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Characterization of hydrology and water quality at a restored oxbow : ecosystem services achieved in year one

Bryce Jordan Haines
University of Iowa

CHARACTERIZATION OF HYDROLOGY AND WATER QUALITY AT A RESTORED OXBOW: ECOSYSTEM SERVICES ACHIEVED IN YEAR ONE

by

Bryce Jordan Haines

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Thesis Supervisors: Professor Larry J. Weber
Adjunct Assistant Professor Keith E. Schilling

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Bryce Jordan Haines

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
in Civil and Environmental Engineering at the December 2017 graduation.

Thesis Committee: ___________________________________

Larry Weber, Thesis Supervisor

____

Keith Schilling, Thesis Supervisor

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Ricardo Mantilla

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Chris Jones

Abstract

Conservation practices are needed to reduce nitrate loss across the Midwest. Different riparian wetland designs have been investigated, but the physical, chemical and biological processes controlling nutrient cycling in restored oxbows are not well understood. A restored oxbow's influence on nutrient cycling was investigated by studying the hydrogeology and water quality at a recently reconstructed oxbow site adjacent to Morgan Creek in Linn County, Iowa. Over a one-year period, the lentic oxbow's nitrate loading was found to be dominated by flood pulses. Nitrate concentrations in the stream ranged from 7.38 – 12.95 mg l^{-1}, concentrations were consistently low in the oxbow ranging from < 0.10 – 5.35 mg l^{-1}, and the lowest nitrate concentrations were detected in the groundwater ranging from 0.10 to 3.4 mg l^{-1}. Following a spring flood event, an in-situ sensor measured the nitrate concentration in the oxbow. Nitrate retention efficiency was estimated to be 0.30 g N m^{-2} d^{-1} or a 74.2% reduction efficiency. The observed nitrate reduction was compared to a first order denitrification model. The observed nitrate reduction measured in the oxbow followed a linear decay rather than an exponential decay suggested by first order kinetics.

Public abstract

Natural streams freely meander throughout floodplains creating ideal habitat conditions for a diverse population of species. Meandering streams have the ability to create oxbows, which are crescent shaped lakes that are cut off from the main channel. Oxbows provide favorable conditions for nutrient reduction, wildlife, flood storage, and recreational uses. However, benefits provided by natural streams have decreased because of land alteration caused by urban development and intense agricultural practices. As a result, stream straightening and channelizing has reduced the formation of new oxbows, and sediment has filled in historic locations. The reduced number has decreased the ecological services once provided by oxbows.

Interest to regain ecosystem services provided by oxbows has resulted in new methods to reconstruct oxbows once filled in with sediment. The restoration process involves excavating out the sediment to increase water storage. As a result, water provides year round habitat for a variety of aquatic and terrestrial species. Auxiliary benefits of restored oxbows include improved water quality because of their ability to retain nutrients due to improved conditions for nutrient cycling. Overall, restored oxbows have been found to be a cost effective option that quickly transition into an ecological hotspot providing habitat, water storage, recreational activities, and nutrient cycling benefits.

Table of contents

List of tables

List of figures

Chapter 1: Introduction

1.1 Background

Water quality continues to be impaired in the Midwest because the amount of nutrients applied as fertilizer in agricultural fields and produced through mineralization is greater than what can be transformed into crop biomass (Carpenter et al. 1998). Consequently, the imbalance of nutrients leads to widespread nutrient export into streams and rivers via surface water runoff and groundwater discharge as baseflow or tile drainage. Excessive nutrients in rivers and streams from the Midwest are impacting both local (USEPA, 2013) and regional bodies of water including the Gulf of Mexico Hypoxia zone. The EPA set a goal to reduce the extent of the Gulf of Mexico hypoxia zone by 45% by the year 2035. In efforts to meet this goal, states across the Midwest are working to reduce nutrient runoff by adopting conservation practices outlined in their nutrient reduction strategies.

The focus to improve and protect water supply for human consumption and ecosystems have become important goals in policy making (Dosskey, 2010). Conservation practices are great tools to aid in the protection and enhancement of water quality. To mitigate the Gulf of Mexico hypoxia zone, Fink (2007) suggested conservation practices include the restoration of 2 million hectares (ha) of wetlands located near river floodplains. These floodwater buffer zones provide an abundant amount of ecosystem services (Opperman et al., 2010; Schilling et al., 2015) that include protection of biodiversity (Tockner and Stanford, 2002), increased floodplain habitat for aquatic species (Jones et al., 2015; Costanza et al., 1997), floodwater storage (Opperman et al., 2009), recreation (Golet et al., 2006) and nutrient retention (Vidon et al., 2004; Krause et al., 2008).

Floodplains are beneficial because they provide important controls on the exchange of water and nutrients between streams and riparian zones (Schilling et al., 2012; Dahm et al., 1998; Takatert et al., 1999; Ward et al., 1999; Barett et al., 2012). However, the hydrology and geomorphology of many floodplains have been significantly altered across the Midwest. As a result, these degraded floodplains have reduced capacity for a variety of important ecological processes. Large-scale agricultural and urban development practices on floodplains have compromised fluvial dynamics and water quality of streams (Bayley 1995; Ward et al., 1999; Goetz et al., 2015). Furthermore, stream straightening and incising reduces the meandering effects of rivers, degrading water quality and riparian habitat while increasing flooding.

1.2 Restored oxbows

Oxbows are an example of a floodplain feature created by fluvial dynamics. Oxbow lakes are formed when a river cuts off a meander loop caused by stream migration (Wohlman and Leopold, 1957). The resulting scar is often connected to shallow groundwater that provides standing water year round (Jones et. al., 2015). The connection between aquatic and terrestrial species found in river floodplains make the location of oxbows among the most biologically diverse systems in the world (Bayley 1995; Ward et al. 1999; Goetz et al., 2015) As a result, they provide habitat diversity, floodwater storage, and treatment of nutrient loads (Schilling et al., 2017). However, continuous accumulation of sediment within floodplains reduces oxbow's capacity to hold water. Consequently, these systems transition from a lentic to terrestrial zone (Schilling et al., 2017).

The United States Fish and Wildlife Service (USFWS) and local agencies recognize the importance of oxbows and have been developing new methods to improve fish habitat and floodplain productivity through oxbow reconstruction. Strategic Habitat Conservation (SHC) is a program within USFWS that provides conservation efforts focused on strategic, accountable and adaptive actions to meet conservation demands of the 21st century. The SHC program is currently working to restore oxbows to improve habitat conditions for an endangered fish species known as the Topeka Shiner (*Notropis topeka*). Topeka Shiners desire pool-like areas outside of the main stream. Oxbows provide ideal off-channel conditions because the slow moving water and abundant habitat create a suitable environment for both the survival and reproduction of these fish. The USFWS started an initiative to improve habitat conditions for the Topeka Shiner in 2002 with a focus to restore oxbows across the Des Moines Lobe. Their project area included the Boone River watershed (BRW) and Raccoon River watershed located in central Iowa. Although the main objective of the USFWS projects are focused on the recovery of the

Topeka Shiner, auxiliary benefits such as improving water quality by treating nutrient loads have been documented (Schilling et al., 2017, Jones et al., 2015).

1.3 Project description

The practice of restoring oxbows has been well established in the Des Moines Lobe, but this thesis focuses on the investigation of one of the first restoration projects in eastern Iowa (Figure 1.1). A one-year study was conducted to evaluate the effects of a newly restored oxbow on floodplain ecosystem services, including the oxbow's effects on site hydrogeology, watershed hydrology, nutrient processing, and fish colonization. The objective of this project was to follow an oxbow from its initial restoration, and monitor the oxbow's effects on water quality and ecological benefits within the floodplain during its first year of function. More specifically, the following questions were investigated in this project.

1. How does hydrology and hydrogeology of the floodplain affect transport of water and its constituents into oxbow?
2. What is the N retention capacity for the restored oxbow and can N retention be modeled using a first order denitrification model?
3. What are the ecological benefits provided from a recently restored oxbow?

In conjunction with USFWS, the Linn County Conservation Board (LCCB) funded the restoration of a degraded oxbow along Morgan Creek in Linn County, Iowa (Figure 1.1). The project objectives set forth by LCCB aimed to improve the smallmouth bass fishery in the Cedar River, reduce nutrient and sediment loading into Morgan Creek and the Cedar River, provide water storage during high flow events, and restore ecological function in the riparian zone of Morgan Creek. In-kind contributions provided by The Nature Conservancy (TNC) and IIHR – Hydroscience and Engineering provided support and assistance as well as tools to monitor the restored oxbow.

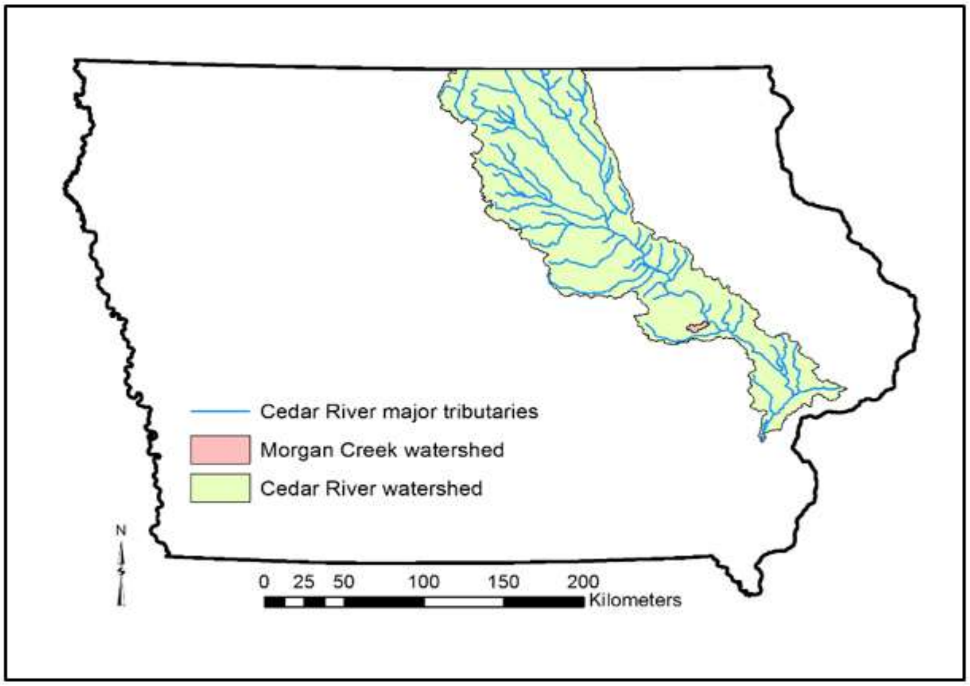

Figure 1.1. Location of Morgan Creek watershed (shown in red), which is a tributary to the Cedar River Basin in east central Iowa.

1.4 Chapter summary

In order to meet the goal set by the EPA to reduce the extent of the Gulf of Mexico Hypoxia zone by 45%, widespread conservation practices must be implemented. This thesis describes a specific floodplain enhancement technique that involves restoring oxbows. Restored oxbows improve ecosystems, flood storage, and water quality in degraded floodplains. The effects of a restored oxbow in eastern Iowa were investigated to monitor and quantify the improvement of water quality and ecological benefits. A one-year study was conducted on site to evaluate the effects of a restored oxbow on hydrogeology, watershed hydrology, nutrient processing, and fish populations.

Chapter 2: Literature review

2.1 Introduction

This chapter provides a literature review based on research related to nutrients and the use of wetlands to alleviate the nutrient problem. The main objective of this chapter is to introduce a new technique that involves restoring oxbows with a goal to increase nutrient cycling and improve the ecological benefits of the site. Governing processes in nutrient cycling are introduced to inform readers about the main controls studied in the project.

Humans have significantly increased the use of fertilizers since the 1950 resulting in excessive transport of nutrients to the Gulf of Mexico (Mitsch, 2006; NOAA.gov). Approximately 21,000,000 tons $year^{-1}$ of nitrogen is applied to the Mississippi River Basin (MRB) (Mitsch, 2001). Factors driving nutrient discharge into waterways include crop production, precipitation, temperature, and other environmental variations (Hunt, et. al., 2005). As a result, approximately 1.5 million tons of nitrogen is transported into the Gulf of Mexico per year (Mitsch, 2001). Excessive nutrients, specifically nitrogen and phosphorus, stimulate large algal blooms in the Gulf. The bacteria that decompose dead algae consume large amounts of oxygen. Consequently, dissolved oxygen (DO) becomes depleted in the water. When DO is below 2 mg l^{-1}, the oxygen deficient water is considered to be hypoxic. Large algal blooms that result from upstream nutrients have produced hypoxia zones in the Gulf of Mexico covering an average area of 15,000 km^2 each year (Mitsch, 2006). To reduce both excessive nutrient runoff as well as the size of the hypoxia zone, the Gulf of Mexico Hypoxia Task Force was formed. To achieve the goal set forth by the Hypoxia Task Force, nutrient loading into the Gulf must be reduced 45% by the year 2035. In order to achieve this goal, the use of conservation practices must be implemented across the Midwest to reduce nutrient runoff (Biennial Report, 2015).

2.1.1 Current methods to mitigate excess nutrient export

The Gulf of Mexico Hypoxia Task Force requested twelve states along the MRB to create their own nutrient reduction strategy to implement conservation practices. The Iowa Nutrient Reduction Strategy (INRS) is an approach aimed to assess and reduce nutrients delivered to Iowa waterways and the Gulf of Mexico (Iowa State University, 2015). The program outlines strategies for both point source polluters such as wastewater treatment plants, as well as non-point source polluters including farmland and urban areas. Techniques used to reduce non-point source pollution for agricultural lands include edge-of-field practices, improved land use management, and controlled fertilizer application (Biennial Report, 2015). Examples of edge-of-field practices aimed to reduce excess nutrients include vegetated buffer zones, woodchip bioreactors, and wetlands. Research found nitrate removal using these practices to range from 40 – 91% (INRS, 2013). While these practices offer benefits near field edges, there is a need to implement more of these constructed systems at a landscape scale to meet the goals of the Hypoxia Task Force.

2.1.2 Restored floodplains

According to Mitsch et al. (2001, 2005) and Mitsch and Day (2006), 2 million ha of restored wetlands in the MRB are necessary to mitigate the Gulf of Mexico hypoxia zone. An ideal location for restored wetlands is in riparian zones because they provide a nexus between nutrient rich waters and wetlands (Fink et al., 2007). Riparian zones typically provide optimal nutrient cycling conditions because the depth to groundwater is shallow, diverse plant communities are provided, support of large soil microbial populations, and anaerobic saturated soils are present (Hunt et. al., 2007). Unlike edge-of-field practices where productive farmland may be converted to conservation areas, floodplains are typically unused lands that have the potential to provide ecosystem services.

Floodplains are highly productive ecosystems because of the high heterogeneity of habitat resulting from seasonal flood pulses (Luz-Agostinho et al., 2008). The flood zone is dry during low flow periods resulting in a terrestrial region, and transitions to an aquatic environment during high flow periods (Lubinski, 1999). Hydrologic variability results in high plant diversity that is essential for fish habitat and spawning, and an important component in nutrient cycling processes (Lubinski, 1999). The delivery of nutrient rich waters during flood pulses as well as solar energy and diverse habitat conditions are important for several biological processes that enhance nutrient cycling (Jung-Chen Huang, et al., 2011). As a result, floodplains provide one of the most productive locations to restore wetlands (Fink et al., 2007). Increasing connectivity between rivers and their respective floodplains allow floodwaters to deposit sediment and chemicals into riparian wetlands. Therefore, wetlands have the ability to reduce nutrient loads in stream and rivers by acting as nutrient sinks. However, the design and connection of constructed or restored wetlands significantly influence their ability to retain sediment and pollutants (Fink et al., 2007).

2.1.3 Restored oxbows

One approach to enhance floodplain functions includes restoring oxbows. Oxbows are crescent-shaped lakes that are formed when the meander of a migrating stream disconnects from the current stream channel. The location allows seasonal floodwaters to deposit both sediment and chemicals (Fink et al., 2007). Unfortunately, frequent flooding and altered land use leads to the continuous accumulation of sediment. As a result, the volume of water retained in these systems is reduced. To increase water capacity, oxbows can be restored by removing excessive sediment within the lake. The excavated soil also reconnects the lake to groundwater providing flood storage, nutrient cycling, and fish habitat. Previous efforts for restoring oxbows focused mainly on improving fish habitat, but there is limited research on nutrient cycling (Harrison et al., 2011, 2014; Jones et al., 2015, Schilling et al., 2017). To optimize the design of restored oxbows to mitigate nutrient runoff, a better understanding of nutrient cycling within these systems is necessary.

2.2 Nutrient cycling

Biogeochemistry (physical, chemical, and biological processes) controls the form, transformation, and fate of nutrients through a system (Inglett et al., 2008). Two main biological processes influence nitrate removal: plant uptake and denitrification. These two mechanisms are affected by the interaction of chemical and physical processes, which are influenced by hydrologic conditions such as river to floodplain connection, hydraulic retention time, water depth, and floods (Fink, et al., 2007). Wetlands promote ideal conditions for denitrification, but the physical, chemical, and biological mechanisms that control nitrate removal remain uncertain in restored oxbow settings (Harrison et al., 2011).

Biological uptake from plants, algae, and microbes only provide short-term retention of nitrogen. As a result, complete nitrogen removal is not obtained (Harrison et al., 2012). Permanent removal occurs when anaerobic microbes convert NO_3^- into nitrogen gasses (N_2O and N_2) (Harrison et al., 2012). This process is referred to as denitrification. A wetland's potential to perform denitrification is an important component in nutrient cycling because it permanently reduces the nutrient load into the MRB. Wetland soils contain an abundant supply of organic carbon, as well as saturated conditions that create the anaerobic environment necessary for denitrification (Harrison et al., 2012)

It is difficult to distinguish how nitrogen is reduced because it can be retained through plant assimilation or lost through denitrification. However, methods have been developed to measure denitrification rates in the sediment. The ^{15}N-enriched "push-pull" groundwater tracer method measures the rates in the benthic zone (Harrison et al., 2011). Denitrification rates were measured in three constructed wetlands and two relict oxbows during the summer and winter of 2008. Nitrate reduction assumed to be denitrification was found to range from 38 to 57% in the summer months, and 87 – 97% in the spring months (Harrison et al., 2012). However, more research is needed in various climates to further understand how restored oxbows respond to different temperatures and climates (Fink et al., 2007).

A more common method used to determine nitrate reduction is to measure the total amount of nitrate retained by assimilation and denitrification. Research conducted on riparian wetlands and oxbows found nitrate removal in these restored wetlands or created oxbows ranged from 23 to 87% (Huang et al., 2011; Fink & Mitsch, 2007; Harrison et al, 2011, 2014; Moreno et al, 2007; Jones et al., 2015, Schilling et al., 2017). Differences in nitrate removal among wetlands may be attributed to the age, establishment of plant and microbial community, and the degree of connection to the floodplain and stream. It is thought that nutrient removal may not be as productive at the beginning stages of restored wetlands because there is a need to establish a well-balanced plant to microbial interaction (Mitsch and Jorgensen, 2004; Moreno, 2007).

2.3 Hydrology

Hydrologic regimes of watersheds are altered by urbanization and agricultural practices. These practices increase the extent of impermeable surfaces, which prevents water's ability to infiltrate. As a result, increased runoff leads to the transport of sediment, nutrients, and pollutants into streams and rivers (Fink et al., 2007). Therefore, a better understanding of how wetlands react to hydrologic events is important to determine how wetlands respond with respect to nutrient cycling (Fink et al., 2007).

