Short-term Geomorphic Effects of Hofmann Dam Removal on the Des Plaines River

by Tyler Burk, Bachelor of Civil Engineering

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ABSTRACT

SHORT-TERM GEOMORPHIC EFFECTS OF HOFMANN DAM REMOVAL ON THE DES PLAINES RIVER

by

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There are an estimated two million low-head dams fragmenting rivers throughout the U.S. Low-head dams, historically installed to power mills and factories and now typically used to provide water storage for irrigation, interrupt the natural transfer of sediment downstream by creating pools upstream that widen the river and allow finer sediment to deposit in the river bed. By 2030, over 70% of the low-head dams in the U.S. will be considered past their design life expectancy. These factors have led to an increase in dam removals, including Hofmann Dam in northern Illinois. Constructed in 1950 on the Des Plaines River in Lyons, IL, the dam was removed in 2012 to improve the aquatic health of the river and for safety reasons. Utilizing topographical cross section data collected by IDNR one year prior and three years post removal, as well as collecting additional topographic surveys and gravel data in fall 2017, I analyzed channel characteristics using ArcMap and HEC-RAS to determine how the river has responded to the removal. Upstream of the dam within the impoundment, erosion occurred immediately after dam removal and is still occurring five years later resulting in an increase in the thalweg depth and a decrease in channel width. Downstream of the dam, the eroded sediment was deposited one-year after

removal but this decreased with increasing downstream distance from the dam. Five years after removal, the deposited sediment has begun to erode and will continue until bedrock is reached. Finally, according to preliminary modeling, the removal of Hofmann Dam and the erosion and deposition near the dam has resulted in the increase in average water velocity during flood conditions and the creation of riffles and runs.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Background

There are an estimated 2,000,000 low-head dams, less than 25 feet in height, that are altering natural flow, inhibiting sediment transport, preventing fish migration and impacting water quality conditions of nearly ever river throughout the United States (Collier, Webb, & Schmidt, 1996). The Hofmann Dam was one of these dams affecting the Des Plaines River in Lyons, IL, 15 miles southwest of Chicago. From 1827 to 2012, Hofmann Dam served as a run of river dam in the Des Plaines River, first as a horseshoe shape timber dam, which helped power a sawmill, to finally a 258 ft. long, 11 – 13 ft. tall concrete dam constructed in 1950. In June 2012, the Hofmann Dam was notched and then completely removed in September 2012 as a part of the Hofmann Dam Ecosystem Restoration Improvement Project. The removal released an impounded surface water area of approximately six acres and reconnected 6.5 miles of river, allowing sediment to freely travel downstream for the first time in 185 years. The Hofmann Dam Ecosystem Restoration Improvement Project was led by the Illinois Department of Natural Resources (IDNR) to determine how the river was responding to the removal by collecting fish and sediment samples and, most importantly for this study, cross sectional topographic surveys.

Objectives

The IDNR conducted surveys one year prior to the dam removal and every year for three years post removal at multiple locations upstream and downstream of the dam. This study utilizes these surveys along with additional surveys and gravel counts taken in 2017, five years after the removal, to address the following research questions:

(1) How has the channel shape responded to the dam removal both upstream and downstream of the dam site?

Performing topographical surveys at the previously established locations upstream and downstream of the dam allows for the creation of cross sectional graphs which visually and statistically represent channel changes year to year and total cross sectional change. They also help determine how far upstream the dam has influenced river morphology. The cross sections upstream that are far enough away as to not be affected by the impoundment can be used as controls. After the dam removal, the elevation of the riverbed immediately upstream of the dam is likely to decrease in the main river channel due to sediment mobilization and transport downstream due to the reduction of water retention time. I hypothesize this mobilized sediment is deposited downstream of the dam increasing the riverbed elevation. I also hypothesize the remnants of the Hofmann Dam on both sides of the river has created areas of slower flows downstream of these obstructions that allows for large amount of fine sediment to be deposited in these pools.

(2) How do sediment size distribution and sediment characteristics differ upstream and downstream of the dam site?

I hypothesize that the sediment which was mobilized upstream of the removed Hofmann Dam and deposited downstream is mainly smaller, fine sediment trapped amongst the larger material. This can result in the sediment size distribution downstream having a D_{50} (particle size that 50% of the samples are equal to or smaller than) lower than the D_{50} upstream of the dam. To obtain these values, a Wolman Pebble Count, procedure to measure sizes of random particles using a gravelometer, of 250 samples is conducted upstream and downstream of the dam to determine the sediment size distribution. Core samples can also be taken with the material collected processed through sieve analysis to determine sediment size distribution in given areas. Sediment size distribution is an important factor in the diversity of aquatic life in the river by providing shelters and nutrients to a variety of species. Too much sediment can choke the river causing poor water quality and deposition to destroy habitats, while too little sediment, typically caused by dams, can strip the river of nutrients and cause reduced riparian zones and wetlands that depend on the sediment transportation.

(3) Has the topographical changes caused by the Hofmann Dam removal modified flow characteristics of the Des Plaines River?

The collection of cross sectional and sediment size distribution data upstream and downstream of the Hofmann Dam allows for the creation of models using HEC-RAS, Hydraulic Engineering Center – River Analysis System, to determine how the river channel will respond to certain flow events. The HEC-RAS software allows us to accurately predict how the dam affected the river and where flooding may occur post removal. I hypothesize the removal of the Hofmann Dam from the Des Plaines River will cause the channel width to narrow and the water depth to decrease causing the average flow velocity to increase as compared to pre removal conditions.

The results of this study provide insight into the sediment trapping ability of low-head dams and channel changes following dam removal. There is an increasing number of low-head dam removal projects on degraded rivers throughout U.S. with goals similar to the Des Plaines River but extensive geomorphic research has not been completed before and several years after the removal to show how a river responds to these removals. Also the studies that have been completed focused on rivers and dams on both the east and west coast of the United States with few projects in the Midwestern geographic region. Due to the significant increase in dam removal projects throughout the U.S., 606 in the past 10 years compared to just 34 in the

1980s, this knowledge will allow future projects to more precisely determine when and where dredging is required, potentially lowering project costs and leading to additional removal projects. By collecting quantifiable data on these changes, this research provides insight into where, when and how much sediment may be mobilized, transported and deposited in the river system following the removal of a low-head dam. This knowledge can then be used on future projects to better determine pre-removal management practices such as location and quantity of dredging.

Organization of Research

This thesis consists of six chapters. Chapter I is an introduction that is followed in Chapter II by a literature review outlining the types of dams and roles they play, the negative impacts of low-head dams and how rivers have responded to removals. Chapter III describes the study area including climate and geology as well as the summary of the research conducted by the IDNR. Chapter IV outlines the field and laboratory methods and analysis used to answer the research questions. Chapter V includes the results of the study. Chapter VI discusses the findings and potential opportunities for future research and, finally, Chapter VII concludes the work.

CHAPTER II

LITERATURE REVIEW

Introduction

The United States Army Corps of Engineers (USACE) recognizes over 87,000 dams currently installed on rivers throughout the United States with approximately half of these dams being considered low-head dams with heights less than 25 feet. (USACE, 2013). However, there are an estimated 2,000,000 low-head dams, not documented by the USACE, littered around the U.S. (Collier et al., 1996). Dams are constructed with four main designs: gravity, embankment, arch and buttress. Low-head dams are most commonly designed as gravity dams which uses the weight of the concrete and masonry to resist the flow of the river and provide stability. Dams have been constructed to provide recreational benefits, flood control and electric storage but low-head dams were mainly installed to provide power for now abandoned mills or storage for irrigation for continually reducing farmland. The changing landscape and improved technology has left millions of low-head dams not only useless, but dangerous to human and environmental health.

Dams alter the natural flow of rivers by inhibiting sediment transport, preventing migration of fish and other aquatic species and causing water quality conditions to change from a free flowing lotic system to a stagnant lentic system. Dams, especially low-head dams, can also be deadly to humans by trapping unsuspecting kayakers and fishermen in a dangerous recirculating current caused by falling water over the dam. As a result of these negative effects along with 1.4 million dams being past their shelf life by 2030, dam removal projects have seen a significant increase in the U.S. (Maclin & Sicchio, 1999). Research has been conducted on several low-head dams and low-head dam removal projects such as the

Stronach Dam removal in Michigan and four similar low-head dams in Illinois with varied results. The studies showed the dams in Illinois retained an insignificant amount of sediment in the reservoir upstream of the dam while the similarly designed Stronach Dam reservoir was filled with vast amounts of sediment which was released downstream after the dam was removed (S. J. Csiki & Rhoads, 2014; Burroughs et al., 2009). Due to no two rivers, landscapes and dams being exactly the same, geomorphic research needs to be conducted before and after low-head dam removal to determine how quickly rivers recover to a near equilibrium state and ultimately to use this information to ensure the river has a positive response after the dam is removed.

Types of Dams

There are four main types of dams. They are gravity, embankment, arch and buttress. A gravity dam, straight or curved, is a dam designed and shaped that its weight is sufficient to ensure stability against the forces of the water (Bureau of Reclamation, 1976). The British Dam Society (BDS) describes an embankment dam as a dam typically comprised of compacted earth or rock with a core made of impermeable material and is similar to gravity dams; whereas, they rely on their weight to with stand the forces of the water (BDS, 2010). The embankment dam is the most common type of dam in the U.S. (USACE, 2013). Arch dams are concrete dams which are curved upstream that use their weight and the canyon walls to distribute the loads applied by the water (Bureau of Reclamation, 1977). An example of an arch dam is the Hoover Dam. Finally, buttress dams are made of concrete or masonry and have a water tight wall upstream supported by a triangular shaped wall, buttresses, which support the force from the reservoirs (BDS, 2010). Embankment, gravity and buttress dams can be utilized in both narrow and wide valleys; whereas, arch dams are typically constructed in gorges or narrow cannons (BDS, 2010).

Low-head dams comprise the vast majority of dams in the U.S. and have been typically designed as gravity dams. There are several different definitions of a low-head dam but the one most commonly used refers to a low-head dam as a “constructed barrier in a river with a hydraulic height not exceeding 25 feet” (ICF Consulting, 2005). This definition includes run-of-river dams where water continually overflows the dam, and small dams with a structural height not exceeding 50 feet. This particular study will focus on this specific type of dam.

Roles of Dams

Dams have an important role in the infrastructure of the U.S. providing a variety of economic and social benefits. The Federal Emergency Management Agency (FEMA) lists these benefits as recreational, flood control, water storage (fire protection), irrigation, mine tailing storage, electric generation, debris control and navigation (FEMA, 2016). Of these benefits, recreation, flood control and water storage for fire protection and farm usage are the three primary purposes for dams in the U.S., making up more than 70% (USACE, 2013). Hydroelectric dams, touted as a solution for clean, renewable energy, comprise only three percent of all dams but they generate approximately 10% of the energy used in the U.S. (FEMA, 2016). Even though dams are categorized using their main beneficial purpose, most dams are considered multipurpose, providing a variety of benefits for the surrounding population. These benefits are more pronounced with larger dams, greater than 25 ft. tall, than for low-head dams due to the importance of ensuring the large dams continuing to serve their original purpose.

Low-head dams retain smaller amounts of water and are now typically installed for irrigation and water storage. They also serve an initially unintended benefit by providing a barrier to invasive aquatic species that have wreaked havoc on native fish populations (ICF

Consulting, 2005). Historically, low-head dams were constructed to power mills and other industries typically located near small rivers (Walter and Merritts, 2008). With the majority of these factories having closed their doors and the invention of modern electrical grids and water distribution, low-head dams no longer serve their original purpose and are detrimental to the health of the river.

Dams impact ecosystems in a variety of ways by altering the natural cycle of flow, transforming the biological and physical characteristics of river channels and floodplains and fragmenting the continuity of rivers (Petts, 1984). Dams alter natural flow by blocking the river, storing excess runoff, or releasing water according to human needs (Poff et al., 1997). This alteration of flow leads to a decreased diversity of fauna that cannot tolerate the altered conditions, changes the water quality parameters from a lotic or free flowing state to a lentic or stagnant state, and traps sediment upstream of the dam, preventing necessary nutrition from being transported downstream (Bednarek, 2001).

Impacts of Low-Head Dams

Sediment

A river acts a natural conveyor belt system carrying sediment from upstream and gradually depositing it downstream. Dams interrupt this process by having the sediment deposited upstream of the dam in the slower moving reservoir, reducing the reservoir volume and raising the streambed (Kondolf, 1997). During a low flow condition, the dam creates a reservoir with a near uniform surface elevation upstream determined by the slope of the channel (S. J. Csiki & Rhoads, 2014). This causes bed shear stress to be reduced allowing sediment to deposit in the area of the reservoir instead of naturally depositing in the river downstream. The stored sediment is typically contained within the reservoir until a high discharge event occurs or the impediment is removed.

Due to the top of most low-head dams being lower than the channel banks, low-head dams frequently become completely submerged during high discharge events. High flow conditions cause the slope of the water surface to increase, reducing or eliminating the reservoir, increasing velocities and bed shear stress (S. J. Csiki & Rhoads, 2014). The higher velocities and bed shear stress causes the entrainment, mobilization and transportation of previously stored bed material (S. J. Csiki & Rhoads, 2014). When the flow reaches a level where the dam becomes completely submerged, the characteristics of the flow begin to depend more on the channel characteristics downstream and less on the impediment created by the dam (S. J. Csiki & Rhoads, 2014). During this condition, deposition of sediment behind the dam will be nonexistent and the material will pass over the dam without obstruction. Also at higher flow conditions, low-head dams can also act as a forward-facing step, creating a turbulent roller upstream of the dam (S. Csiki & Rhoads, 2010). Depending on the intensity of the flow, rollers can cause bed scour immediately upstream of the dam further reducing sediment storage (S. J. Csiki & Rhoads, 2014).

This phenomenon became evident in a study of four low-head dams in central and southern Illinois. Researchers found there was not any significant sediment storage occurring upstream of the dam suggesting that sediment storage is temporary (S. J. Csiki & Rhoads, 2014). There was not a pronounced wedge of sediment and although some trapping of fines existed, it was not substantial enough to produce a distinct morphological signature (S. J. Csiki & Rhoads, 2014). Although these conditions were observed at several low-head dams, this is by no means a constant for all low-head dams throughout the U.S and, in fact, may be a rarity. The majority of low-head dams studied have shown significant sediment deposition in the upstream reservoirs with dams such as the Stronach Dam in Michigan causing such a large amount of sediment to be deposited that the hydroelectric turbines had to be shut off (Burroughs, Hayes, Klomp, Hansen, & Mistak, 2009).

Water quality

The interruption of normal hydrologic river functions caused by dams not only effects the transportation of sediment but also influences the water quality by changing physical and chemical dynamics of the water (H. John Heinz III Center for Science & the Environment, 2002). This results in the impounded water changing from a lotic state, free flowing water with rapids and pools, to a lentic state, a body of standing water such as ponds and lakes. Some of the major changes in water quality parameters surrounding dams are oxygen depletion, temperature modification, pH imbalance, and increased contaminant concentrations (H. John Heinz III Center for Science & the Environment, 2002). Oxygen depletion occurs because the impoundment floods surrounding vegetated areas, causing them to decompose which uses a substantial amount of dissolved oxygen (DO) from the water (H. John Heinz III Center for Science & the Environment, 2002). The stagnant water behind dams also causes the water temperatures and evaporation to increase resulting in the water being more acidic (H. John Heinz III Center for Science & the Environment, 2002). Finally, the longer retention times allows for contaminants, such as heavy metals, to be constantly deposited into the sediment of the reservoir, increasing in concentration (H. John Heinz III Center for Science & the Environment, 2002). This sediment would then need to be excavated to ensure the high concentrations do not cause damage downstream. Native aquatic species have narrow conditions in which they survive and the water quality changes caused by dams can be detrimental to their survival while allowing invasive species, suited for these conditions, to flourish.

Ecology

The diversion of water caused by low-head dams has been shown to cause numerous negative ecological effects in a river system. Some of these effects include impeding migration routes, fragmenting habitat, and causing a decline in biodiversity and a reduction in riparian plant communities (Benstead, March, Pringle, & Scatena, 1999). By reducing the amount of free-flowing areas with physical characteristics such as riffles and runs while increasing impounded areas with deep, uniform velocity waters, low-head dams reduce the habitat heterogeneity of the river (Santucci Jr, Gephard, & Pescitelli, 2005). Habitat heterogeneity plays a key role in the abundance and diversity of fish and other aquatic species because of the more unique and numerous habitats for different species to thrive (Santucci Jr et al., 2005). The impounded areas cause the river system to become more homogenous allowing only biota which favor lentic systems to become abundant. Studies conducted on the Fox River, Milwaukee River and several other Wisconsin rivers showed habitat quality, index of biotic integrity (IBI) scores, and macroinvertebrate communities more degraded in the impounded areas of low-head dams than in free-flowing areas (Santucci Jr et al., 2005).

Dam Removals and a Streams Response to Removals

Dam removal is becoming a more popular topic throughout the U.S. with low-head dam removals increasing from 34 in the 1980s to 320 from 2012 – 2016 (USACE, 2017). There are six main categories of reasons for dam removal; ecology, economics, failure, recreation, safety and unauthorized dams (FEMA, 2016). Ecological impacts, such as restoring fish passages, improving water quality and remediating the watershed area, along with economic impacts, continually increasing maintenance and repair costs, are the two most cited reasons for removing a dam (FEMA, 2016). Removal of low-head dams, also known as “drowning machines", for safety reasons has also been increasing to protect unsuspected kayakers and anglers from the turbulent waters that flow over the dam (FEMA, 2016). Most removal projects cite multiple reasons for removing a low-head dam such as removal to improve safety for kayakers and to allow native migratory fish to swim upstream unimpeded which will improve the recreational benefits of the river. One example of a low-head dam removed for multiple reasons is the Stronach Dam.

The Stronach Dam was constructed as a 4.5 m tall hydroelectric dam in 1912 on the Pine River in Manistee Co., Michigan (Burroughs et al., 2009). Due to the large sediment load on the Pine River, the reservoir created by the Stronach Dam was quickly filled with an estimate of 789,000 cubic meters sediment causing a reduction in the usage of the turbines and eventually the decommissioning the dam as a hydroelectric dam (Burroughs et al., 2009). The dam was gradually removed from 1997 through 2003 releasing vast amounts of stored sediment downstream. However, the amount of sediment released downstream was estimated at 92,000 cubic meters over a 10 year period or only 12% of the stored sediment (Burroughs et al., 2009). This percentage of sediment mobilization reflects similar values obtained when researchers analyzed the effects of a dam failure incident in Ohio and a dam removal project in Wisconsin which resulted in 9 – 13% and 8 – 14% mobilization, respectively (Burroughs et al., 2009). With the relatively small percentage of sediment mobilized and transported downstream and the cost to remove to large amounts of sediment, it may be more economical to manage the transport of sediment utilizing collection devices than to remove sediment.

The greatest amounts of erosion occurred near the Stronach Dam site with the magnitude of erosion weakening as it progressed upstream (Burroughs et al., 2009). It took approximately five years for net erosion to be observed at the furthest location upstream of the reservoir, which was 3.89 km from the dam (Burroughs et al., 2009). The incision created upstream after the removal increased the slope of the banks while decreasing the river width to an extent that the average width in the reservoir was nearly the same as the upstream reference width (Burroughs et al., 2009). The slope in the reservoir increased from 0.13% to 0.21% leading to not only average water velocities increasing but also the variability of velocities increasing causing a more diverse stream flow (Burroughs et al., 2009). The higher velocities also increased the average substrate size and diversity in the reservoir (Burroughs et al., 2009). Downstream of the dam, approximately 15% of the sediment eroded from the impoundment upstream was retained within 1 km of the dam (Burroughs et al., 2009). This resulted in a substantial decrease in water depth, increase in width of the river and an increase in water velocities (Burroughs et al., 2009). The majority of the mobilized sediment was deposited on the floodplain during high flow periods with the remaining trapped in a reservoir downstream (Burroughs et al., 2009).

Dam Removal Monitoring

The changes measured following the removal of the Stronach Dam are important to consider when determining the impacts of a future dam removal project. With the relatively small percentage of sediment mobilized and transported downstream, 8 – 14%, and the cost to remove to large amounts of sediment, it may be more economical to manage the transport of sediment. The cost to dredge one cubic meter of sediment can range from $4 to $8 depending on the soil type, depth of removal and many other variables. Removing all of the sediment stored in the reservoir upstream of the Stronach Dam would cost more than $2 million. This could potentially bankrupt a project and prevent future dam removal projects from taking place. The use of sediment traps and collection devices may collect enough sediment to eliminate dredging while protecting the health of the river downstream.

The mobilization of sediment upstream of the dam can create an incising of the channel which may reduce the connectivity with potential floodplain wetlands (Burroughs et al., 2009). Regulatory agencies may require remedial action to prevent the wetland area from being affected or the wetland may be need to be replaced at a new location (Burroughs et al., 2009). However, the increased width to depth ratio from the deposition of sediment downstream of the dam can lead to an enhanced floodplain connection and the reintroduction of historic wetland or the creation of new ones (Burroughs et al., 2009). The increased water velocities, variability of water velocities and creation of new riffle and pool bedforms are all important in providing diverse habitat conditions for different species and life stages of aquatic invertebrates and fish (Burroughs et al., 2009). Ensuring these conditions are created following the removal of the dam will lead to the increased functionality of the river because bedform diversity influences sediment transport and sorting which influences nutrient cycling which drives habitat suitability of stream biota (Gordon, 2004).

