Continue to refine and implement the Status and Trends Program to assess coldwater systems... Explore additional methods to supplement standard fisheries techniques (e.g., **remote sensing**, citizen scientist, and eDNA).

(p. 8)

and

“Limited MDNR Fisheries Division Research Section staff time is available for investigating and providing science-based input on issues pertaining to inland trout management. Adequate Research Section staffing is needed to provide thoughtful, science-based input on inland trout management issues.”

(p. 6)

Based on these recommendations, the strengths of this research can alleviate many of the issues facing trout habitat management including maximizing time, identifying areas of

inadequate instream cover, identifying instream habitat changes in regard to LW, and overall provide more rapidly available, spatially continuous data on streams managed for trout.

Beyond increasing information available to management, cooperation and citizen involvement in the upkeep of rivers could increase with the use of this study's methods. The cooperation between river interest groups such as the Pine River Association and the USFS or MDNR much of the time is limited to once yearly floats with management personnel and interested parties (Pine River Association, 2017). The 3D point cloud and orthomosaic produced with this method could allow for more productive cooperation between these groups. The logistics of a meeting between management personnel and a river association are much easier to manage if an entire day floating the river is not necessary. The management personnel or river association could examine the point cloud and orthomosaic for areas of concern at multiple short meetings each year, thus focusing the annual float trips on problematic areas.

Limitations

Data collection

Limitations on data collection were related to flight time and distance. While one of the strengths of the research was the spatial extent covered during data collection, the work could cover even more ground with a few adjustments. The DJI Inspire 1 was equipped with four batteries capable of approximately 15 minutes of flying time each for a total of 60 minutes of flight time. The batteries were completely exhausted collecting imagery over 2.41 miles of river, so each battery was capable of covering 0.603 miles of river. To survey 8.16 miles in a day with a crew of three (one RPIC, two VOs), the Inspire 1 would require 14 fully charged batteries. The Inspire 1 comes with one battery, meaning an additional 13 would need to be purchased. A

battery for the Inspire 1 costs \$159, for a total of \$2,067 for batteries on top of the cost for the UAS itself (DJI, 2019).

The FAA Part 107 regulations govern UAS flight. One of these regulations involves keeping a direct line-of-sight (LOS) to the UAS. The RPIC or a VO must always be in visual contact with the aircraft. In open, level settings this rule may not inhibit flight operations, but in a wooded river valley maintenance of LOS was a difficulty. The VOs for the flights in this study found high ground whenever possible and communicated with the RPIC via two-way radio. The inconvenience of walking up hills to find advantageous viewpoints was weighed against the extremely short-range LOS could be maintained from the riverside.

Takeoff and landing sites were numerous, if not perfect. The most common situation was a sand bar or open bank near the river. The margin for error varied at different sites and resulted in the final flight ending in a crash. The battery limitations also played a role in the crash, as it happened because the final battery was low, and attempting to automatically Return to Home in the wooded environment, hitting a tree in the process. If the researcher had more batteries the limits of the battery would not have been pushed. If the takeoff and landing site was more open, the UAS would also have been able to land safely. The nature of the terrain and vegetation in northern Michigan make these types of takeoff and landing sites common and an inherent weakness for this method of data collection.

The flights were undertaken in free flight mode through the Pix4Dcapture application. The sinuous nature of the river and variability of LOS for every flight location made pre-planned flight paths impractical. The free flight mode was able to gather imagery adequate for the purposes of the study, but the flight path was difficult to keep directly over the river, resulting in

nadir images being off center. This resulted in relief displacement as discussed in the results section.

Identifying fluvial LW with this method was also limited by environmental factors, including water level, foliage, and weather. The ideal conditions for this method involve leaf-off conditions, low and clear water, complete high cloud cover, no wind, and no snow on the ground. Even during leaf-off conditions coniferous trees blocked or shaded areas of the river, potentially hiding LW. The leaf-off conditions also created false positive classifications of LW for live, standing trees, which without leaves have a similar spectral signature as LW. There were a few small areas of snow left on the ground, which was also mistaken spectrally for LW in the classification process.

Spring in Michigan involves run-off from snow melt and often high levels of precipitation. This raises and dirties the river, resulting in less than ideal through-water imagery. On the day of data collection for this study the river was running 400 ft³ per second higher than the 79-year average for that date. The water was dark, rendering much of the river bottom invisible to the camera. This resulted in a lack of points on the river surface in the 3D point cloud.

High cloud cover and low wind made the weather conditions nearly ideal for data collection. However, the wind did make obtaining perfect nadir images difficult, and there were issues with reflections on the river surface. The reflections resulted in false inverted points in the 3D point cloud. These points extended below the river surface and were mostly removed by imposing a processing area in Pix4Dmapper during the creation of the point cloud. The

processing area bounded the point cloud from an area just under the river surface to above the tree tops vertically and a small buffer on either side of the river horizontally.

Data processing

The final parameters for Pix4Dmapper resulted in a point cloud, orthomosaic, and DSM in 7.02 hours of processing time during which the researcher was able to perform other tasks. However, the trial and error portion of finding the correct combination of images and parameters to reduce noise in the point cloud and artifacts in the orthomosaic took many iterations of the processing. The use of the Pix4D proprietary software reduces the utility of the specific parameters found to be successful with the methods in this study. Pix4D is a black box tool, meaning the underlying algorithms for SfM, bundle adjustments, and point cloud densification are undisclosed. This led to issues understanding why some images would not calibrate during initial processing although their EXIF data showed all parameters congruent with the images successfully calibrated. The other issue with Pix4Dmapper is the cost, as a single device license costs \$4990 for lifetime access or \$292 per month for access for two devices with data limits (Pix4D, 2019). Between the costs for the UAS, batteries, and Pix4Dmapper a government agency or private company would spend nearly \$9,000 to get started, not to mention the cost of an employee with the expertise to maximize the possibilities of the new equipment.

The final image selection shows more than half of the imagery collected during flight operations to be redundant or useless for this study's purpose in the wooded river valley environment. Oblique images introduced noise and artifacts to the data products while the nadir imagery taken from off river center caused relief displacement of trees. Out of 1249 total images taken, 523 were used during the final processing, of which 500 were correctly calibrated. Most

of the images removed were obliques, while some nadir images which did not show the river or were blurry were removed as well. The resulting collection of images suffered from a lack of overlap in some areas. The lack of overlap resulted in errors and artifacts in the orthomosaics and point cloud.

Data analysis

The orthomosaic used for classification suffered from areas of brightness, which obscured the difference between LW and the ground. The relief displacement present due to the off center nadir imagery caused some living trees to appear to be laying over the river causing issues with misclassification of living trees as LW, while making manual identification of LW more complicated. The analysis focused on LW above the water line but in certain areas LW was clearly visible below the water during manual identification. The SMS and classification process were not able to pull this LW out, rendering a large amount of LW essentially invisible if the process was completely automated. Some of the artifacts from the data processing were spectrally and spatially similar to LW, resulting in some misclassification of non-existent objects as LW.