Conditions such as flood depth, duration, and frequency impact the efficiency of wetlands (Harrison et al., 2014; Fink et al., 2007). Hydraulic connection describes how wetlands are connected to the river through its floodplain and this connectivity controls the quantity and transport of water, sediment, and nutrients into the system (Katarzyna, 2009; Van den Brink et al., 1993). Hydrology has a major influence on the dynamics of nitrogen and phosphorous (Harrison et al., 2014). Several studies have examined various types of connections and how these connections influence nutrient retention. Connections include overbank flooding, pumped stream water, and stream connected channels. (Fink et al., 2007; Katarzyna et al., 2009; Harrison et al., 2011). Results show that the degree of connection plays a major role in nutrient removal because nutrient retention depends on the source and residence time of water in the system (Harrison et al., 2014).

2.4 Groundwater

Water quality and quantity are influenced by the connection of groundwater and surface water (Winter, 1998; Castro and Hornberger, 1991; Bencala, 1993; Stanford and Ward, 1992, 1993; Brunke and Gonser, 1997). The exchange between these two sources affects the biota and metabolism of ecosystems (Brunke and Gonser, 1997). The success of wetland projects depends on how these restored systems are connected to their floodplains. Understanding the effects of restoration on floodplain connection and river flow is essential to evaluate the success of the project (Clilverd et. al., 2016). The magnitude of the interaction between groundwater and surface water is predicted to be a major factor in solute retention (Dahm et al., 1998). Therefore, a further understanding of how surface water and ground water interact in restored oxbows will provide important insight for stream restoration projects.

Factors controlling the exchange of water and solutes between surface and ground water include aquifer geometry, hydraulic conductivity, and hydraulic gradient (Harvey et al., 1996). The rate of exchange between surface and subsurface water can be quantified using Darcy's Law. The hydraulic gradient is the difference between water elevations of two different points over the distance. Hydraulic conductivity describes the ease of which a fluid moves through a medium. Soils with higher sand content typically have higher hydraulic conductivity, whereas sediment with higher clay content typically restricts flow resulting in lower hydraulic conductivity values. The rate of ground water flow depends on the aquifer's hydraulic conductivity, which can be difficult to determine due to the heterogeneity of typical floodplain alluvium. Despite the simplicity of Darcy's law, the heterogeneity of hydraulic conductivities and hydraulic gradients can be difficult to interpret. The hydraulic gradient is affected by varying elevations of both groundwater and stream water flow. The exchange between groundwater and surface water is an important aspect in quantifying nutrient cycling and understanding the source and flow paths of ground water is necessary to understand nutrient loading and cycling.

In addition to ground water and surface water interactions, soil chemistry and lithology play an important role for nutrient cycling and residence time. The distribution of varying grain size and roundness and sphericity of grains is important for the exchange processes between ecological systems (Wiens, Crawford and Gosz, 1985; Gibert et al., 1990; Vervier et al., 1992, Brunke and Gosner, 1997). Fluctuating water table conditions during wet and dry periods are responsible for creating time-varying saturated and unsaturated zones in the soil column. These variable zones provide aerobic and anaerobic conditions that are important for controlling nitrification and denitrification processes. Water table fluctuations in floodplains also occur as a result of changes in the hydrology of the stream and variations in stream stage (Schilling et al., 2006). Variability in nutrient dynamics within floodplain sediments is also due to variations in the sources of organic matter and nutrients (Dahm, et. al., 1998). Overall, an understanding of the soil composition and chemistry provides insight on how the geology of the site may affect nutrient cycling.

2.5 Summary

Some research has been conducted on restored oxbows and their ability to cycle nutrients, but few studies have investigated the effect of surface water to ground water interactions and hydrologic events on nutrient retention at oxbow sites (Harrison, 2014; Jones et al., 2015; Schilling et al., 2017). To increase the implementation of restored oxbows, a better understanding of the biogeochemical processes that govern nutrient cycling and how oxbows interact within floodplains is needed. Once we understand how these processes respond to different hydrologic events, we can better assess the effectiveness of restored oxbows and improve the design to increase nutrient cycling.

Chapter 3: Methods and materials

3.1 Introduction

In this chapter the procedures, techniques, models, and equipment used to obtain and process data for this project are presented. The location and process to restore an oxbow are discussed, and methods used to investigate the geology, hydrogeology, hydrology, water quality, and ecology are described.

3.2 Site description

The study site is located adjacent to Morgan Creek in Linn County, Iowa (Figure 3.1). Morgan Creek drains 49.3 km^2 and discharges into the Cedar River. The upstream drainage area of the site is 32 km^2. The catchment area draining directly to the oxbow is 0.011 km^2.

Figure 3.1.Watershed boundary of Morgan Creek located in Cedar Rapids, Iowa.

3.3 Restoration process

IIHR – Hydroscience and Engineering worked with TNC to identify potential locations for a restored oxbow in Morgan Creek watershed using high-resolution ground elevation data. Light Detection and Ranging (LIDAR) data was used to obtain elevation datasets to identify potential restoration sites. The Morgan Creek oxbow appeared as a sediment filled scar on the land surface that had minimal water capacity (Figure 3.2a). The dysfunctional oxbow likely provided minimal benefits in terms of habitat, flood storage, and nutrient cycling. Using funding from LCCB, restoration began at the site on August 2nd, 2016. Excavation of the oxbow spanned over two days and involved the use of an excavator and bulldozer. Guided by personnel from the USFWS, the oxbow was reconstructed by excavating approximately 2,500 m^3 of post settlement alluvium to a basal gravel layer (Figure 3.2b). Total cost of restoration was approximately $28,000.

The shape of the oxbow followed the former stream channel and the depth was based on reaching a layer of coarse-textured alluvium at an elevation similar to the streambed of the existing channel. The elevation relationship suggested the gravel layer was connected to the former streambed. The surface area of the oxbow covered 1,760 m^2 when completely filled with water. The surface area was estimated using GPS continuously measuring the coordinates around the perimeter of the oxbow. The coordinates were formatted into a shapefile and ArcGIS was used to estimate the total surface area of the oxbow.

The oxbow was surveyed and averaged into three different cross sections with various depths. The center of the oxbow measured to a depth of approximately 1.6 m, whereas the two arms averaged approximately 0.75 m during wet periods. During the investigation, the arms of the oxbow were dry during the summer and winter months. The staggered arm depths were designed to promote vegetative growth while the center of the oxbow provided year round water. The banks were graded to a 4:1 slope. The hydrologic connection of the oxbow is considered to be lentic, that is, the oxbow is only connected to the stream during above bank flow periods. As a result, low flow periods provided a quiet water environment in the oxbow.

Figure 3.2. The transition of a restored oxbow from the initial "scar" in June, 2016 (a), post construction in August 2016 (b), to the completed project with established vegetation along the perimeter of the oxbow in May, 2017 (c).

3.4 Geology

Geophysics was used at the site to characterize spatial patterns in the subsurface. Electrical Resistivity (ER) methods were used to estimate the thickness of the subsurface sediments (Muchingami et al., 2012). The ground's resistivity was measured by inducing a current through stainless steel electrodes, and the electrodes measured the corresponding potential difference to estimate a resistivity value (Telford et al, 1990). The ER system used for this study was an Advanced Geosciences Inc. (AGI) SuperSting R8, 8 channel ER meter. Two transects were surveyed to evaluate geological variation in the area. After processing and inversion of the ER data, results were compiled as a two-dimensional model representing the bulk electrical resistivity (Ohm-meters).

A surface geophysical survey of the oxbow site was conducted using a Geonics EM-31 unit. The EM-31 used an electromagnetic (EM) induction technique that penetrates to a depth of 6 m into the ground (www.geonics.com). The EM-31survey was conducted by walking in a series of straight-line transects across the surveyed site. The parallel transects were oriented in a north-south direction and separated by 4 m. Ground conductivity readings at each measured point were recorded a GPS location. The measured points were contoured with the kriging method in ArcGIS to show how ground conductivity patterns varied at the site. To keep the units consistent for the two geophysical methods performed in this study, ground conductivity was converted to resistivity (Ohm-meters).

3.4.1 Soil sampling

Local geology is important for both the movement of groundwater and transport of nutrients, and understanding how this geology varies spatially and vertically provides insight on surface and groundwater interaction.

Soil samples were collected from eight different borehole locations surrounding the oxbow site. Samples were gathered from soil cuttings obtained using a hand auger during well installation. Soil samples were classified in the field and taken to the lab for further analysis.

Particle size analysis was performed using a Sedigraph. The method uses two principles to describe the soil grain size distribution. The first principle was based on a sedimentation theory known as Stokes' law, which states a particle will reach terminal velocity in a fluid when the gravitational forces balance the buoyant forces. To determine the relative mass of the particle, the Beer-Lambert-Bouguer law was used to measure the absorption of X-rays that were projected through the sample. A detailed description of the technique used for the SediGraph is reported in ISO 13317-3:2001 (www.iso.org). Results from the SediGraph were classified using a soil texture triangle.

3.5 Monitoring wells

A network of monitoring wells was installed to understand the spatial and temporal variations in groundwater flow direction and water quality (Figure 3.3). In June 2016, eight monitoring wells were installed using a hand auger to a depth of approximately 2 m. Well depths depended on the ability for the borehole to remain open while the wells were installed. The 3.2 cm diameter wells consisted of a 1.5 m factory-slotted white polyvinyl chloride (PVC) well screen, and a PVC riser that extended the well above the land surface. Silica sand was poured around the well screen to provide a filter pack in the borehole, and bentonite clay sealed the top of the borehole to prevent surface water intrusion. Wells were configured as three transects to understand the variation of groundwater flow and gradient through each transect. Two well transects were located parallel to Morgan Creek, and one was perpendicular to the stream. One pressure transducer was installed in Well 5 to monitor the groundwater table and a second transducer measured the stage depth of the oxbow.

The wells were located using a GPS, and each well casing was surveyed according to a benchmark well. The surveyed wells allowed for an accurate measurement of the hydraulic gradient across the site. The hydraulic gradient is a measure of the difference in depth to the water table over the length of a flow path. Well development was achieved by surging water out of the well with the use of a Wattera inertial lift pump. The wells were purged until the water appeared to be free of fine sediment.

Figure 3.3. Location of eight groundwater monitoring wells installed to measure groundwater quality and hydraulic gradient. Transect 1 is composed of wells 1-4, transect 2 is wells 7-8, and transect 3 include wells 5-2.

3.5.1 <u>Hydraulic conductivity</u>

Slug tests were performed to estimate the hydraulic conductivity of the aquifer. Slug tests are conducted by displacing water that causes an immediate change in the static water level. A slug can be an added volume of water or a solid cylinder that is inserted into the water column. The response of the water table caused by the immersion of a slug is an immediate change in the water level. The return of the groundwater table is analyzed to estimate the hydraulic conductivity. A pressure transducer monitored the recovery of the water table that measured every 0.25 seconds per reading. The results were post processed in Aqtesolv using the Bouwer and Rice method. This method was originally proposed to describe partially or fully penetrating wells in unconfined aquifers (Brown, 1995). The Bouwer and Rice method is based on the following assumptions. The drawdown of the water table surrounding the well is negligible, the flow in the unsaturated zone, as well as the capillary fringe, is ignored, the well is 100% hydraulically efficient, and the aquifer is isotropic and homogeneous (Bouwer and Rice, 1976). The hydraulic conductivity (K) described by Bouwer and Rice is derived from the Thiem equation that assumes steady state flow.

$$K = \frac{r_c^2 \ln(\frac{R_e}{R_w})}{2L} \frac{1}{t} \ln \frac{y_0}{y_t} \tag{1}$$

where r_c is the radius of casing, R_e is "effective radius over which y is dissipated" which is a non-dimensional ratio (Bouwer and Rice, 1976), R_w is the radius of borehole, L is length of the well screen, y_0 is the head change at t_0, and y_t is change of head at time t.

The head displacements measured from slug tests performed in the field were plotted on a logarithmic scale on the vertical axis against time on the horizontal axis. Under the assumptions provided for Bouwer and Rice, a linear portion within the plot determines y_t as the y-intercept and *t* is the slope of the linear line. The analysis of hydraulic conductivity for the six wells can be seen in Appendix D.

3.5.2 Groundwater flow

Water table depths were measured during the field-sampling period using a Solinist water level meter. Well 5 and the oxbow contained pressure transducers that continuously measured the water table depth at a 15-minute sampling interval. The pressure transducer in well 5 was installed August 2016 and collected data until June 2017. The pressure transducer in the oxbow was installed April 2017 and ended June 2017.

The mean hydraulic gradient was obtained through field measurements of the water table levels in the monitoring wells and averaged over the sampling period. Three (i) transects including wells 1-4, 7-8, 5-2 were used to estimate the hydraulic gradient:

$$i = -\frac{dh}{dl} = \frac{h_A - h_B}{\Delta L} \tag{2}$$

Where h is the height of water table at a well, and L is the distance between two wells.

Darcy's Law describes the flow through a porous medium, which was used to estimate the groundwater flow rates and seepage through the oxbow.

$$v = -\frac{K * i}{n} \tag{3}$$

Where K is the hydraulic conductivity (m/d), n is the effective porosity, and i is the hydraulic gradient.

The hydraulic conductivity (K) was averaged using slug tests conducted in the monitoring wells across the site. The mean hydraulic gradient was obtained through bi-weekly measurements of the water table through the use of the monitoring wells. The effective porosity was assumed to be 0.25 for the floodplain alluvium (Schilling, et al., 2017). The rate of groundwater flow (v) was multiplied by the upgradient saturated thickness of the oxbow (107m long and 1.2m water depth) to estimate the daily groundwater seepage rate into the oxbow.

3.5.3 Water quality sampling

Groundwater and surface water samples were collected using a peristaltic pump. The sampling period ranged from June to October 2016, and April to June 2017. A total of seven sampling events were conducted in 2016 and five events were conducted in 2017. Water quality parameters were measured in the field with a YSI Model 556 water quality meter. The measured parameters included temperature, specific conductivity (SC), dissolved oxygen (DO), and oxidation-reduction potential (ORP). Grab samples were collected and taken to the laboratory to measure nitrate-N (NO_3^-), chloride (Cl^-), sulfate (SO_4^-), and dissolved reduction potential (DRP). Laboratory samples were prepared in the field by filtering samples through a 0.45 µm glass fiber filter, transported on ice and analyzed within 12 h of collection.

3.6 Hydrology

Precipitation data was collected from an Iowa Flood Center (IFC) rain gauge. The station is composed of two rain buckets controlled by a tipping mechanism that measured precipitation to an accuracy of 0.127 mm. The rain gauge is located 0.30 km from the border of the watershed, and 4.49 km from the centroid of the watershed. A bridge sensor operated by IFC provided the stage depth of Morgan Creek. The stream gauge is located 2.06 km downstream of the oxbow site and was installed by IFC in December of 2011. The gauge measured the stream depth at a 15-minute interval. The gauge was attached to a bridge and used a sonar signal to measure the distance to the water surface elevation. A map showing the location of each gauge is shown in Figure 3.4.

Figure 3.4. Morgan Creek watershed showing the location of the restored oxbow site (red triangle) in relation to the IFC stream gauge (yellow cross) and rain gauge (blue circle).

3.6.1 Stage - volume relationship

A depth-volume relationship was developed to calculate the volume of water in the oxbow for a specified stage. Cross sectional profiles were created by surveying the site for depths and measuring the widths of the oxbow. The cross sections were divided into two shapes to improve estimates of the area (Figure 3.5). The oxbow was assumed to be represented by a trapezoidal shape containing a triangular bottom. The distance between cross sections were measured, and the volume was estimated by multiplying the distance to the cross-sectional areas. The cumulative volume of each section was summed to estimate the total volume of the oxbow. The stage elevation of the water surface was measured from a pressure transducer installed in the oxbow that allowed for the estimation of water volumes based on the stage of the water surface elevation.

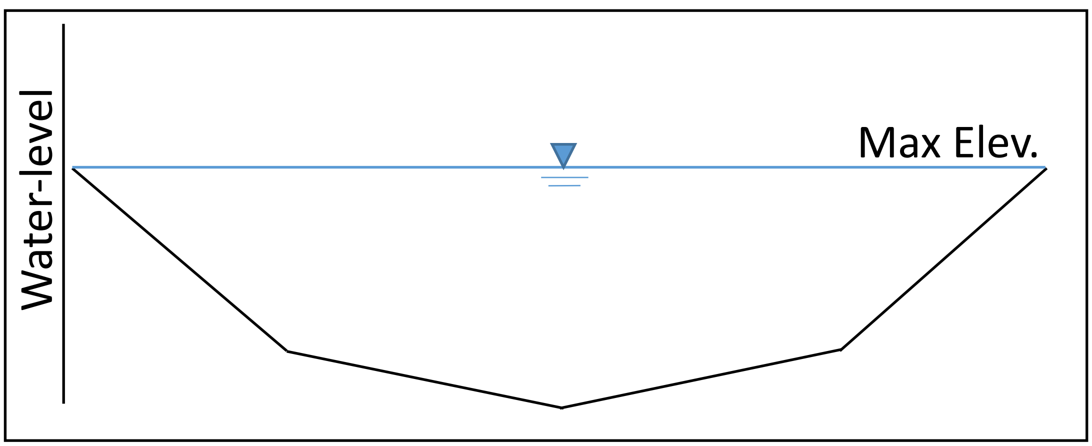

Figure 3.5. Conceptual drawing of a cross sectional view of the oxbow.

A daily water budget for the oxbow was used to determine the outflow of groundwater from the oxbow. The daily change in volume was determined by the stage-volume relationship using a pressure transducer in the oxbow to measure the stage. The inflow seepage rate was determined using average hydraulic gradients measured across the site to determine the groundwater flow velocity (v) which was multiplied by the upgradient saturated thickness of the oxbow (107m long and 1.2m water depth) to estimate the daily groundwater seepage rate into the oxbow. The outflow seepage rate was calculated using the average daily change in volume over the study period and adding inflow seepage rate, then subtracting the evapotranspiration (ET) rate. Monthly

ET rate was obtained from the Iowa Environmental Mesonet. Daily hydrologic budgets enabled estimation of nitrate loading and retention rates.

3.7 Hydrologic simulation

A hydrologic model for Morgan Creek was developed in Hydrologic Engineering Center - Hydrologic Modelling System (HEC-HMS) to simulate the runoff response of the watershed. The HEC-HMS version 4.0 was chosen to model this watershed. The goal of the model was to simulate hydrographs for flood events to estimate the time of concentration and peak discharge. The model included direct runoff, which was determined by combining near surface flow and overland flow, and baseflow that was described by the combination of water infiltration from land surface and subsurface flow.

Watershed characteristics were obtained using Hydrologic Engineering Center's Geospatial Hydrologic Modeling (HEC-GeoHMS). HEC-GeoHMS is an automated program provided by ArcGIS, which is a geographic informational system that more accurately describes sub basin characteristics compared to manual methods. HEC-GeoHMS processes data that allows the import of a watershed directly into HEC-HMS to run hydrologic simulations. The first step was to perform terrain preprocessing. Terrain preprocessing describes the drainage of the watershed and allows stream and subbasin delineation within the watershed. The input data required is a digital elevation map (DEM), which is a 3D model of the terrain's surface. A 1 m resolution DEM was used for this model provided by the Iowa Geological and Water Survey (Iowa Geological and Water Survey, 2010). After the watershed model was generated based on physical parameters, a series of estimated hydrologic parameters was generated.

Hydrologic parameters describe the movement of water through the watershed. Water movement is controlled by precipitation, evaporation, streamflow, and retention of water. HEC-GeoHMS assisted in estimating each parameter based on physical data obtained from the DEM as well as additional input files such as land use and soil type. HEC-HMS estimated the outflow discharge by subtracting losses such as evaporation and retention, transformed excess precipitation through each subbasin, routed water through the stream reaches, and added baseflow to the outflow data. The following hydrological methods were used to estimate runoff in Morgan Creek watershed.