Like the Stronach Dam, millions of dams are beginning to reach the end of their design life which means they either need to be repaired or removed to prevent a catastrophic failure and potential loss of life or to improve the environmental and aesthetic aspects of the river. The decision between whether or not to repair or remove the dam often lies with how much repair or removal will cost. Typically the cost of removal of small dam removal ranges from $100,000 to $1 million while the cost to repair the same would be at least three times more and can be as much as ten times more than removal (Maclin & Sicchio, 1999). These values also do not include the cost to continue to operate, maintain the dam or future repairs, liability costs and environment costs associated with keeping the dam in service.

With the variability in the previously mentioned projects, more research needs to be performed to gain a better understanding of these outcomes. There are examples of projects performing geomorphic analysis before and after dam removal but very few projects are studied in detail (ICF Consulting, 2005). Monitoring is a necessary measurement to be able to determine the performance of dam removal projects and allow for theories to be developed to better determine what, when, where and how measurements should be taken

(ICF Consulting, 2005). With this knowledge, models may able to be created to better predict the changes pre and post removal.

Although low-head dam removal has been an increasingly used option to help restore disconnected rivers, few studies have been completed providing geomorphological data showing how the river responded to the dam removal. Measurements have been predominately taken and analyzed on the larger dam removal projects and are not useful for smaller low-head dams. Also the data obtained from all removal projects can only be used to analyze that specific dam. With the vast number of variables associated with each individual river such as slope, sediment type and volume of water, accurate predictions on how a river will respond to a dam are difficult to make and can lead to the degradation of the river and unnecessary construction costs. By performing and comparing short term analysis before and after dam removal of the river bed topography and sediment size distribution up and downstream of the dam, more accurate plans can be developed to ensure the health of the river is maximized when dams are removed in the future while minimizing the costs to remove the dams. This information will further promote the removal of the aging dam infrastructure leading to a healthier river system throughout the country.

CHAPTER III

STUDY AREA

Upper Des Plaines River Watershed Setting

The Upper Des Plaines River watershed begins in southeastern Wisconsin in the counties of Racine and Kenosha and continues approximately 60 miles south into Illinois extending through Lake and Cook Counties (Fig 1). The watershed has a total area of approximately 636 square miles, 133 in Wisconsin and 504 in Illinois, with a variation in elevation from 600 to 900 feet (NAVD88) (U.S. Army Corps of Engineers, 2015). The region was greatly affected by the most recent glacial advance, the Wisconsinan cycle, causing the area to have a rounded topography and glacial drift soils with the most common soil associations being Morely-Markam-Askum, Urbanland-Markham-Askum and Elliot-Ashkum-Varna (U.S. Army Corps of Engineers, 2015). These soils cover the underlying bedrock with a thickness of approximately 400 feet in the northern portion, decreasing to less than 25 feet in the southern portion, except near the Hofmann Dam. This area near the Hofmann Dam, within the banks of the Des Plaines River, is the only area in the watershed where bedrock is exposed.

The climate of the Upper Des Plaines River watershed is defined as humid continental, with warm, humid summers and cold winters (U.S. Army Corps of Engineers, 2015). The region has an average annual temperature of 49.65°F with a range from an average high of 74.0°F in July to an average low of 23.8°F in January (National Oceanic Atmospheric Administration, 2010). The area receives approximately 30 to 40 inches of rainfall and 25 inches of snowfall per year (U.S. Army Corps of Engineers, 2015). Precipitation is typically higher in the summer months than in the rest of the year. August has the highest average precipitation with 4.90 inches and January has the lowest average with 1.73 inches (National Oceanic Atmospheric Administration, 2010).

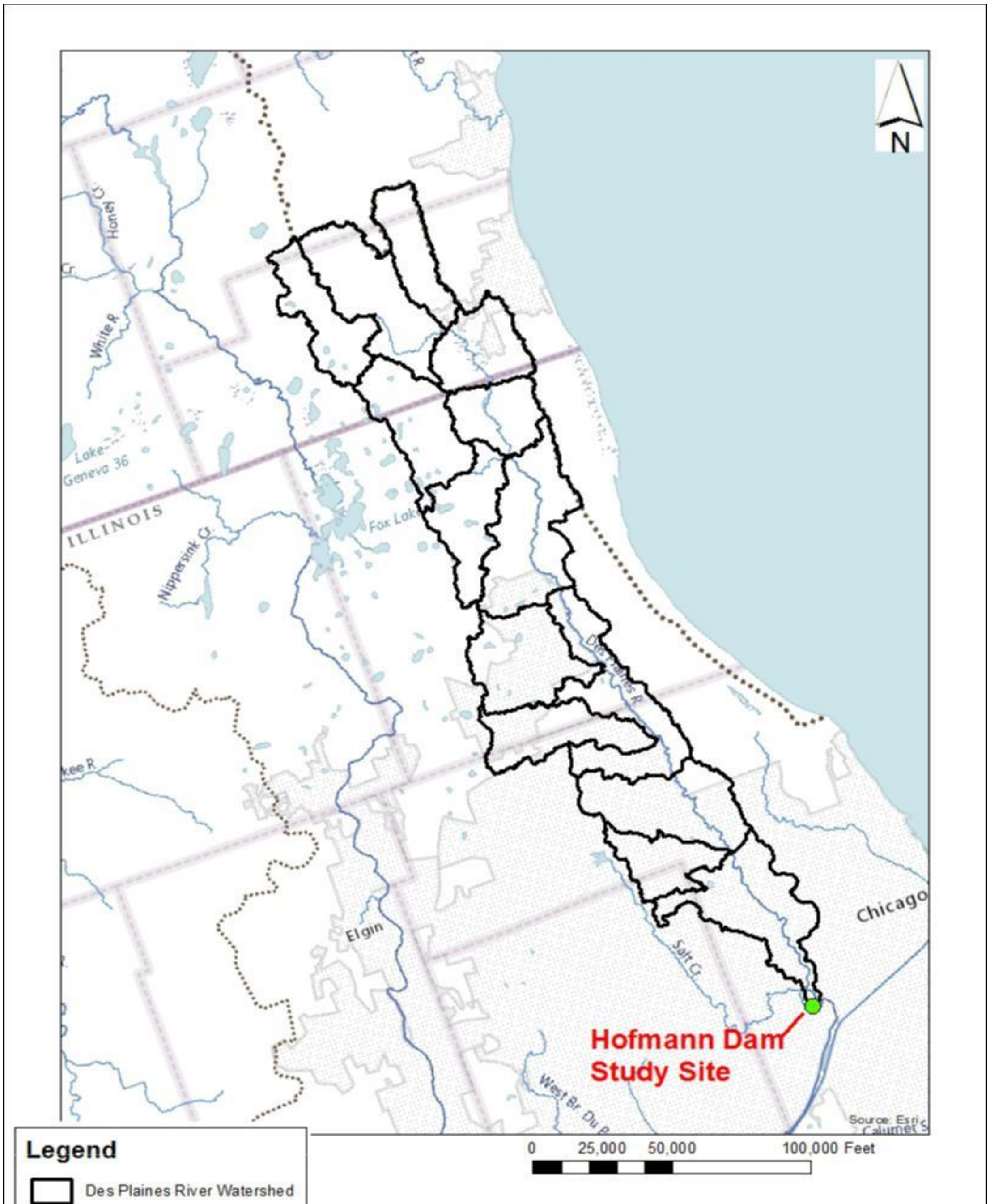

Figure 1: Upper Des Plaines River Watershed Boundary (Created by Tyler Burk; Basemap provided by ESRI)

The land use in the northern portion of the watershed consists mainly of agricultural farmland with pockets of residential areas. (U.S. Army Corps of Engineers, 2015). As the river migrates south, the residential land use area begins to increase until it becomes the predominant land use type near the urban Chicago, IL region. In Wisconsin, agriculture land covers 68.3% of the area and only 11.8% of the watershed is urban (U.S. Army Corps of Engineers, 2015). In Illinois, 57.4% of the land is urban and 19.6% is agricultural (U.S. Army Corps of Engineers, 2015). Overall, the Upper Des Plaines River watershed is comprised of mainly urban land, 50%, and agricultural area, 26% with the remaining area consisting of parks, forests, grasslands, and wetlands (U.S. Army Corps of Engineers, 2015).

Other than the Des Plaines River, the watershed consists of sixteen tributaries, five in Wisconsin and eleven in Illinois (U.S. Army Corps of Engineers, 2015). The largest tributary, Salt Creek, located in Illinois, has a stream length of 43.4 miles and a drainage area of 160 square miles (U.S. Army Corps of Engineers, 2015). The shortest tributary, Jerome Creek in Wisconsin has a stream length of 1.7 miles and a drainage area of 5.9 square miles.

Des Plaines River

In the Upper Des Plaines River watershed, the Des Plaines River has an overall stream length of 86 miles (U.S. Army Corps of Engineers, 2015). The river starts as a prairie creek in Wisconsin, transitions into a suburban stream as it enters northern Illinois and finally expands to a large urbanized river at the Hofmann Dam site. Past the Hofmann Dam in what is considered the Lower Des Plaines River watershed, the Des Plaines River further increases into a channelized major industrial waterway, with frequent barge traffic. It flows approximately 50 miles south until it eventually converges with the Kankakee River to form the Illinois River. For this project I will only focus on the section of the river in the upper watershed.

A United States Geological Survey (USGS) stream gage, #05532500, is located just downstream of the Hofmann Dam in the Des Plaines River and has collected river discharge and stage measurements since 1914. The average monthly discharge collected at this gage was observed to be the largest in April with a monthly discharge of 1,320 cubic feet per second and smallest in October with an average of 491 cubic feet per second (Fig. 2). The gage also collected the annual peak discharge events. In 2013, the largest peak discharge ever recorded by the stream gage was measured at 12,200 cubic feet per second, considered a 500-year flood event (Fig. 3). This discharge produced a gage height of 11.42 feet, nearly four feet above the flood stage height of 7.5 feet. The following year, the fifth largest discharge event in the last 40 years was measured at 8,010 cubic feet per second (Fig. 4).

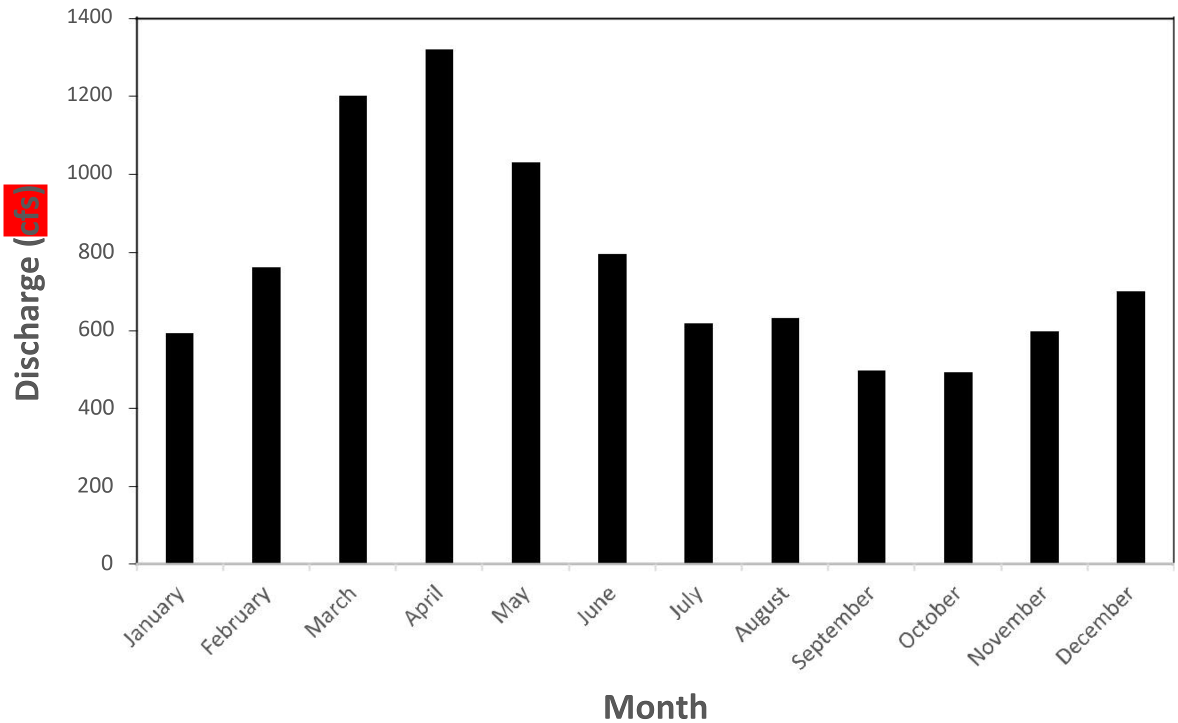

Figure 2: Average monthly discharge for the Des Plaines River at USGS stream gage 05532500 (USGS, 2018)

Figure 3: Image of the Hofmann Dam during 500-year flood in April 2013 (Image by I Grew Up In Riverside, IL Blog)

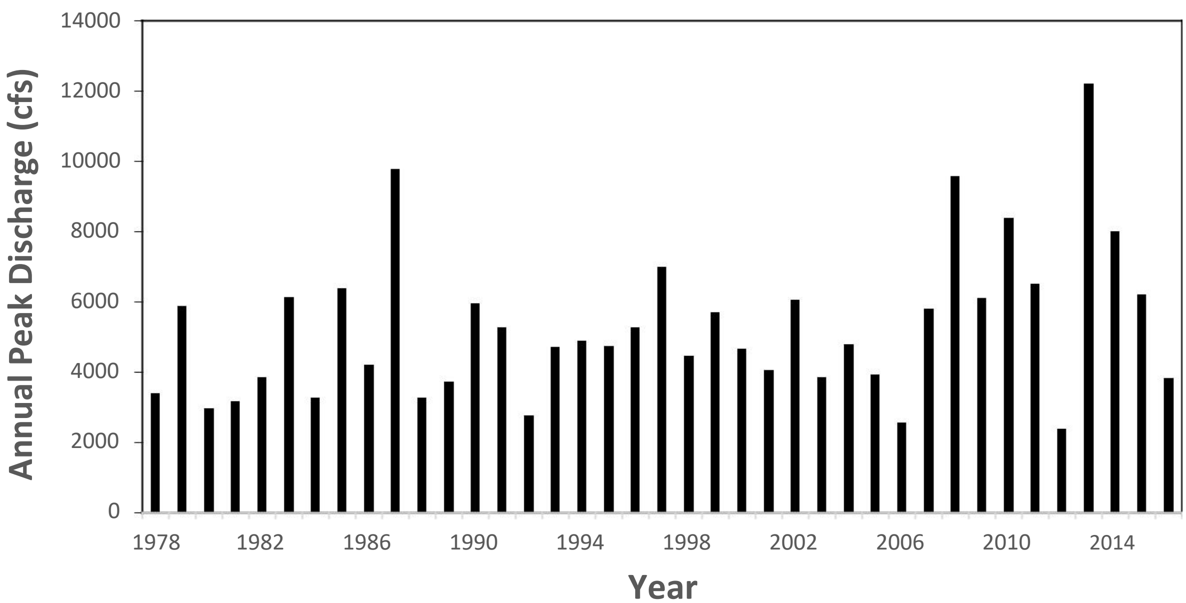

Figure 4: Annual peak discharge for the Des Plaines River, 1978 – 2016 (USGS, 2018)

Hofmann Dam and Study Site

At a site of a natural waterfall created by a limestone shelf, the original timber dam was constructed in 1827 to power the first sawmill in the Chicago, IL area (Illinois Department of Natural Resources, 2018). Over the next eighty years, several dams with different designs and construction materials were built on the Hofmann site. In 1908, a horseshoe shaped concrete dam was constructed along with an embankment wall and the Hofmann Tower to create the Niagara Park alongside the Des Plaines River (Fig. 5) (Illinois Department of Natural Resources, 2018). Finally, the most recent Hofmann Dam was constructed in 1950. The low-head concrete dam had a height that ranged from 11 to 13 feet and a length of 258 feet (Fig. 6). The Hofmann Dam fragmented 6.5 miles of the river and created an impoundment area of approximately 6 acres (EPA, 2012).

As a part of the Hofmann Dam Ecosystem Restoration Improvement Project, which sought to restore the connectivity of 58 miles of the Des Plaines River, improve fish habitat and water quality and expand recreational use, the Hofmann Dam was removed in 2012 during a low flow period. Starting in June, the dam was notched to allow for the impoundment to slowly drain (Fig. 7) (Illinois Department of Natural Resources, 2018). The removal process continued until the dam was removed on July 18, 2012, leaving two 54 feet long sections on each side of the river to protect the existing retaining wall (Fig. 8 & 9). With the water levels receded after the removal, the remnants of the 1908 horseshoe shaped dam were discovered and eventually removed in September 2012 (Illinois Department of Natural Resources, 2018).

To ensure the newly exposed banks do not erode as the river tries to carve a new path, riprap was installed in the river and on the banks up and downstream of the Hofmann Dam. Upstream of the dam, approximately 7,500 tons of riprap was positioned to protect the exposed sediment deposited in the former impoundment, which contained varying levels of contaminants such as polynuclear aromatic hydrocarbons (PAHs), pesticides and pollutant metals (Fig. 10) (EPA, 2012). Along with the riprap, silt turbidity curtains were installed in the dam impoundment to trap sediment and prevent it from being transported downstream and the banks were vegetated with native plant species (Fig. 10) (EPA, 2012). An additional 1,000 tons of riprap was placed downstream of the dam where a scour trench had formed as a result of the shear stress created from the water flowing over the dam (EPA, 2012).

The Hofmann Dam site, located in Riverside, IL, is located in an urbanized area. A park called the Indian Gardens is located on the left bank and follows the river upstream of the dam past the location of the former impoundment (Fig. 11). The Hofmann Tower and apartment complexes are located on the right bank of the river (Fig. 11). Downstream of the dam, the Swan Pond Park is located on both sides of the river (Fig. 11). These parks and urbanized areas allow for easy access to the river and Hofmann Site.

Figure 5: Horseshoe shaped Hofmann Dam constructed in 1908 with Hofmann Tower (IDNR)


Figure 6: Hofmann Dam constructed in 1950 and impoundment created by the dam (IDNR)

Figure 7: Notching of the Hofmann Dam, June 2012 (IDNR)

Figure 8: Removal of the Hofmann Dam with 30 foot long section remaining on right bank, looking upstream (IDNR)

Figure 9: Removal of the Hofmann Dam with 30 foot long section remaining on left bank, looking upstream (IDNR)

Figure 10: Riprap and silt turbidity curtain installed in the former Hofmann Dam impoundment (IDNR)

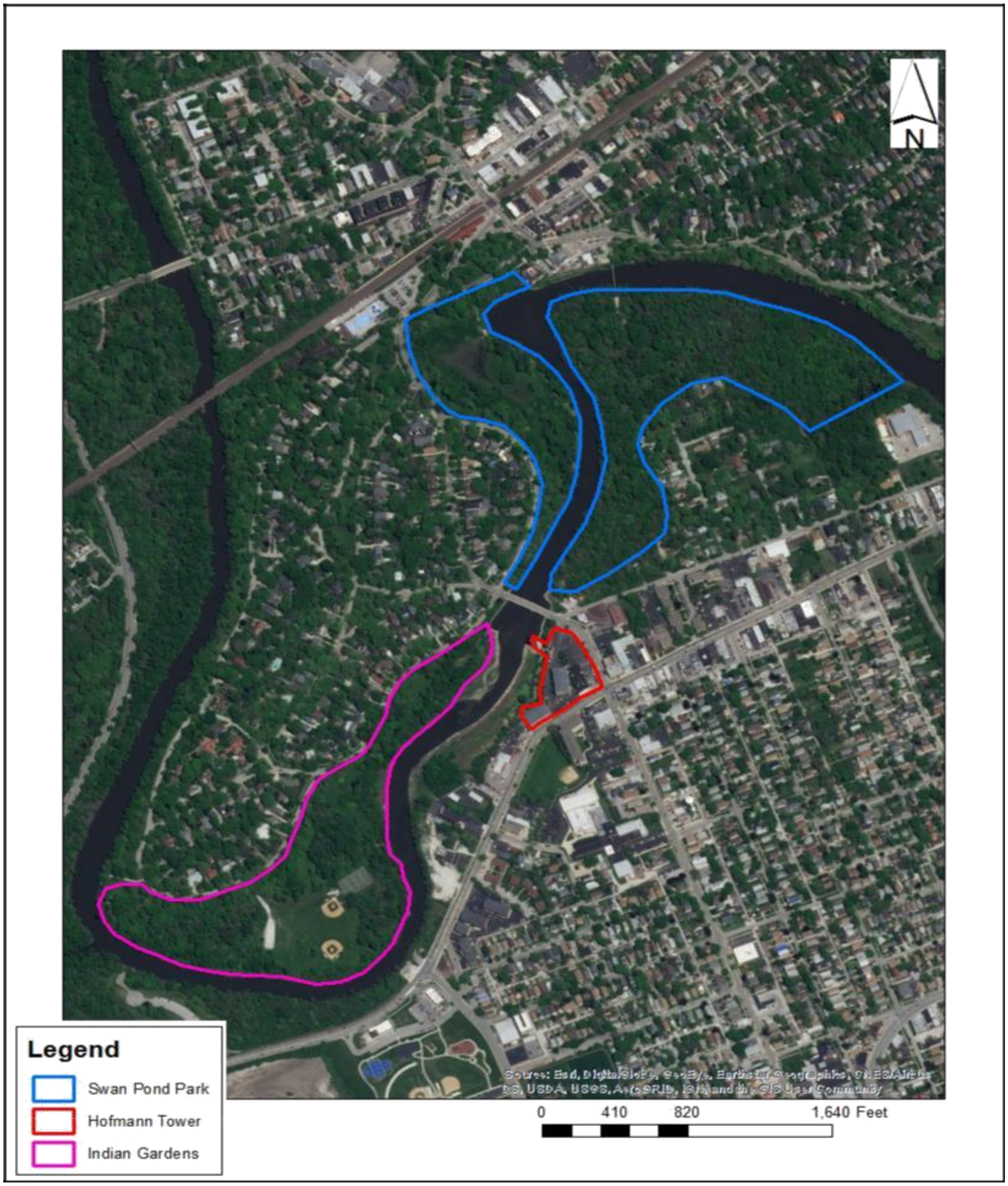

Figure 11: Location of Swan Pond Park, Hofmann Tower and Indian Gardens (Created by Tyler Burk; Basemap provided by ESRI)

CHAPTER IV

METHODS

General Approach

To analyze the potential geomorphic changes occurring up and downstream of the Hofmann Dam, this project used cross-sectional surveys and sediment samples collected by the Illinois Department of Natural Resources prior to the removal of the Hofmann Dam and up to three years post removal. Additional fieldwork consisting of cross-sectional surveys, using a TOPCON HiperV GPS system, and particle size analysis, using a gravelometer and the Wolman Pebble Count methods was performed in 2017 and 2018 to allow for comparison over a five-year span. Plots and graphs for each cross-section surveyed as well as the sediment size distribution upstream and downstream of the dam were created to determine the location and timeframe of erosion and deposition in the riverbed. Finally, the data was entered into HEC-RAS software, which calculated the change in velocity, depth and shear stress from year to year for a given flow condition.