The highly complex spectral and spatial nature of the wooded fluvial environment caused the SMS to struggle to pick out individual objects. The pieces of LW were often broken into multiple segments due to their spectral differences (bark still on, partially shaded, partially underwater, uneven weathering patterns). Similarly, during the accuracy assessment ground – truthing following supervised classification, the areas of leafless trees overhanging water and LW made determining the correct class of pixels difficult, as the orthomosaic was often somewhat blurry in these areas of high spatial detail. The blurriness was likely caused by the

slight movement of branches between image taking and the difficulty during the SfM process of matching keypoints on these repetitive, small, partly obscured features.

Management and safety evaluations

The point cloud and orthomosaic were useful to identify potentially hazardous river LW river blockages. However, further critical inspection of LW for snagging, strainer, or overhead clearance hazards was impossible for a variety of reasons. The lack of river surface points made overhead clearance, recommended by the American Whitewater Association in Colburn (2012) to be 3 feet for kayaks and canoes and 6 feet for rafts, impossible to accurately judge. The snagging potential of some LW was visible, but many of the smaller branches were undefined or too noisy to definitively judge their hazard level (Figure 25). Strainer hazards were also somewhat visible, but the point cloud was too noisy to tell exactly how porous a LW jam was (Figure 25).

The point cloud lacked data in many areas where there was overhead cover blocking the images. The angle of the images also reduced the density of the point cloud in objects such as LW jams or small branches under other small branches, rendering the details of these features indistinct.

The point cloud and orthomosaic would be useful in a rough estimate of trout habitat quality, but the inability to see through water limits the effectiveness of the current study for this purpose. Overhead cover and visible large wood surface area could be assessed, but much of the wood enhancing trout habitat occurs below the surface. Clear water conditions would allow for a better estimation of total LW in a river.

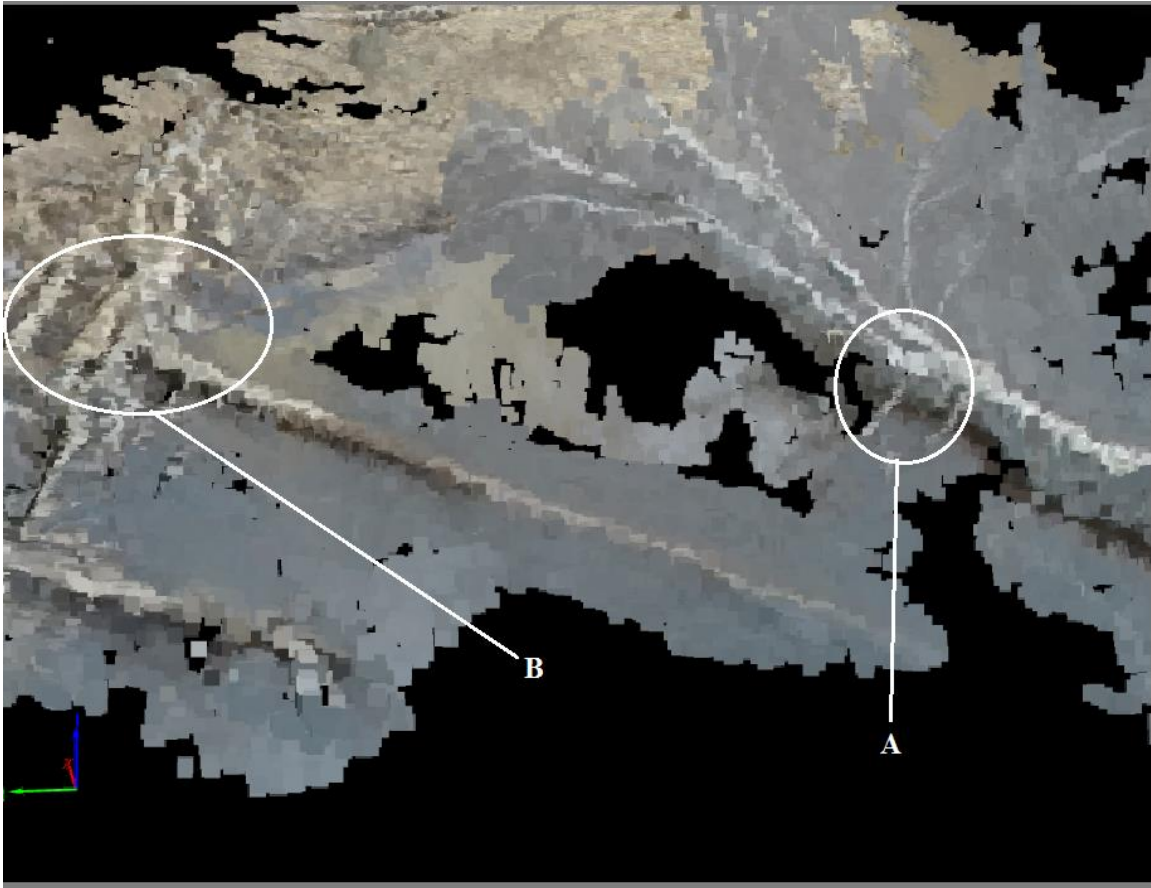


Figure 25: Potential hazards identified with the 3D point cloud. A) potential snagging hazard, B) potential strainer hazard.

Future research

The next step for this methodology of LW identification via UAS-SfM would be to refine the data collection procedure. Better data collection methods would increase the spatial extent of the method and create higher quality data products, becoming more helpful in managing LW in rivers for the best balance between recreation and ecology.

First, the flight operations would be streamlined, with only one down and up leg for each flight, as opposed to four in the current study. This would double the spatial extent covered with the same amount of battery power, decreasing the batteries required for a day's work with a DJI Inspire 1 to 7. With the spatial extent doubled and the battery price halved, the economics look more attractive. The savings could then be applied elsewhere

The use of oblique aerial imagery would be discontinued for wooded environments such as the PM, with only nadir imagery captured from the UAS. To fill in the areas blocked in nadir imagery, the researcher would apply the savings on battery costs to two Garmin VIRB Ultra 30 GPS-enabled digital cameras. The VIRB Ultra 30 costs \$400, two would be necessary for the data collection. The cameras would be mounted on a telescoping pole in the canoe the researcher used for transport down the study area. A camera would point to each side of the canoe, capturing GPS-tagged images of the river level features possibly blocked in nadir images. This technique would avoid much of the noise found in the aerial oblique images shooting through vegetation, while also increasing the detail of the LW features at river level. Collecting images in this manner would not increase the workload of the researcher, as the canoe must travel the river to reach the takeoff and landing sites for the UAS anyway.

The time frame for operations would also theoretically increase, as the canoe-mounted cameras would be able to see under the canopy during leaf-on conditions, this would allow the researcher to collect data during the summer, when low, clear water conditions are prevalent. This would increase the penetration of the water surface by the nadir imagery, increasing the visibility of LW under the water surface without resorting to expensive technology such as FluidCam1, presented by Chirayath and Earle (2016) or highly complex post-collection

refraction corrections as presented by Dietrich (2016). Image collection in summer could also reduce shading and sun glint due to the angle of the sun being more directly overhead.

Increasing the temporal window for effective operations would improve the applicability of this data collection method to change based studies, such as fluctuation of LW through all four seasons, or bank erosion during the high recreational use period of summer.