3.7.1 Runoff volume

The Soil Conservation Service (SCS) Curve Number (CN) method estimates the volume of water lost in a watershed. The SCS Curve Number is a function of cumulative precipitation, land cover, soil type, and antecedent moisture conditions. The following equation describes the SCS CN method:

$$P_e = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{4}$$

Where P_e is excess precipitation, P is precipitation, I_a is the initial abstraction, and S is described by the SCS method as the estimated amount of water that is lost before runoff begins. This is known as initial abstraction (I_a), which describes the loss of water through evaporation, vegetation, surface depressions and infiltration.

$$I_a = .2S \tag{5}$$

Where S is the potential maximum retention

$$S = \frac{1000}{CN} - 10 \tag{6}$$

The maximum retention is a function of the Curve number, which is dependent upon the type of land use, soil type, and antecedent moisture conditions. The land use was obtained as a shapefile from National Land Cover Database (Fry et al., 2011). The soil type was obtained from SSURGO database (Soil Survey Staff, 2014).

3.7.2 Direct runoff

To simulate the process of direct runoff caused by excess precipitation, a unit hydrograph for each subbasin must be calculated. The hydrograph is based on the time of concentration and lag time for a storm event. The time of concentration is measured as the longest time it takes for a droplet of water to travel through a watershed to its outlet. The lag time is defined as the time for the center mass of water to reach the hydrograph peak. The SCS Unit Hydrograph Model was used to estimate the response of each subbasin to rain events. The methods used in SCS Unit Hydrograph were as followed in the SCS Technical Report 55 (1986) and the National Engineering Handbook (1971). The peak discharge at any time t is related by:

$$U_p = C\frac{A}{t_p} \tag{7}$$

Where C is a conversion constant (2.08 in SI), A is the watershed area and the time of peak also known as the time of rise.

3.7.3 Baseflow

Baseflow is the portion of flow provided to the stream via groundwater. Although baseflow typically does not play a significant role in the formation of flood hydrographs, it plays a role in the recession of the hydrograph. To describe the contribution of groundwater to streamflow in this study, the exponential recession model was adopted. This method is often used to explain drainage from natural storage in a watershed (Linsley et al., 1982). It describes the relationship of baseflow Q_t at any time t, related to an initial baseflow value as:

$$Q_t = Q_0 K^t \tag{8}$$

Where Q_0 is initial baseflow, and K is an exponential decay constant.

3.7.4 Channel flow

To describe channel flow, a routing method estimated the downstream hydrograph provided an upstream input hydrograph. The resulting hydrograph was determined by applying the continuity and momentum equations. The Muskingum model was chosen to estimate the storage in a stream reach. It is governed by the following continuity equation:

$$I - O = \frac{dS}{dt} \tag{9}$$

Where I is the inflow rate, O is the outflow rate, S is equal to the storage, and t is the time. The storage of a reach using the Muskingum method is shown

$$S = K[xI + (1 - x)O] \tag{10}$$

Where K and x are storage parameters. X ranges from 0.0 to 0.5 and K can be estimated in the following equation

$$K = \frac{L}{V_w} \tag{11}$$

where L is the length of the reach, and $V_w$is the wave velocity.

3.7.5 Hydrologic calibration

An estimated hydrograph was provided by IFC through the use of stream gauge data. IFC created a method to estimate hydrographs based on rating curves derived from hydraulic models in HEC-RAS. Although physical observations of discharge are ideal to calibrate a hydrologic model, limited time and resources prevented the collection for this project. As a result, it was assumed the stream discharge followed the rating curve estimated by IFC for Morgan Creek. The rainfall data provided by IFC was combined with the rating curve to calibrate the model to specific storm events.

Model calibration utilized the hydrograph provided by IFC to estimate the Muskingum model parameter K. The parameter was estimated at the interval between similar points on the inflow and outflow hydrographs. Once K was estimated, X was estimated by a trial and error method. This optimization procedure was iterated until the resulting hydrograph created the best fit to the synthetic hydrographs.

3.8 Event calibration

The rating curve was applied to storms throughout 2016, and modeled in HEC-HMS to calibrate the hydrologic model based on observed events. Two storm events in June and August of 2016 are presented to show the comparison between the simulated and the estimated hydrograph using the rating curve method (Figure 3.6 and 3.7). The percent error between the simulated and rating curve hydrographs for the June and August floods was 7.5 and 20%, respectively.

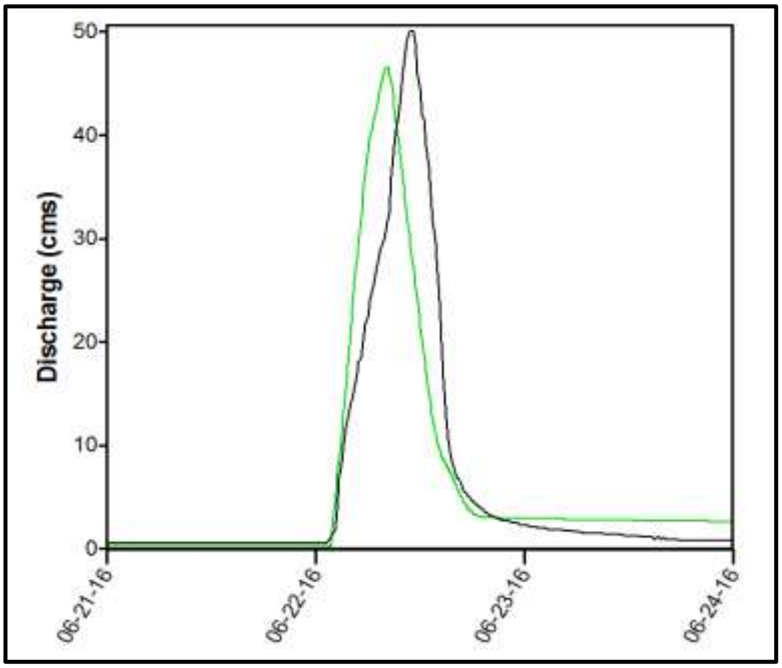

Figure 3.6.Simulated (green) compared to observed (black) hydrograph of Morgan Creek from flood event during June, 2016.

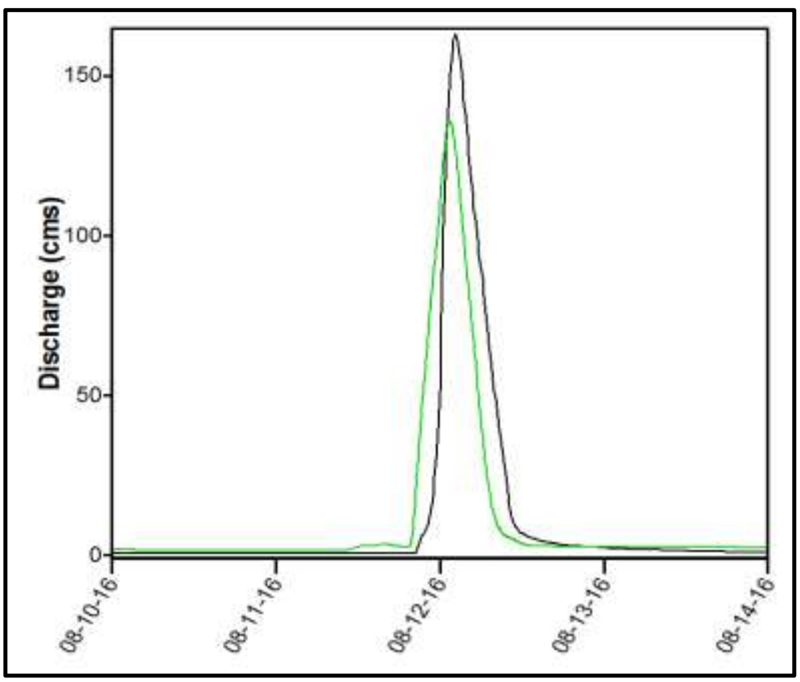

Figure 3.7. Simulated (green) compared to observed (black) hydrograph of Morgan Creek from flood event during August, 2016.

3.9 Nutrients

Nitrate-nitrite as nitrogen (NO_x-N) was quantified using the Hach Nitratax SC plus, 2-mm path length (Hach Company, 2011). The sensor was installed on the northern bank of the oxbow following a flood event to measure the nitrate concentration in the oxbow. The detectable nitrate concentration for this sensor ranged from 0.1 - 25 mg L^{-1}. A CR1000 data logger continuously recorded nitrate concentration and water temperature at a 5-minute interval (Campbell Scientific Inc.).

Inflow nitrate load to the oxbow was estimated by the volume of water in the oxbow after a flood pulse multiplied by the nitrate concentration in the oxbow. The amount of NO_3^- delivered to the wetland for one flood event was estimated as the difference between input loads caused by groundwater seepage and flood waters and exported loads caused by groundwater seepage. Areal retention rate for NO_3^- (g N m^{-2} day^{-1}) was calculated by dividing the amount of NO_3^- (mass) by the time (d) for the oxbow to return to a stable concentration and by the surface area of the oxbow. To estimate the percent of NO_3^- retained in the oxbow, the load exported from groundwater seepage was compared to the total load in the oxbow.

A mathematical approach was developed to predict nitrate reduction in wastewater treatment systems following a first order decay reaction (Kadlec and Knight, 1996; Reed et al., 1995). The method assumes the system follows a steady state plug flow reaction. The same method was adapted for modeling denitrification kinetics in wetlands. Although plug flow conditions for wetlands are dependent on the length-width ratio, vegetation, and hydraulic conductivity, and steady state cannot be assumed during flood pulses, the method was found to adequately describe storm water wetlands using the same equations currently employed for wastewater treatment wetlands (Carleton et al., 2010). The rate of nitrate loss by denitrification from the water column is assumed to be proportional to the concentration of nitrate. As a result, nitrate is expected to follow an exponential decay governed by the following equation:

$$\mathrm{C_t} = \mathrm{C_0}\mathrm{e}^{-\mathrm{k}*\mathrm{t}} \tag{12}$$

Where C_t is the concentration at any time, C_0 is the initial concentration, k is a rate decay coefficient shown in equation 12, and t is the time.

The removal rate coefficient for nitrate is temperature dependent. The modified Arrhenius equation was used to describe the temperature dependence for denitrification:

$$k = k_{20}\theta^{(T-20)} \tag{13}$$

Where k is the removal rate coefficient (day^{-1}); k_{20} is removal rate coefficient at 20 °C (day^{-1}); θ is the temperature coefficient; and T is the water temperature (°C)

3.10 Fish survey

To estimate the fish population and species richness in the oxbow, a three-pass depletion method was performed using a fish seine. The three-pass depletion is ideal if the stream or body of water is small and it contains a small fish population (< 2,000 individuals) (Lockwood and Schneider, 2000). The multiple pass depletion method relies upon consistent probability to catch fish and can be estimated using the following equations:

$$T = \sum_{i}^{k} C_i \tag{14}$$

$$X = \sum_{i=1}^{k} (k-i)C_i \tag{15}$$

Where T is the total number of fish caught in all passes, i is the pass number, k is the number of total passes, C_i is the number of fish caught in i^{th} sample, and X is an intermediate statistic used in equation (15).

The maximum likelihood estimate of N is determined iteratively until:

$$\left[\frac{n+1}{n-T+1}\right] \prod_{i=1}^{k} \left[\frac{kn-X-T+1+(k-i)}{kn-X+2+(k-1)}\right] \leq 1.0 \tag{16}$$

Where n is the smallest integer to satisfy equation (15). The following equations calculate the probability to capture fish (p), and the variance of N.

3.11 Chapter summary

The methods and procedures presented in this chapter described the processes used in this study to investigate the hydrogeology, hydrology, water quality, and ecological benefits found in an eastern Iowa restored oxbow site. Groundwater flow direction and water quality were evaluated using monitoring wells. Groundwater information was combined with application of two geophysical methods to further characterize site conditions. A HEC-HMS model was constructed to simulate the watershed's response to hydrologic events. Nitrate retention was estimated using information provided from an *in-situ* nitrate sensor and a stage-volume relationship to estimate load fluxes of nitrate. The nitrate retention measured in the oxbow was compared to a first order denitrification decay to estimate the role of denitrification in the oxbow. Lastly, a fish survey was conducted to estimate the total population of fish in the oxbow.

Chapter 4: Results - initial conditions

4.1 Introduction

The purpose of this chapter is to describe the characterization of the hydrogeology and water quality conditions of the oxbow site. Furthermore, the watershed's response to summer flood events was investigated to understand nutrient loading and connection characteristics. The substrate and local geology of the site were assessed using two geophysical methods and soil sampling for grain size distribution. Groundwater monitoring wells provided insight on spatial variations in hydraulic gradient, hydraulic conductivity and groundwater quality. Surface water samples were also collected to understand the similarities between groundwater and surface water and to understand water quality characteristics throughout the site.

4.2 Site characterization

The geology of the study site was investigated vertically and spatially using two geophysical methods. An ER analysis was performed prior to the oxbow being restored to measure the vertical variation of soil resistivity (Fig 4.1 & 4.2). Transect line one was located on the western edge of the oxbow whereas transect line two surveyed the eastern edge of the oxbow. The resistivity ranged from 25 – 150 ohm-m in both transects and based on correlations established at other sites; the variations of different geologic materials were interpreted. Higher resistivity values shown in red correlate to coarser sediments such as sand and gravel, whereas lower resistivity values shown in blue signify finer sediment such as clay. The focus of the study was on shallow groundwater so the depth of the survey extended to approximately 30 feet deep. It should be noted that the resistivity values themselves do not represent the characteristics of the overall soil; rather, the spatial variation of values is more important for the interpretation of results.

Transect one suggested that downgradient alluvium of the oxbow was likely composed of loam with a fine portion of sand (Figure 4.1). The northern edge of the survey indicated a layer of loam overlying a region of highly resistive substrate close to the surface. The highly resistive substrate upgradient of the oxbow was similar to results found in transect 2. This region was interpreted to be bedrock. The assumption was verified in the field because significant amounts of float, which are broken pieces of bedrock, were noticed on the surface of the agriculture field. This suggests the depth to bedrock is shallow, and float easily migrated to the surface during freeze-thaw cycles. The highly resistive region in the center of the transect was likely caused by standing water in the oxbow depression, which interfered with the transmission of the electrical signal.

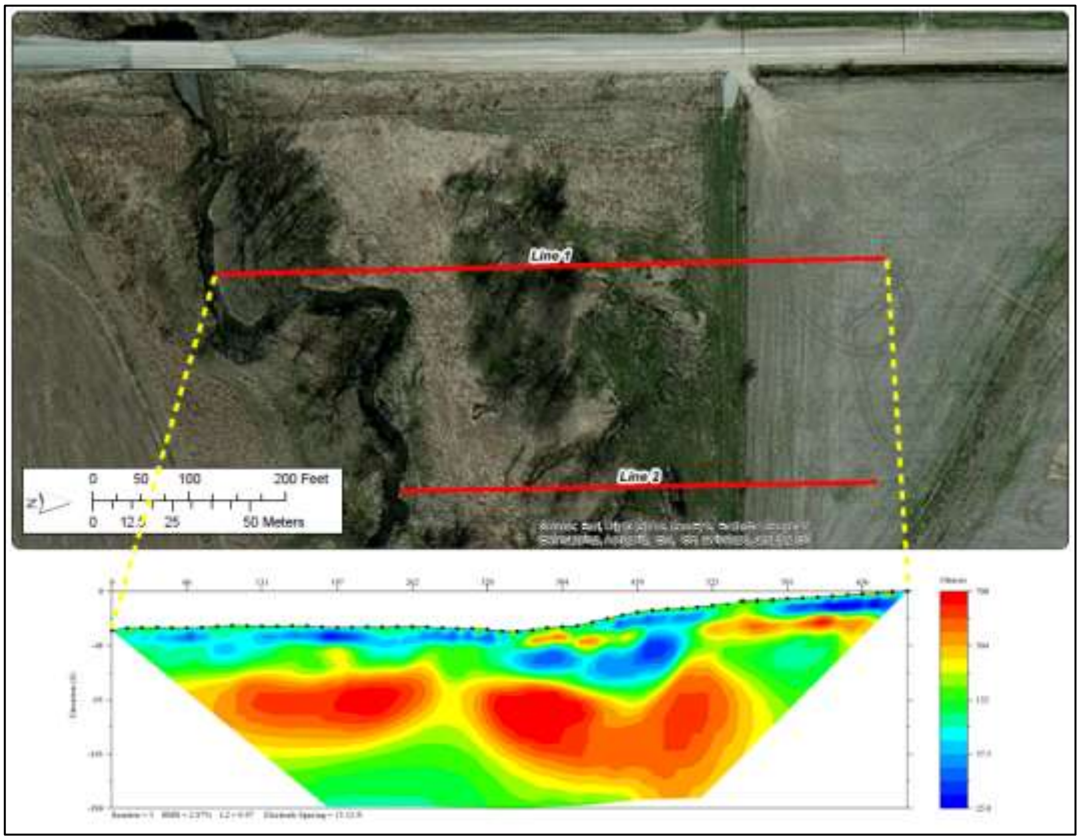

Figure 4.1. Electrical resistivity survey showing substrate from transect line 1.

The downgradient region of transect two was found to be more homogeneous compared to transect one (Figure 4.2). The sediment composition was interpreted to consist of a layer of loam overlying sandy loam. As mentioned before, the region located upgradient of the oxbow showed higher resistive values that suggests bedrock was close to the surface.

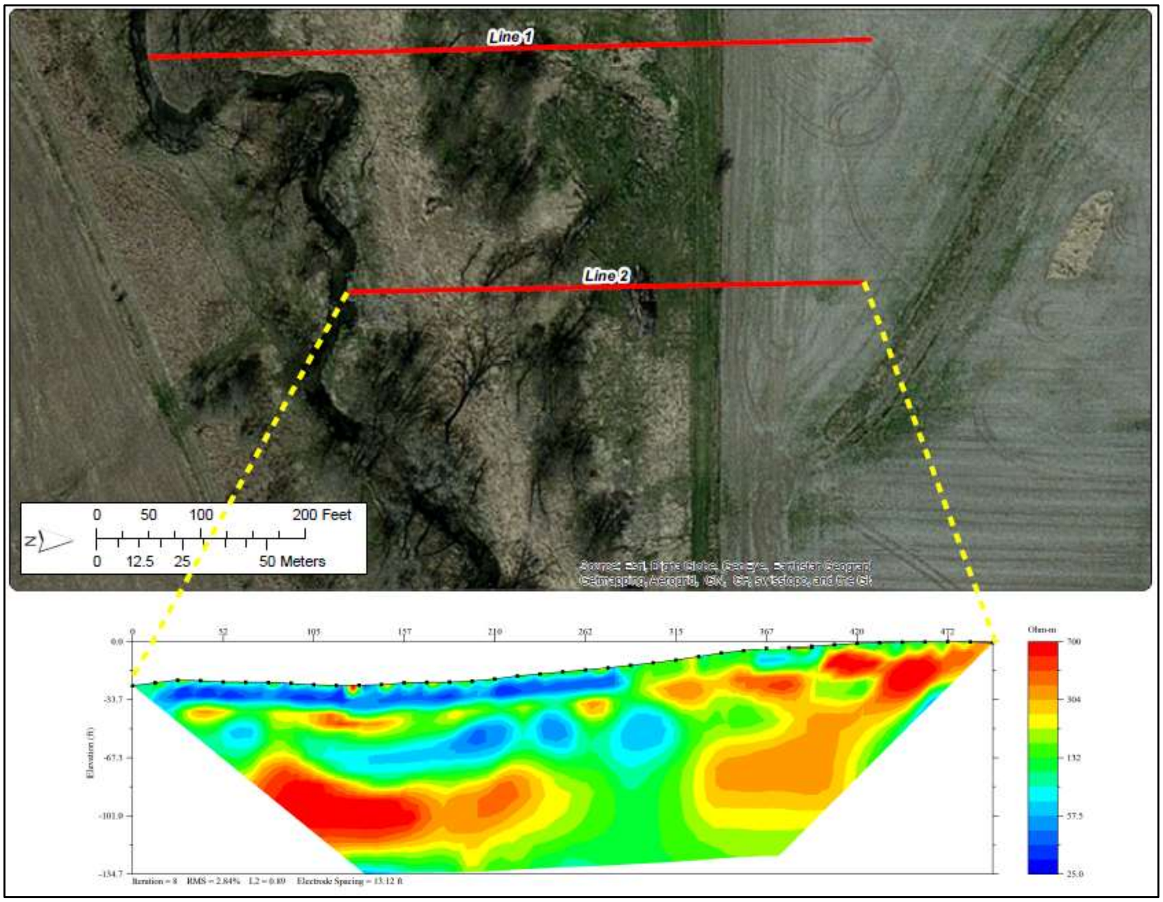

Figure 4.2. Electrical resistivity results showing substrate conductivity in transect two.