Field Work

IDNR data collection

To determine the change in the river bed topography upstream and downstream of the dam, the Illinois Department of Natural Resources (IDNR) established locations for twenty cross sections to be measured; seventeen upstream and three downstream of the dam. The IDNR deemed these locations to be areas of concern where erosion may occur. They chose to monitor these sites to determine if preventative measures were required, such as revegetation or riprap, to ensure the banks of the river remained stable. The twenty cross sections were measured by the IDNR using a Geodimeter Total Station to determine horizontal and vertical measurements.

The Geodimeter Total Station collects data with an accuracy of approximately 2” to 5” using electrical scans to detect the location and elevation of a pole-mounted prism. Data was collected at various cross sections just prior to removal of the dam and at least once post removal with several cross sections being measured once a year for three years following removal. To ensure the cross sections were measured on the same line every year, a traverse line was strung across the river from established start and end locations. The IDNR surveyed each of the cross sections at various dates. Table 1 details the number of times and when each cross section was measured.

In 2001, 2006 and 2011, the United States Army Corps of Engineers (USACE) contracted a geotechnical firm to perform sediment probing and sample collection immediately upstream of the dam at mid-stream and bank locations. The main objectives of this study were to determine the physical characteristics of the sediment upstream of the dam for engineering purposes and to identify any potentially harmful substances such as semi volatile organics, PCBs and pesticides. For this study, the grain size distribution calculated from the 25 samples collected in 2011 will be used to compare with the sediment collected upstream of the dam in 2018 (Fig. 13).

Table 1. Cross sections and survey years.

New Cross Section Name	IDNR Cross Section Name	IDNR Data Collected
XS1	9	2012, 2013, 2014 2015
XS2	7	2012, 2013
XS3	5	2012, 2013
XS4	30001	2013
XS5	30000	2013, 2014, 2015
XS6	4	2012, 2013
XS7	10000	2012, 2013
XS8	10001	2012, 2013
XS9	10002	2012, 2013
XS10	10003	2012, 2013
XS11	50	2013, 2014, 2015

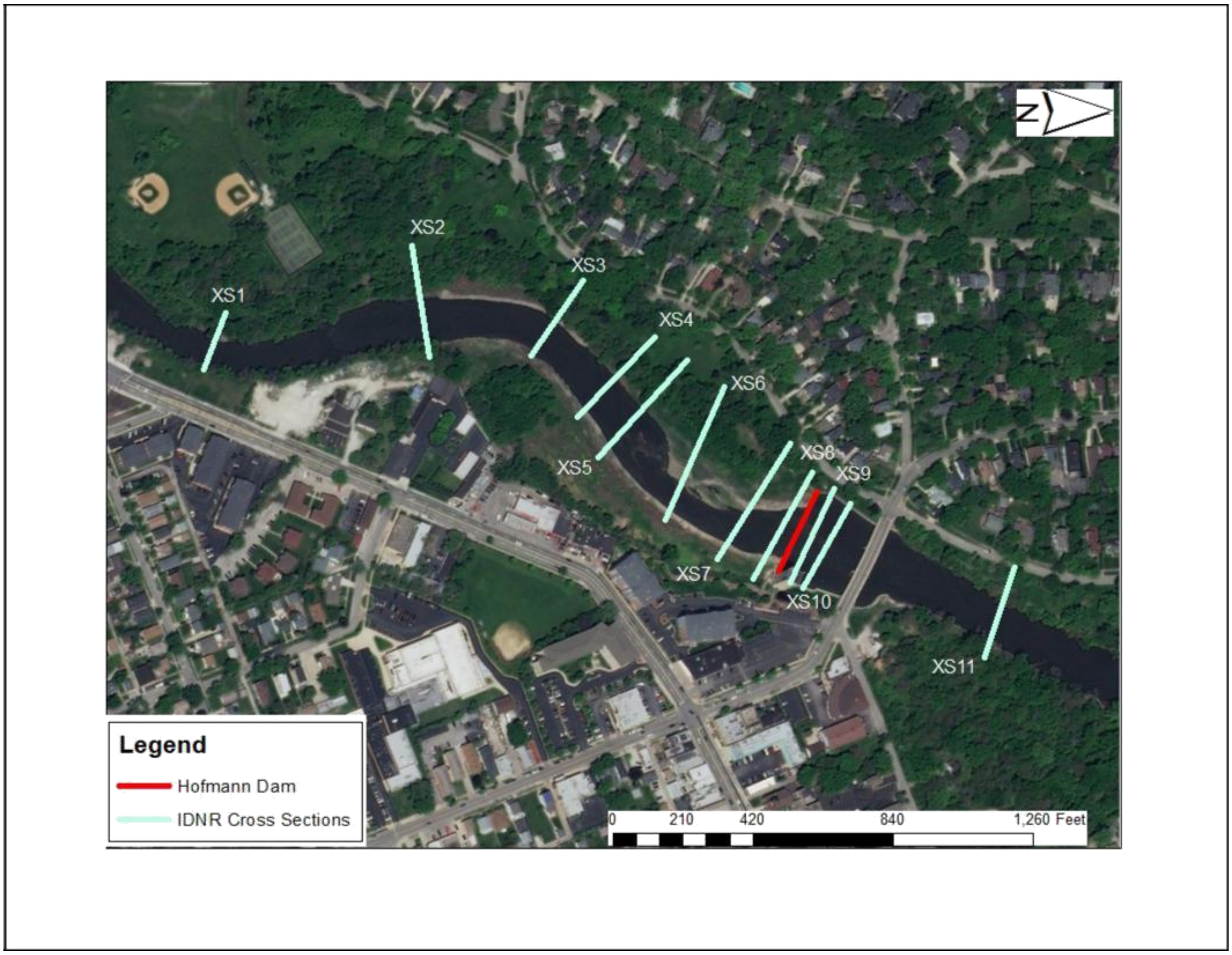

Figure 12: IDNR cross-section locations with the Hofmann Dam (Created by Tyler Burk; Basemap provided by ESRI)

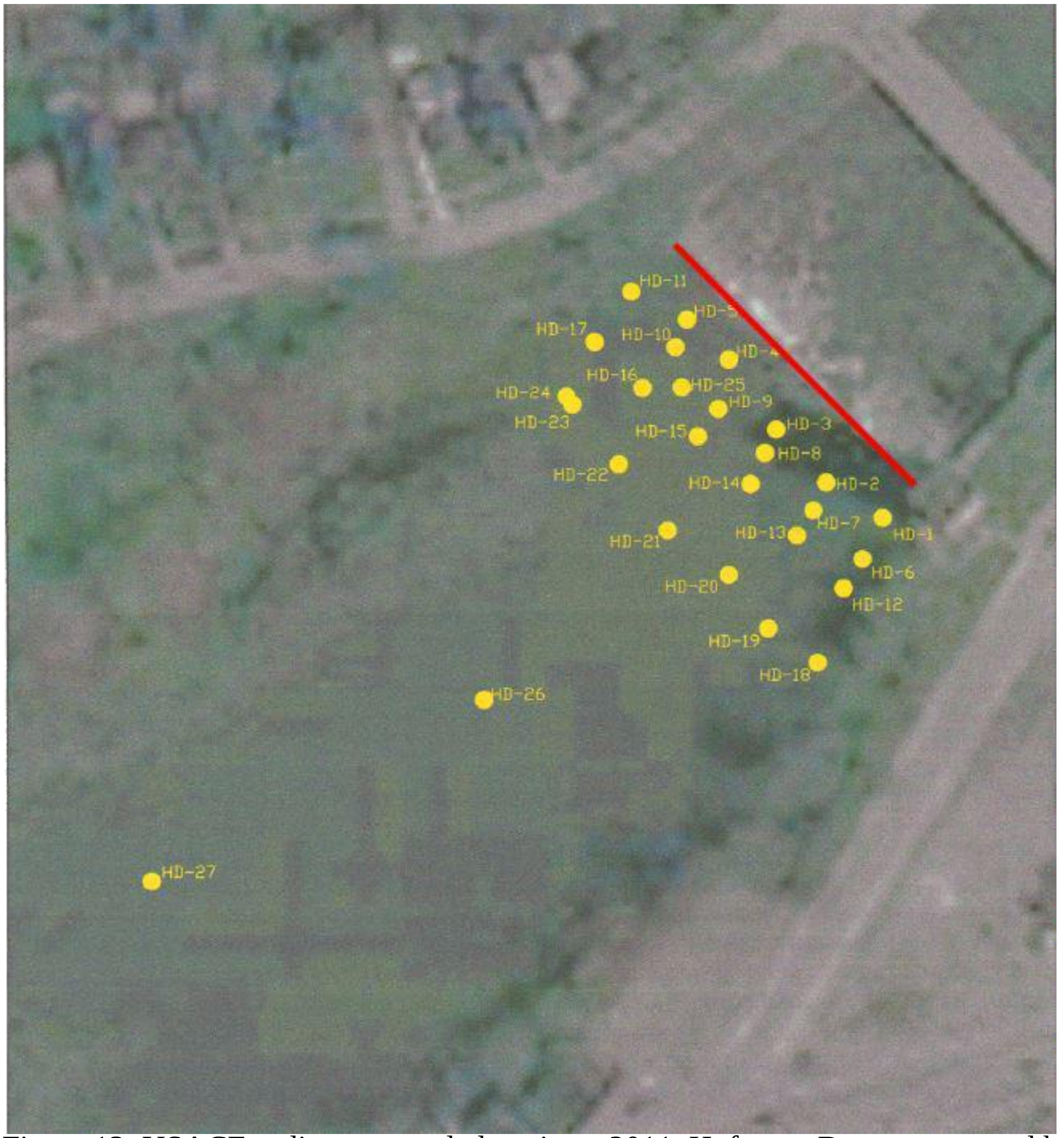

Figure 13: USACE sediment sample locations, 2011. Hofmann Dam represented by red line (IDNR, 2015)

2017 – 2018 data collection

To determine changes five years after dam removal, I identified particular cross section within the IDNR data set to replicate for this study. Seven of the twenty cross sections were located far upstream at a distance that would not be affected by the removal of Hofmann Dam and were not surveyed for this project. Thirteen cross sections were measured five years post removal using a TOPCON HiperV GPS system but due to equipment errorонly eleven cross sections were measured with enough precision to compare before and after results (Fig. 12). To locate the 11 cross section start and end points established by the IDNR before the removal, I used a metal detector to identify previously installed railroad spikes. These spikes were detected and exposed using shovels for only four of the eleven cross sections, XS4 through XS7. For the remaining cross sections, a Trimble GeoExplorer GPS was used to locate the approximate start and end cross section coordinates provided by the IDNR. Depending on the number of satellites detected by the GPS unit at the time of measuring, the accuracy of measurement is within 3 to 15 feet. After the railroad spikes or GPS coordinates were found, surveying flags and spray paint were used to mark each location to ease future locating and improve accuracy of future measurements.

To determine water depths, I used the United States Geological Survey (USGS) stream gage #05532500 which is located approximately 200ft downstream of the dam at the Joliet Rd. bridge. On an initial site visit in July 2017, I determined that to safely cross the river at each cross section the gage height needed to be near 2.0ft. This gage height correlates with 25th percentile of discharge for the Des Plaines, resulting in a small window to collect data. A flow condition with a gage height between 2.0 and 3.0 feet was observed in three distinct separate windows of time, September to October, December to January and mid-March to April, from July 2017 through March 2018 (Fig. 14). These three windows correspond to the dates of the field-collected data.

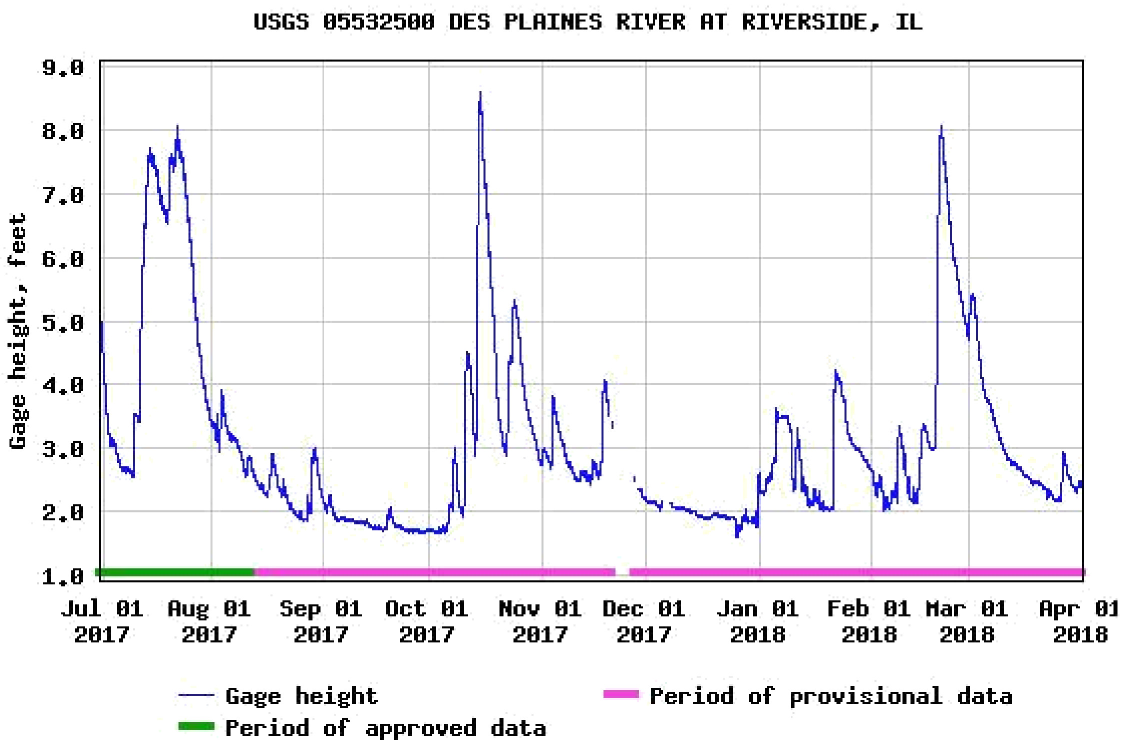

Figure 14: USGS stream gage #05532500 gage height from July 2017 through March 2018 (USGS, 2018)

With the start and end points located and the river at a safe flow condition, I surveyed each identified cross section. To ensure the cross sections were measured in a straight line, a tape measure was strung from the start point on the left bank looking downstream to the edge of the river. Due to the size of the river, length of the cross sections and conditions such as a 15 ft. tall retaining wall at some cross sections, the tape measure could not be strung all the way across the cross section. Because of this limitation, a spotter was positioned at the start of the cross section to communicate with the surveyor to limit straying from the predetermined path.

Cross section measurements were taken using a Topcon HiPer V Global Navigation Satellite System (GNSS). This system consists of a base and rover GNSS antenna, tripod, rover pole and data collector tablet. To use the system, the base antenna was mounted on the tripod in an open area with minimal vegetative coverage to allow for the collection of GPS data throughout the time of surveying which was used for correcting the rover measured data in OPUS (described in next section). The height of the antenna was measured and recorded. Next, the rover antenna was mounted on the rover pole with the height of the antenna also measured and recorded. The rover pole and mounted antenna were then placed on the starting point of a cross section and using the data recording tablet a point was collected and named. Points were then collected approximately every 15 feet along the tape measure but this varied widely with the points collected in the river. Where possible the data was collected in one straight line from start to finish. However, due to conditions being unsafe in the deeper areas of the river, data was collected from the start point until the last point deemed safe to collect in the river then collected from the end point of the cross section to as close as possible to the previously established last point deemed to be safe to collect. To ensure the highest possible accuracy of data, approximately 0.5 inches in latitude, longitude, and elevation, points were only collected when the system was in a RTK fixed status.

To determine the surface particle size distribution upstream and downstream of the Hofmann dam, the Wolman pebble count procedure was used to collect and analyze particle samples. The reach identified for particle collection begins at cross section XS11 downstream of the dam and continued to XS5 upstream. The Wolman collection procedure starts at the location furthest downstream in the reach. The first sample was collected by picking up the first particle that touched the index finger at the tip of the collector’s toe. This particle was measured using a gravelometer to determine the intermediate axis of the sample by recording the maximum size of the opening on the template the particle will not fit through (Fig 15.) The sample was discarded downstream to avoid repeated measurements.

Samples were then collected using this process while following a predetermined zigzag pattern upstream across the river channel to the dam until 200 samples were collected (Fig. 16). However, due to safety concerns with the river conditions, a modified zigzag pattern had to be used. Samples were collected starting on one side of the channel and wading into the river until the samples could not be collected due to water depth. The collector then returned to the same bank to continue upstream sample collecting. After collecting samples on one side the of the river, the process was repeated on the opposite side, trying to match the pattern previously established as close as possible, until a minimum 200 samples were collected upstream and downstream of the dam, for a total of at least 400 samples.