As the distance of a camera to its subject decreases, the spatial coverage of each image diminishes as well. The number of images needed for adequate overlap on both sides of the river may prove to be excessive. Even with more images the data processing and analysis of the data products would remain the same as the current study. Depending on the aim of the research (LW identification or volume measurement, bank erosion, riparian vegetation) high quality GCPs could be recorded with an RTK GPS to increase the spatial accuracy of the data products. The higher quality raw data would theoretically lead to higher quality data products and better performance for both manual identification of LW and hazards and supervised classification.

Conclusion

LW is acknowledged to be an essential element of a stream ecosystem (Gurnell, Gregory & Petts, 1995; Miller, 2010). The study of LW in a stream environment has long been restricted to short (<300 meter) samples of river due to the time consuming nature of the data collection (Woodget, Austrums, Maddock, & Habit, 2017). These types of studies led to the paradigm of a River Continuum Concept, where rivers gradually change in a predictable manner as they flow downstream. Recently, Hubbart, Kellner, Kinder, & Stephan (2017) and Knehtl, Petkovska, & Urbanič (2018) called these studies outmoded, and inefficient. The River Continuum Concept developed from these studies has also been challenged and replaced with the nested hierarchical

structure described by Woodget et al. (2017). Studies with greater spatial extent, spatial resolution, and temporal resolution are necessary to understand a river under this new paradigm. Thus, UAS-SfM studies of the fluvial environment have proliferated (Dietrich, 2017; Dauwalter, 2017; Jugie et al., 2018; Marteau, Vericat, Gibbins, Batalla, & Green, 2017; Rusnák, Sládek, Kidová, & Lehotský, 2018).

The management of a river for both ecological and recreational benefits has long been studied, with the conclusion that more information increases the effectiveness of said management (Wohl, 2017). The conclusions of scientific researchers coincide, then, with management needs, as spatial extent, spatial resolution, and temporal resolution combine to supply more data, faster, and more efficiently. A management tool must be cost effective and time efficient or no one would adopt it, unless forced to. The UAS-SfM tool presented in this thesis for LW management follows the guidelines laid down by Woodget et al. (2017, p. 3), “...an ideal approach for quantifying physical habitat parameters should also be practical, logistically feasible, cost effective as well as objective and repeatable.”

The process of this thesis was practical, as shown by the use of commercially available equipment and short data collection time. The process was logistically feasible, as a team of three accomplished the stated data collection mission. The process would be cost effective if scaled up to large scale monitoring efforts on multiple rivers. The process was objective in the sense that it identified LW to help with balancing recreational and ecological management. Finally, the process was repeatable by following the Methods section, and most of all improvable, as discussed in the Future Research section.

The objectives outlined in the Introduction were to first demonstrate a UAS-SfM data collection / processing combination could identify LW in a Michigan river. Second, to compare the data on LW jams from 2010 to the data collected in 2019. Finally, to discuss the advantages and disadvantages of the UAS-SfM process for enhancing LW management. The objectives were satisfied as LW was successfully identified both manually and automatically via supervised classification, the location of jams in 2010 and 2019 were compared and found in both years to preferentially reside in areas of high river sinuosity, and the strengths and limitations of the process were discussed and determined to be a viable tool for limited application in LW management, with the potential for more specific and useful applications if some modifications were made to future research.

Recreational use. Ecological health. Better information has the potential to enhance both in fluvial systems. The once yearly floats with government personnel and interested citizens to assess an environment that changes daily, and even hourly, did not supply enough information to meet the goals of the NSR and MNR Acts or the management objectives of the *Management plan for inland trout in Michigan* by Zorn et al. (2018). The goals of the NSR and MNR Acts include maintaining or improving the fish habitat, maintaining the ecological and scenic integrity of the stream and its environs, and allowing for recreational opportunities consistent with the natural state of the river. The data products supplied by this study can assist with all these goals economically and temporally efficiently. Possible improvements to the methods of this study could increase all of the benefits for all parties involved.

As the human population continues to grow, technology may be able to help us avoid overburdening the environment with our recreational love for it. The river is not the same after

you pass through, unless you are able to hover above it like the UAS in this study. Even the lightest of touches can add up if thousands of hands are doing the touching. Tools such as the process demonstrated here can monitor our effects on and natural processes in the environment. This may allow us to recognize problems before they become insurmountable and lead to catastrophe, as in the case of the Michigan grayling discussed in the Background of this thesis.

Instead of maximizing our recreational use of a river by clearing away all potentially hazardous LW, we can monitor LW in the river and selectively prune it when the hazard is judged too great and the fluvial environment can handle the loss. Without the knowledge provided by monitoring tools, there is no basis for understanding how to manage LW. We can be wiser than the brook trout eating every dainty caddis morsel drifting above its dinner table until they are gone or the char is gorged. If we love the river, we must manage it with knowledge provided by monitoring, leavened with the wisdom that degradation is inherent to use and slake our thirst for nature with small sips, or the river will drown under the tide of humanity.

Appendix A

Workflow and tools for large wood risk assessment

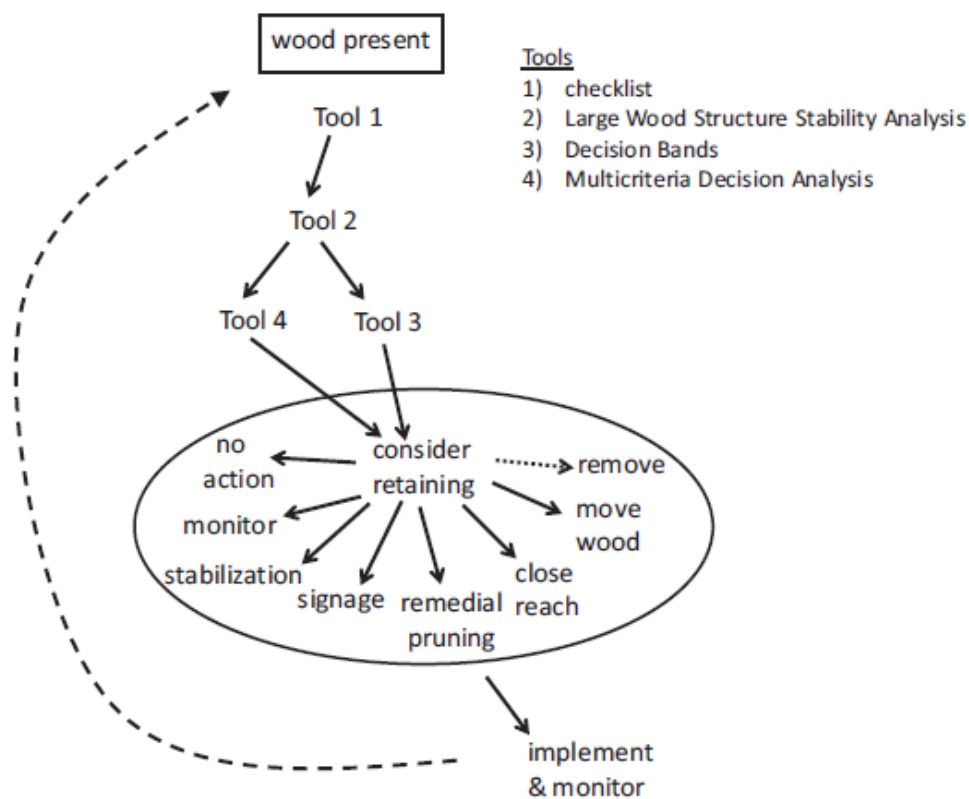


FIGURE 3. Illustration of the Sequence of Tasks, and Associated Tools, Which Can Be Used to Assess Hazards Created by Large Wood in Streams. The arrow from the lower portion of the figure back to the top rectangle indicates that, after implementation and monitoring, the whole process may be repeated, starting with use of tools, and retained wood reassessed.