The EM survey was conducted after construction of the oxbow. Ground resistivity and surface elevation were correlated. Soil resistivity was found to decrease in lower elevated regions. On the other hand, regions higher in elevation correlated with increased soil resistivity. The 1 m DEM showed how surface elevation varied throughout the site (Figure 4.3). The historic stream channel is represented by a dark red color. The former stream channel was verified using aerial photography captured in the year of 1930. Regions slightly higher in elevation (> 220 meters above sea level (masl)) such as directly south of the oxbow or along the northern perimeter are represented by lighter orange to yellow. Higher elevations (>240 masl) such as the hillside to the north of the oxbow are shown in green.

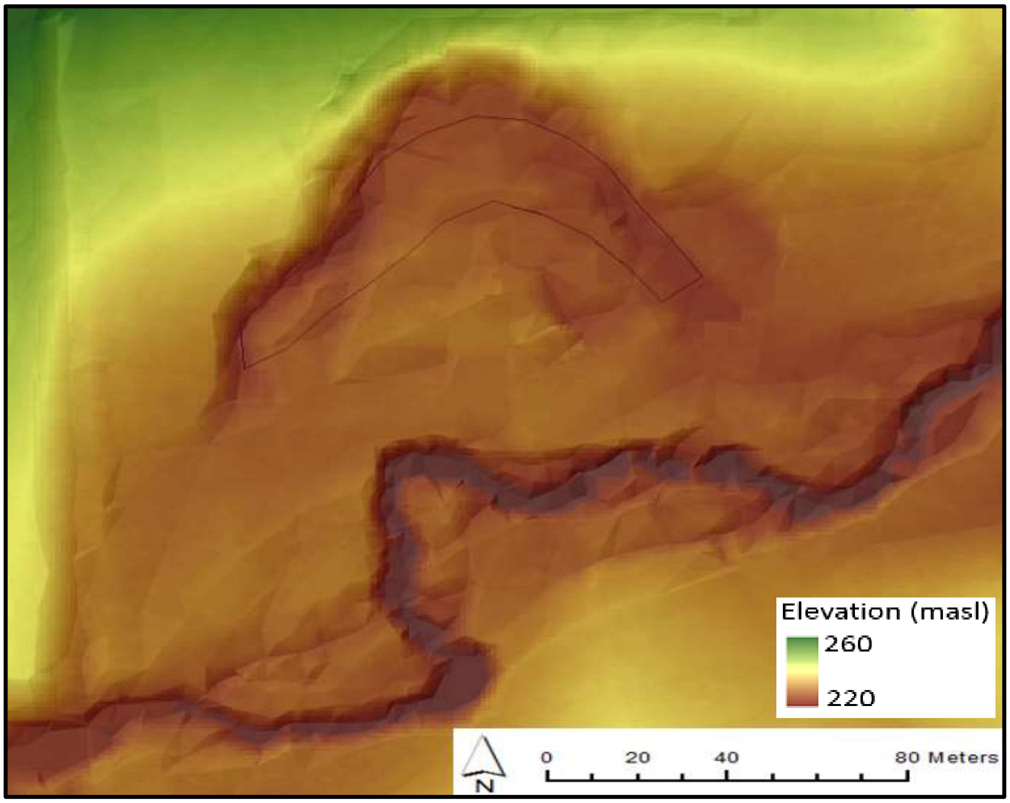

Figure 4.3. Digital Elevation Model (DEM) showing elevation gradient for the oxbow site with an outline of the oxbow shown in black.

EM mapping spatially described the ground conductivity of the site (Figure 4.4). Ground conductivity was converted to resistivity to maintain consistent units. The former stream channel located near the two ends of the oxbow was identified with resistivity values ranging from 16 to 40 ohm-m. Low resistivity is indicative of a greater fraction of silt and clay in the sediment. The southern edge of the oxbow reported resistivity values ranging from 46 to 70 ohm-m. These values correlated to a region composed of sandier sediment. Similar to ER, EM identified a highly resistive region near the northern section of the site. Higher resistivity is more characteristic of permeable sands but is also indicative of bedrock. The highly resistive region supports the assumption that bedrock was located near the surface. The northern perimeter adjacent to the oxbow also contained debris and metal that may have interrupted the EM signal during the survey. Comparing the EM data to historic aerial photos and the DEM, similarities between the elevations are noticed. The lowest resistivity values correlated to the historic stream channel and suggested the former stream channel contained greater fines, and the highest elevations corresponded to highly resistive substrate that was likely bedrock.

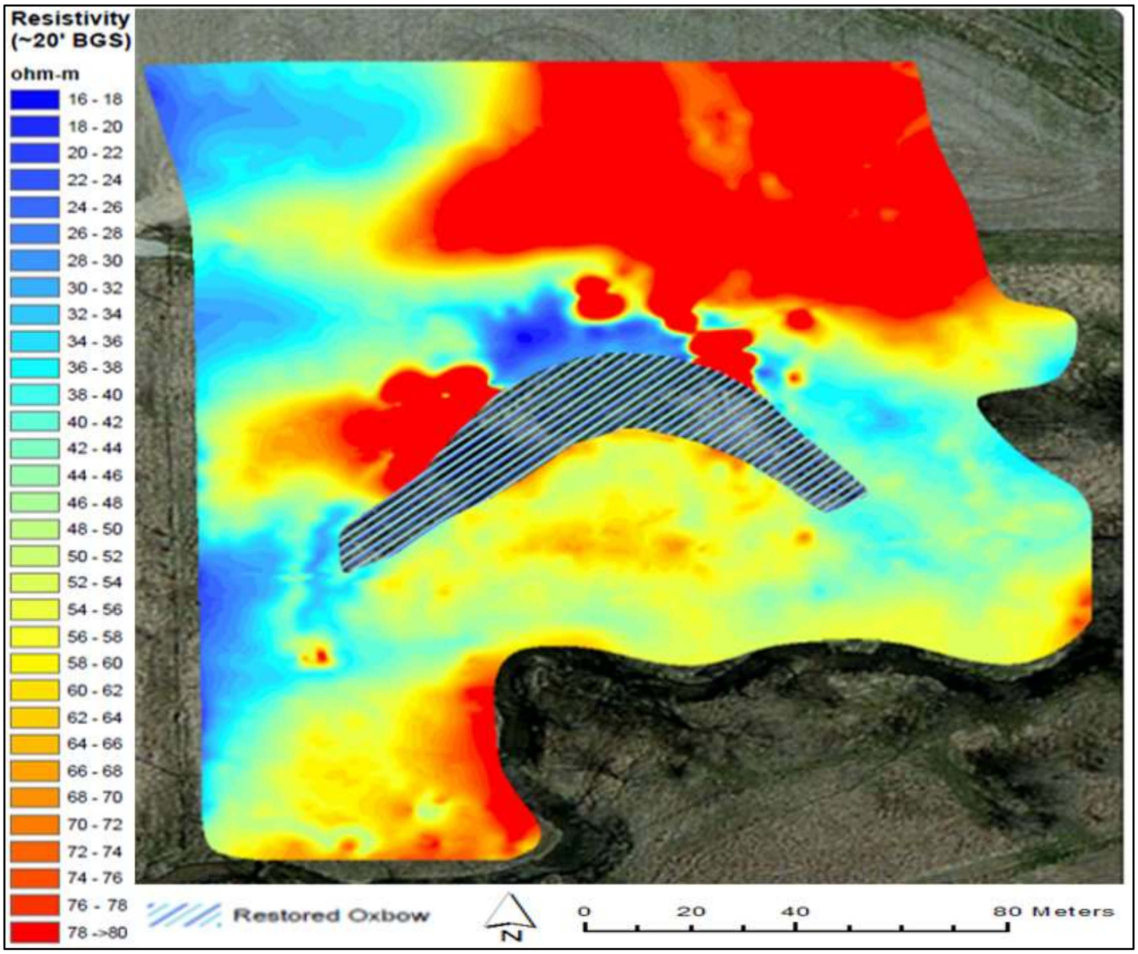

Figure 4.4. Electromagnetic (EM) conductivity describes spatial variance of substrate conductivity across the site.

4.2.1 Sedimentology

The stratigraphy of the site was indicative of a floodplain with sediment composition ranging from clay to sand (averaged sandy loam) (Figure 4.5). The uppermost stratum across the site consisted of a 0.3 to 1.5 m thick layer of black, organic-rich loam to silty loam. In general, this layer was overlying a region of sandy loam that was sitting above sand with fine to coarse gravel. This sand and gravel unit likely indicated the depth of the old streambed. The spatial variation of grain size distribution generally correlates with EM results. Soils at wells 1 and 3 are classified as sandy loam to coarse sand, which coincided with the EM's finding of higher sand content. Field observations of soil composition are shown in Appendix C.

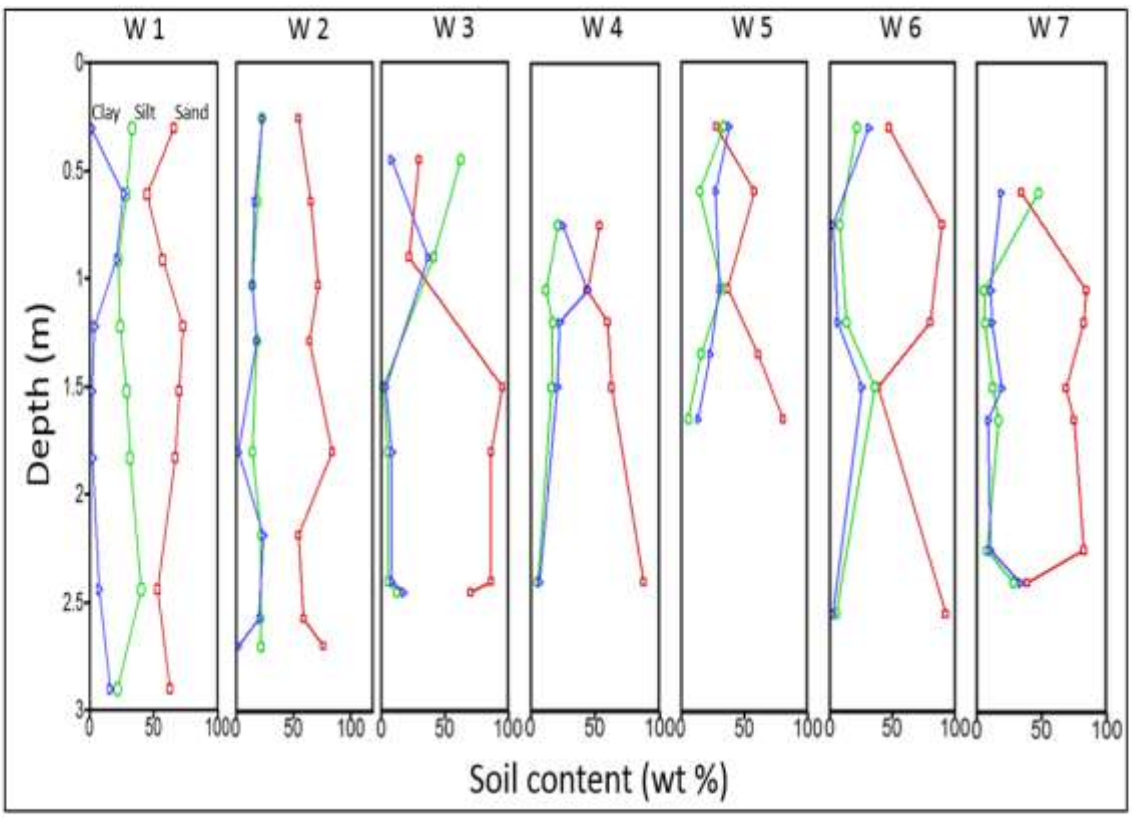

Figure 4.5. Soil gradation of percent clay, silt, and sand for wells one to seven.

4.3 Hydrology

Iowa's climate consists of a humid continental zone that typically experiences hot and humid summers, cold winters, and wet springs (Richardson, 1994). The average annual precipitation from 1981 – 2015 for Linn County is 920 mm (PRISM Climate Ground and Oregon State University (2004)). On average, the region receives nearly half of its rain from April through July, with averages exceeding 110 mm $month^{-1}$ (Figure 4.6)

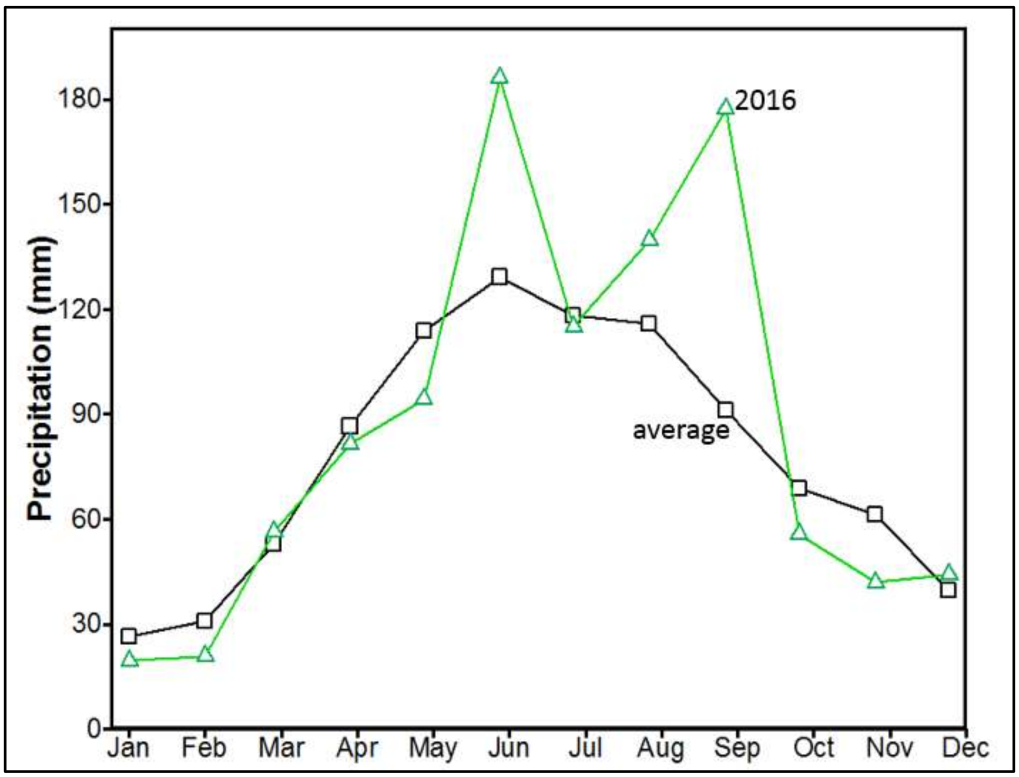

Figure 4.6. Monthly average precipitation for years 1981 - 2010 shown in black, and year 2016 shown in green.

Annual precipitation for 2016 was measured from a rain gauge provided by IFC (Figure 4.6). The annual precipitation totaled 1034 mm, which was 112% of the long term average. The monthly averages for 2016 compared to long term values were within 20 mm per month, except for the months of June, August, and September. These rainier months coincided with increased periods of stream flow measured in Morgan Creek.

4.3.1 Stream hydrology

Morgan Creek was considered to flood when the water surface elevation exceeded 222.63 masl, which corresponded to a stream depth of approximately 1.58 m. Peak discharge required to initiate overbank flooding into the oxbow was estimated to be 8 m^3s^{-1}. Data gathered from the period from December 2011 to June 2017 showed Morgan Creek flooded 17 times during this period (Figure 4.7). However, the stream did not flood from the end of 2011 through 2012, which coincided with the 2012 drought. The wet spring of 2013 caused Morgan Creek to flood frequently. A total of six separate flood events occurred over a span of six months. Based on the period of record, Morgan Creek is above bank full on average 3.1 times per year. The flood probability in Morgan Creek suggested the stream is flashy because it often quickly reacted to small intense precipitation events that caused rapid rates of change in stream flow.

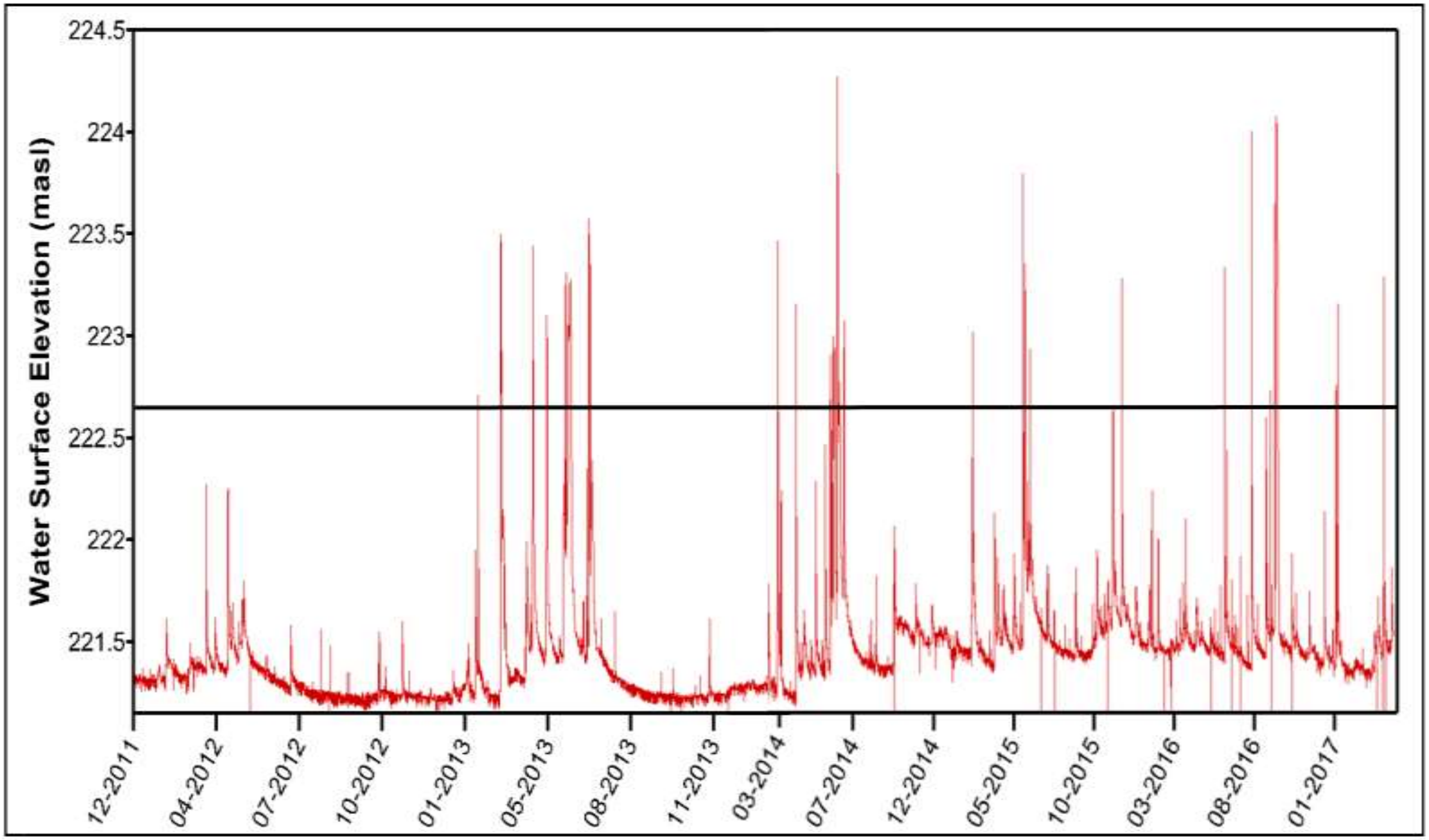

Figure 4.7. Water surface elevation of Morgan Creek from the years of 2011 to 2017 provided from IFC stream gauge in Meters above Mean Sea Level (masl). The black line shows flood elevation of the stream.