Figure 15: Gravelometer template (Keen-Zebert, 2007)

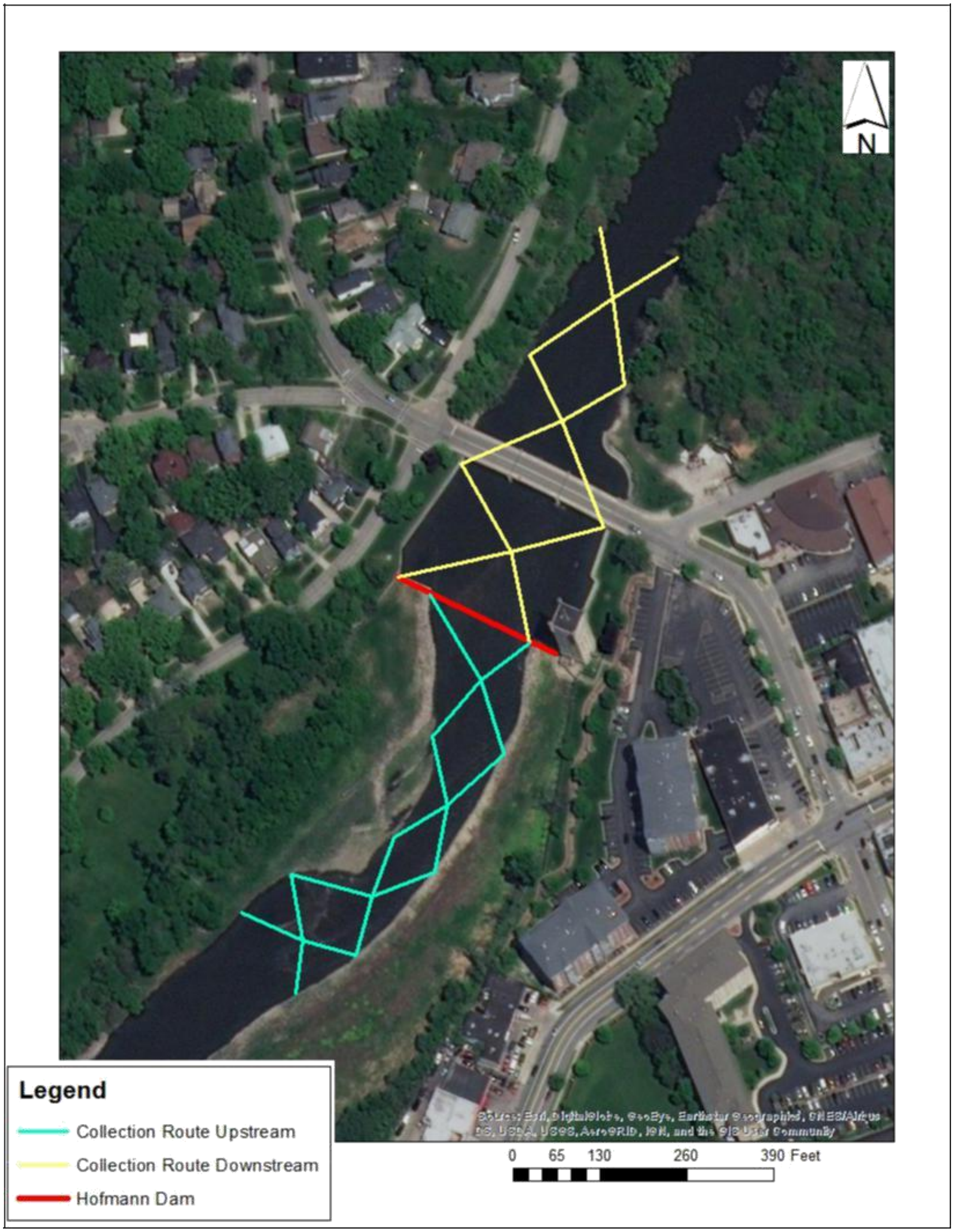

Figure 16: Wolman pebble count sampling route upstream and downstream of Hofmann Dam (Created by Tyler Burk; Basemap provided by ESRI)

Laboratory Methods & Calculations

GPS data

The latitude, longitude and elevation data collected using the Topcon HiPer V Global Navigation Satellite System base antenna was processed and corrected using the National Oceanic and Atmospheric Administration's (NOAA) Online Positioning User Service (OPUS). OPUS allows a user to upload a survey-grade GPS data file to the National Spatial Reference System to improve the accuracy of the collected data (National Oceanic Atmospheric Administration, 2018). OPUS improves the accuracy of the data by adjusting the coordinates collected using the average coordinates from three independent Continuously Operating Reference Station (CORS) baselines near the project site (National Oceanic Atmospheric Administration, 2018). This adjustment allows for the base antenna coordinates to be accurate within a half of an inch (National Oceanic Atmospheric Administration, 2018). After the data is submitted through the OPUS website, OPUS sends the base antenna corrected coordinates file to the user's email address.

After receiving the corrected file from OPUS, the corrected data along with the coordinates collected using the Topcon rover antenna was uploaded to Topcon MAGNET Tools software. This software allows users to input their rover collected GPS data and OPUS corrected base antenna data to generate adjusted latitude, longitude and elevation data for each point collected. It also provides accuracy information for each point in the form of a standard deviation value for latitude, longitude and elevation. To ensure the data collected has the highest precision, rover collected points with standard deviations greater than four inches were not graphed or plotted.

With the data collected from the rover for each cross section accurately adjusted and outliers with large error values removed, the elevation and distance from origin were graphed with the IDNR collected data using a smooth scatter plot chart to allow for a visual comparison of change from year to year. By plotting this data, it also allows for the calculation of change in area under the cross section curve. The linear trapezoidal method was used to approximate the area under the curve using the following formula to calculate the area for each point and summing all areas together for each year. The summed areas were then compared to determine the location of erosion and deposition upstream and downstream of the Hofmann Dam.

$$\text{Area} = \frac{1}{2} * (y_1 + y_2) * (x_1 - x_2)$$

y = elevation (ft)

x = distance from origin (ft)

Gravel size distribution analysis

The bed surface gravel measured upstream and downstream of the Hofmann Dam were charted and sorted by particle size class. The frequency of each particle size class was counted to determine the percentage and cumulative percentage of each size class. The cumulative percentage was plotted versus the log scaled particle size class diameter (mm). This graph allows for the determination of the particle size that correlates with the specific cumulative percentage classically used to compare different river segments. The median grain size is the particle size diameter in which 50% of the sediment by weight is larger, and 50% is smaller (Gordon et al., 2004). In other words, it is the median diameter of the sediment sample. In addition the d_5, d_{16}, d_{84}, and d_{90} were determined. The d_{84} value, for example, is the 84^{th} percentile, or the particle size diameter in which 84% of the sediment by weight is smaller and is one standard deviation away from the mean (Gordon et al., 2004).

HEC-RAS

For preliminary analysis, Hydraulic Engineering Center – River Analysis System, HEC-RAS, a one-dimensional model developed by the U.S. Army Corps of Engineers, was used to determine cross-sectional average velocities, water surface elevations and water depths for the pre and post dam removal conditions. To determine these values the cross-sectional topographic data for 2012 and 2018 were input into the model as well as the field measured water elevation, riverbank location, and distances between each cross-section. Discharge values for the 2, 5, 10, 20, 50, 100, 200, and 500-year flood events were incorporated into the model (Table 2). This study will focus on the 2-year, 20-year and 100-year flood conditions and the changes which have occurred after the removal of the dam. These flood conditions were chosen to represent bank full conditions, a historic flood event and an event in between the two.

Table 2. Discharge values for the Des Plaines River for a given flood condition based on pre removal conditions (U.S. Army Corps of Engineers, 2015)

Flood Condition	**Discharge (ft^3/s)**
2-year	4130.05
5-year	5710.03
10-year	6720.03
20-year	7670.00
50-year	8869.99
100-year	9750.04
200-year	10619.84
500-year	11760.15

CHAPTER V

RESULTS

Cross-Sectional Analysis

Field surveys

Topographical measurements were taken at eleven cross-sections in the Hofmann Dam site. Measurements were taken by the IDNR in 2012 (before dam removal), 2013, 2014 and 2015 (Fig. 12). Cross-section XS1 is located just upstream of the former impoundment created by the Hofmann Dam and is the furthest upstream cross-section. Cross-sections XS2 through XS8 are located within the former impoundment, with XS2 being furthest upstream and XS8 being closest to the Hofmann Dam. There are three cross sections downstream of the dam, XS9 through XS11, the furthest downstream cross section. The results of the topographical measurements were plotted on a smooth line scatter plot to determine the location and timeframe of erosion and deposition. Erosion and deposition are characterized below in terms of the elevation of the channel at key points (channel depth) and cross-section area (percent change from year to year).

The data I collected in 2018 for cross-section XS1 contained large errors for the majority of the points collected on the right bank likely due to the antenna being obstructed by tree cover and not being recorded as an RTK fixed location. Therefore, I isolated points along the left bank that contained minimal error and will use these for cross-sectional analysis for cross-section XS1 (Fig. 17). The data collected by the IDNR at XS1 shows minimal erosion on the left bank from 2012 to 2013, approximately 60 feet from the origin, but the majority of the topography remained constant from year to year with only a 0.01% change in area from 2013 to 2014 and 2014 to 2015 (Table 3).

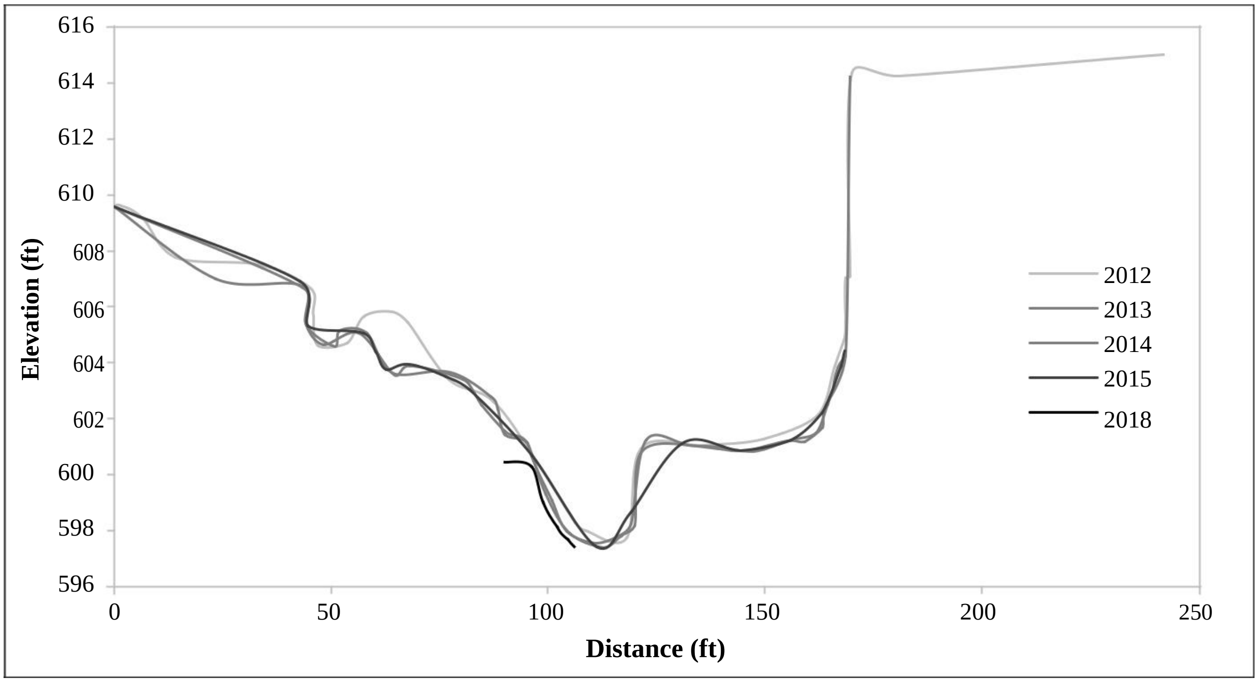

Figure 17: Cross-section XS1, located upstream of former dam impoundment area, looking downstream.

The remaining cross-sections, with the exception of cross-section XS6 did not contain major errors and so surveys were taken across the channel until the water depth was too deep to survey. The main channel at cross-section XS2 shows a pattern of incision with a decrease in channel elevation from 598.02 in 2012 to 596.97 in 2018 (Fig. 18). The right bank of XS2 is also continuing to erode with the largest decrease in elevation 250 feet from the origin and an overall change in area of 0.16% (Table 3). Cross-section XS3 experienced both deposition on the right bank in 2013 and erosion within the main channel in 2018, causing the channel to become flatter and wider (Fig. 19).

Table 3. Year to year and cumulative change in area for each cross-section based on trapezoidal area method

Cross-Section	Survey Year	Cross-Section Area (ft^2)	Year to Year Percentage Change	Year to Year Erosion or Deposition	Cumulative Percentage Change	Cumulative Erosion or Deposition
XS1	2012	63,158.8	-	-	-	-
	2013	63,118.7	0.06%	Erosion	0.06%	Erosion
	2014	63,111.9	0.01%	Erosion	0.07%	Erosion
	2015	63,121.1	0.01%	Deposition	0.06%	Erosion
	2018	I.D.	I.D.	I.D.	I.D.	I.D.
XS2	2012	96,261.2	-	-	-	-
	2013	96,196.4	0.07%	Erosion	0.07%	Erosion
	2018	96,102.4	0.10%	Erosion	0.16%	Erosion
XS3	2012	102,054.5	-	-	-	-
	2013	102,128.9	0.07%	Deposition	0.07%	Deposition
	2018	102,000.6	0.13%	Erosion	0.05%	Erosion
XS4	2013	114,211.9	-	-	-	-
	2018	114,069.6	0.12%	Erosion	0.12%	Erosion
XS5	2013	114,119.3	-	-	-	-
	2014	114,105.6	0.01%	Erosion	0.01%	Erosion
	2015	114,068.3	0.03%	Erosion	0.04%	Erosion
	2018	114,048.1	0.02%	Erosion	0.06%	Erosion
XS6	2012	105,125.2	-	-	-	-
	2013	104,958.5	0.16%	Erosion	0.16%	Erosion
	2018	104,959.0	0.00%	Deposition	0.16%	Erosion
XS7	2012	98,949.2	-	-	-	-
	2013	98,857.0	0.09%	Erosion	0.09%	Erosion
	2018	98,684.8	0.17%	Erosion	0.27%	Erosion
XS8	2012	144,161.1	-	-	-	-
	2013	143,813.8	0.24%	Erosion	0.24%	Erosion
	2018	143,533.9	0.19%	Erosion	0.44%	Erosion
XS9	2012	91,855.1	-	-	-	-
	2013	92,446.0	0.64%	Deposition	0.64%	Deposition
	2018	92,371.4	0.08%	Erosion	0.56%	Deposition
XS10	2012	83,431.5	-	-	-	-
	2013	83,394.1	0.04%	Erosion	0.04%	Erosion
	2018	83,349.3	0.05%	Erosion	0.10%	Erosion
XS11	2013	83,337.7	-	-	-	-
	2014	83,327.6	0.01%	Erosion	0.01%	Erosion
	2015	83,346.8	0.02%	Deposition	0.01%	Deposition
	2018	83,247.0	0.12%	Erosion	0.11%	Erosion

I.D. = Insufficient Data

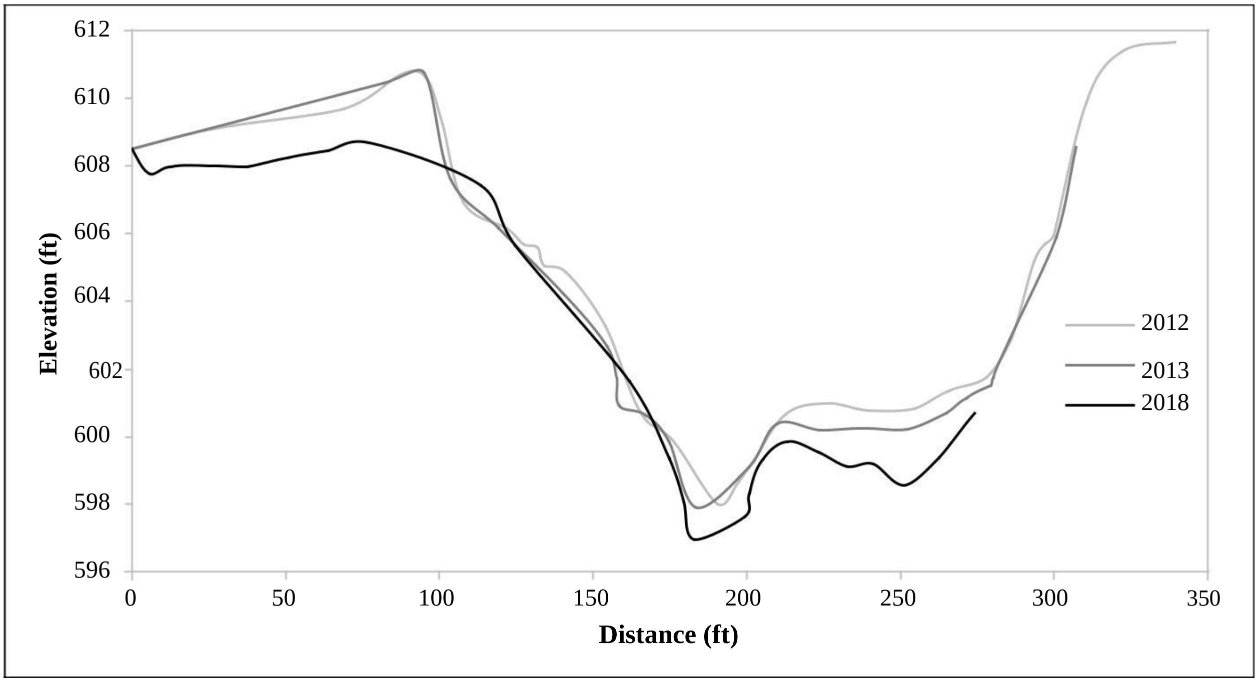

Figure 18: Cross-section XS2, located at the start of former dam impoundment area, looking downstream.

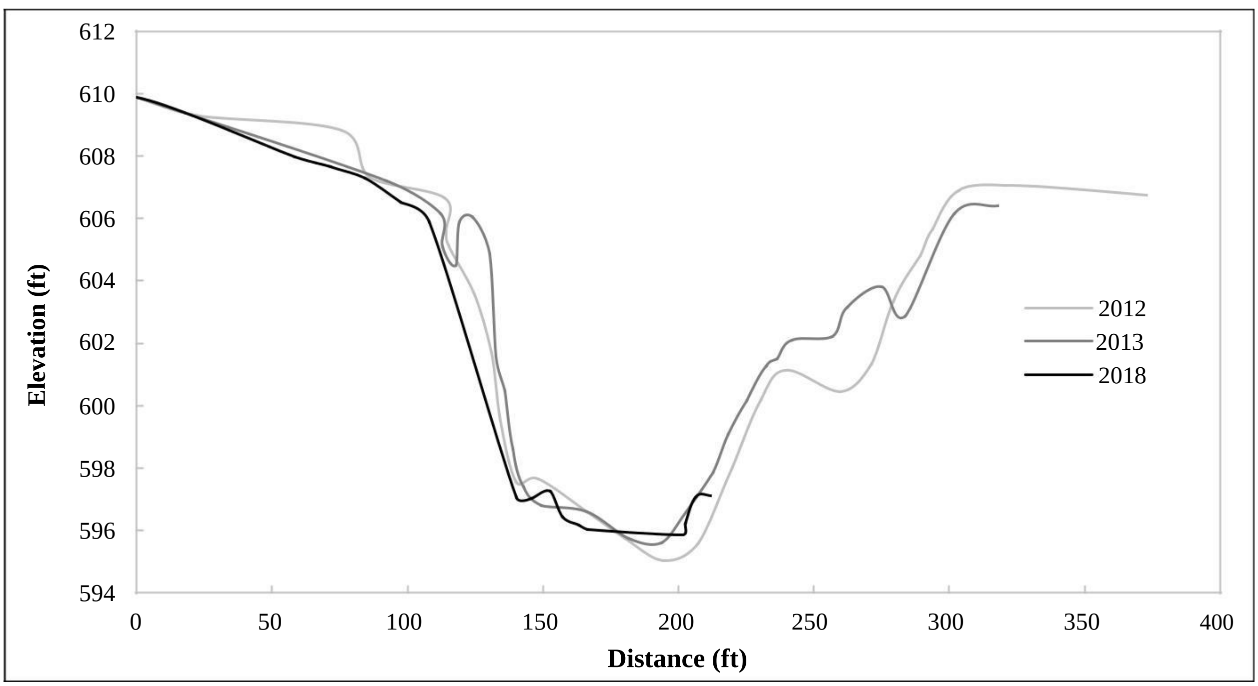

Figure 19: Cross-section XS3, located in former dam impoundment area, looking downstream.

The IDNR did not collect data in 2012, pre Hofmann Dam removal, for both cross-sections XS4 and XS5. The channel for XS4 has been flattening and widening, similar to XS3, with erosion occurring on the left bank and left side of the channel from 2013 to 2018 (Fig. 20). Cross-section XS5 experienced the least amount of change in area caused by erosion from year to year with 0.01%, 0.03% and 0.02% change for 2014, 2015 and 2018, respectively (Table 3). The topographic data collected for XS5 did not show a consistent pattern of deposition or erosion from year to year except for the left side of the channel near 250 feet from the origin which experienced erosion in 2014, 2015 and 2018 (Fig. 21). Similar to XS1, the data collected in 2018 for cross-section XS6 had a large error deviation for the elevation values, particularly on the left bank. However, in the main channel an incision occurred between 2012 and 2013, decreasing the channel elevation from 598.5 feet to 594.6 feet (Fig. 22).