(from Wohl 2016)

1. *Imminent Threat to Public Safety*
 - a) Has a river recreation accident involving the wood been reported?
If yes, remove.
If no, proceed to consider retaining.
 - b) Does the wood accumulation have crevices that can trap recreational users (i.e., is it porous) **and** completely span the active river channel in a location and season known for high recreational use?
If yes, remove.
If no, proceed to consider retaining.
2. *Imminent Threat to Property and Infrastructure*
 - a) Has the wood already damaged a facility or public or private structure?
If yes, remove.
If no, proceed to consider retaining.
 - b) Could the wood potentially create, or increase the extent of, damage to a facility or public or private structure that may cause loss of function to the facility or structure?
If yes, remove.
If no, proceed to consider retaining.
3. *Legalities*
For any reason, are you legally bound to extract the wood?
If yes, remove
If no, proceed to consider retaining
4. *Overall*
If the answer to all of the preceding questions was a clear 'no,' retain wood.
If the answers involved some qualifications, proceed to Tools 2-4 and consider retaining.

FIGURE 4. Tool 1: Checklist for Initial Assessment of Individual Wood Pieces or Wood Accumulations.

(from Wohl 2016)

Appendix B

Table of field techniques for surveying individual and accumulations of LW and calculation methods for derived variables

Variable	Unit	Method	Instruments	Note
INDIVIDUAL PIECES				
Structural properties				
Dimensions				
Diameter	cm	Breast-height; beginning of tree-top; mid-length; both ends	Calliper; tape; measuring rod; visual estimate	Rounded to whole cm; estimate by eye is in cm or to size class
Length	m	Total length of piece; length of trunk; bankfull length; length in channel zones	Tape; electronic distance meter (EDM)	Rounded to whole cm or dm
Rootwad diameter	m	Minimum and maximum transverse dimension	Tape; EDM	
Surface area	m ²	Calculated as surface area of truncated cone		
Quantity				
Number of pieces	#	Counted; estimated		
Volume of an individual piece	m ³	Huber formula; ^a Smalian formula; ^b Ellis formula ^c		
Volume of all pieces (total volume)	m ³ /m ² , m ³ /ha, m ³ /10 m, m ³ /20 m, m ³ /100 m, m ³ /1 km	Sum of the volume of individual pieces		Total volume is related to unit channel area or unit channel length
Mass of all pieces	kg/m ² , t/ha			Wood density 500 kg/m ³ used arbitrarily
Surface area of all pieces	m ² /100 m ²			Surface area is related to unit channel area
Position				
Geographical position	φ, λ	Determination of geographical coordinates	GPS	
Position within a channel		Visual choice of position category; various systems of position category		
Orientation	°	Measurement at intervals 0–360°, with 0° for tree-top downstream, 180° for tree-top upstream; multiply choice: parallel, diagonal, transverse to flow; multiply choice: parallel, transverse, diagonal with rootwad upstream, diagonal with rootwad downstream	Compass; visual estimate	Angle between axis of the piece and flow direction
Inclination	°		Inclinometer	Angle between the piece axis and horizontal plane

(Macka et al. 2011)

Appendix C

Table of typical properties of major survey approaches and advances in survey techniques related to UAS and SfM

Table of typical properties of major survey approaches

	Without SfM	With SfM
Spatial extent (km ²)	TS, dGPS: <1.0 TLS: <5.0 AP: <50 ALS, MBES: <100	Ground-based platform: 0.01 to 1.0 Airborne platform < 5.0
Spatial density (pts/m ²)	TS, dGPS <5.0 AP: <10 ALS, MBES: <10 TLS: <10,000	1 to 10,000
Point acquisition rate (pts/hr)	TS: 10 ² dGPS: 10 ³ AP, MBES: 10 ⁴ ALS, TLS: 10 ⁶	Millions
Point accuracy (m)	TS: <0.001 dGPS: <0.005 TLS, MBES: <0.05 ALS: <0.2 AP: <0.5	0.01 to 0.2

SfM spatial density and point accuracy are dependent on image resolution (pixel size), surface texture and lighting and distance of camera from surface of interest. ALS: airborne laser scanner; AP: aerial stereo-photogrammetry; dGPS: differential global positioning system; MBES: multi beam echo sounder; TLS: terrestrial laser scanner; TS: total station.

(from Carrivick and Smith 2018)

TABLE 2 Attribution of recent advances in knowledge and understanding in the fluvial and aquatic sciences due both to the uptake of SfM workflows and to the co-evolution of consumer grade UAV/drone technology

Advances linked mainly to SfM-MVS photogrammetry workflow	Advances linked mainly to (image acquisition method) UAV/drone development
<ul style="list-style-type: none"> • Democratized 3D topography surveys; inexpert operation of hardware and software • Spatial density rivaling that of LiDAR or MBES • Point precision and accuracy rivaling that of LiDAR or MBES • Automatic generation of orthophotograph (stereo-photogrammetry can also do this) • Spans spatial scales • Archival analysis • Repeatable and attractive for repeat surveys and thus change detection 	<ul style="list-style-type: none"> • Low financial cost acquisition • Very fast acquisition • Spatial coverage rivaling that of LiDAR or MBES • Direct georeferencing

(from Carrivick and Smith 2018)

Appendix D

Limitations and potential solutions for UAS imagery used in the SfM process

Table 4. Ecosynth: challenges and potential solutions.

Challenges	Solutions
Uneven point cloud coverage	<ul style="list-style-type: none"> • Modify SIFT parameters [42] • Apply additional computer vision analysis [46] • Improve the geometry and density of image acquisition
Accurate georeferencing	<ul style="list-style-type: none"> • Field placement of georeferenced markers
Optimal image acquisition	<ul style="list-style-type: none"> • Improvements in hobbyist aircraft for remote sensing [15] • Further testing to optimize image acquisitions: overlaps, numbers of photographs, pixel resolutions, angles, altitudes, geometries
Poor canopy penetration	<ul style="list-style-type: none"> • Combine ground and aerial photography within Ecosynth • Leaf-off image acquisitions
Limited spatial extent	<ul style="list-style-type: none"> • Higher altitudes • Longer flights • Merging of multiple image acquisitions
Image processing time	<ul style="list-style-type: none"> • Advances in computer vision algorithms

Dandois and Ellis (2010)