After the restoration of the oxbow in August 2016, Morgan Creek flooded on six occasions according to the IFC stream gauge (Figure 4.8). Flood events connected the main channel to the oxbow for a total time of 46.25 hours. The first point of connection during floods was located on the eastern segment of the oxbow, where the stream bank is at the lowest elevation. As a result, floodwater propagated from the downstream reach of Morgan Creek and caused the flood water to backfill into the oxbow. This flood dynamic is only important when Morgan Creek is at minor flood stage, which is at an elevation slightly greater than 222.6 masl.

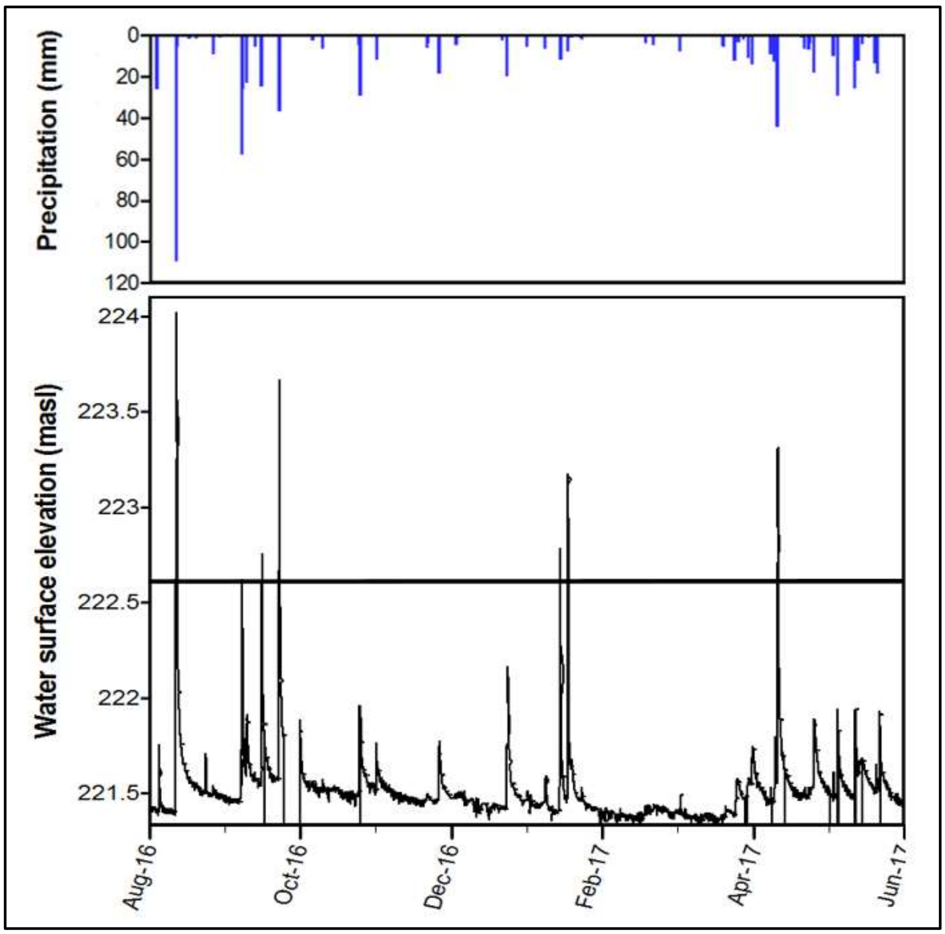

Figure 4.8. Water surface elevation and precipitation provided by IFC for Morgan Creek beginning after the restoration of the oxbow in August, 2016.

Storm intensities after August 16, 2016 that produced floods in Morgan Creek ranged from 8.38 mm on January 19th, 2017 to 110.10 mm on August 11th, 2016. The maximum water surface water elevation of the stream after oxbow restoration was 224 masl, which corresponded to a stream depth of approximately 3 m.

The flood of August 11th, 2016 was the second largest flood during the period of record. A precipitation event produced 110.10 mm of rain over a span of 14 hours. As a result, the surface elevation of Morgan Creek rose to 224 masl, with an estimated peak discharge of 163 m^3s^{-1}. The stream flooded for approximately 13 hours. A minor flood occurred on September 16th, 2016 responding to a 35.30 mm precipitation event. This small flood likely resulted from saturated antecedent soil conditions. The surface elevation of the stream peaked at 222.76 masl, which connected the stream to the floodplain for four hours. The approximate peak discharge was 10 m^3s^{-1}. On September 23rd, 2016, Morgan Creek reacted to a storm event that produced 37.34 mm of precipitation over the watershed. Morgan Creek's water surface elevation increased to a maximum stage of 223.67 masl that connected the stream to the floodplain for 13.25 hours. The approximate discharge of Morgan creek was estimated to be 90 m^3s^{-1}. Two more floods occurred in January, each caused by minor precipitation events. The winter season prevented water from infiltrating into the frozen ground causing Morgan Creek to flood for a total of 10.5 hours.

4.3.2 Stage-volume relationship

A stage-volume relationship was created to estimate the volume of the oxbow corresponding to a specific elevation (Figure 4.9). The lowest elevation measured at the center of the oxbow was 226.60 masl. The oxbow is considered to be at full capacity when stage elevation is 228.66 masl. The maximum elevation is constrained by the eastern edge of the site, and corresponds to an oxbow volume of approximately 3,040 m^3. The stage-volume slope increases after 227.2 masl corresponding to the inundation of the two arms of the oxbow.

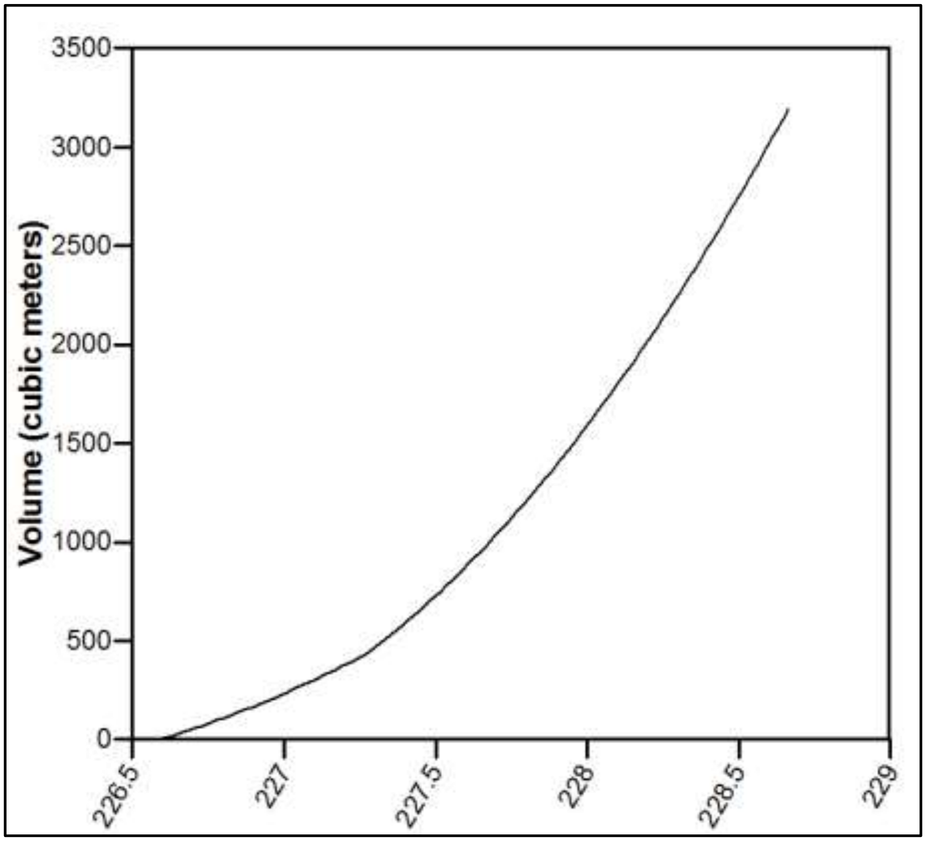

Figure 4.9. Stage-volume relationship. Note that 226.6 m is equal to the bottom of the oxbow. Maximum storage volume is approximately 3,040 m^3.

4.4 Groundwater

The water table in the floodplain fluctuated considerably throughout the monitoring period. The groundwater depth was monitored continuously in well 5 (Figure 4.10). The groundwater followed a similar trend to the stream elevation of Morgan Creek. The water table showed rapid response to precipitation events and drastically rose during flood pulses. In 2016, the depth of the water table for well 5 ranged from -2 m below ground surface to 0.65 m above land surface.

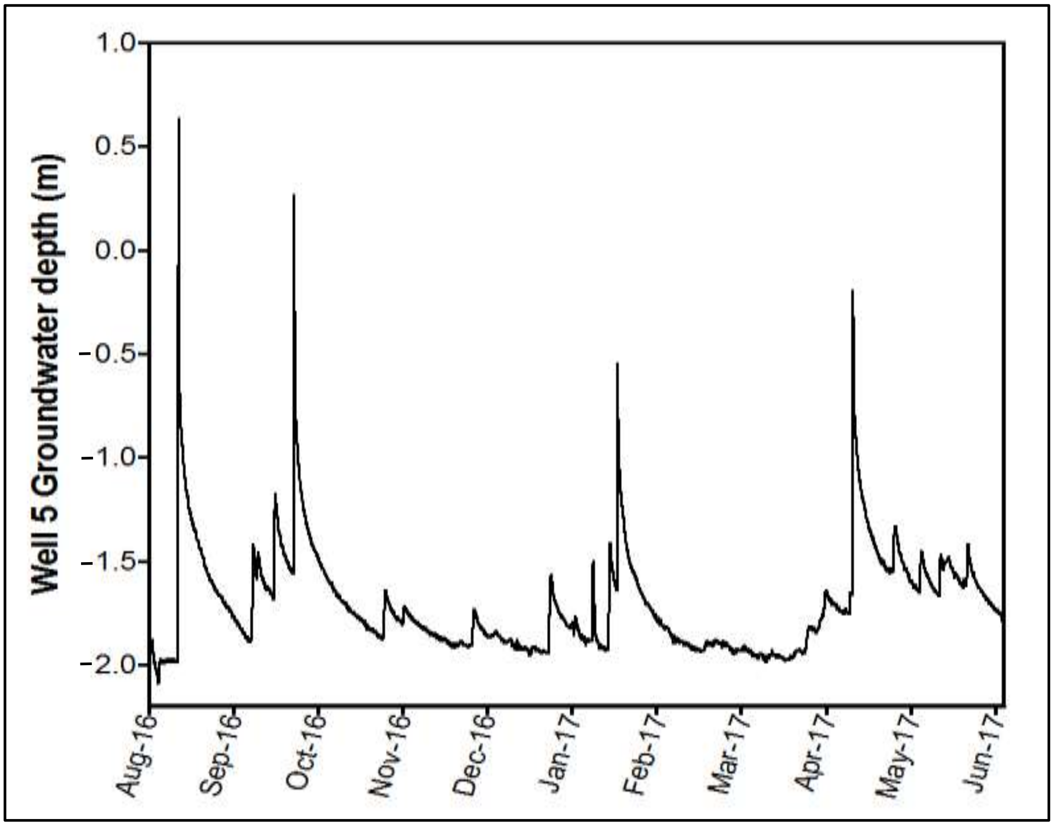

Figure 4.10. Depth to water in meters for well 5 after the oxbow was restored.

Water table measurements taken during field sampling were used to estimate hydraulic gradients and groundwater flow direction. Groundwater flows in a southeast direction downgradient of the oxbow. The hydraulic gradient represented in Figure 4.11 was measured from the field sampling date of September 12^{th}, 2016, which approximates the average hydraulic gradient observed from 2016 to 2017. Although the downgradient hydrogeology was characterized, upgradient groundwater was not investigated due to the shallow bedrock, which prevented the installation of monitoring wells. However, the flow direction upgradient of the oxbow is assumed to follow a similar southeastern flow that was observed in the downgradient region of the oxbow.

Figure 4.11. Groundwater flow direction estimated on September 12th, 2016 which flowed in a southeastern direction towards Morgan Creek.

The horizontal hydraulic gradient was calculated based on the measured water table depth and distance between wells. During the investigation, the hydraulic gradient averaged 0.0023 for transect one (wells 1 and 4), 0.0015 for transect two (wells 7 and 8), and 0.0039 for transect three (wells 5 and 2). These gradients were averaged from field measurements that ranged from June 29th, 2016 to May 23rd, 2017 to estimate a hydraulic gradient of 0.0026 across the site.

The hydraulic conductivity was estimated using slug tests and ranged from 0.17 to 12.53 m day^{-1} (Table 4.1). The average downgradient hydraulic conductivity was estimated to be 4.02 m day^{-1} across the site. Horizontal groundwater flow entering the oxbow can be estimated if an assumed saturated cross section upgradient of the oxbow had dimensions of 1.2m x 107 m. With an understanding of the average hydraulic gradient of 0.0026, hydraulic conductivity of 4.02 (m day^{-1}), and an effective porosity of 0.25, an estimated groundwater flow velocity of 0.042 m day^{-1} was determined. The cross-sectional area multiplied by the groundwater flow velocity estimated a groundwater seepage rate of approximately 5.37 m^3 day^{-1}. Therefore, groundwater discharge is relatively small compared to the size of the oxbow.

Table 4.1. Hydraulic conductivity measured using the Bower and Rice method for wells 1-5 and 7.

Well #	Hydraulic Conductivity (m day^{-1})
1	5.27
2	0.62
3	4.45
4	12.53
5	1.10
7	0.17
average	4.02

4.5 Water quality

Water samples were collected from June 2016 to April 2017. This period established the baseline conditions that described the average water quality for the site during the study. Samples were collected on eight occasions from the monitoring wells and stream, and sampled on six occasions from the oxbow. Water quality constituents measured included Dissolved Oxygen (DO), Oxidation-Reduction Potential (ORP), pH, specific conductance, Nitrate (NO_3), sulfate (SO_4), Chloride (Cl^-), and Dissolved Reactive Phosphorous (DRP) (Table 4.2).

Table 4.2. Water quality summary of nutrients and water chemistry measured from June 29th 2016 to April 13th, 2017.

Site		Depth to water (m)	Temp °C	pH	Spec Cond µS/cm	DO mg/L	ORP mV	NO_3-N mg/L	Cl^- mg/L	SO_4^- mg/L	DRP mg/L
W 1	Mean	1.22	17.86	7.14	1.16	1.54	-9.84	2.15	41.98	61.04	0.14
	St dev	0.12	1.71	0.33	0.22	0.55	56.35	1.33	9.48	20.60	0.16
W 2	Mean	1.47	17.79	7.00	1.09	1.56	-30.59	0.44	18.40	100.65	0.15
	St dev	0.13	2.00	0.18	0.11	0.44	63.36	0.71	23.21	50.28	0.13
W 3	Mean	1.19	17.22	7.01	0.82	1.28	-12.93	2.48	46.43	100.65	0.16
	St dev	0.12	2.28	0.24	0.03	0.48	45.77	0.66	7.57	50.28	0.24
W 4	Mean	1.01	17.23	6.94	0.93	1.12	-38.41	0.10	9.76	52.24	0.09
	St dev	0.15	3.13	0.31	0.15	0.56	68.07	0.00	10.71	53.07	0.06
W 5	Mean	0.96	16.64	7.22	0.51	1.86	7.23	0.32	6.89	11.16	0.11
	St dev	0.24	2.69	0.38	0.08	1.34	41.07	0.38	1.31	2.44	0.04
W 6	Mean	1.58	16.93	7.18	0.57	2.95	17.41	0.20	10.16	15.72	0.10
	St dev	0.18	1.86	0.23	0.04	1.50	29.99	0.24	3.79	7.72	0.01
W 7	Mean	1.47	17.16	7.26	0.65	2.61	16.88	0.27	15.94	25.81	0.17
	St dev	0.18	1.97	0.19	0.08	1.36	35.64	0.29	17.64	25.72	0.13
W 8	Mean	0.91	18.88	7.18	0.71	3.10	-12.39	0.32	5.68	98.40	0.40
	St dev	0.18	2.59	0.25	0.11	2.20	40.10	0.25	1.33	58.32	0.25
Stream	Mean	—	18.36	7.75	0.44	8.49	-5.11	8.84	25.86	23.54	0.17
	St dev	—	3.09	0.07	0.14	1.82	48.25	1.22	3.11	2.56	0.08
Oxbow	Mean	—	16.67	7.66	0.43	6.17	-10.63	0.55	7.48	6.82	0.85
	St dev	—	2.38	0.25	0.13	3.32	70.99	0.65	2.08	0.85	0.87

The spatial patterns of dissolved oxygen, specific conductivity, and chloride provided further insight on how groundwater interacts with the oxbow. Based on the concentrations of DO and specific conductivity, the site was separated into two different regions. The first region was located near Morgan Creek, which included wells 1 to 4. The second region was adjacent to the oxbow that included wells 5 to 8.

Groundwater DO measured in the region closer to Morgan Creek (Wells 1 - 4) generally ranged between 1.12 to 1.56 mg l^{-1} (average 1.35 mg l^{-1}). In contrast, groundwater DO near the oxbow (Wells 5 – 8) ranged between 1.86 mg l^{-1} to 3.10 mg l^{-1} (average 2.63 mg l^{-1}). DO in the surface water including both Morgan Creek and the oxbow ranged between 3 to 12 mg l^{-1} (average 8.34 and 7.77 mg l^{-1}, respectively). The results showed wells located adjacent to the oxbow measured higher in DO, coinciding with higher DO levels in the oxbow of 7.77 mg l^{-1}. Increased DO in the groundwater near the oxbow suggested the oxbow might have influenced local water quality in the groundwater.

Specific conductivity is the measure of how well water conducts electrical current. Specific conductivity followed a similar pattern as DO, where concentrations varied depending on the two regions. Specific conductivity in the groundwater near Morgan Creek (wells 1 - 4) ranged from 771 to 1430 µS cm^{-1} (average 997 µS cm^{-1}), whereas specific conductivity in the groundwater near the oxbow (wells 5 to 8) ranged from 367 to 847 (average 610 µS cm^{-1}). The surface water in the stream and oxbow ranged from 228 to 556 µS cm^{-1} (average 442 and 433 µS cm^{-1}, respectively). The data suggested the oxbow might be contributing to lower specific conductivity in downgradient groundwater. In wells near Morgan Creek, groundwater specific conductance in wells 1 to 4 was much higher than surface water. Comparing DO and specific conductivity data, hydraulic head data indicated that Morgan Creek was a gaining stream where groundwater flowed into the stream during low stream flow. The patterns in the groundwater quality data support the idea of a southeasterly flow of groundwater.