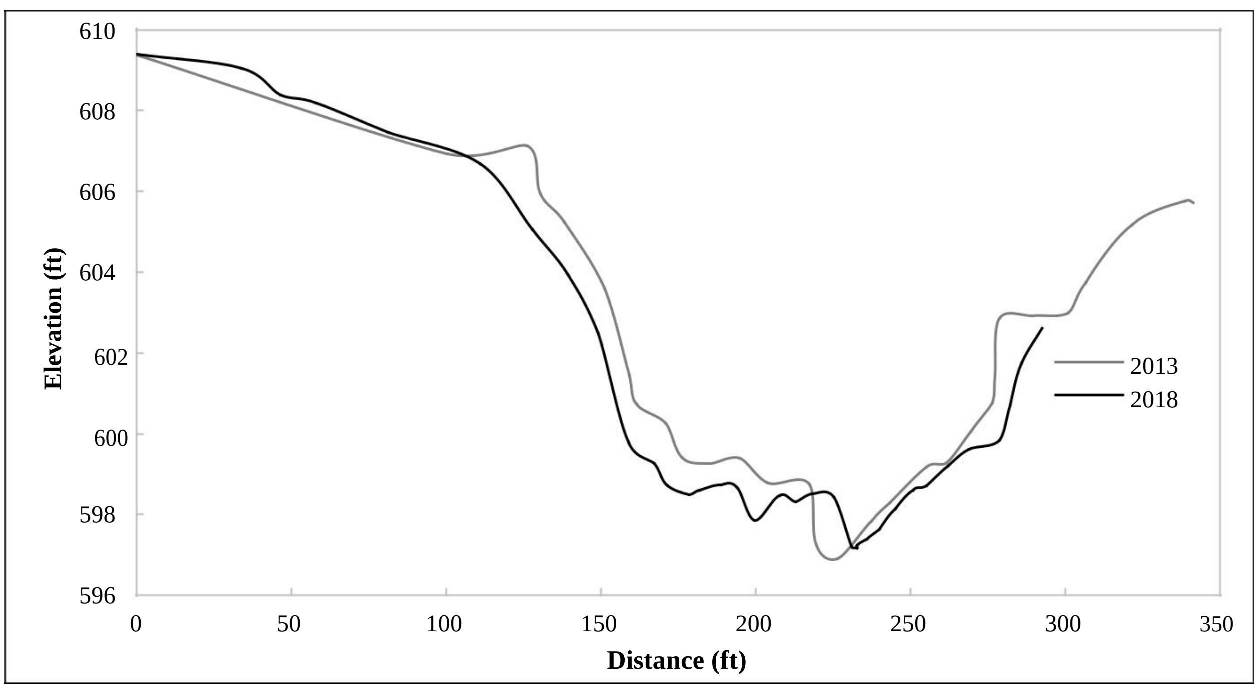

Figure 20: Cross-section XS4, located in former dam impoundment area, looking downstream.

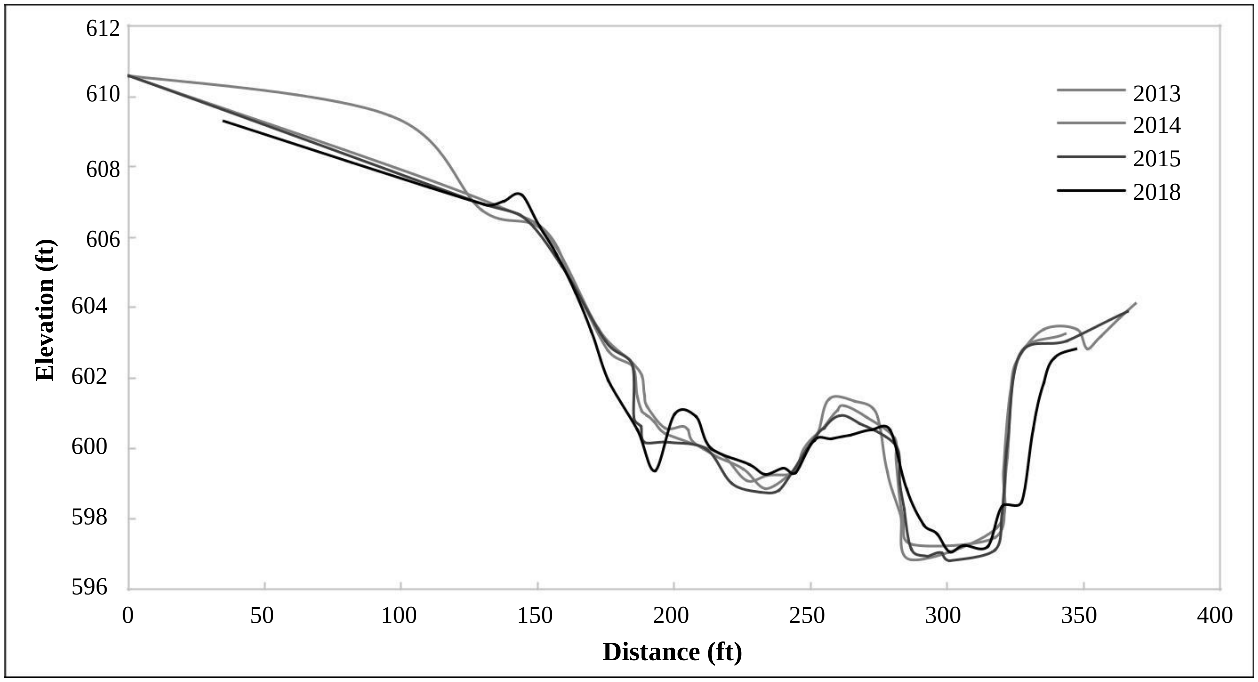

Figure 21: Cross-section XS5, located in former dam impoundment area, looking downstream.

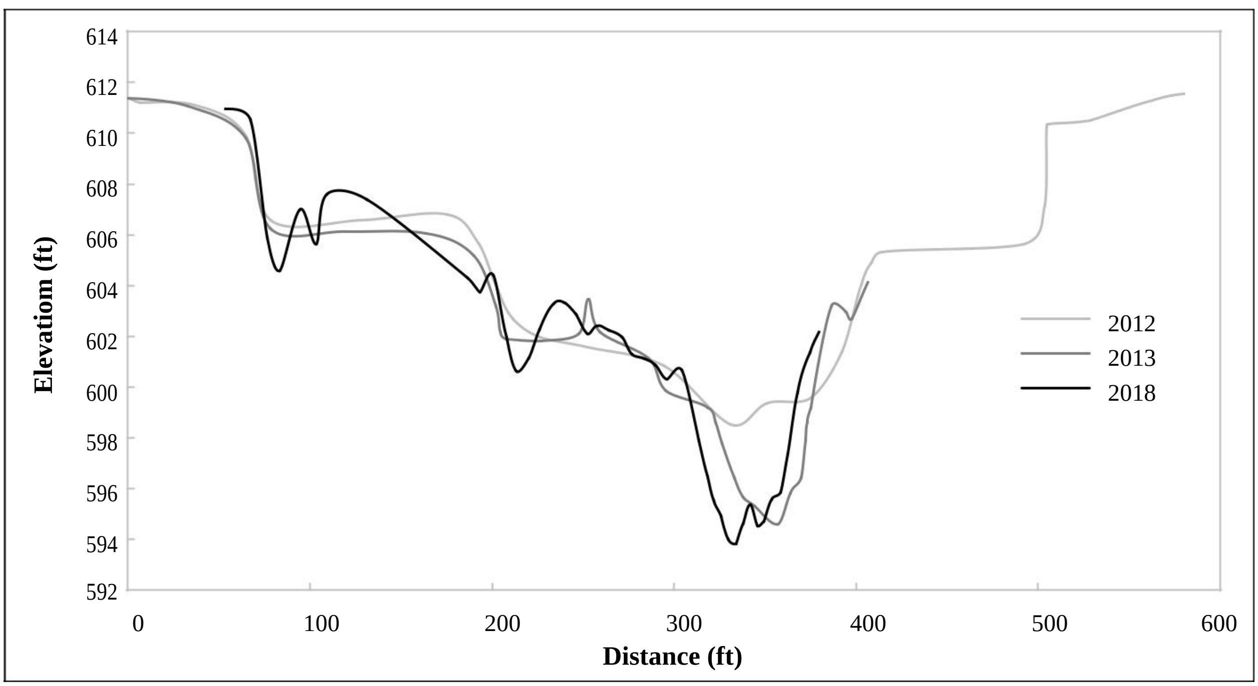

Figure 22: Cross-section XS6, located in former dam impoundment area, looking downstream.

The two cross-sections closest to the Hofmann Dam, XS7 and XS8, experienced the largest amount of cumulative erosional area change from 2012 to 2018 with 0.27% for XS7 and 0.44% for XS8 (Table 3). For cross-section XS7, incision in the thalweg occurred after the removal in 2012 and in 2018 erosion occurred predominately on the left bank (Fig. 23). A thalweg shift occurred from 125 feet from the origin to the left side of the channel at cross-section XS8 from 2012 to 2013 creating an island bar between 150 and 175 feet from the origin. The channel also had a substantial decrease in elevation from 598.4 feet to 596.1 feet. In 2018, the channel widened at XS8 and the thalweg transitioned to the right side of the channel with an elevation of 595.3 feet (Fig. 24).

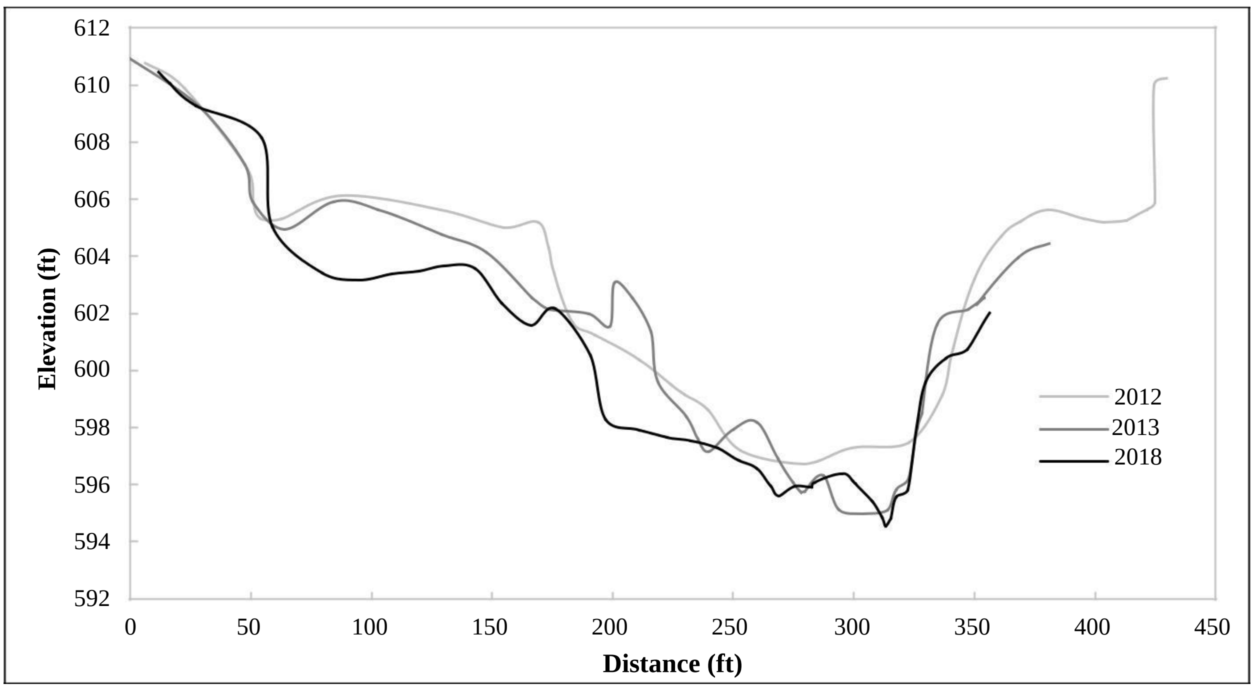

Figure 23: Cross-section XS7, located in former dam impoundment area, looking downstream.

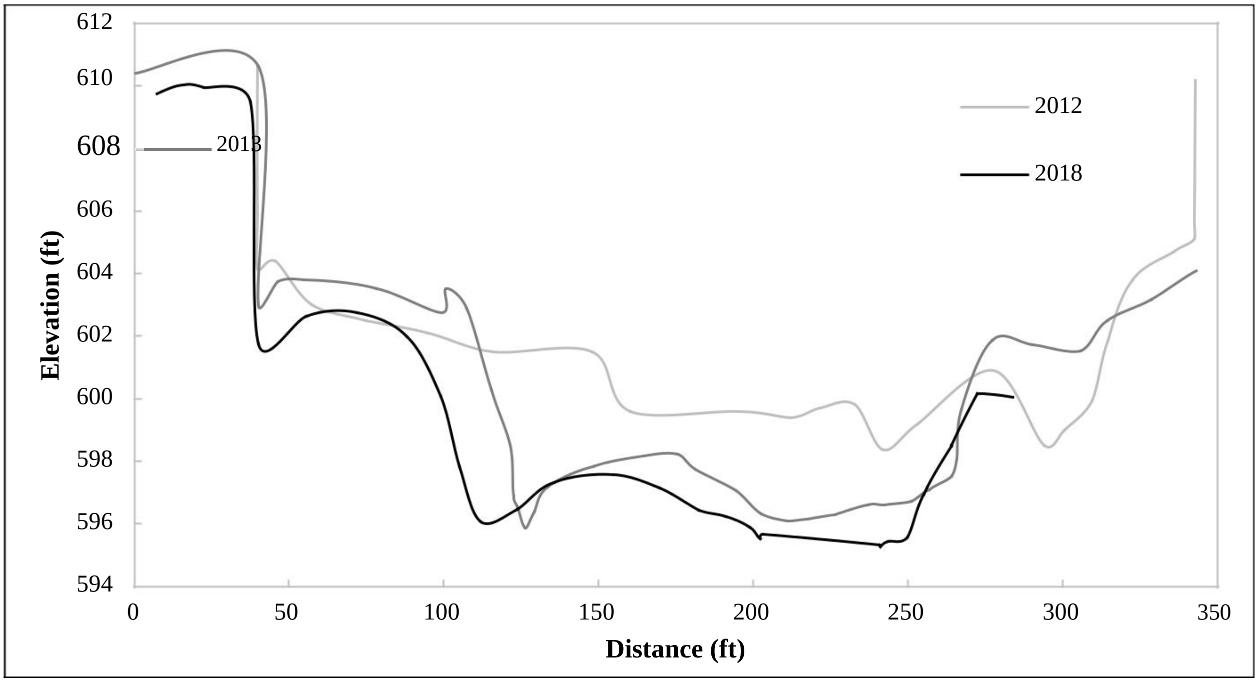

Figure 24: Cross-section XS8, located in former dam impoundment area, looking downstream.

Of the three cross-sections located downstream of the Hofmann Dam, only one cross-section, XS9 experienced measurable deposition with a change in area of 0.64% (Table 3). The deposition created two island bars between 30 and 50 feet from the origin, downstream of the remnants of Hofmann Dam, and 100 to 150 feet from the origin (Fig. 25). From 2013 to 2018, erosion was occurring in the main channel at XS9 between 150 and 200 feet from the origin with a change in area of 0.08% (Fig. 25). Erosion in the thalweg migrated downstream to cross-section XS10 resulting in an elevation change of 1.53 feet between 2012 and 2013 and a continued change occurred between 2013 and 2018. However, due to unsafe conditions, the thalweg was unable to be measured (Fig. 26). At the furthest downstream cross-section, XS11, minimal change in area occurred: 0.01%, from 2013 to 2015 (Table 3). In 2018, erosion occurred throughout the channel with a decrease in bed elevation from 593.43 to 592.73 feet (Fig. 27).

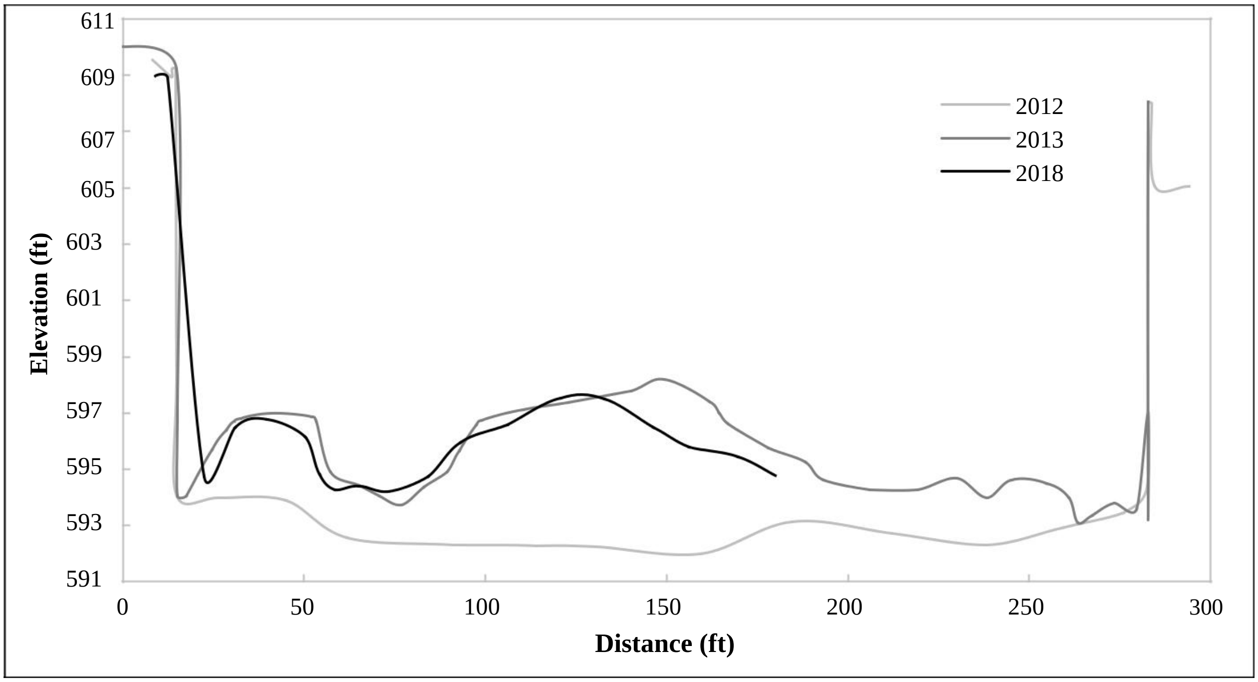

Figure 25: Cross-section XS9, located downstream of Hofmann Dam, looking downstream.

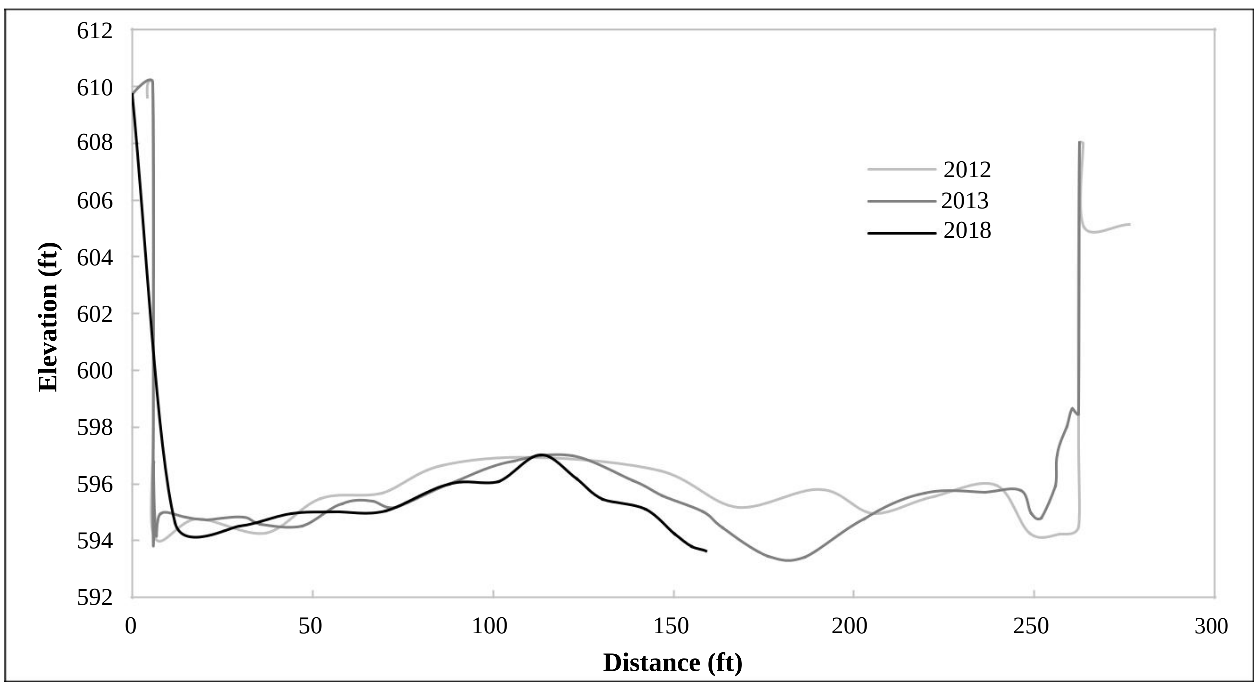

Figure 26: Cross-section XS10, located downstream of Hofmann Dam, looking downstream.