Appendix E

Forward and side-lap relationship to flight altitude and RMSE

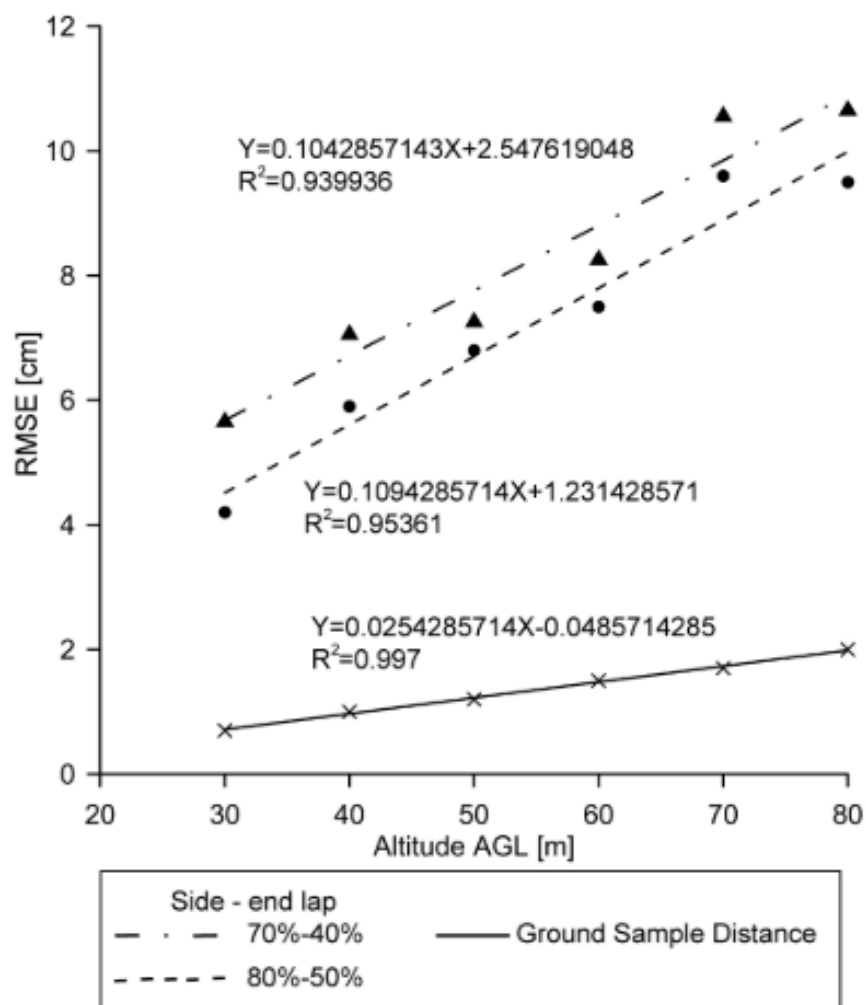


Figure 9. Linear model analyzing forward and side lap settings against altitude AGL and RMSE.

(Mesas-Carrascosa et al. 2016)

Appendix F

Example of large wood identification using SfM data products

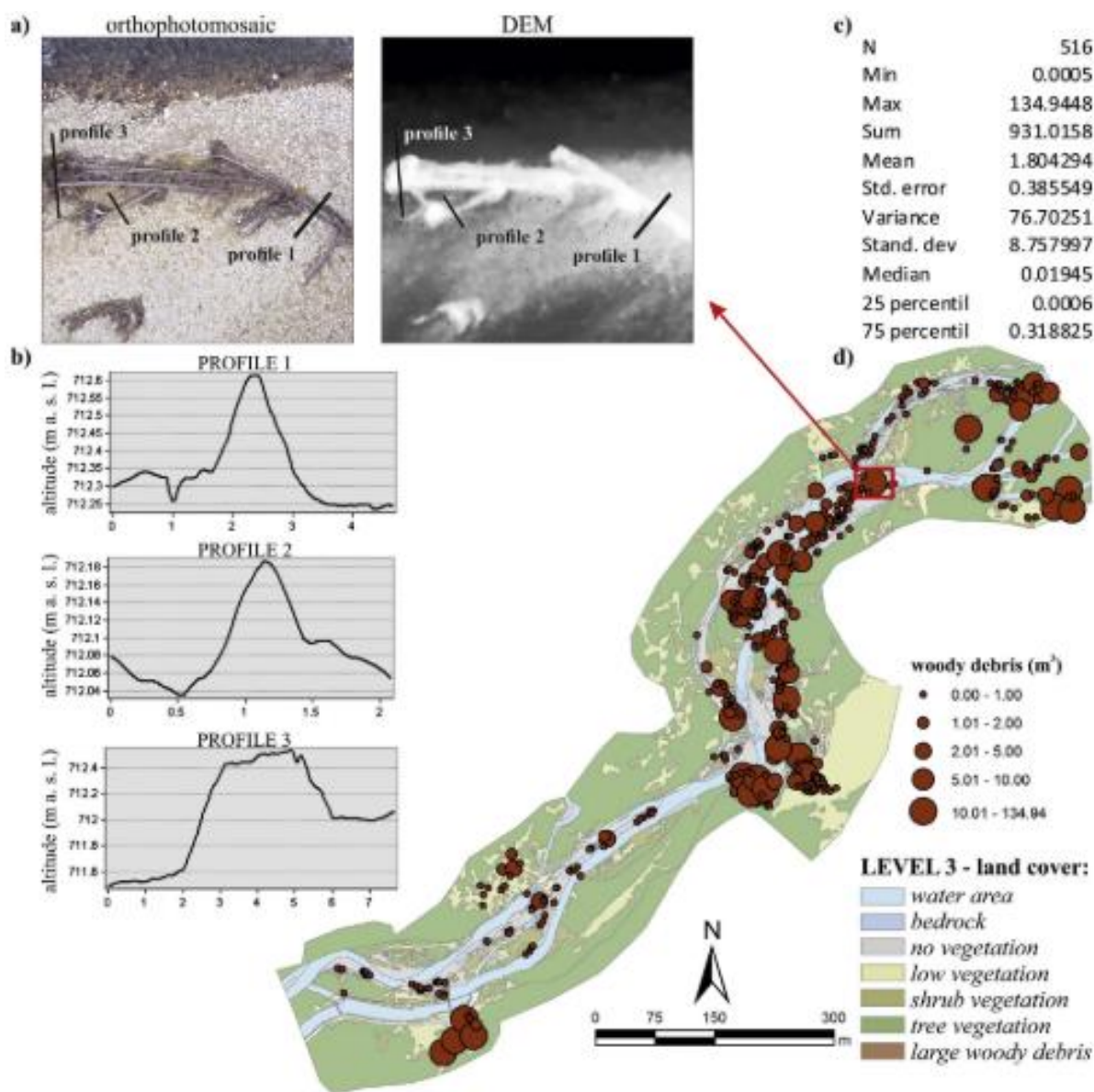


Fig. 10. Woody debris accumulation identification (a) on the orthomosaic and digital elevation model with (b) 3 cross-sections plotted on woody debris. Statistical distribution (c) of values calculated from 516 woody debris spots and (d) spatial distribution of woody debris accumulation in the study area.