Chloride is often used as a groundwater tracer because it is a non-reactive solute. Chloride concentrations varied more than DO and specific conductivity throughout the site, and the wells along Morgan Creek showed different patterns of this solute. Wells 1 and 3 were consistently highest and averaged 44.2 mg l^{-1}, whereas wells 2 and 4 were consistently lower, and averaged 14.1 mg l^{-1}. The chloride concentrations in the surface water of Morgan Creek differed from the chloride levels of the oxbow. Morgan Creek's chloride concentration averaged 25.9 mg l^{-1}, while the oxbow averaged 7.5 mg l^{-1}. Although wells 1 and 3 showed high concentrations of chloride similar to Morgan Creek, the levels for wells 1 and 3 exceeded the concentration found in Morgan Creek. A possible explanation for the increased chloride concentrations may be due to a deposited source (i.e. salt) surrounding the two wells. The wells near the oxbow (wells 5 - 8) exhibited similar chloride concentrations (9.7 mg l^{-1}) to the oxbow (7.5 mg l^{-1}), suggesting a possible connection between the oxbow and local groundwater.

ORP in the groundwater (wells 1 - 8) varied from -122 to 95 mV (averaged 35 mV). ORP in the surface water for both the oxbow and stream ranged from -147 to 86 mV and averaged -7.9. Ground water pH values for wells 1 to 8 all measured around neutral and averaged 7.12. The pH of surface water for both Morgan Creek and the oxbow averaged 7.92.

4.5.1 Nutrients

Nitrate-N concentrations across the study site varied (Table 4.3). Nitrate-N measured in Morgan Creek ranged from 7.38 to 11.4 mg l^{-1} (average 8.84 mg l^{-1}), nitrate-N in the monitoring wells ranged from <0.1 to 3.4 mg l^{-1} (average 0.79 mg l^{-1}), and nitrate-N in the oxbow ranged from <0.1 to 1.8 mg l^{-1} (average 0.55 mg l^{-1}). Nitrate-N levels below the detectable limits were common in the groundwater throughout sampling period (34 out of 59 samples). However, nitrate-N was consistently detected in two wells. Nitrate-N concentrations in wells 1 and 3 averaged 2.15 mg l^{-1} and 2.48 mg l^{-1}, respectively. Although these two wells consistently measured > 1.0 mg l^{-1}, overall the nitrate-N concentrations in floodplain groundwater were consistently lower than those detected in Morgan Creek.

Nitrate-N concentrations varied temporally during the 2016 monitoring season. Flood events occurred during the months of August, September, and January. Although two flood events in January 2017 were not sampled due to the winter season, the August and September floods were sampled before and after each pulse. The first flood event occurred on August 12th, 2016. Water samples collected prior to the event showed water quality at the baseline concentrations, with no detectable nitrate-N concentration in the oxbow. Water samples collected 4 days after the flood event showed nitrate-N concentration in the oxbow of 1.0 mg l^{-1}; Morgan Creek, 8.6 mg l^{-1}; and the range of nitrate-N concentrations in the groundwater wells below the detectable limits except for wells 1 and 3. After 30 days, nitrate-N in the oxbow was below the detectable limits, which suggested the total time necessary for the oxbow to reduce a concentration of 1 mg l^{-1}, or approximately a 2.88 kg load of after the flood, was less than 30 days.

Table 4.3. Nitrate-N concentrations measured across the site from 8 grab samples ranging from June 2016 to April 2017.

	NO_3-N Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	4.56	0.69	3.34	0.10	1.26	0.10	0.10	0.10	11.44	0.10
7/13/2016	2.44	0.10	2.27	0.10	0.50	0.10	—	—	9.99	—
7/28/2016	3.03	0.10	3.41	0.10	0.10	0.10	0.10	0.49	8.28	—
8/16/2016	1.40	0.10	2.51	0.10	0.10	—	0.57	0.10	8.55	0.95
9/12/2016	0.80	2.25	2.51	0.10	0.10	0.10	0.10	0.76	8.64	0.10
9/26/2016	1.84	0.10	2.35	0.10	0.10	0.79	0.85	0.10	8.75	1.83
10/12/2016	3.00	0.10	2.35	0.10	0.10	0.10	0.10	—	7.73	0.22
4/13/2017	0.10	0.10	1.12	0.10	0.28	0.10	0.10	0.40	7.38	0.10
Mean	2.20	0.44	2.48	0.10	0.32	0.20	0.27	0.32	8.84	0.55
St. dev	1.30	0.71	0.66	0.00	0.38	0.24	0.29	0.25	1.22	0.65

The second flood event occurred on September 23rd, 2016. Water samples were collected three days after the flood event. The concentration of nitrate-N in the oxbow measured 1.8 mg l^{-1}, while the range of nitrate-N in the groundwater remained below the detectable limits except for wells 1 and 3. The next sample period occurred on October 12th, 2016 and nitrate-N concentration in the oxbow was 0.2 mg l^{-1}. After 19 days, the oxbow removed approximately 4.86 kg N delivered by the flood. However, it should be noted the flood events in August and September 2016 did not have a complete water budget performed so the inputs and outputs due to groundwater seepage were not accounted for.

4.6 Summary

In conclusion, the geology of the floodplain site was characterized to be a typical floodplain alluvium, with regions of lower resistivity near the southern ends of the oxbow's arms, and higher resistivity in the northern and southern portions of the site signifying bedrock and sandier sediment, respectively. The average hydraulic conductivity was estimated to be 4.02 m day^{-1}, with a hydraulic gradient of 0.0026 corresponding to an average groundwater seepage flow of 5.37 m^3 day^{-1}. Nitrate-N in the groundwater and oxbow were often below detectable limits during low flow periods. Floods provided the main source of nutrient loading into the oxbow. Nitrate-N concentration in the oxbow was found to slightly increase after flood events and was reduced within 30 days of each pulse. Groundwater nitrate-N concentrations did not generally respond to summer and fall flood events. Groundwater near the oxbow showed similar DO and specific conductivity values as the oxbow surface water, suggesting there was a connection between the oxbow's surface water and the local groundwater.

Chapter 5: Results - April, 2017 flood event

5.1 Introduction

The oxbow site flooded on April 15th, 2017. The results showed how the oxbow and surrounding groundwater responded to a spring flood transporting a high nitrate-N load. An in-situ nitrate sensor was installed after the flood to measure the reduction of nitrate-N concentration in the oxbow. The observed nitrate-N reduction was compared to a first order denitrification model to estimate the influence of denitrification.

5.2 Hydrology

Spring season is one of the rainiest periods with the months of April and May averaging 200 mm of precipitation. (PRISM Climate Ground and Oregon State University (2004)). Comparing spring 2017 to the long-term trends, the months of April and May were wetter than average when the two months combined to produce 267 mm of precipitation. Morgan Creek flooded on April 15th, 2017. The stream responded to a precipitation event of 44.7 mm that fell over a span of 7.5 hours. The highest precipitation intensity was equivalent to 23.2 mm $hour^{-1}$, which corresponded to a 2-year return period (Sudas, 2013). Five days prior to the flood, the watershed received a total of 23 mm of precipitation. The timing of the intense storm event was significant because the saturated moisture content of the ground resulted in less infiltration and increased runoff.

5.2.1 Hydrologic simulation

Morgan Creek's hydrologic response was simulated for the flood event of April 2017 (Figure 5.1). The model was important to understand the inundation period of the oxbow. The model simulated seven days to capture the extent of the precipitation event. The discharge of Morgan Creek increased from approximately 0.5 m^3s^{-1} to 41.5 m^3s^{-1} over a span of 30 hours. Seven hours after the peak, the stream quickly receded to stabilize around 2.8 m^3s^{-1}. The flood caused the oxbow to be connected to the stream for approximately 8.75 hours.

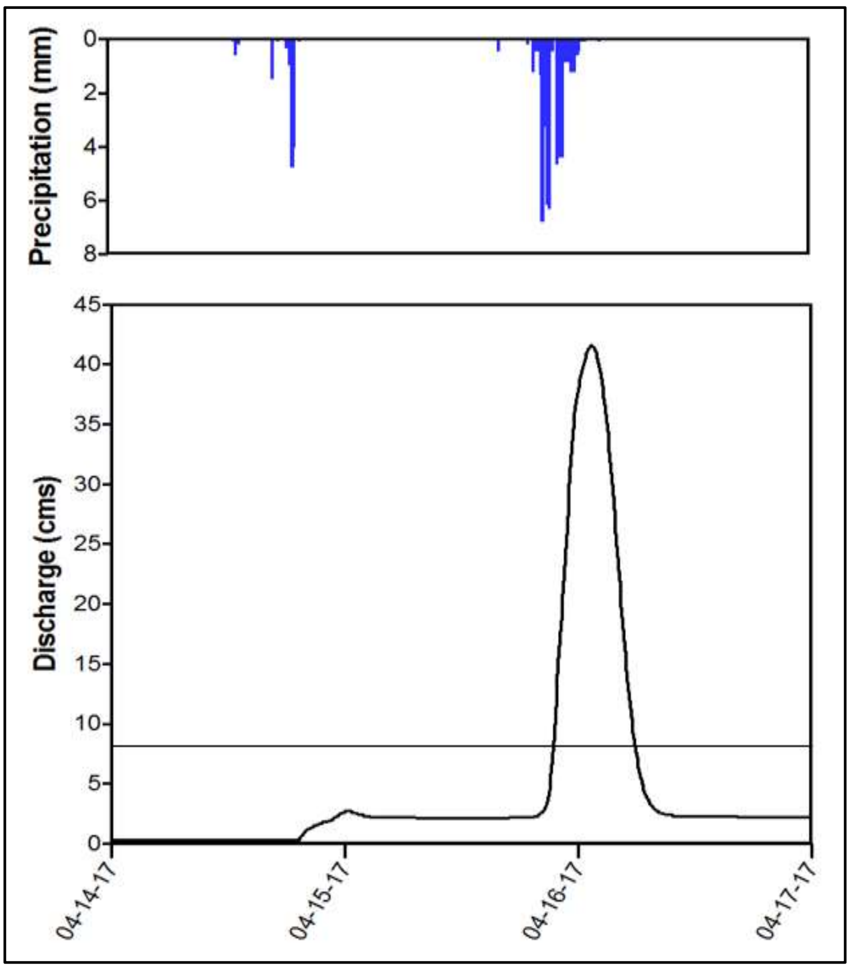

Figure 5.1. Hydrologic simulation of discharge peaking at 41.5 m^3s^{-1} for the April, 2017 flood event.

5.3 Water table

Prior to the flood event, the depth to water table for the year of 2017 was similar to what was observed in 2016. However, the water table rapidly increased during the flood of Morgan Creek (Figure 5.2). On April 15th, 2017 the water table rose 1.5 m from approximately -1.7 to - 0.2 m below the ground surface. The groundwater response coincided with both the hydrograph and the surface elevation of the stream.

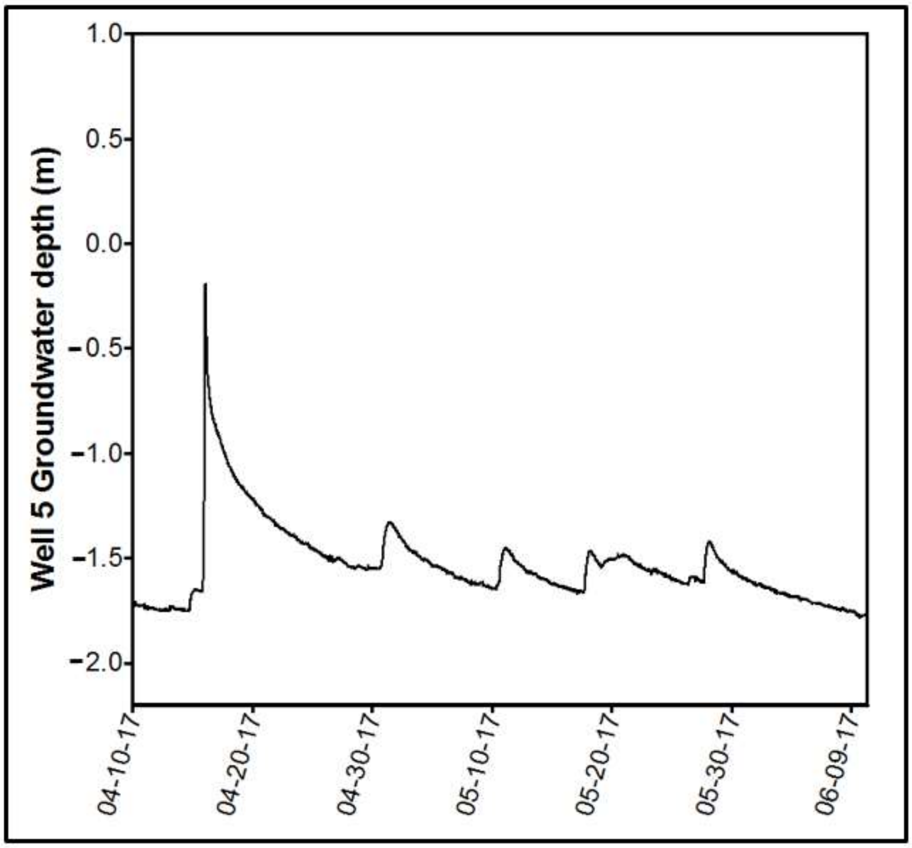

Figure 5.2. Depth to water in well 5 responding to flood event of April 2017.

Horizontal groundwater flow entering the oxbow after the April flood pulse was estimated using an upgradient cross-section with the dimensions of 1.2m x 107 m. The average hydraulic gradient across the site after the flood was measured to be 0.0085. With an average hydraulic gradient of 0.0085, hydraulic conductivity of 4.02 (m day^{-1}), and an effective porosity of 0.25, the groundwater flow velocity was estimated to be 0.13

m day^{-1}. The upgradient cross sectional area multiplied by the groundwater flow velocity estimated a groundwater seepage rate of approximately 17.5 m^3 day^{-1} into the oxbow.

The monitoring of the oxbow's surface water began on April 19th, which was three days after the flood of Morgan Creek. The surface water stage was measured with a transducer and combined with the stage-volume relationship to calculate the water volume in the oxbow (Figure 5.3). Initial volume of the oxbow was estimated to be 3,040 m^3 and it receded to 1,735 m^3 at the end of the monitoring period. The average groundwater seepage rate exported from the oxbow was estimated using the average daily difference in water volume and water budget. The daily groundwater seepage rate out of the oxbow was estimated to be 37.4 m^3 day^{-1}. The water volume in the oxbow followed a similar pattern compared to the groundwater table where rapid increases caused by precipitation events were followed by slow decrease in the volume of water.

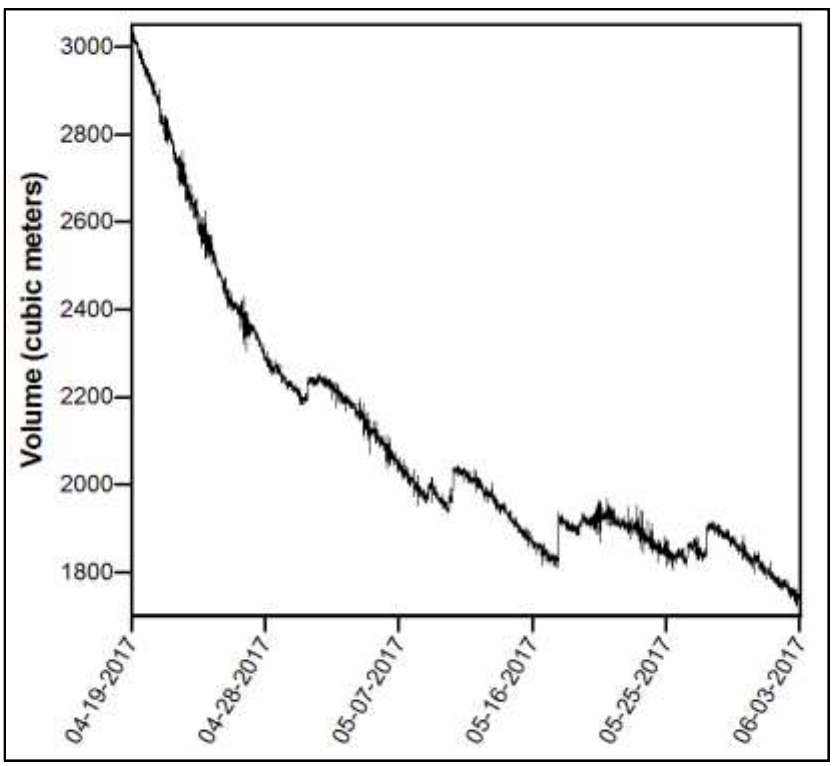

Figure 5.3. Volume of oxbow after April 2017 flood estimated from surface water depth measured by transducer located near the bank of the oxbow.

5.4 Water quality

Water samples were collected at the site on four occasions from May 3rd, 2017 to June 2nd, 2017 (Table 5.1). This period isolated how water quality characteristics responded following a spring flood event. Samples were collected on four occasions from the monitoring wells, the stream, and the oxbow. The water quality parameters investigated included Dissolved Oxygen (DO), Oxidation-Reduction Potential (ORP), pH, specific conductance, Nitrate-N (NO_3), sulfate (SO_4), Chloride (Cl^-), and Dissolved Reactive Phosphorous (DRP) and data are reported in (Table 5.1).

Table 5.1. Water quality summary of nutrients and water chemistry measured from May 3rd to June 2nd, 2017.

Site		Depth to water (m)	Temp ˚C	pH	Spec Cond µS/cm	DO mg/L	ORP mV	NO_3-N mg/L	Cl^- mg/L	SO_4^- mg/L	DRP mg/L
W 1	Mean	1.17	15.30	7.25	1.39	0.98	47.70	0.56	28.3	39.06	1.26
	St dev	0.06	3.21	0.34	0.23	0.22	21.66	0.22	21.50	16.71	0.77
W 2	Mean	1.42	14.36	7.09	0.78	1.39	47.98	1.04	36.0	48.74	0.30
	St dev	0.12	2.13	0.37	0.14	0.25	15.59	0.63	22.06	28.42	0.24
W 3	Mean	1.07	14.48	7.07	0.76	1.38	42.73	2.57	44.6	65.03	0.07
	St dev	0.08	3.05	0.45	0.08	0.21	30.19	0.56	4.41	19.12	0.03
W 4	Mean	0.90	14.21	6.94	0.82	1.30	53.35	0.39	15.1	21.85	0.24
	St dev	0.05	2.67	0.50	0.16	0.21	33.42	0.26	16.87	13.35	0.16
W 5	Mean	0.94	13.67	7.32	0.42	2.14	40.80	0.48	9.7	12.14	0.11
	St dev	0.04	2.74	0.49	0.05	0.74	39.02	0.37	3.36	3.18	0.03
W 6	mean	1.50	12.79	7.16	0.47	3.03	53.13	0.40	10.8	10.81	0.10
	St dev	0.03	1.41	0.40	0.05	2.06	28.00	0.28	4.02	1.85	0.04
W 7	Mean	1.37	14.35	7.85	0.62	3.49	51.23	1.03	10.2	11.39	0.16
	St dev	0.05	2.03	0.31	0.08	0.73	29.48	0.62	4.34	3.05	0.03
W 8	Mean	0.85	15.05	7.13	0.65	5.46	39.03	0.49	3.8	92.45	0.61
	St dev	0.04	3.02	0.32	0.16	2.06	29.96	.04	0.97	9.91	0.10
Stream	Mean	—	17.07	7.72	0.47	9.54	30.15	11.41	20.5	18.16	0.13
	St dev	—	6.48	0.21	0.04	1.01	35.24	1.27	2.83	1.51	0.03
Oxbow	Mean	—	18.54	8.88	0.24	11.47	-33.00	0.66	7.9	7.25	0.53
	St dev	—	1.72	0.47	0.04	2.08	20.56	.69	0.77	0.21	0.25

The spatial patterns of dissolved oxygen, specific conductivity and chloride remained similar between 2016 and 2017. Similar patterns in the concentration of DO for the wells adjacent to Morgan Creek (wells 1 to 4) were found between 2016 and 2017. Results showed DO remained low, ranging from 0.98 to 1.30 mg l^{-1}, and averaged 1.26 mg l^{-1} for 2017 compared to 1.38 mg l^{-1} for 2016. However, DO in the groundwater near the oxbow (wells 5 to 8) was higher after the flood event in 2017. DO concentrations ranged from 2.14 to 5.46 mg l^{-1}, and averaged 3.53 compared to 2.63 mg l^{-1} in 2016. Higher DO concentration in groundwater near the oxbow coincided with higher DO values measured in the oxbow. DO values in the oxbow ranged from 9.8 to 14.5 mg l^{-1} and averaged 11.47 mg l^{-1} compared to 6.17 mg l^{-1} in 2016.