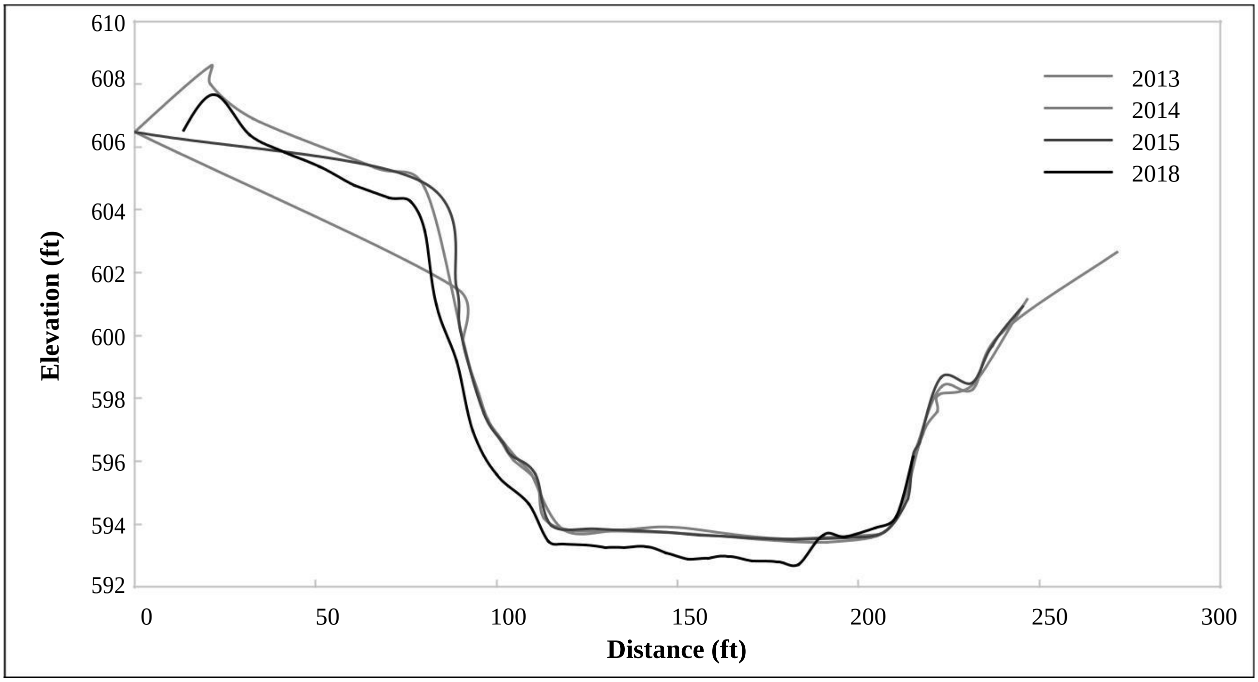

Figure 27: Cross-section XS11, located downstream of Hofmann Dam, looking downstream.

Statistical analysis

I conducted a repeated measures ANOVA test using the statistical software R for both the upstream and downstream cross sections to determine the statistical significance of channel changes represented by the thalweg riverbed elevation. Table 4 shows the average riverbed elevation for each cross-section for the surveyed years below the elevation cap of 606 feet. The null hypothesis for the repeated measures ANOVA study was that the means of the average elevations for each year are all equal. If one of the means of average elevation were significantly different than the other two groups then the null hypothesis would be rejected. Upstream of the dam, the null hypothesis that there was no significant average elevation change upstream of the dam from 2012 to 2013 to 2018 could not be rejected (p value = 0.290) (Table 5). A post hoc analysis was also completed and confirmed there was no significant elevation change. In addition, the null hypothesis for no change downstream of the dam could not be rejected (p = 0.852) (Table 5) meaning that like the upstream elevations, there were no statistically significant changes in average elevation downstream. Therefore, any changes observed in stream depths upstream or downstream of the dam are not statistically significant.

Although the null hypotheses for both the upstream and downstream cross-sections failed to be rejected, the strip chart and plot of means for the upstream cross-sections showed a trend of decreasing average elevations for each cross-section from 2012 to 2013 to 2018 (Fig. 28A & Fig. 29A). The downstream cross-sections average elevations did not have a distinguishable trend from year to year with a slight increase in average elevation from 2012 to 2013 and slight decrease from 2013 to 2018 (Fig. 28B & 29B).

Table 4. Average elevation for each year at each cross-section upstream and downstream of the Hofmann Dam

Cross Section	Year	Average Elevation (ft.)
XS1	2012	602.74
	2013	602.37
	2018	600.45
XS2	2012	602.52
	2013	602.25
	2018	601.68
XS3	2012	601.64
	2013	601.22
	2018	599.92
XS6	2012	599.33
	2013	598.82
	2018	599.12
XS7	2012	598.08
	2013	599.66
	2018	600.22
XS8	2012	599.58
	2013	598.76
	2018	597.94
XS9	2012	593.66
	2013	595.43
	2018	595.68
XS10	2012	595.61
	2013	595.53
	2018	595.12
XS11	2012	597.00
	2013	596.31
	2018	596.45

Table 5. Repeated measures ANOVA results for upstream and downstream cross sections

Source	SSn	SSd	DFn	DFd	F	p	Mauchly's p
Upstream	1.956	6.970	2	10	1.406	0.2897	0.0923
Downstream	0.219	2.617	2	4	0.167	0.8517	0.365

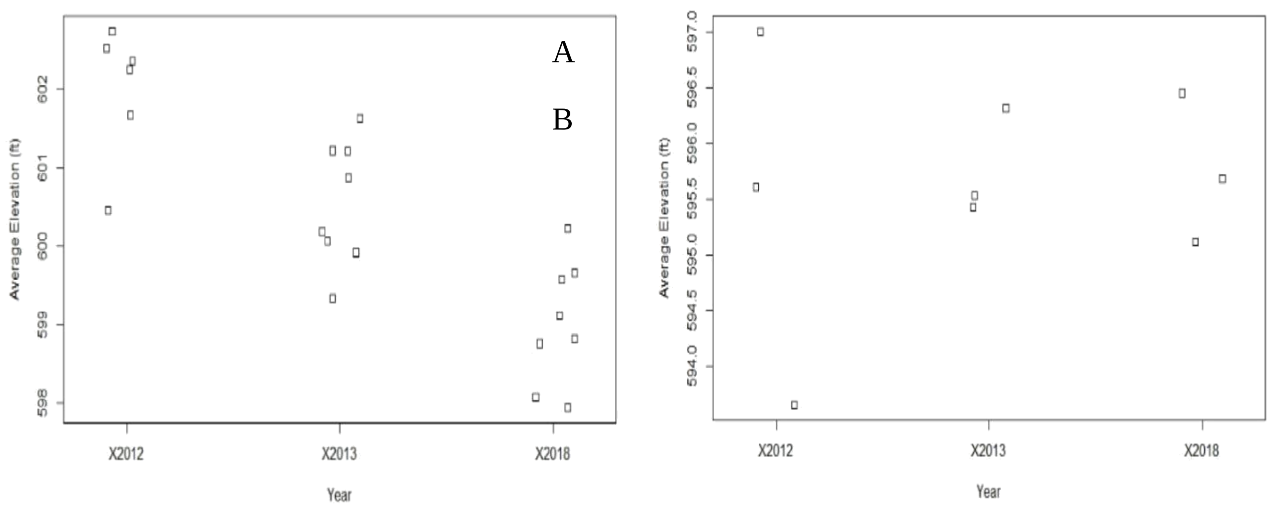

Figure 28: Strip chart of the average elevation of the cross-sections for a given year. A = Upstream of Hofmann Dam, B = Downstream of Hofmann Dam

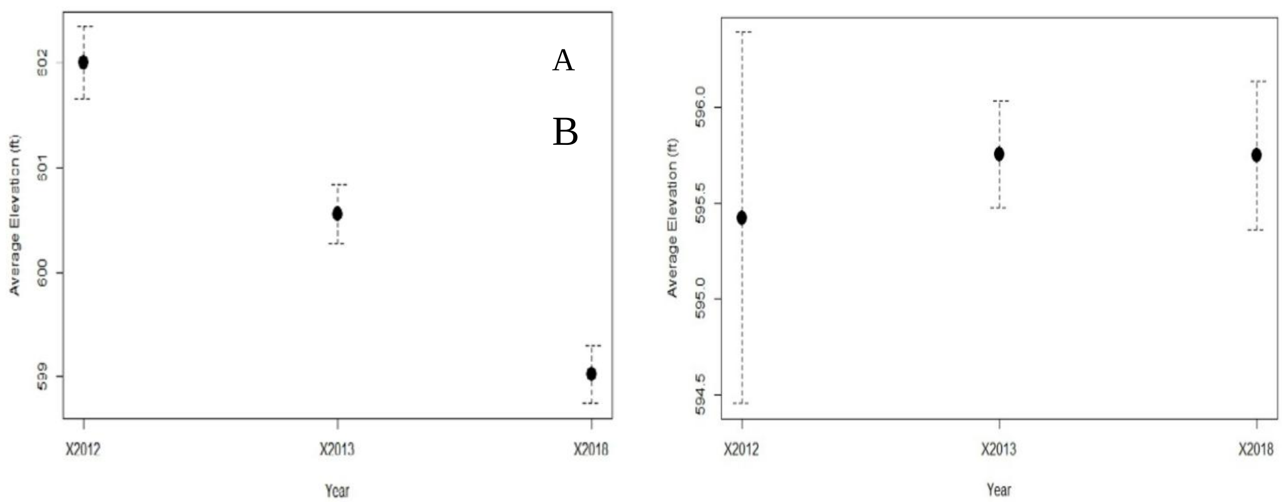

Figure 29: Plot of means for a given year of the average depth of the cross-sections. A = Upstream of Hofmann Dam, B = Downstream of Hofmann Dam

Sediment Characteristics

The particle size distributions of bed sediment upstream and downstream of the Hofmann Dam were plotted on cumulative particle size distribution curves to determine the median particle size (50th percentile, d_{50}), and coarse particle size (84th percentile, d_{84}), as well as d_5, d_{16}, and d_{90} (Fig. 30). These values are shown in Table 6. The upstream d_5, d_{16} and

d_{50} particle sizes are larger than the equivalent percentiles for downstream. The d_{16} dimensions for the upstream survey is 1.38 inches, which represents very coarse gravel. The downstream survey d_{16} dimensions of 0.63 inches equates to a coarse gravel. The median particle size for the upstream survey is described as a small cobble with a size of 3.15 inches. Downstream of the dam, very coarse gravel defines the 2.20 inches median particle size. The two largest percentiles measured, d_{84} and d_{90}, were identical for both the upstream and downstream surveys with values of 6.30 and 6.69 inches, respectively. These particles sizes correlate to a large cobble.

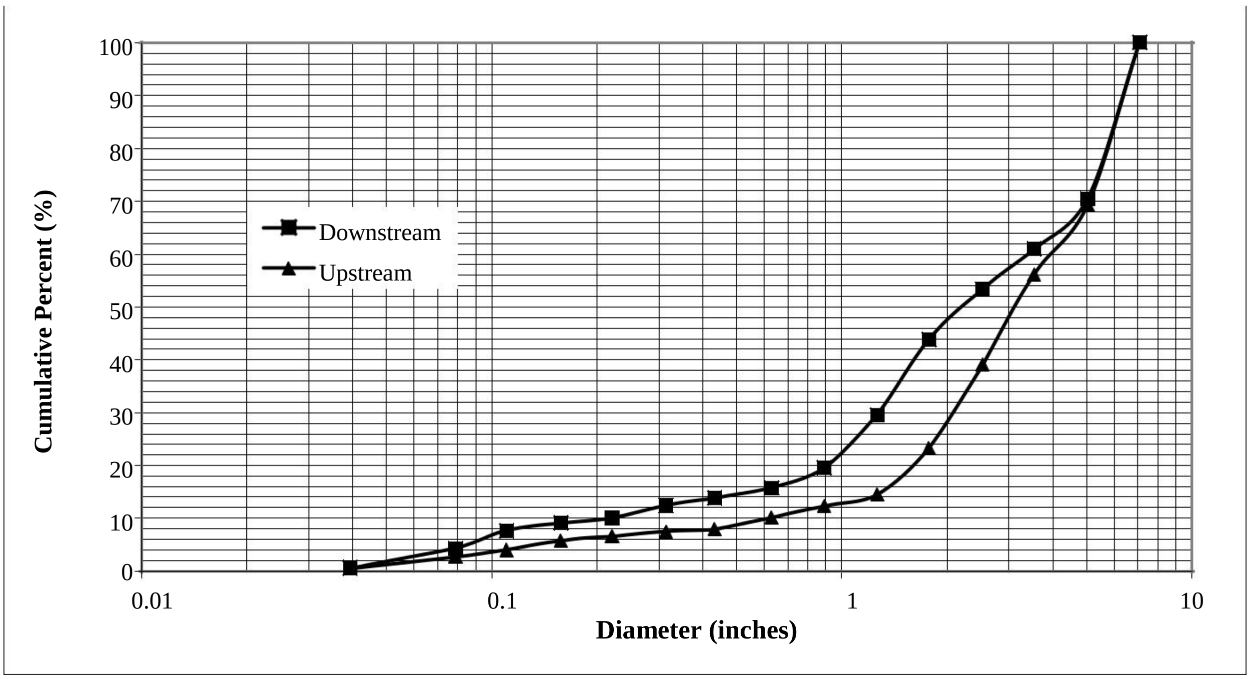

Figure 30: Cumulative particle size distribution curves for upstream and downstream of the Hofmann Dam collection areas.

Table 6. Cumulative particle size values for upstream and downstream of Hofmann Dam collection areas

Location	Diameter Values				
	d_5 (in)	d_{16} (in)	d_{50} (in)	d_{84} (in)	d_{90} (in)
Upstream	0.15	1.38	3.15	6.30	6.69
Downstream	0.09	0.63	2.20	6.30	6.69

HEC-RAS Analysis

The HEC-RAS models were run to determine the average depth and average velocity at each cross-section before removal in 2012 and after the Hofmann Dam was removed in 2018 for 2, 5, 10, 20, 50, 100, 200 and 500-year flood conditions. The results of the 2, 20, and 100-year flood conditions are presented here to represent bank full conditions, a historic flood event and an event in between the two. The results for the remaining flood conditions as well as the calibration error of the model can be found in Appendix A.

Upstream of the dam at cross-section XS3, before the dam was removed, average depths increased with increasing flood intensities but average velocities decreased (Table 7). After removal, average depths still increased with increasing flood intensities, while, average velocities also increased with increasing flood intensities. Confirming the data shown in the cross-section graphs, average water depths increased after removal at cross-section XS3. However, at cross-section XS8, average water depths decreased after removal even with the cross-section data indicating erosion occurred throughout the channel.

Immediately downstream of the Hofmann Dam at cross-section XS9, average depths decreased after the dam removal (Table 8). The decrease in average depth caused the average velocities to increase after removal. After removal, at XS9, average velocities increased from

2-year, 5.28 ft/s to a 20-year flood condition, 5.68 ft/s but decreased to 5.35 ft/s at a 100-year flood condition (Table 8). Average depths and average velocities at cross-section XS10 remained relatively constant before and after dam removal with an average change in average velocity of 0.23 ft/s and depth of 0.36 feet.

Table 7. Average depth and average velocity for given flood conditions upstream of the Hofmann Dam

	Cross-Section							
	XS3				XS8			
	Pre Removal		Post Removal		Pre Removal		Post Removal	
Flood Condition	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)
2-year	5.28	4.99	7.84	3.31	11.94	2.95	8.83	4.72
20-year	8.56	4.27	11.09	3.67	14.60	3.48	11.71	5.94
100-year	10.20	4.27	12.73	3.90	15.75	3.71	13.25	6.07

Table 8. Average depth and average velocity for given flood conditions downstream of the Hofmann Dam

	Cross-Section							
	XS9				XS10			
	Pre Removal		Post Removal		Pre Removal		Post Removal	
Flood Condition	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)	Depth (ft)	Velocity (ft/s)
2-year	9.28	4.07	8.10	5.28	10.70	5.02	10.43	4.89
20-year	12.01	4.72	10.99	5.68	12.96	6.10	13.35	6.07
100-year	13.16	4.92	12.70	5.35	14.40	6.76	14.83	6.17

CHAPTER VI

DISCUSSION

Discussion

Although I found no significant statistical relationship in the data, I found larger patterns with regard to the impact of the Hofmann Dam removal along the Des Plaines River. *Overview*

Channel shape response differed upstream and downstream of the dam site. Erosion occurred immediately after the removal of the Hofmann Dam creating an incision that migrated upstream to furthest upstream cross-section, XS2, between 2013 and 2018. This incision caused the channel to increase in depth and decrease in width throughout the impoundment. Although erosion occurred rapidly after removal, it is still occurring at cross-sections XS2, XS4, XS7 and XS8 with elevation changes of more than 1 ft. measured within the channel between 2013 and 2018. Downstream of the dam, an increase in the riverbed elevation was only measured at cross-section XS9, the closest cross-section to the dam, between 2012 and 2013. After this initial deposition, erosion began to occur at cross-sections XS9 and XS10 between 2013 and 2018 and will likely continue until bedrock is reached at an elevation of 593.0 ft. The removal of the Hofmann Dam had decreasing effects with increasing downstream distance.

Sediment size distribution and sediment characteristics differ upstream and downstream of the dam site. Deposition of the fine sediment that was eroded from the impoundment area was only measured downstream of the remnants of the Hofmann Dam. The remaining sediment was likely deposited further downstream of the study site and on the

flood plains after the two large flood events in 2013 and 2014. Although fine sediment was only detected in these two areas, the erosion and deposition of coarse gravels and small cobbles, 0.6 to 3.2 inches in size, immediately downstream of the dam resulted in the particle size diameters for the d_5, d_{16}, and d_{50} to be smaller downstream than upstream of the dam.

Topographical changes caused by the Hofmann Dam removal have modified the flow characteristics of the Des Plaines River. The increased depths of the riverbed created by the incision caused the average flow velocities to decrease in the furthest upstream cross-sections within the impoundment area. However, the increased depth with the narrowing of the channel at upstream cross-sections closest to the dam, XS7 and XS8, increased the average flow velocities causing the creation of riffles and runs. These riffles and runs stretched downstream to XS9 where the decrease in riverbed depth also resulted in the average flow velocities to increase. The decreasing downstream effects of the Hofmann Dam removal resulted in minimal change in average water depth and average flow velocity for the cross-sections furthest downstream, XS10 and XS11.

Upstream

Immediately after the removal of the Hofmann Dam the Des Plaines River channel upstream of the dam began to narrow. This narrowing occurred throughout the 6-acre impoundment area within one-year after the removal. Measurable changes were observed at each cross-section upstream of the dam except for the only cross-section upstream of the former impoundment, XS1, which likely did not experience any changes because it was not impacted by the impoundment or dam. Also occurring directly after removal within the previous lacustrine environment, an incision formed near the base of the riprap installed during removal on the right bank. Similar to the channel narrowing, the incision, which created a defined thalweg, migrated upstream. However, the incision took between 2013 and 2018 to migrate to the upper reaches of the impoundment. These geomorphic changes were influenced by the placement of riprap on both banks preventing the natural migration of the river and causing the thalweg to increase in depth, thus adjusting its channel morphology to accommodate the flows.

Located approximately 1,850 feet upstream of the dam, outside of the dam impoundment, cross-section XS1 was not expected to experience measurable geomorphic changes. This was proven accurate with the cross-sectional measurements displaying consistent measurements from 2012, 2013, 2014 and 2015, expect for slight erosion of a mound in 2013 at 60 feet from the origin (Fig. 17). Due to the consistency of the surveys taken at this location for the following two years, it may be that this mound measured in 2012 was caused by a measurement error. The most notable erosion that occurred upstream of the dam was at XS2, near the upper reaches of the impoundment 1,000 feet from the dam, where the thalweg increased in depth and the right bank eroded. For this project, a notable change in either erosion or deposition is defined as a change in the riverbed elevation of at least one foot from year to year. The pronounced change in area as a result of the depth of the thalweg increasing by 1.0 ft. occurred between 2013 and 2018 but the exact timeframe is unknown due to missing data in the intervening years. This delayed response mimics the effects of the removal of Stronach Dam with the migration of the incision taking approximately six years to reach the farthest upstream extent of the original impoundment, 3.9 km or 12,700 feet from the dam (Burroughs, Hayes, Klomp, Hansen, & Mistak, 2009).

Further downstream, the 7,500 tons of riprap installed on the banks begins to have an effect on the topographic changes. This becomes evident at XS3 where deposition is visible on the right bank and both banks increasing in slope between 2012 and 2013. This was also evident within the HEC-RAS models which showed an increase in average water depths after the removal of the dam. The increasing slopes on the banks are also prominent at cross-section XS6 confining the channel to a width of 52 feet, the narrowest width throughout the study area (Fig 31 and Fig 32). Narrowing the channel resulted in increased flow velocities, as evidenced within the HEC-RAS model that caused the thalweg to quickly increase in depth by 3.9 feet between 2012 and 2013 to adjust to flow conditions. This change in elevation was the second largest change in riverbed elevation behind only that that occurred at cross-section XS8. Erosion continued in the thalweg between 2013 and 2018 increasing the depth another 0.7 feet but nearly 85% of the change in channel depth and approximately 99% of the change in cross-section area occurred within the first year after removal.

Figure 31: Satellite image of Hofmann Dam study site, 2012 (Google Earth, 2018)

Figure 32: Satellite image of Hofmann Dam study site, 2013 (Google Earth, 2018)

As expected and historically measured at both low-head dam removals like the Stronach Dam and large dam removals like the Elwha Dam in Washington State, the largest changes in cross-sectional area occurred closest to the Hofmann Dam at cross-sections XS7 and XS8 (Burroughs et al., 2009; Warrick et al., 2015). With its right bank located on the outside edge of a bend reinforced by riprap, an incision formed quickly creating a thalweg at the base of the riprap at cross-section XS7 between 2012 and 2013, similar to XS6 (Fig. 32). This incision caused the thalweg to increase 2.3 ft. in depth, the third largest increase in the impoundment area. However, unlike XS6, the change in cross-section caused by erosion between 2013 and 2018 was larger than between 2012 and 2013. This erosion occurred predominantly on the left bank, which has shallower sloped banks and is less fortified by riprap. During high flow events, the left bank becomes inundated and the stored sediment deposited by the slower water velocities when Hofmann dam was in operation begin to mobilize and the sediment is transported downstream. This results in the channel becoming wider and flatter near the dam. The closest upstream cross-section to the dam, XS8, confirmed this trend was continuing up until the base of the dam remnants.