(from Rusnak et al. 2018)

Appendix G

Remote Pilot sUAS license

UNITED STATES OF AMERICA XI
 DEPARTMENT OF TRANSPORTATION • FEDERAL AVIATION ADMINISTRATION

IV NAME
DANIEL JOSEPH GERKE

V ADDRESS
 [REDACTED]

VI NATIONALITY USA SEX HEIGHT WEIGHT HAIR EYES
 IVa D.O.B. [REDACTED] M 73 205 BROWN BROWN

IX HAS BEEN FOUND TO BE PROPERLY QUALIFIED TO EXERCISE THE PRIVILEGES OF

II REMOTE PILOT
 III CERTIFICATE NUMBER [REDACTED]
 X DATE OF ISSUE 31 JAN 2019

XIV *OK Elmer*
 VB ACTING ADMINISTRATOR





Appendix H

USFS permission letter



United States
Department of
Agriculture

Forest
Service

Huron-Manistee National Forests
Supervisor's Office

1755 South Mitchell Street
Cadillac, MI 49601-8533
231-775-2421
FAX: 231-775-5551

File Code: 2710

Date: December 11, 2018

Dan Gerke
MS Student, Western Michigan University
1824 Maplerow Ave.
Grand Rapids, MI 49534

Dear Mr. Gerke:

It has been determined that a special use authorization is not required for your proposed *UAV-assisted Identification and Management of Large Woody Debris in the Pere Marquette River, Michigan* Project on the Huron-Manistee National Forests (HMNF). Please carry a copy of this letter while conducting activities on National Forest System (NFS) lands.

Activities described in your April 2018 correspondence are expected to have such nominal effects on NFS lands that it is not necessary to establish terms and conditions in a special use authorization (36 CFR 251.50€(1)). As described in your proposal, the objectives of this research are to use photomosaics to determine areas where large woody debris (LWD) may pose a safety hazard, total volume of LWD in the river and identify standing trees likely to be recruited as LWD. You propose to use Unmanned Aerial Vehicles (UAVs) to fly over the Pere Marquette River corridor from McDougall's Access to Rainbow Rapids Access. The UAV flight time frame will be once during maximum foliage (July-August), once soon after foliage is gone (November) and once the following spring (March 2019). The UAV-obtained images will be formed into high resolution GSP-linked photomosaics of the river corridor.

This determination was made in part because your proposed activities would involve the following:

- You propose to conduct three UAV flights during 2018 and 2019.
- When research is complete, all equipment and materials from sampling sites will be removed.

Please observe the following practices to reasonably minimize impacts to NFS lands and resources:

1. Pilot with follow all applicable Federal Aviation Administration rules and regulations.
2. Drive vehicles on open roads only, or those roads specifically approved by the District Ranger. Vehicle travel will be consistent with Motor Vehicle Use Maps. You can obtain a map at the local district offices.
3. Decontaminate all equipment and personal gear to prevent the spread of aquatic invasive species.
4. Follow all general forest rules.



Any deviations from the activities described in your April 2018 project proposal could result in the need for a Special Use authorization. Submit any requested changes to Huron-Manistee National Forests, Resource Information Manager, Trevor Hobbs (trevor.hobbs@usda.gov)

Please provide copies of all reports and publications that result from this project to the Resource Information Manager, Trevor Hobbs, USDA-Forest Service, 1755 S. Mitchell Street, Cadillac, MI 49601. We look forward to continuing coordination with you and receiving project research results. If you have questions, please contact Trevor at (231) 775-5023, ext. 8701

Sincerely,

LESLIE AURIEMMO
Forest Supervisor

cc: Heather Gott, Dave Jaunese, Jake Lubera

Appendix I

Pix4D quality report

Quality Report



Generated with Pix4Dmapper version 4.3.33

! **Important:** Click on the different icons for:

- ?** Help to analyze the results in the QualityReport
- i** Additional information about the sections

💡 Click [here](#) for additional tips to analyze the QualityReport

Summary i

Project	PM_nadir_trimmedproc_area
Processed	2019-06-13 14:23:08
Camera Model Name(s)	FC350_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	2.34 cm / 0.92 in
Area Covered	0.381 km ² / 38.1321 ha / 0.15 sq. mi. / 94.2753 acres
Time for Initial Processing (without report)	13m:28s

Quality Check i

? Images	median of 37633 keypoints per image	✓
? Dataset	500 out of 523 images calibrated (95%), 419 images disabled, 8 blocks	⚠
? Camera Optimization	0.36% relative difference between initial and optimized internal camera parameters	✓
? Matching	median of 1580.22 matches per calibrated image	✓
? Georeferencing	yes, no 3D GCP	⚠

Preview

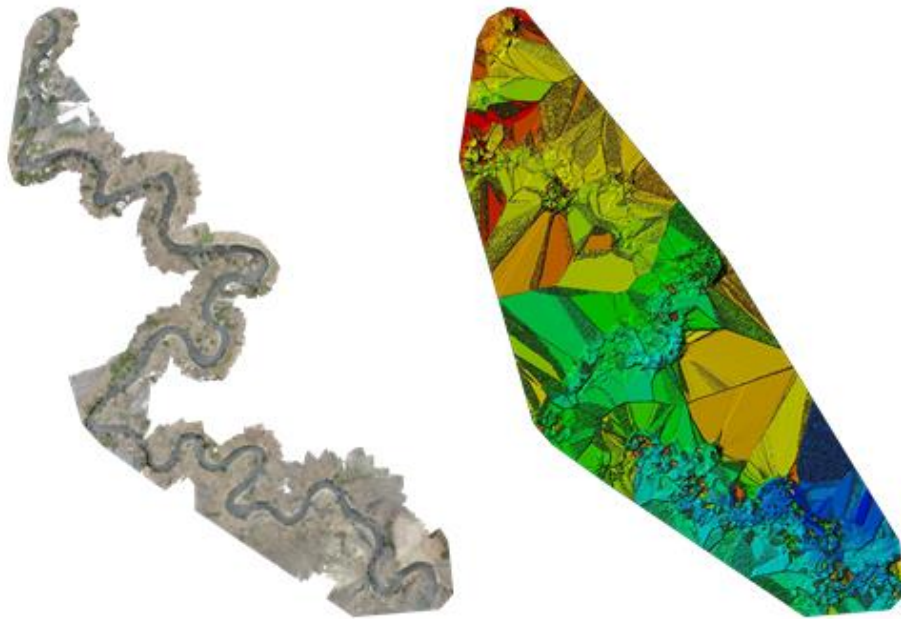


Figure 1: Orthomosaic and the corresponding sparse Digital Surface Model (DSM) before densification.