Chloride followed similar patterns compared to 2016. Chloride levels were higher in wells 1 to 3 that ranged from 28.3 to 44.6 and averaged 36.3 mg l^{-1}. Morgan Creek averaged 20.5 mg l^{-1}, while wells 4 to 8 and the oxbow averaged 6.9 and 7.9 mg l^{-1}, respectively. Specific conductivity appeared to follow similar trends as DO. Specific conductivity in wells 1 to 4 averaged 937 µS cm^{-1} and wells 5 to 8 averaged 538 µS cm^{-1}. In general, the ORP average for 2017 was higher than 2016 with an overall average of 47 mV compared to 35 mV in 2016. ORP was higher for the periods sampled after the flood, and then significantly dropped in June 2017 to an average of 7 mV. pH averaged 7.28 for wells 1 to 8, and 7.72 for Morgan Creek. However, the pH in the oxbow was more basic ranging from 8.57 to 9.57 and averaged 8.88 compared to 7.66 for year 2016. This was believed to be caused by increased CO_2 levels in the water due to algae respiration. Dissolved reactive phosphorus concentrations ranged from 0.04 to 1.98 mg l^{-1} and averaged approximately 0.35 mg l^{-1} across the wells.

5.4.1 Nutrients

As stated previously, nitrate-N loading into the oxbow was dominated by flood events. After the flood of April 2017, nitrate-N levels across the site were the highest recorded since sampling began in June 2016 (Table 5.2). Nitrate concentrations were detected in all eight groundwater wells and the oxbow extending over a period of approximately seven weeks. Nitrate-N levels in the groundwater in wells 1 to 8 ranged from 0.4 to 2.71 mg l^{-1} and averaged 1.0 mg l^{-1} for the months of April and May. The next sampling period on June 2nd showed that nitrate-N concentrations across the site were significantly lower. Nitrate-N was only detected in three wells and averaged 0.61 mg l^{-1}.

Table 5.2. Nitrate-N concentrations across the site during field sampling periods.

	NO_3-N Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	0.9	1.00	2.20	0.80	1.1	0.90	0.80	—	9.50	1.8
5/12/2017	0.38	1.21	1.98	0.41	0.44	0.37	1.71	0.54	12.93	0.40
5/23/2017	0.4	1.87	2.71	0.26	0.27	0.28	1.44	0.44	12.13	0.31
6/2/2017	0.47	0.10	3.41	0.10	0.10	0.10	0.10	0.48	11.06	0.10
Mean	0.56	1.04	2.57	0.39	0.48	0.40	1.03	0.49	11.41	0.66
St dev	0.22	0.63	0.56	0.26	0.37	0.28	0.62	0.04	1.27	0.69

Two methods were used to measure nitrate concentration in the oxbow. An *in situ* sensor was installed in the oxbow to measure nitrate-N concentration at a 5-minute interval (Figure 5.4). Field samples were also collected from the oxbow on four occasions spanning seven weeks after the flood and analyzed in the lab. Nitrate-N concentration in the oxbow ranged from an initial value of 5.25 mg l^{-1} on April 18th, and ended at 0.73 mg l^{-1} on June 2nd. The initial nitrate-N concentration in the oxbow after the flood receded on April 16th was not measured. However, an estimated initial nitrate concentration of 5.35 mg l^{-1} was approximated from a linear regression obtained from the observed nitrate concentration data. On May 9th, 21 days after the flood, nitrate concentration in the oxbow measured 0.7 mg l^{-1}. After May 9th, the concentration in the oxbow remained nearly constant averaging approximately 0.7 mg l^{-1}, which was assumed to be the baseline concentration.

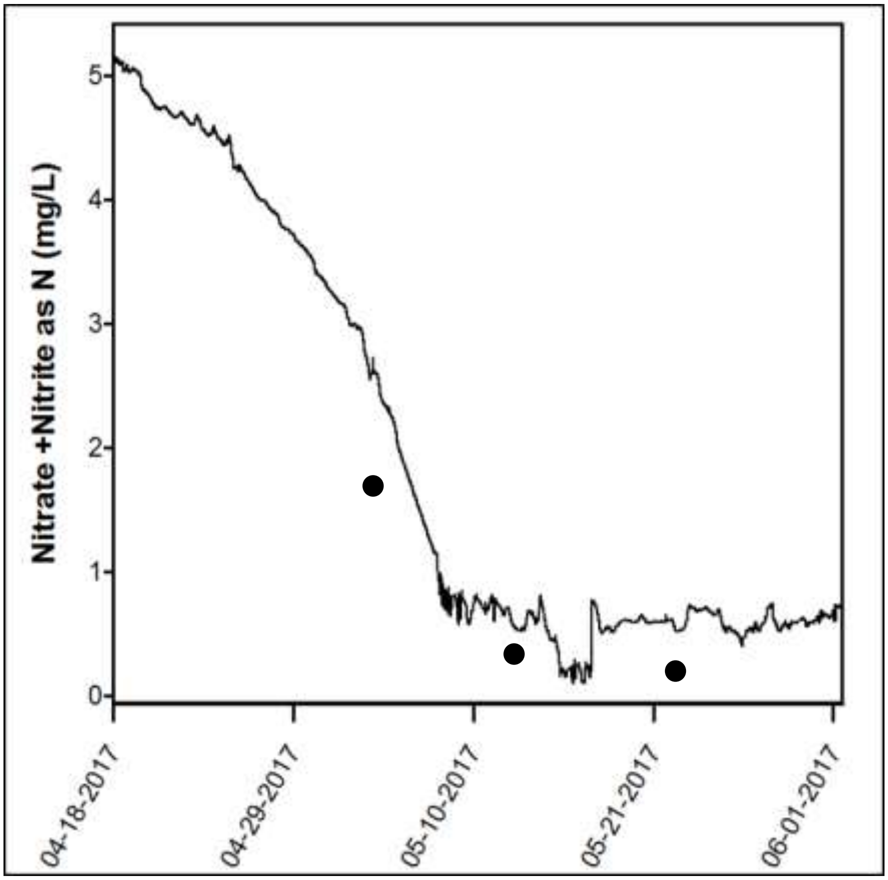

Figure 5.4. Nitrate concentration measured in the oxbow by the *in-situ* sensor ranging from 5.2 to 0.7 mg l^{-1} with field samples shown as dots.

For the April 2017 flood event, a water budget allowed for the estimation of nitrate-N loads into the oxbow (Table 5.3). The total nitrate-N load input into the oxbow including groundwater seepage and the flood pulse was combined to estimate the input load to be approximately 14.74 kg N. The baseline concentration of 0.7 mg l^{-1} was not included in the input load. The exported nitrate-N load caused by groundwater seepage out of the oxbow was estimated based on daily averages of nitrate concentration in the oxbow multiplied by the average daily loss caused by groundwater seepage of 37.4 m^3 day^{-1}. The total exported load out of the oxbow was assumed to be 3.78 kg over the 21-

day period. The retention rate for the oxbow was estimated to be 0.30 g NO_3^--N m^{-2} d^{-1}, with a retention efficiency of 74.2%.

Table 5.3. Nitrate-N mass balance for the oxbow during April 2017 flood pulse.

	Concentration (mg l^{-1})		Load (g)		Retention	
	Inflow	Outflow	Inflow	Outflow	Rate (g NO_3^--N m^{-2} d^{-1})	Efficiency (%)
NO_3^- - N	4.65	2.11	14736	3784	0.30	74.2

Due to the time of the flood event, no vegetation was established within or surrounding the oxbow. Also, algae growth was assumed to be at a minimum due to the season and cooler April temperatures. Therefore, it was assumed that denitrification was the main biogeochemical process to reduce nitrate. Denitrification was estimated using a first order decay equation shown in black in Figure 5.5. The fitting parameter for the denitrification model of nitrate reduction is the rate coefficient (k). The first order decay described the time sequence of NO_3^- concentration and it was multiplied by the volume of water in the oxbow to estimate a nitrate load (kg) in the oxbow. Parameter estimation created the "best" fit for the first order decay to the nitrate concentration measured by the *in situ* sensor. The temperature was measured by the nitrate sensor measuring at a 5-minute interval. The temperature coefficient of $\theta = 1.2$, and the rate coefficient was estimated to be 19.24 ($year^{-1}$). The k_{20} measured 17.9 ($year^{-1}$).

The observed nitrate concentration in the oxbow was multiplied by the volume of water to estimate nitrate mass in the oxbow shown as the green line in Figure 5.5. The observed load followed a linear decay, rather than an exponential decay predicted by the first order decay. However, the first order decay and observed load in the oxbow intersected after 21 days at a load of 0.6 kg of nitrate. The predicted nitrate reduction compared to the observed followed a similar reduction rate. Although the observed reduction did not follow an exponential decay as predicted by the first order exponential decay, the constant slope decrease suggests nitrate-N follows a linear decay for this restored oxbow system. However, the predicted and observed nitrate reduction rates appear to correlate with each other.

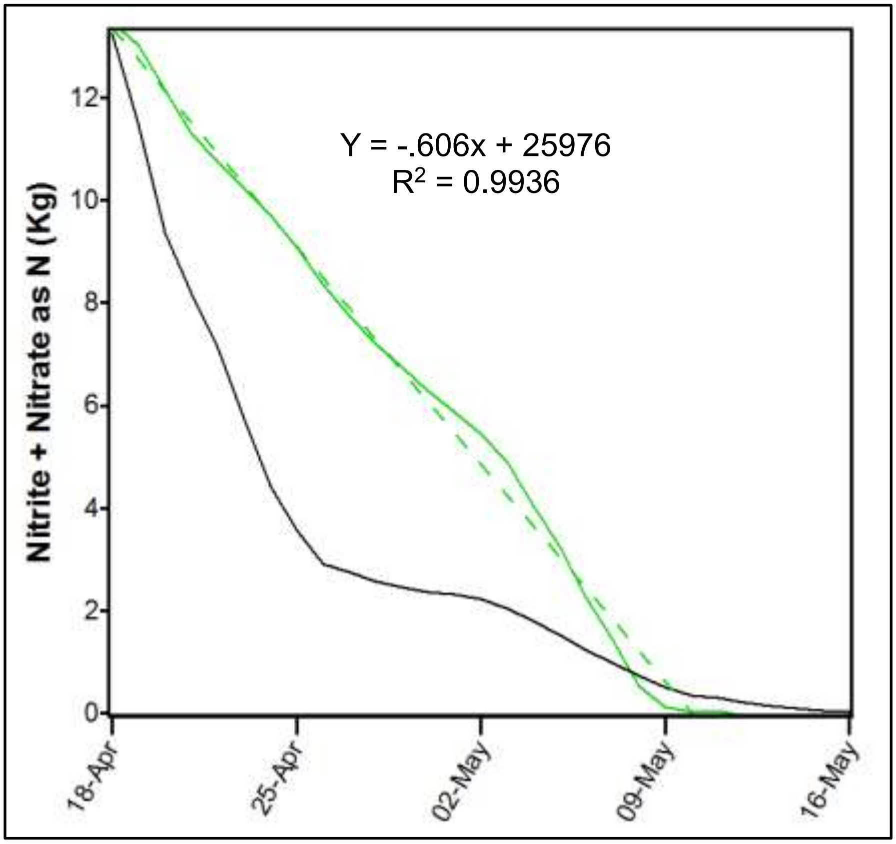

Figure 5.5. Daily NO_3^--N load detected by sensor (green) plotted against an estimated denitrification first order decay (black).

5.5 Ecological assessment

Morgan Creek was the source for aquatic species to migrate into the oxbow. The stream was connected to the oxbow for 46.25 hours following restoration. As a result, aquatic species such as fish were able to enter the oxbow during this time. To understand the colonization of fish in the oxbow, a fish survey was conducted to estimate the species richness and population. The fish survey was performed on May 22nd, 2017. The survey was conducted in partnership with Aleshia Kenney of USFWS who provided expertise and equipment. The sample collected a total of 343 adult sized fish (Table 5.4). According to the multiple pass depletion, the total population is estimated to be 462 fish total. There were two spawns of green sunfish that were not counted due to an overabundance of young fish. The species of fish included Creek Chub (*Semotilus* *atromaculatus)*, Johnny Darter (*Etheostoma nigrum*), Green Sunfish (*Lepomis cyanellus*), Sand Shiner (*Notropis stramineus*), Bluntnose minnow (*Pimephales notatus*), Black Bullhead (*Ameiurus melas*), and White Sucker (*Catostomus commersoni*).

Table 5.4. Seven fish species collected from fish seine conducted in the oxbow on May 23rd, 2017.

Species	1	2	3	Total	%
Creek chub	54	30	24	108	31
Johnny darter	0	8	5	13	4
Green sunfish	26	16	15	57	17
Sand shiner	24	7	2	33	10
Bluntnose minnow	63	31	19	113	33
Black bullhead	1	11	5	17	5
White sucker	0	1	1	2	1

5.6 Chapter summary

On April 15th, 2017, Morgan Creek watershed received 44.7 mm of precipitation. The day following the storm, Morgan Creek flooded reaching a peak discharge of approximately 41.5 m^3s^{-1}. The event delivered an estimated 14.76 kg of nitrate-N into the oxbow. Over a span of 21 days, the oxbow reduced the nitrate concentration to levels below 0.7 mg/l. Overall water quality characteristics remained similar to pre flood event conditions, with the exception of ground water nitrate concentrations. Nitrate was found to increase slightly across the entire site after the flood but declined to below detectable limits after approximately 49 days. The retention rate provided from the oxbow was estimated to be 0.3 g NO_3^--N m^{-2} d^{-1} with a retention efficiency of 74.2%. A denitrification first order decay model was compared to data collected from an *in situ* nitrate sensor. The model parameters including rate coefficient (k), k_{20}, and θ, were estimated to be 19.24 $year^{-1}$, 17.9 $year^{-1}$, and 1.20 respectively. The observed reduction of nitrate measured by the sensor did not follow a conventional exponential decay simulated by the model, but rather a linear decay. Finally, a fish survey was performed after the flood and a total of seven different fish species were collected, with an estimated total fish population of 462.

Chapter 6: Discussion

6.1 Introduction

Our study of the Morgan Creek oxbow in east central Iowa focused on understanding the hydrogeology and nutrient dynamics of a restored oxbow. Study results demonstrated that a restored oxbow can successfully be reconnected to groundwater and provide nutrient treatment after flood events. A first order denitrification model was compared to the observed nitrate reductions in the oxbow to estimate the contribution of nitrate reduction processes.

6.2 Site characterization

Morgan Creek exhibits traits typical of small watersheds in eastern Iowa. The third order stream follows a dendritic drainage basin. According to IFC stream gauge, the return interval for a flood in Morgan Creek is 0.32 years, or a probability of 3.1 floods $year^{-1}$. The hydrologic response for Morgan Creek is comparable to similarly sized watersheds in the region. Morgan Creek experiences rapid rates of change in discharge, which is consistent with smaller watersheds that behave flashier than larger, more stable streams (Baker et al., 2004).

Ground water movement found in eastern Iowa correlates to surface water and topographic divides (Kunkel et al., 1968). The local groundwater flow system is recharged by areas located in higher elevations and discharge into adjacent lows within a particular drainage system (Becher et al., 2001). The same groundwater flow system was observed for Morgan Creek where groundwater flows from upgradient regions towards the stream in a southeastern flow direction. The estimated hydraulic conductivity was found to be similar to small stream aquifers in eastern Iowa. The average hydraulic conductivity for an alluvial composition consisting of sand, gravel, silt, and clay for small streams in the Cedar River basin was approximately 8.56 m day^{-1} (Kunkel et al., 1968). The hydraulic conductivity in Morgan Creek is consistent with these findings ranging from 0.17 to 12.53 m day^{-1} with an average of 4.02 m day^{-1}.

The water table surrounding the oxbow is variable and fluctuates according to seasonal climate and precipitation events. A rise in the water table is commonly observed when water infiltrates into the ground converting the zone of capillary fringe to standing water (Gillham 1984). The water table at the Morgan Creek site was found to rise from 0.25 to 2.5 m over the span of several hours following precipitation events. Similarly, Schilling (2007) found the water table beneath row crops to rise from 0.5 to 1.0 m in the span of several hours after rainfall events. Increased water table depths improve the interaction to the root zone of vegetation, which provides an important role in nutrient cycling. The depth to water table near the oxbow is typically < 2.0 m, which provides water contact with vegetation roots and organic-rich riparian soils (Hill, 1996). It was found the root zone of many different plants have the potential to reach several meters beneath the surface (Sprackling & Read, 1979; Canadell et al., 1996). However, most roots occur in the upper 1 m of soil due to the lack of oxygen at deeper depths (Jackson et al., 1996; Baker et al., 2001). As a result, significant groundwater contact with vegetation roots typically occurs at depths less than 1.0 m, which was periodically found in this study.

Fluctuations in water level can influence nutrient cycling in wetlands (Hunt et al., 2007; Harrison, 2014). Different zones such as deep pools, shallow water areas, and temporarily inundated sections can foster NO_3-N removal in sediments (Hernandez and Mitsch, 2007; Harrison, 2014). The design of the Morgan Creek oxbow created different hydrologic zones and varied temporally after flood events. The oxbow initially flooded to a level above normal stage and slowly regressed to normal stage. This change in depth throughout the shallow zones of the oxbow allowed for increased contact between vegetation and nutrient rich waters.

6.3 Water quality

Nitrate-N concentration in Morgan Creek was comparable to streams in eastern Iowa with similar drainage areas and land cover. Morgan Creek's drainage area at the point where water samples were collected is 32 km^2. The land cover in Morgan Creek consisted of approximately 66% agricultural, 25% grass or deciduous cover, and 9% of roads, structures and other (Fry, J., et al., 2011**)**. Mean nitrate-N concentration in Morgan

Creek ranged from 5.90 to 12.20 mg l^{-1} during the sampling period. Rapid Creek is a small stream located 40 km southeast of Morgan Creek with a drainage area of 15.5 km^2 where samples are taken. The land cover in Rapid Creek consists of 72% agricultural, 24% grass or deciduous cover, and 4% of roads, structures and other (Fry, J., et al., 2011**)**. Mean nitrate-N concentrations in Rapid Creek range from 7.50 to 13.50 mg l^{-1}. Other streams in east central Iowa such as Clear Creek ranged from 3.20 to 11.60 mg l^{-1} of NO_3-N. It can be concluded that Morgan Creek's nitrate-N concentrations are similar to small streams across eastern Iowa in the Southern Iowa Drift Plain.

Groundwater nitrate-N concentrations in the floodplain were low compared to Morgan Creek. Stream nitrate-N concentrations averaged 8.40 mg l^{-1} (ranged from 5.90 to 12.20 mg l^{-1}) whereas nitrate-N concentrations in wells 1 to 8 ranged from 0.10 – 3.41 mg l^{-1} (averaged 0.79 mg l^{-1}). Wells 1 and 3 consistently measured above this floodplain average. Concentrations in these wells may be higher due to greater hydraulic conductivity and the position of the wells related to the former stream channel observed in aerial imagery. Schilling et al. (2012) found similar differences in nitrate-N concentrations between stream and groundwater at an eastern Iowa floodplain site located near the Cedar River. The flood plain groundwater averaged less than 0.20 mg l^{-1} while the Cedar River averaged 5.50 mg l^{-1} (ranged from 2.00 to 8.10 mg l^{-1}).