Similar to the other cross-sections in the impoundment area, erosion occurred quickly and an incision formed a thalweg at XS8 after the dam was removed. Initially, the thalweg was located near the left bank after erosion caused a change in riverbed elevation of 5.6 ft., the largest in the impoundment area. However, sediment continued to be eroded with a similar change in area between 2012 and 2013, 0.24% and 2013 to 2018, 0.19%. The erosion between 2013 and 2018 removed another 1.3 ft. of sediment near the right bank and createda new thalweg location. Like XS7, the riprap on the right bank limited erosion with the change in cross-section area predominantly occurring in the channel and the left bank even with large amounts of riprap installed. Due to the shallow left bank slope at XS7, the water that inundates this area during high discharge events continues to flow downstream behind the higher sloped riprap bank at XS8 and continuing until the dam (Fig. 33). The water erodes the unprotected soils behind the riprap causing the riprap to migrate further into the bank, widening and flattening the river channel. Measurements from 2013 to 2018 at XS8 provide evidence of the migration of the bank and flattening occurring (Fig. 33 and Fig. 34). This flattening allowed for the creation of riffles and runs near the dam increasing the habitat heterogeneity of the river (Benstead, March, Pringle, & Scatena, 1999). Along with the visual confirmation of riffles and runs created, the HEC-RAS models calculated an increase in average water velocity and decreased in average water depths after the removal of the dam.

Figure 33: Satellite image of Hofmann Dam study site, 2017 (Google Earth, 2018)

Figure 34: Satellite image of Hofmann Dam study site, 2018 (Google Earth, 2018)

Downstream

Similar to previous work on dam removals, I found primarily erosion occurring upstream of the impoundment (Burroughs et al., 2009). Therefore, deposition of this eroded sediment was expected downstream of the dam. At the cross-section closest to the dam, XS9, deposition occurred throughout the channel one year post removal. The largest change in elevation was measured in the middle of the channel with approximately 6.3 ft. of sediment deposited. This deposition caused the average water depths to decrease and average water velocities to increase after the dam removal as an adjustment to the new channel shape. The main areas of deposition were located in the center of the channel with the creation of an island bar and just beyond the remnants of the dam on the left bank. The island bar is approximately 60 feet wide near the dam, tapering further downstream, and 100 feet long and consists of similar size coarse gravel with a sediment size class range of 0.63 inches to 2.20 inches (Fig. 34). This range is not consistent with the core samples collected within the impoundment area by the IDNR prior to removal (Table 9) meaning that likely other sediment material, and not material initially behind the dam, has deposited here in the time since removal. This leads to the possibility that there may have been significant changes in sediment composition at this site over time. The sediment class range collected from the island bar in 2018 is larger than the largest sediment collected in the 12 core samples collected in the impoundment prior to removal (Table 6 and Table 9). The source of the larger gravel in the island bar could be from the riprap placed on the upstream banks or from the material used to fill the scour trench created at the base of the dam by water flowing over Hofmann Dam prior to removal just upstream from XS9 (Fig. 35).

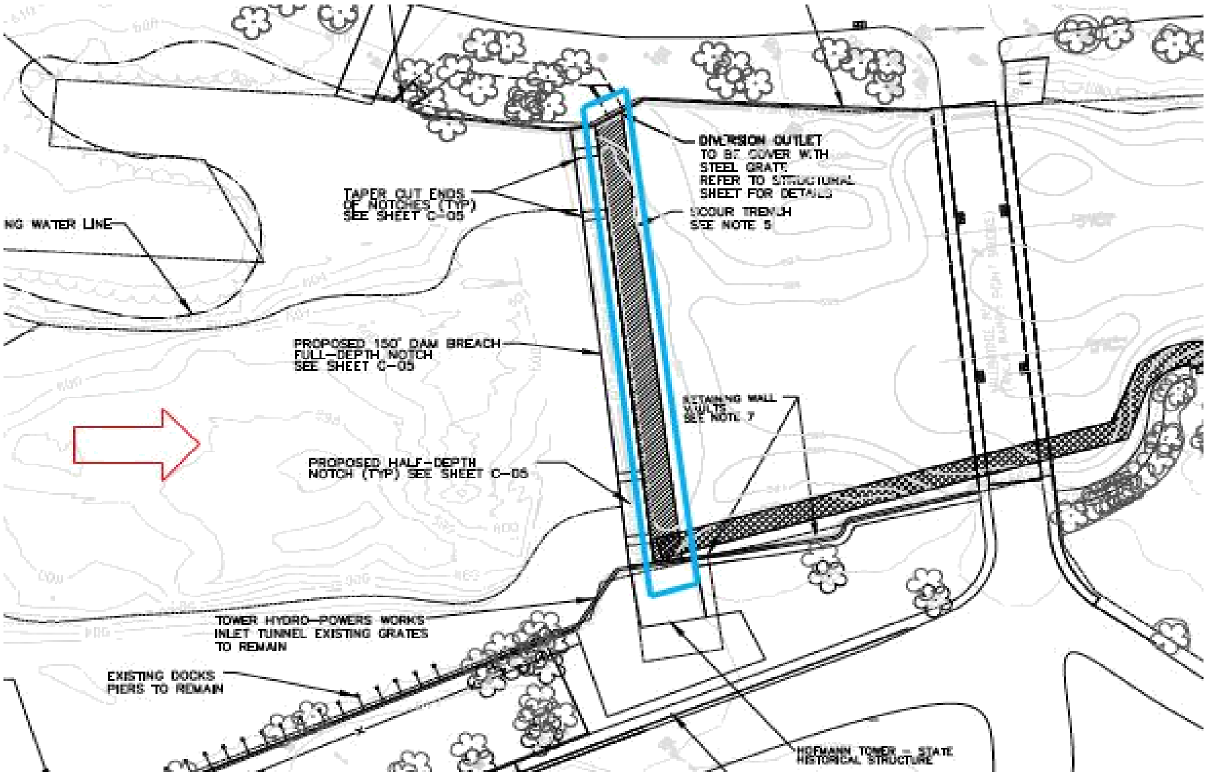

Figure 35: Location of scour trench (blue) downstream of the former Hofmann Dam. The red arrow represents direction of flow (modified from IDNR, 2015).

The other location of measurable deposition downstream of the dam is where fine sediment material deposited just downstream of the remnants of the dam on the left bank can be observed. When the dam was removed, portions of the dam were left on the far right and far left banks of the river to protect the embankment walls from erosion (Fig. 35). On the left bank, the remaining 54 foot long piece of the dam along with the abrupt widening of the river channel, created a lentic condition where the remaining dam portion blocks water flow such that flows are slow enough to allow for the deposition of approximately 3.1 ft. of fine sediment (Fig. 25). Deposition of fine sediments only occurred behind the remaining dam on the left bank and not the right bank likely due to the location of the left bank dam remnants being on the inside edge of a bend where slower flows and deposition naturally occurs. This area has remained unchanged from 2013 to 2018 and will likely remain this way until a flow condition is large enough to inundate the dam remnants. A core sample was taken at this location but due to time constraints has yet to be analyzed for comparison. The remaining fine sediment, silts and clays, previously present in the impoundment (IDNR core samples) were likely transported further downstream, outside of the study area, and deposited in the flood plain, rather than in the stream, during high flow events. This assumption is evident in the changes measured in the remaining two downstream cross-sections XS10 and XS11 where erosion primarily occurred.

Table 9. Cumulative particle size values for core samples collected by IDNR prior to removal

IDNR Core Sample	**Diameter Values**			
	$\mathbf{d_{10}}$	$\mathbf{d_{30}}$	$\mathbf{d_{60}}$	$\mathbf{d_{100}}$
#8	0.010	0.049	1.795	41.667
#10	0.010	0.200	4.626	62.336
#11	0.007	0.016	0.154	6.562
#12	0.007	0.016	0.049	6.562
#16	0.013	0.207	2.516	62.336
#17	0.010	0.030	0.105	6.562
#18	0.007	0.023	0.062	6.562
#19	0.013	0.072	0.384	31.168
#21	0.902	2.195	5.417	62.336
#22	0.007	0.023	0.305	62.336
#23	0.023	0.213	0.538	31.168
#24	0.007	0.016	0.059	62.336

Instead of the expected measurable deposition at cross-sections XS10 and XS11, erosion occurred post dam removal. With the location of XS10 being only 50 feet downstream of the dam, deposition was assumed to occur after the dam removal similar to what was observed at XS9. The thalweg at XS10 transitioned from the left bank to near the center of the channel in line with the edge of the dam remnants on the right bank. This incision continued to increase in depth while migrating toward the island bar in the middle of the stream from 2013 to 2018 with the depth of the thalweg unable to be measured due to safety issues. Although the thalweg increased in depth by approximately 2.4 ft., the largest decrease in riverbed elevation downstream of the dam, the average water velocities and depths did not experience significant changes after removal. The channel at XS10 may have been at sediment storage capacity with the appearance of a small island bar present before the dam removal in 2012 (Fig. 26). Mobilized sediment became trapped at the start of the bar causing the island bar to migrate upstream past cross-section XS9 to the Hofmann Dam. When the sediment storage capacity was reached just downstream of the dam, the incision began to also migrate upstream. This is evident by the erosion of the right side of the island bar and the creation of a thalweg at XS9 in 2018. In the future, this incision will likely continue to increase the depth of the thalweg until it reaches bedrock at an elevation of approximately 593.0 feet (IDNR, 2015).

At XS11, it is likely minimal measurable changes occurred due to it being the furthest cross-section downstream at a distance of approximately 400 feet from the dam. The leads to the conclusion that while deposition occurred minimally close to the dam, this effect diminished with increasing distance from the dam. Unfortunately, the IDNR did not collect data for XS11 before the removal in 2012 but the following three years did not experience any significant erosion or deposition within the channel despite a 500-year flood in 2013 and a 100-year flood in 2014. The HEC-RAS model results show a similar result where minimal changes in channel depth led to minimal changes in velocity this far downstream from the dam removal. It was not until between 2015 and 2018 where erosion occurred within the center of the channel and at left bank causing a decrease in riverbed elevation of approximately 0.8 ft. Despite the lack of any major flood events that were larger than a 10-year flood condition, erosion still occurred due to normal discharges present within the channel.

Although measurable deposition downstream of the dam was predicted to occur, this assumption should have been reconsidered with the data provided from the removal of the Stronach Dam showing only 14% of the sediment eroded from the impounded area was retained in the river within 1 kilometer downstream of the dam. Along the Des Plaines River, the two large flood events occurring after the removal likely transported much of the sediment downstream past the last cross-section XS11. It was also likely deposited within the surrounding 100 year flood plain shown in Figure 36. Therefore, the adjustments on the Des Plaines River are similar to those on the Pine River where the Stronach Dam was removed.

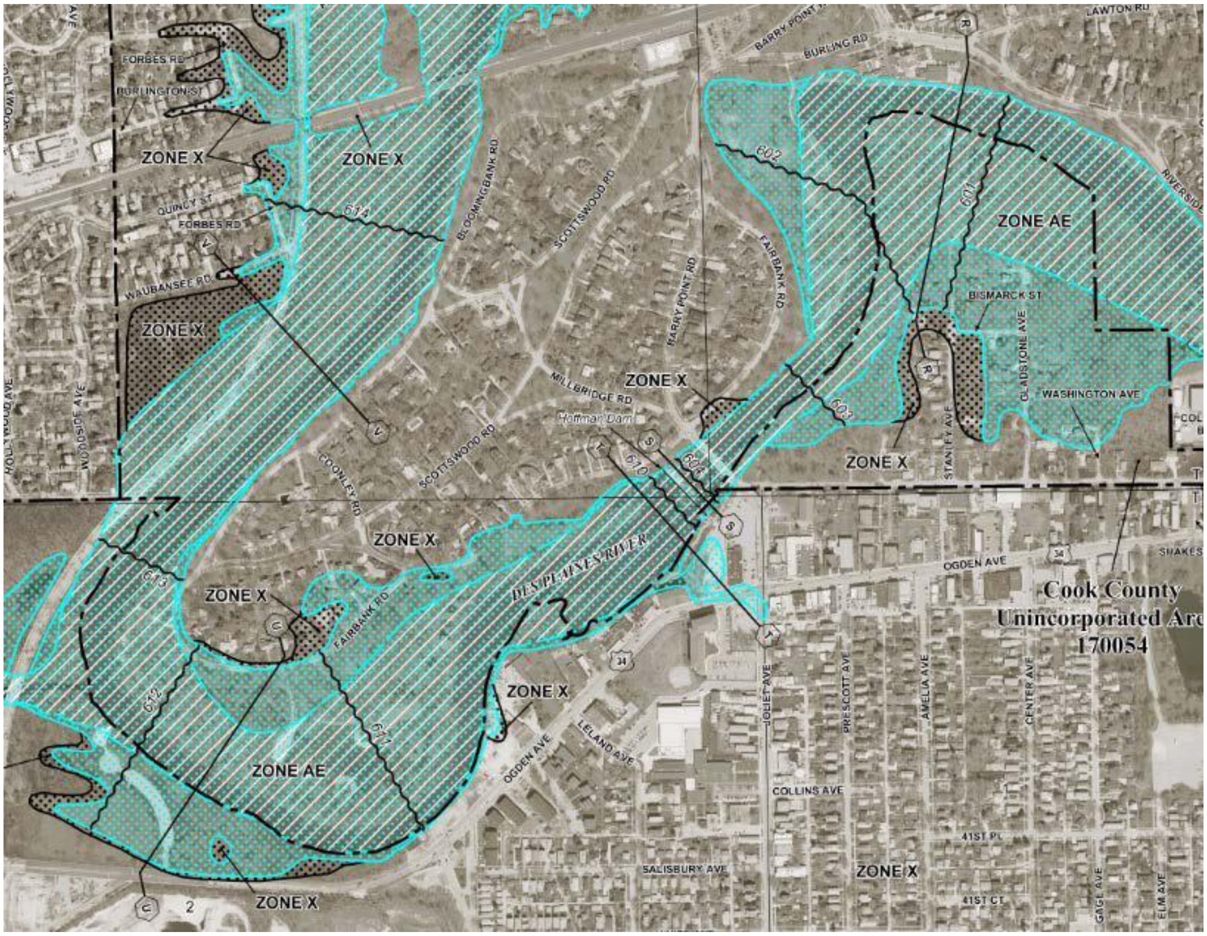

Figure 36: Des Plaines River 100-year flood plain represented by the hatched blue area (FEMA, 2008)

Overall impacts

The measurements performed upstream of the Hofmann Dam showed that erosion within the channel and along the banks coincided with channel narrowing throughout the impoundment area. Although it took between 2013 and 2018 for erosion to be measured at the upper reaches of the impoundment, it occurred relatively quickly after the removal with the majority of the cross-sections experiencing the largest change in area within one year of dam removal. These findings are similar to previous studies where other researchers have found that rivers respond more quickly to the effect of dam removal than was predicted (Burroughs et al., 2009; Warrick et al., 2015).

Cross-sectional area changes, however, continued to occur at the cross-sections closer to the dam with XS7 actually experiencing a larger overall change between 2013 and 2018 than between 2012 and 2013. Therefore, the most significant and longer reaching effects occur with close proximity to the dam. Similarly, downstream of the dam, cross-section XS9 was the only cross-section to experience measurable deposition of the mobilized upstream sediment resulting in a lower d_5, d_{16} and d_{50} sediment size than the upstream values. Five years after the removal, this deposited sediment has begun to erode leading to the creation of riffles and runs stretching from approximately 100 feet upstream of the dam to 80 feet downstream. The increased connectivity of the river with the dam removal and creation of riffles and runs has allowed for increased species migration and are indicators for increasing habitat heterogeneity. These changes mimic what was measured after the removal of the Stronach Dam but due to the complexity and diversity of each removal project these changes may not be representative for every project.

Significance

This study provides further insight into the influence dam removal has on the geomorphological changes within the impoundment area as well as downstream of the dam. Previous research has shown the speed at which erosion occurs within the impoundment with the highest percentage of change occurring not only within the first year but within the first weeks after removal (Burroughs et al., 2009; Warrick et al., 2015). I have found similar results within the Des Plaines River where most of the change occurs close to the dam and within the first year after removal. Other work has also shown that the majority of the sediment stored within the impoundment remains in place with typically less than 15% of the sediment being eroded and transported downstream (Burroughs et al., 2009). Although the exact amount of sediment eroded in the Hofmann Dam impoundment is unknown, analysis of the cross-sectional graphs and aerial imagery indicate the vast majority of the stored sediment has remained stored on the banks of the river. Also the analysis of the cross-sections and particle size distribution shows a similar trend compared to previous studies that show that the mobilized sediment is not deposited immediately downstream of the dam but is transported and deposited on the flood plain of the river.

The objective of this study was to help improve the understanding of the timeframe and location of the geomorphological changes within the river caused by a planned low-head dam removal. Because of the nearly 2.5 million aging dams fragmenting rivers and disrupting natural ecosystems throughout the United States, an enhanced understanding on how rivers in different geographic areas will respond to the removal of dams is important to ensure the success of the rivers aquatic organisms. These results are important considering the increased number of dam removals in the last decade and the increasing number of dams aging beyond their shelf life, particularly within this geographic region. In order to gain a complete understanding of how the removal of low-head dams impact the fluvial geomorphological conditions of the river, pre and post removal data for different ecosystems is vital.

Limitations of Study

The results of this study are constrained by several limitations. The first and most problematic limitation was the size of the Des Plaines River and the overall study site. On the initial site visit to analyze the feasibility of the study it was determined that the river could be safely waded across at normal river conditions. However, when I started collecting points on the next visit, I quickly realized the varying depth of the riverbed along with the water velocity made wading across the entire river highly dangerous. To ensure accurate data and overall safety, measurements had to be collected starting from one side of the river and stopping when the conditions were deemed unsafe. After using the only bridge to cross the river near cross-section XS10, the process was repeated trying to match the established path meeting in the same location on the river.

The depths of the river also forced the gravel count collection paths to be modified because the collector was unable to reach the riverbed at some locations to retrieve a sample safely. These adjustments did not allow me to sample in the deeper areas of the river and the time to collect the data increased significantly. Despite this, I feel that adequate data was gathered to compare cross-sections and sediment size throughout the study period. In addition, due to the data collection modifications, the overall size of the study site had to be reduced. Initially, the furthest upstream cross-section was located approximately 4,000 feet upstream of the Hofmann Dam, making the overall length of the site almost one mile long. With the width at each cross-section ranging from 200 to 400 feet, the time to collect the data with only a three-person team would have limited the feasibility of the project. Even though I could not sample more cross-sections upstream of the dam, it appears that the effects of dam removal diminished with distance from the dam and I was likely to find only minimal changes.

The second limitation was the location of the study site. Located in Riverside, IL, the trip to the study site from my graduate school, Southern Illinois University Edwardsville, was approximately 5 hours in length. To ensure accurate data was gather, organization was crucial so each trip to the site was successful. On one trip where data was collected at 15 cross sections, an antenna was not installed on the GPS rover. This resulted in the topographic data having an error margin of 1.5 meters, effectively making the data unusable. Also to ensure a 10-hour trip would be productive, weather patterns and the USGS stream gage had to be monitored constantly to ensure the water level was at a height that would be safe to wade. With the highly urbanized area surrounding the river, a small rainstorm would cause the river height to rise rapidly therefore I could only conduct field work on days these height could be avoided.

Finally, the third limitation was the accuracy of the field equipment. The TOPCON GPS Unit in an open area without tree cover affecting the data sent to the satellites records data with survey grade accuracy. However, this equipment requires the data to be analyzed and adjusted in the laboratory to determine the accuracy. With newer GPS technology released containing real time mapping to a portable tablet, any errors with the data would have been detected in the field saving multiple trips to the field. Also to detect the start and end points to each cross-section established by the IDNR, a handheld GPS device was used to map the locations. With the majority of the start and end points located in areas with tree cover, the data collected by the GPS unit was only accurate to several feet. Finally, IDNR data was collected using a total station and the equipment I had available was a survey grade GPS. I expect that any differences in accuracy and collection are minimal.

Suggestions for Future Research

Future research on the Des Plaines River near the Hofmann Dam site could focus on several issues. Detailed aerial imagery along with LiDAR collected by the State of Illinois before the removal of the dam could be used to map pre-removal data to compare post removal data collected using drone technology. Although this data will not show the changes in the river channel, it will allow for the accurate determination of the change in river channel planform, river width and potentially in the amount of sediment stored above bankfull and along the channel. This data could be used to compared with previous studies to help future projects protect the connectivity of the river flood plain and monitor important areas such as wetlands that may be located downstream of the dam.