Calibration Details

Number of Calibrated Images	500 out of 942
Number of Geolocated Images	942 out of 942

Initial Image Positions



Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

② Computed Image/GCPs/Manual Tie Points Positions

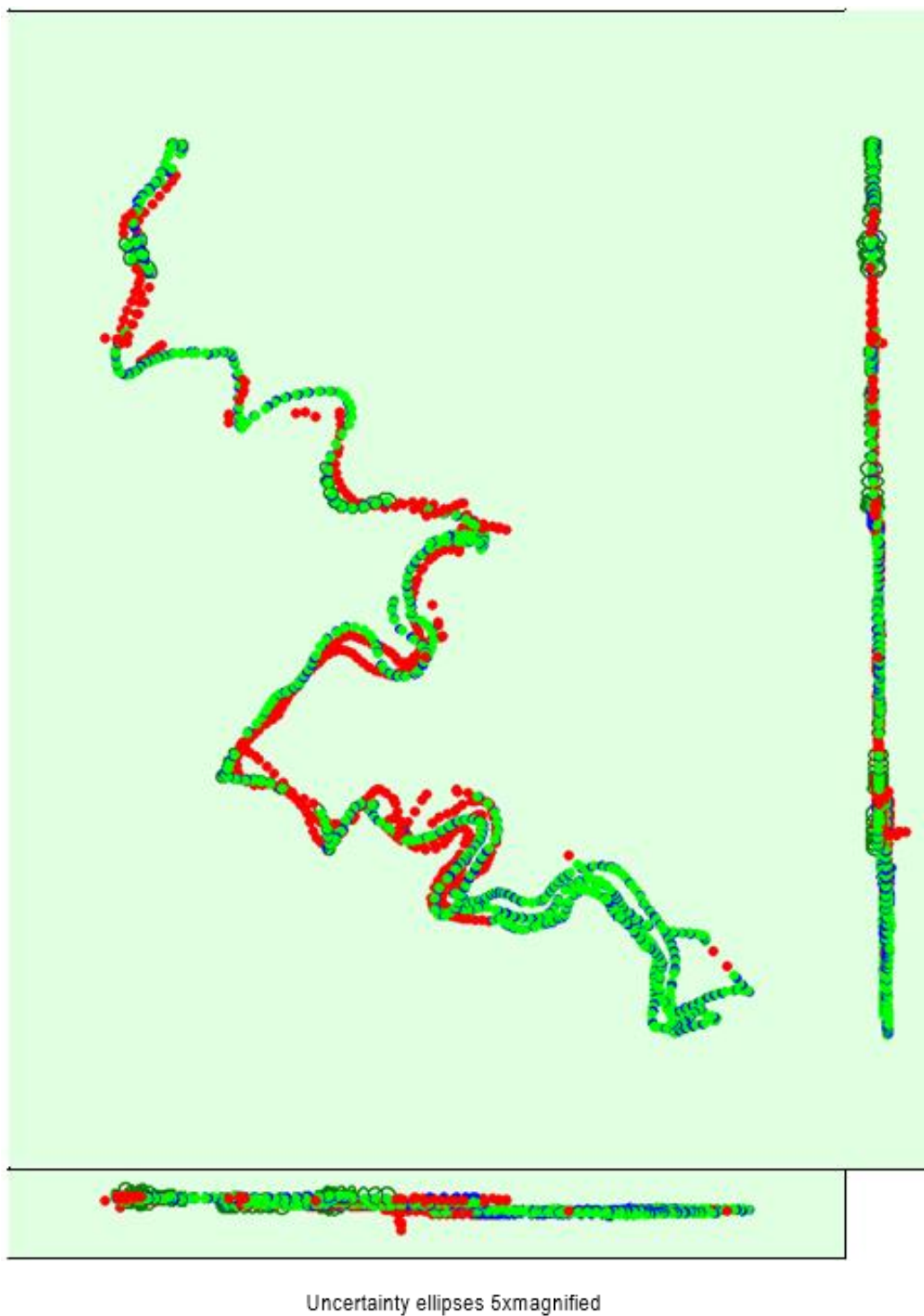


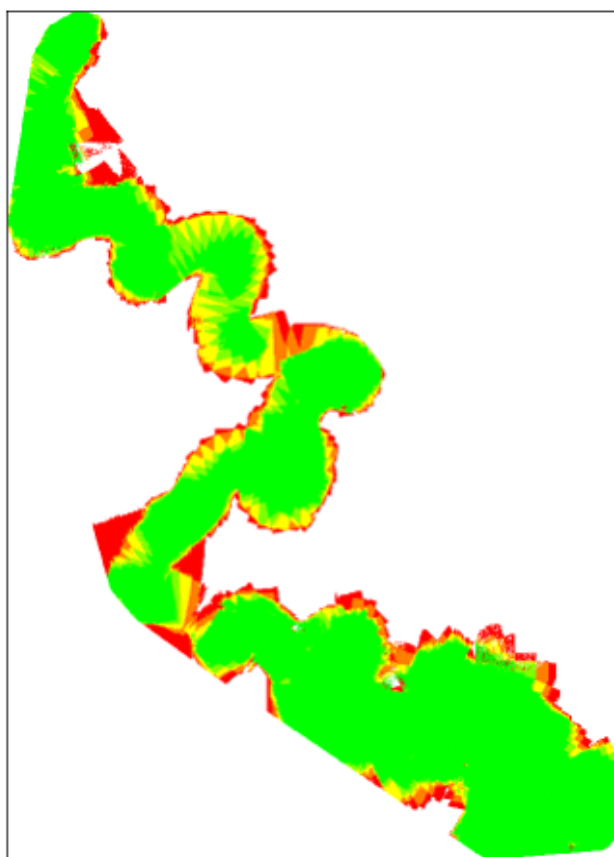
Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

🔍 Absolute camera position and orientation uncertainties



	X[m]	Y[m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.638	0.635	1.104	0.310	0.303	0.282
Sigma	0.449	0.455	0.678	0.279	0.293	0.390

🔍 Overlap



Number of overlapping images: 1 2 3 4 5+

Figure 4: Number of overlapping images computed for each pixel of the orthomosaic. Red and yellow areas indicate low overlap for which poor results may be generated. Green areas indicate an overlap of over 5 images for every pixel. Good quality results will be generated as long as the number of keypoint matches is also sufficient for these areas (see Figure 5 for keypoint matches).

Bundle Block Adjustment Details

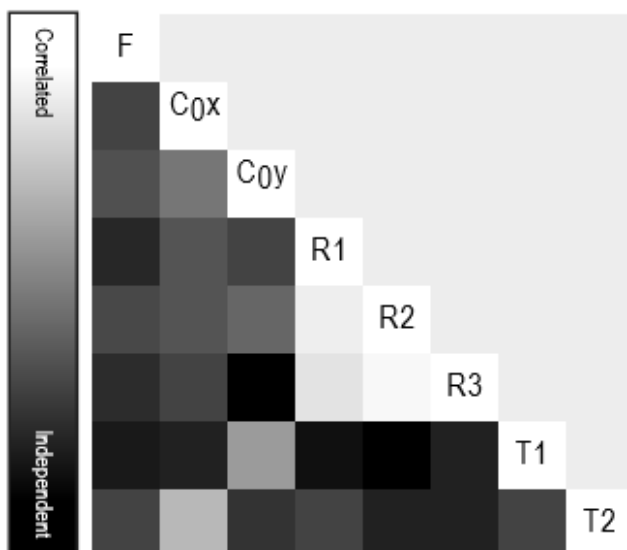
Number of 2D Keypoint Observations for Bundle Block Adjustment	1026574
Number of 3D Points for Bundle Block Adjustment	375548
Mean Reprojection Error [pixels]	0.205

Internal Camera Parameters

FC350_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC350_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.130	0.106	-0.016	-0.000	0.000
Optimized Values	2294.170 [pixel] 3.623 [mm]	1996.641 [pixel] 3.153 [mm]	1500.177 [pixel] 2.369 [mm]	-0.130	0.106	-0.016	0.000	0.000
Uncertainties (Sigma)	0.278 [pixel] 0.000 [mm]	0.143 [pixel] 0.000 [mm]	0.149 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, i.e. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.



The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table



	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	37633	1580
Min	20741	85
Max	62192	10746
Mean	38716	2053

3D Points from 2D Keypoint Matches



	Number of 3D Points Observed
In 2 Images	239884
In 3 Images	72330
In 4 Images	30577
In 5 Images	14767
In 6 Images	7914
In 7 Images	4222
In 8 Images	2324
In 9 Images	1294
In 10 Images	759
In 11 Images	550
In 12 Images	364
In 13 Images	194
In 14 Images	130
In 15 Images	82
In 16 Images	58
In 17 Images	34
In 18 Images	20
In 19 Images	10
In 20 Images	11
In 21 Images	6
In 22 Images	7
In 23 Images	4
In 24 Images	6
In 25 Images	1

2D Keypoint Matches

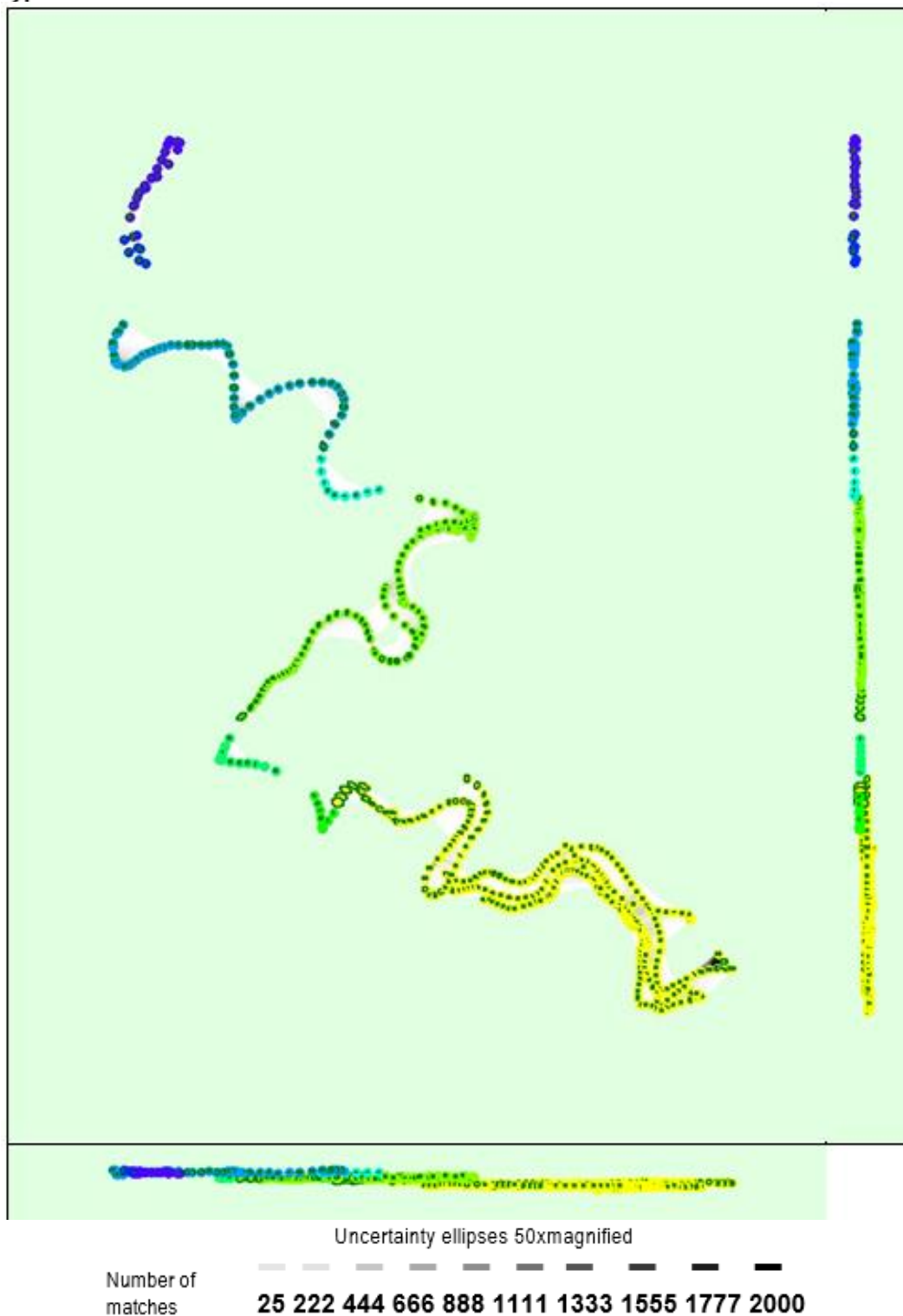


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X[m]	Y[m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.046	0.042	0.041	0.040	0.039	0.027
Sigma	0.026	0.020	0.027	0.020	0.019	0.010

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	MaxError [m]	Geolocation Error X[%]	Geolocation Error Y[%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.20	0.00
-6.00	-3.00	4.40	3.20	2.00
-3.00	0.00	40.20	44.40	52.40
0.00	3.00	51.80	48.40	42.20
3.00	6.00	3.60	3.80	2.20
6.00	9.00	0.00	0.00	1.20
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		-0.000000	0.000000	-0.000000
Sigma [m]		1.587059	1.589030	1.624783
RMS Error [m]		1.587059	1.589030	1.624783

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X[%]	Images Y[%]	Images Z [%]
[-1.00, 1.00]	99.40	99.20	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	2.685
Phi	2.590
Kappa	8.267

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-6700 CPU @3.40GHz RAM: 32GB GPU: AMD Radeon(TM) R7 350X(Driver: 22.19.172.258)
Operating System	Windows 10 Enterprise 2016 LTSC, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTMzone 16N (EGM96 Geoid)

Processing Options

Detected Template	No Template Available
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use GeometricallyVerified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto,no

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1 (Original image size, Slow)
Point Density	Optimal
Minimum Number of Matches	4
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample DensityDivider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Time for Point Cloud Densification	02h:00m:25s
Time for Point Cloud Classification	05m:43s
Time for 3D Textured Mesh Generation	10m:18s

Results

Number of Processed Clusters	8
Number of Generated Tiles	1
Number of 3D Densified Points	33169604
Average Density(per m ³)	545.9

DSM, Orthomosaic and Index Details



Processing Options



DSM and Orthomosaic Resolution	1 xGSD (2.34 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: yes
Grid DSM	Generated: yes, Spacing [cm]: 10
Time for DSM Generation	01h:02m:05s
Time for Orthomosaic Generation	03h:29m:42s
Time for DTM Generation	00s
Time for Contour Lines Generation	00s
Time for Reflectance Map Generation	00s
Time for IndexMap Generation	00s

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