Additionally, more extensive research could be done on the particle size distribution analysis. Combining the gravel counts performed in this study with additional core samples and grab samples upstream and downstream will provide a more accurate representation of the riverbed. This data could then be compared to the core samples collect by the Illinois Department of Natural Resources before the removal of the Hofmann Dam resulting in a better understanding of where the sediment was deposited within the river channel.

Finally, cross-sectional surveys could be performed 10, 15 and 20 years after the removal. Most research identifies the significant changes that occur immediately after the removal but few have continued to analyze the river several years after the removal to determine if changes are continuing to occur. With the results of this study showing erosion in the impoundment up to five years after the removal, can erosion still be occurring in measurable amounts in 10 to 20 years after removal? This analysis could help future projects accurately plan the need and location of dredging as well as determine if stream bank protection is required.

CHAPTER VII

CONCLUSION

In conclusion, although the geomorphic effects of dam removal on a river follow a certain trend, the location and extent of these effects vary widely for each dam removal project due to the complexity and uniqueness of each river system. The effects from the removal of the Hofmann Dam on the Des Plaines River occurred immediately after the removal but changes are still occurring upstream and downstream of the former dam five years after the removal. Results from this study can provide further knowledge that the Hofmann Dam Ecosystem Restoration Project achieved its goal of restoring the Des Plaines River to a free flowing channel and created more complex channel conditions that could improve fish and aquatic species habitat. With the aging dam infrastructure and increasing public desire to protect and restore rivers throughout the United States, these results can also help ensure the success of future dam removal projects.

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APPENDIX A

Table A1: HEC-RAS analysis for a 2-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	608.56	608.96	0.002181	5.02	0.39	10.70
9	598.16	607.45	607.71	0.001375	4.07	0.32	9.28
8	595.21	607.15	607.28	0.000664	2.95	0.22	11.94
7	597.05	606.36	606.59	0.001396	3.97	0.32	9.32
6	596.98	606.10	606.33	0.002795	3.81	0.30	9.12
5	598.69	604.72	605.18	0.005826	5.41	0.50	6.04
4	596.88	604.07	604.40	0.001059	4.63	0.37	7.19
3	598.52	603.81	604.20	0.00231	4.99	0.50	5.28
2	592.13	603.87	603.90	0.001028	1.41	0.07	11.75
1	594.29	603.67	603.74	0.00522	2.03	0.13	9.38
0	593.57	601.35	601.64	0.002193	4.40	0.32	7.78

Table A2: HEC-RAS analysis for a 2-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	607.25	607.64	0.001959	4.89	0.37	10.43
9	597.51	605.61	606.04	0.002806	5.28	0.44	8.10
8	596.03	604.86	605.22	0.001378	4.72	0.32	8.83
7	597.31	604.20	604.66	0.003132	5.35	0.46	6.89
6	593.21	604.10	604.30	0.001484	3.35	0.23	10.89
5	589.99	603.64	603.84	0.00174	3.84	0.28	13.65
4	594.69	603.31	603.58	0.000889	4.13	0.33	8.63
3	595.44	603.28	603.44	0.000557	3.31	0.26	7.84
2	591.73	603.18	603.25	0.002761	1.90	0.12	11.45
1	592.06	602.99	603.05	0.004481	1.97	0.12	10.93
0	592.88	600.85	601.15	0.002191	4.43	0.33	7.97

Table A3: HEC-RAS analysis for a 5-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	609.84	610.33	0.002142	5.54	0.40	11.98
9	598.16	608.83	609.12	0.001314	4.46	0.32	10.66
8	595.21	608.53	608.69	0.000666	3.18	0.23	13.32
7	597.05	607.68	607.94	0.001543	4.27	0.33	10.63
6	596.98	607.41	607.68	0.002831	4.10	0.30	10.43
5	598.69	606.27	606.63	0.004902	4.99	0.46	7.58
4	596.88	605.61	605.97	0.001361	4.76	0.41	8.73
3	598.52	605.51	605.81	0.001087	4.33	0.37	6.99
2	592.13	605.54	605.61	0.001298	1.67	0.08	13.42
1	594.29	605.31	605.41	0.005716	2.33	0.14	11.02
0	593.57	602.82	603.15	0.002192	4.76	0.33	9.25

Table A4: HEC-RAS analysis for a 5-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	608.43	608.89	0.002049	5.54	0.39	11.61
9	597.51	606.92	607.41	0.002427	5.51	0.42	9.42
8	596.03	606.20	606.66	0.001522	5.41	0.35	10.17
7	597.31	605.74	606.17	0.002276	5.35	0.41	8.43
6	593.21	605.68	605.87	0.00152	3.74	0.23	12.47
5	589.99	605.18	605.45	0.001713	4.07	0.28	15.19
4	594.69	604.95	605.18	0.000779	3.94	0.31	10.27
3	595.44	604.92	605.09	0.000414	3.44	0.24	9.48
2	591.73	604.82	604.89	0.002941	2.17	0.12	13.09
1	592.06	604.59	604.69	0.004793	2.26	0.13	12.53
0	592.88	602.33	602.69	0.002191	4.79	0.33	9.45

Table A5: HEC-RAS analysis for a 10-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	610.66	611.15	0.001979	5.74	0.39	12.80
9	598.16	609.61	609.94	0.001535	4.56	0.34	11.45
8	595.21	609.28	609.45	0.000734	3.31	0.24	14.07
7	597.05	608.40	608.69	0.001537	4.36	0.33	11.35
6	596.98	608.14	608.43	0.002732	4.27	0.30	11.15
5	598.69	607.09	607.41	0.004786	4.66	0.44	8.40
4	596.88	606.46	606.79	0.001317	4.49	0.40	9.58
3	598.52	606.36	606.63	0.00084	4.27	0.33	7.84
2	592.13	606.40	606.43	0.001463	1.84	0.09	14.27
1	594.29	606.14	606.23	0.006034	2.53	0.14	11.84
0	593.57	603.51	603.90	0.002191	5.05	0.34	9.94

Table A6: HEC-RAS analysis for a 10-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	609.12	609.65	0.002075	5.84	0.40	12.30
9	597.51	607.74	608.23	0.002145	5.61	0.41	10.24
8	596.03	606.99	607.51	0.001684	5.71	0.37	10.96
7	597.31	606.56	607.02	0.00204	5.41	0.39	9.25
6	593.21	606.50	606.76	0.001584	4.00	0.24	13.29
5	589.99	606.04	606.30	0.001653	4.23	0.28	16.04
4	594.69	605.81	606.07	0.000634	3.94	0.29	11.12
3	595.44	605.77	605.97	0.000379	3.54	0.23	10.33
2	591.73	605.68	605.77	0.003091	2.36	0.13	13.94
1	592.06	605.45	605.54	0.005053	2.46	0.13	13.39
0	592.88	603.08	603.48	0.002191	5.02	0.34	10.20

Table A7: HEC-RAS analysis for a 20-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	611.22	611.78	0.002	6.07	0.39	13.35
9	598.16	610.17	610.50	0.001645	4.72	0.35	12.01
8	595.21	609.81	610.01	0.000807	3.48	0.25	14.60
7	597.05	608.83	609.15	0.001647	4.56	0.35	11.78
6	596.98	608.56	608.89	0.002947	4.56	0.32	11.58
5	598.69	607.68	608.01	0.003726	4.53	0.40	8.99
4	596.88	607.19	607.48	0.000994	4.36	0.35	10.30
3	598.52	607.09	607.38	0.000705	4.27	0.31	8.56
2	592.13	607.12	607.19	0.001607	2.00	0.10	14.99
1	594.29	606.86	606.99	0.006303	2.69	0.14	12.57
0	593.57	604.10	604.56	0.002188	5.31	0.34	10.53

Table A8: HEC-RAS analysis for a 20-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	609.78	610.33	0.002021	6.10	0.40	12.96
9	597.51	608.50	608.99	0.001924	5.68	0.39	10.99
8	596.03	607.74	608.27	0.00184	5.94	0.38	11.71
7	597.31	607.32	607.78	0.002007	5.45	0.39	10.01
6	593.21	607.22	607.48	0.001716	4.20	0.25	14.01
5	589.99	606.76	607.05	0.001636	4.36	0.28	16.77
4	594.69	606.56	606.79	0.000556	3.97	0.28	11.88
3	595.44	606.53	606.73	0.000362	3.67	0.23	11.09
2	591.73	606.43	606.53	0.00325	2.53	0.13	14.70
1	592.06	606.17	606.30	0.005329	2.62	0.14	14.11
0	592.88	603.71	604.13	0.00219	5.28	0.34	10.83

Table A9: HEC-RAS analysis for a 50-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	611.84	612.50	0.002058	6.46	0.40	13.98
9	598.16	610.79	611.15	0.001677	4.89	0.36	12.63
8	595.21	610.43	610.66	0.000795	3.61	0.25	15.22
7	597.05	609.48	609.81	0.001665	4.69	0.35	12.43
6	596.98	609.15	609.51	0.003024	4.82	0.32	12.17
5	598.69	608.43	608.73	0.002798	4.40	0.36	9.74
4	596.88	608.07	608.37	0.000775	4.23	0.32	11.19
3	598.52	607.97	608.27	0.000599	4.30	0.29	9.45
2	592.13	608.01	608.07	0.001777	2.17	0.10	15.88
1	594.29	607.71	607.84	0.006612	2.85	0.15	13.42
0	593.57	604.86	605.35	0.002188	5.61	0.34	11.29

Table A10: HEC-RAS analysis for a 50-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	610.86	611.45	0.001732	6.14	0.37	14.04
9	597.51	609.55	610.01	0.002183	5.45	0.40	12.04
8	596.03	608.63	609.22	0.002023	6.07	0.40	12.60
7	597.31	608.23	608.69	0.001941	5.45	0.39	10.93
6	593.21	608.10	608.40	0.00173	4.40	0.25	14.90
5	589.99	607.68	607.97	0.001558	4.49	0.28	17.68
4	594.69	607.48	607.74	0.000479	4.04	0.26	12.80
3	595.44	607.45	607.68	0.000339	3.84	0.22	12.01
2	591.73	607.35	607.45	0.003376	2.69	0.14	15.62
1	592.06	607.09	607.22	0.005545	2.79	0.14	15.03
0	592.88	604.56	605.02	0.002188	5.48	0.34	11.68

Table A11: HEC-RAS analysis for a 100-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	612.27	612.99	0.002103	6.76	0.41	14.40
9	598.16	611.32	611.68	0.001594	4.92	0.35	13.16
8	595.21	610.96	611.15	0.000754	3.71	0.25	15.75
7	597.05	610.04	610.37	0.001479	4.69	0.34	12.99
6	596.98	609.71	610.11	0.003007	4.89	0.33	12.73
5	598.69	609.09	609.38	0.00219	4.23	0.32	10.40
4	596.88	608.83	609.09	0.000629	4.07	0.29	11.94
3	598.52	608.73	608.99	0.000516	4.27	0.27	10.20
2	592.13	608.73	608.83	0.001845	2.26	0.10	16.60
1	594.29	608.46	608.60	0.006599	2.95	0.15	14.17
0	593.57	605.58	606.07	0.002191	5.61	0.34	12.01

Table A12: HEC-RAS analysis for a 100-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	611.65	612.24	0.00157	6.17	0.36	14.83
9	597.51	610.20	610.66	0.00201	5.35	0.39	12.70
8	596.03	609.28	609.88	0.002045	6.07	0.40	13.25
7	597.31	608.89	609.35	0.001822	5.38	0.37	11.58
6	593.21	608.79	609.09	0.001677	4.49	0.25	15.58
5	589.99	608.37	608.66	0.001478	4.53	0.27	18.37
4	594.69	608.20	608.46	0.000428	4.04	0.25	13.52
3	595.44	608.17	608.40	0.00032	3.90	0.22	12.73
2	591.73	608.04	608.17	0.003405	2.79	0.14	16.31
1	592.06	607.81	607.94	0.005591	2.92	0.14	15.75
0	592.88	605.22	605.71	0.00219	5.54	0.34	12.34

Table A13: HEC-RAS analysis for a 200-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	612.76	613.52	0.002098	6.96	0.41	14.90
9	598.16	611.88	612.24	0.001519	4.92	0.34	13.71
8	595.21	611.52	611.71	0.000699	3.74	0.24	16.31
7	597.05	610.66	610.99	0.001277	4.63	0.32	13.62
6	596.98	610.33	610.70	0.003296	4.89	0.34	13.35
5	598.69	609.74	610.01	0.001806	4.10	0.30	11.06
4	596.88	609.48	609.74	0.000539	4.00	0.27	12.60
3	598.52	609.38	609.68	0.000464	4.27	0.26	10.86
2	592.13	609.42	609.48	0.001942	2.36	0.11	17.29
1	594.29	609.12	609.25	0.006601	3.05	0.15	14.83
0	593.57	606.27	606.76	0.00219	5.68	0.34	12.70

Table A14: HEC-RAS analysis for a 200-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	612.47	613.06	0.001433	6.20	0.34	15.65
9	597.51	610.93	611.35	0.001684	5.15	0.36	13.42
8	596.03	609.94	610.50	0.002136	6.04	0.41	13.91
7	597.31	609.51	609.97	0.001843	5.31	0.38	12.20
6	593.21	609.38	609.71	0.001646	4.63	0.25	16.17
5	589.99	608.99	609.32	0.001432	4.59	0.27	19.00
4	594.69	608.83	609.09	0.000416	4.07	0.25	14.14
3	595.44	608.79	609.06	0.00031	3.97	0.22	13.35
2	591.73	608.69	608.83	0.003468	2.89	0.14	16.96
1	592.06	608.43	608.56	0.005697	3.02	0.15	16.37
0	592.88	605.81	606.30	0.002191	5.61	0.34	12.93

Table A15: HEC-RAS analysis for a 500-year flood discharge, 2012

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	597.87	613.45	614.24	0.002025	7.15	0.41	15.58
9	598.16	612.66	613.02	0.001271	4.86	0.32	14.50
8	595.21	612.27	612.50	0.000624	3.77	0.23	17.06
7	597.05	611.38	611.71	0.001114	4.63	0.30	14.34
6	596.98	611.09	611.45	0.003123	4.79	0.33	14.11
5	598.69	610.56	610.79	0.001511	3.97	0.28	11.88
4	596.88	610.37	610.60	0.000456	3.90	0.26	13.48
3	598.52	610.27	610.53	0.000411	4.27	0.25	11.75
2	592.13	610.27	610.37	0.002029	2.49	0.11	18.14
1	594.29	609.97	610.11	0.006602	3.18	0.15	15.68
0	593.57	607.12	607.61	0.002192	5.68	0.34	13.55

Table A16: HEC-RAS analysis for a 500-year flood discharge, 2018

Cross-Section	Channel Elevation (ft)	Water Surface Elevation (ft)	E.G. Elevation (ft)	E.G. Slope (ft/ft)	Channel Velocity (ft/s)	Froude #	Depth (ft)
10	596.82	613.68	614.24	0.00	6.10	0.35	16.86
9	597.51	611.98	612.34	0.00	4.89	0.32	14.47
8	596.03	610.76	611.32	0.00	5.97	0.38	14.73
7	597.31	610.47	610.86	0.00	5.12	0.34	13.16
6	593.21	610.27	610.60	0.00	4.59	0.29	17.06
5	589.99	609.74	610.11	0.00	4.69	0.27	19.75
4	594.69	609.61	609.88	0.00	4.10	0.25	14.93
3	595.44	609.58	609.84	0.00	4.10	0.22	14.14
2	591.73	609.45	609.58	0.00	3.05	0.14	17.72
1	592.06	609.19	609.35	0.01	3.18	0.15	17.13
0	592.88	606.53	607.05	0.00	5.71	0.34	13.65

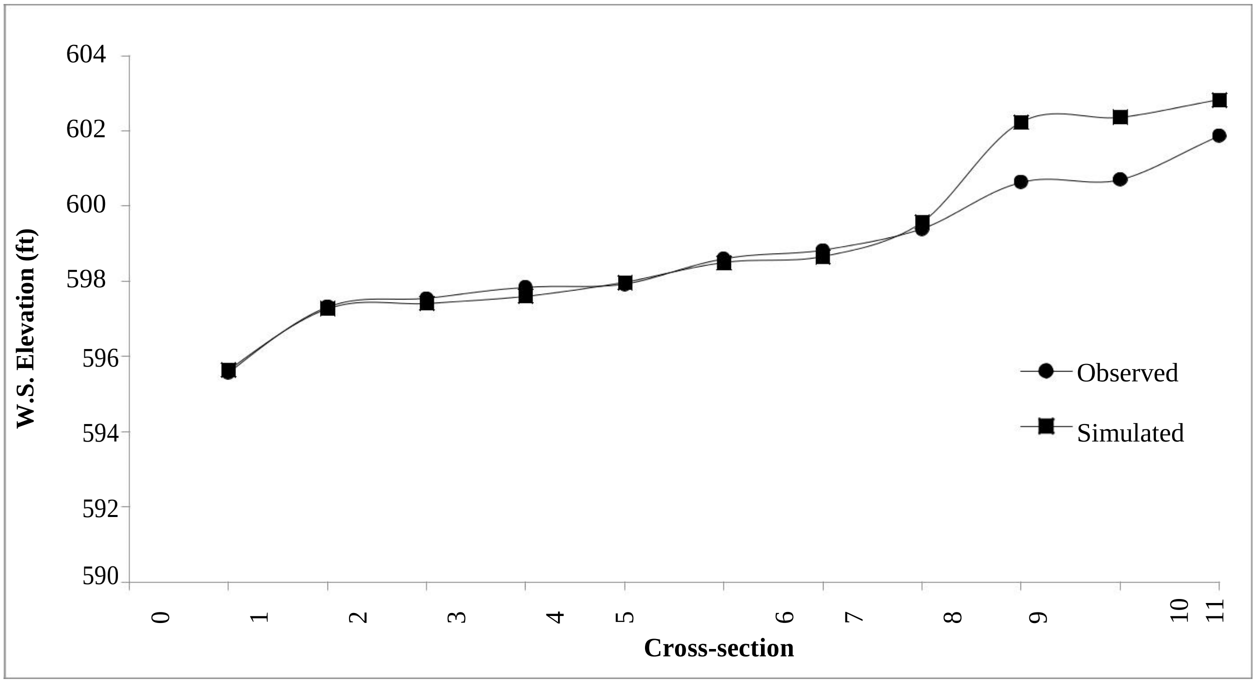

Figure A1: Comparison of observed and simulated water surface elevations for HEC-RAS model.

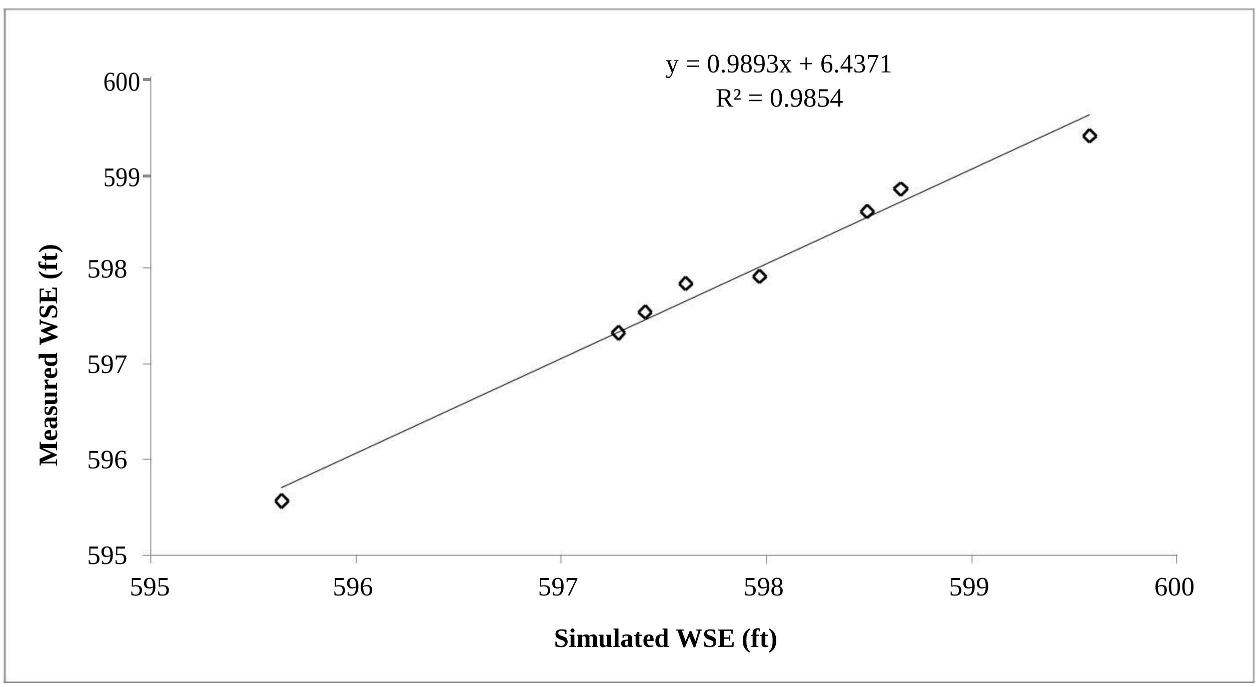

Figure A2: Error analysis of measured verse simulated water surface elevation from HEC-RAS model