6.4 Oxbow nitrate retention

Nitrate-N loading into the oxbow from groundwater was significantly lower than loads provided from the stream. Although we were unable to follow upgradient nitrate-N concentrations, the downgradient concentrations consistently measured < 0.40 mg l^{-1} in wells. Nitrate-N concentrations collected in the oxbow measured below the detectable limits on June 29th, September 12th, and April 13th. These dates coincided with stable streamflow conditions and were well after recent floods. These data suggested the oxbow received insignificant groundwater N loads during low discharge flow periods. Nitrate-N concentrations upgradient of the oxbow are assumed to contain similar concentrations as the downgradient since nitrate-N in the oxbow was < 0.1 mg l^{-1}. Therefore, groundwater nitrate-N loads were insignificant during normal stream flow. This finding coincided with low nitrate concentrations often found in floodplains covered with perennial vegetation and in a restored oxbow setting in Iowa (Schilling et al., 2016; Schilling et al., 2017). For example, nitrate-N concentrations in the floodplain of the Cedar River in Iowa measured less than 0.70 mg l^{-1} (Schilling et al., 2015). Schilling (2017) found low nitrate concentrations in floodplains might be attributed to higher denitrification rates in the soils. Schilling et al. (2015) hypothesized that fine-textured sediments in floodplains lead to favorable biogeochemical conditions necessary for denitrification. Finally, deposited sediment may provide enhanced conditions for biogeochemical activities (Schilling et al., 2016). As a result, groundwater nitrate is likely being further reduced in the floodplain leading to insignificant loads into the oxbow.

The nitrate load into the oxbow was 8.38 g N m^{-2} pulse $^{-1}$ for the flood of April 2017. The exported load was 0.21 g N m^{-2} pulse $^{-1}$. The source and rate for load inputs into our site were comparable to similar studies. Harrison (2014) estimated nitrate load for two relict oxbows in Maryland ranged from 0.32 x 10^{-3} to 10.13 g N m^{-2} pulse $^{-1}$. The exported load ranged from 0.054 to 1.08 g N m^{-2} pulse $^{-1}$.

For the flood event of April 2017, nitrate retention measured 0.30 g N m^{-2} d^{-1}. Mass nitrate retention rates estimated at our site are comparable with other event driven studies. Harrison (2014) estimated nitrate retention for two relict oxbows in Maryland ranged from 0.25 to 2.74 g N m^{-2} d^{-1}. Diversion wetlands in the Illinois Des Plains floodplain estimated overall NO_3-N removal rates ranged from 0.01 to 0.55 g N m^{-2} d^{-1} (mean 0.19 g N m^{-2} d^{-1}) (Kadlec & Knight, 2010). Fink and Mitsch (2007) estimated nitrate retention rates of 0.71 g N m-^{2} pulse $^{-1}$.

The nitrate retention efficiency for the April 2017 event was 74.2%. The retention efficiency for this oxbow is consistent with other oxbows focused on event based data. Harrison et al. (2014) reported the percent retention of nitrate loads delivered to two oxbows during storm events ranged from 23 to 87%. Nitrate removal efficiency ranged from 53 to 98% for a floodplain diversion wetland in Illinois (Kadlec, 2010). Garica-Garcia et al. (2009) reported mean nitrate retention efficiency for two oxbows in Spain was 72.3%. The nitrate retention efficiency for a reconstructed oxbow connected to tile drainage ranged from 44 to 47% (Schilling et al., 2017).

We cannot determine the processes responsible for nitrate-N removal in the oxbow, but denitrification and assimilation are likely the main contributors (Garcia-

Garcia et al., 2009; Harrison et al., 2012; Hansen et al., 2016). Harrison et al. (2012) estimated denitrification rates using an *in situ* ^{15}N-enriched additions during spring and summer and found denitrification and assimilation rates varied by season. During the summer, denitrification accounted for 38 – 57% of ^{15}N transformation and higher assimilation occurred due to vegetation. The spring months resulted in a higher portion of denitrification removing nitrate-N which ranged from 86 -97%, because assimilation was not as active due to the lack of vegetation (Harrison et al., 2012)

The Morgan Creek oxbow site showed seasonal nitrate-N retention in early spring throughout early fall that suggested denitrification is active throughout the year including the months of April and May. During the flood event of April 2017, minimal vegetation and macrophytes were present due to seasonal temperatures, which suggested minimal assimilation (Harrison et al., 2012). Low assimilation rates during spring months were assumed to occur in another oxbow study conducted in central Iowa (Schilling et al., 2017). Harrison et al. (2012) and Phipps and Crumpton (1994) found denitrification occurred year-round in created oxbows, even in cold climates.

Denitrification rates for constructed wetlands were measured and found to vary between 11.80 to 63 mg N m^{-2} hr^{-1} at temperatures ranging from 11 to 27 °C (Fleischer et al., 1994; David et al., 1997; Xue et al., 1999). Based on previous findings from reconstructed wetlands, denitrification rates applied to our site spanning over 21 days (in mg N m^{-2} hr^{-1}) ranged from 10.46 kg N to 55.88 kg N after the April 2017 spring flood event. Thus, the Morgan Creek oxbow data is consistent with similar research showing the oxbow is capable of removing NO_3-N load through denitrification.

Denitrification is affected by dissolved oxygen, organic carbon content, and nitrogen supply (Song et al. 2014; Gu et al. 2012; Hill et al. 2000). DO concentration in the groundwater near the stream ranged between 1.12 to 1.56 mg l^{-1}. However, DO concentration near the oxbow measured between 1.86 to 5.46 mg l^{-1}. There is some evidence that suggests denitrification occurs with DO conditions below 2.00 mg l^{-1} (Cey et al., 1999), while others' research shows DO concentrations need to be less than 1 mgl^{-1} (Rivett et al., 2008). The oxbow may have improved the connection between surface water and groundwater, thus increasing DO concentration in shallow groundwater. Although DO concentrations typically measured greater than 1 mg l^{-1} throughout the site, denitrification may occur in small microclimates where DO was depleted and reducing conditions remained present, as well as in the sediment (Jacinth et al., 1998; Schilling and Jacobson, 2008).

NO_3^- concentration reduced by denitrification was estimated at our site through a first order decay model. The rate coefficient modeled for denitrification ranges from 0.05 – 0.3 day^{-1} (Jorgensen, 1979). The estimated denitrification rate for the Morgan Creek oxbow was estimated to be 0.05 day^{-1}. The temperature coefficient (θ) ranges from 1.04 to 1.20 with a typical value of 1.16 (Jorgensen, 1979). The temperature coefficient used in this model was 1.20.

A nitrate sensor provided real time data concentration in the oxbow. The first order denitrification decay estimated the amount of nitrate that was reduced through denitrification. The denitrification decay and observed concentration were converted to a mass basis and compared to each other. It was found the nitrate reduction in the oxbow followed a linear decrease rather than the simulated exponential decay (Figure 5.4). This shows nitrate reduction for this oxbow does not follow the predicted first order decay caused by denitrification, but rather nitrate reduction follows zero-order decay. The recently constructed oxbow may not have had the necessary time to provide the required environment for ideal denitrification rates. Nutrient removal may not be as productive at the beginning stages of restored wetlands because there is a need to establish well-balanced plant and microbial interaction (Mitsch and Jorgensen, 2004; Moreno, 2007). Denitrification is also affected by the wetland’s age, water temperature, organic carbon, macrophytic type and density, and hydraulic conditions (Sirivedhin et al., 2006). As the oxbow ages, a more diverse and established plant community may affect the microbial community, and increased plant matter in the oxbow has the ability to increase organic carbon in the system making the oxbow more efficient at removing nutrients

A more likely possibility for the lower rate of nitrate reduction observed in the oxbow is the fact that the oxbow is an open system. Consequently, external sources of nitrogen can influence the concentration. External sources may include defecation from wildlife surrounding the oxbow, or residual nitrate leaching from the former upgradient agricultural field. Schilling et al. (2008) found NO_3-N concentrations in leached groundwater to range from < 1.00 to 40 mg l^{-1} due to N mineralization. The rate of NO_3^--

N diffusion may also affect denitrification processes resulting in a delayed response. Bioturbation may have reduced diffusion rates of nitrate-N because invertebrates in aquatic systems influence microbial activities by altering the water and sediment fluxes (Mermillod-Blondin et al., 2006).

6.5 Ecological benefits

Floods that occur in the spring allow fish species to utilize the oxbow as a nursery because of the diverse habitat oxbows offer. Fall floods reconnect the fish to the stream allowing them to migrate downstream into rivers to survive the winter. This cyclical pattern shown in Figure 4.7 improves reproduction rates and increases survival success for aquatic species.

The fish assemblage surveyed in our oxbow showed two different groups of species that typically associate with different habitats. Species that reside in lentic waters were found in the oxbow including Green sunfish (*Lepomis cyanellus*), and Black Bullhead (*Ameiurus melas*). These species are more tolerant of high water temperatures and lower dissolved oxygen concentrations, which are typical of environments found in oxbows (Brungs 1971a, 1971 b; Copes 1975; Koehle and Adelman 2007). Lotic habitats are conducive for species such as the Sand Shiner (*N. stramineus*). These species require flowing water and higher DO concentrations. These conditions are present in oxbows during high flow periods, but after floodwaters recede the species may perish as conditions evolve into a lentic environment (Halyk and Balon, 1983).

Vegetation was not completely established for this recently constructed oxbow during the investigation. However, as plant diversity increases, the primary productivity of the oxbow will increase, improving conditions for denitrification by increasing organic matter in the system (Bouchard et al., 2007; Reddy and Delaune, 2008). Denitrification can also be affected by plant diversity which increases microbial communities and subsurface processes (McGill et al., 2010; Morgan et al., 2008). Although vegetation in the oxbow has not been fully established, nutrient cycling and ecosystem benefits have already been documented during the first year, suggesting the time necessary for these processes to begin is not long.

6.6 Chapter summary

This thesis focused on nitrate retention of a reconstructed oxbow in east central Iowa. Over a one-year period, flood pulses dominated water and nutrient loads into the oxbow. With the understanding of the nitrate mass balance, the oxbow's nitrate retention during an April flood event was estimated to be 0.30 g N m^{-2} d^{-1}. Although we were not able to distinguish between denitrification and assimilation for nitrate-N removal, a first order decay model estimated the time sequence of nitrate reduction due to denitrification. Rate constants were estimated to be k_{20} = 17.9 $year^{-1}$ and an average k = 19.24 $year^{-1}$. The observed nitrate concentration did not exhibit an exponential decay as suggested by the denitrification model, but rather followed a linear decrease suggesting denitrification rates are slower than what is estimated by the first order denitrification model. Lower decay rates for the oxbow could be due to the fact the young oxbow does not provide the established environment necessary for ideal denitrification, or decreased diffusion rates due to bioturbation impact nitrate retention rates. Since the oxbow is an open system there may be additional nitrate sources that are unaccounted for such as wildlife defecation that could alter nitrate retention rates.

Chapter 7: Implications

Implementation of BMPs is an effective way to improve water quality across the Midwest. Practices such as land retirement work well but they take land out of production and are not well implemented. Edge of field practices show potential to substantially reduce nitrate-N while requiring little land to be taken away from crop production (INRS, 2013). Nitrate retention for edge of field practices was estimated by the INRS to range from 32 – 91 percent (Table 7.1). Although nutrient reduction is achieved by these edge of field practices, auxiliary benefits such as habitat for aquatic species (i.e. endangered Topeka Shiner) and waterfowl are not provided with these options (Bakevich et al., 2013; Lagrange and Dinsmore, 1989). Restored oxbows show similar reduction rates compared to other BMPs but provide more ecosystem benefits. The Morgan Creek oxbow exhibited a retention rate of 74%, with similar research conducted on other oxbows ranging from 23 to 98% (Kadlec, 2010; Harrison et al., 2014; Garcia-Garcia et al., 2009; Schilling et al., 2017; Jones et al., 2015).

Table 7.1. Nitrate reduction potential for edge of field practices estimated INRS.

Edge-of-field practice	% Nitrate-N Reduction Average (SD)
Drainage water management	33 (32)
Shallow drainage	32 (15)
Wetlands	52
Bioreactors	43 (21)
Buffers	91 (20)
Saturated buffer	50 (13)

Restored oxbows provide ecosystem services such as habitat and recreational use while still providing nutrient cycling benefits. Consequently, landowners have implemented oxbows to improve water quality and wildlife habitat. An added benefit is that these oxbows are often sited on marginal land unsuitable for other uses (Jones et al., 2015). The cost to reconstruct floodplain oxbows range from ~$10-15,000 each (Schilling et al., 2017). Woodchip bioreactors costing $7-10,000 can treat drainage from 10 to 40 ha without providing habitat benefits (Iowa State University, 2011). CREP wetlands that can treat drainage up to 500 ha cost $400,000 (Christianson et al., 2013). Restored oxbows provide a competitive cost to benefit ratio making them a viable option for nutrient removal systems.

The research demonstrated a restored oxbow’s ability to process nutrients delivered by floods. Other options for restored oxbows include flow through systems (Garcia-Garcia et al., 2009; Mitsch et al., 2014) and N loads fed primarily by tile drainage (Schilling et al., 2017). N loading via flood pulses results in episodic nutrient inputs. If groundwater provides higher nutrient loads, then a lentic oxbow may be able to provide a greater nutrient cycling benefit. Nitrate loads delivered by tile drainage can increase nutrient loading into the oxbow. Schilling (2017) found tile drainage inputs delivered a nitrate concentration ranging from 9 – 17 mg l^{-1} enhancing its capacity for nutrient retention.

Chapter 8: Summary and conclusion

This thesis project was conducted to investigate the ecological effects of a restored oxbow at an eastern Iowa floodplain. During this one-year project the following questions were studied.

1. How does hydrology and hydrogeology of the floodplain affect transport of water and its constituents into oxbow?
2. What is the N retention capacity for the restored oxbow and how does it compare to a first order denitrification model?
3. What are the ecological benefits provided from a recently restored oxbow?

To understand groundwater characteristics, a network of eight groundwater monitoring wells was installed to investigate hydraulic conductivity and groundwater quality. Two geophysical methods were used to understand the site's geology. A HEC-HMS model was constructed to understand the hydrology of the watershed and further investigate the dynamics of flood events. An *in-situ* nitrate sensor was installed to capture the reduction of nitrate provided from a spring flood. The observed nitrate reduction was compared to a denitrification model that followed a first order decay. Finally, a fish survey estimated the species richness and total population of fish that colonized the oxbow since it was restored in August 2016.

The site's geology was characterized both spatially and vertically throughout the floodplain. Geophysical results suggested that the previous stream channel was connected with the oxbow through a region exhibiting lower resistivity. The upgradient region of the site was interpreted to be near-surface bedrock. The sediment composition downgradient of the oxbow is typical of a floodplain alluvium mainly consisting of sandy loam with various pockets ranging from clay to sand.

Monitoring wells provided insight into groundwater flow characteristics. The hydraulic conductivity was estimated using slug tests, and found to range from 0.17 to 12.53 m day^{-1} (average 4.02 m day^{-1}). Typically, hydraulic gradients across the site ranged from 0.0015 to 0.0039 during non-flood periods. The resulting groundwater seepage rate into the oxbow was estimated to be approximately 5.38 m^3 day^{-1}. However, flood events caused greater differences in gradients ranging from 0.0045 to 0.012. The resulting groundwater seepage into the oxbow ranged from 9.37 to 24.33 m^3 day^{-1}. The groundwater flow direction was found to move in a southeastern direction towards Morgan Creek.

Morgan Creek is typical of many low order eastern Iowa streams. Nitrate concentrations throughout the year ranged from 7.38 to 12.20 mg l^{-1} in the stream. In contrast, groundwater nitrate concentration remained < 0.45 mg l^{-1} throughout 2016 in the majority of the wells. This low concentration in the groundwater resulted in negligible inputs of nitrate into the oxbow through groundwater seepage. Higher DO values and lower specific conductivity and chloride concentrations in the wells adjacent to the oxbow were similar to oxbow water indicating a possible downgradient connection.

The stream's hydrology was investigated using a stream gauge sensor and hydrologic model. The HMS model used the SCS curve number with the Muskingum routing method to simulate the hydrology of Morgan Creek. Morgan Creek appeared to be a flashy stream that responded rapidly to intense storm events. Results from HMS appeared to be similar to a synthetic rating curve provided by IFC. A stream gauge measured the surface water record over a six-year period, and on average Morgan Creek flooded 3.1 times per year.

Flood events dominated the nutrient loading into the oxbow. April 2017 Morgan Creek watershed received 44.7 mm of precipitation. The stream responded with an estimated discharge of 41.5 m^3s^{-1} and the spring flood delivered a nitrate load of approximately 14.76 kg into the oxbow. A real time sensor monitored the reduction of nitrate in the oxbow. The nitrate concentration was reduced from 5.2 to 0.70 mg l^{-1} after approximately 21 days in the oxbow. With an understanding of the groundwater input and output seepage rates, the estimated nitrate-N retention for a spring flood in the oxbow was estimated to be 0.30 g N m^{-2} d^{-1} with a 74.2% retention efficiency.

A first order uptake model estimated denitrification. Rate constants were estimated to be k_{20} = 17.9 year^{-1} and k = 19.24 year^{-1}. Since the oxbow is an open system, possible sources of nitrate inputs included wildlife defecation, and unaccounted upgradient nitrate leaching through groundwater seepage. Overall, denitrification appeared to be the main contributor to nitrate retention in the oxbow.

Following the restoration of the oxbow, the colonization by aquatic and terrestrial species occurred. A fish survey was conducted to estimate the quantity and variety of species that colonized the oxbow after a total of 46.25 hours of stream connection. A total of seven species were captured, and the total population was estimated to be around 462 fish. Other aquatic species observed during the survey included a snapping turtle, bullfrogs, tadpoles, and toads. It was observed that the oxbow is utilized by a variety of species including fish, amphibians, reptiles, and birds.

Restored oxbows that are connected to the stream during high flow periods provide valuable ecosystem benefits with some nutrient load reduction. Lentic conditions provided ideal habitat for fish, amphibians, reptiles, and birds at this site. Episodic floods reconnected the oxbow allowing for a flux of aquatic species, and quickly allowing this oxbow to host a variety of species shortly after its conception. Nitrate retention rates observed for this oxbow were comparable to other edge-of-field practices. However, episodic flood events limited consistent nutrient loading into this oxbow. Nonetheless, the Morgan Creek oxbow provided water quality benefits and valuable habitat almost immediately following the restoration.

Appendix A: Pre-flood event field water quality and chemistry

Table A-1. Nitrate concentrations collected from field samples from June 2016 to April 2017 sampling period.

	NO$_3$-N Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	4.56	0.69	3.34	0.10	1.26	0.10	0.10	0.10	11.44	0.10
7/13/2016	2.44	0.10	2.27	0.10	0.50	0.10	—	—	9.99	—
7/28/2016	3.03	0.10	3.41	0.10	0.10	0.10	0.10	0.49	8.28	—
8/16/2016	1.40	0.10	2.51	0.10	0.10	—	0.57	0.10	8.55	0.95
9/12/2016	0.80	2.25	2.51	0.10	0.10	0.10	0.10	0.76	8.64	0.10
9/26/2016	1.84	0.10	2.35	0.10	0.10	0.79	0.85	0.10	8.75	1.83
10/12/2016	3.00	0.10	2.35	0.10	0.10	0.10	0.10	—	7.73	0.22
4/13/2017	0.10	0.10	1.12	0.10	0.28	0.10	0.10	0.40	7.38	0.10
mean	2.20	0.44	2.48	0.10	0.32	0.20	0.27	0.32	8.84	0.55
St. dev	1.30	0.71	0.66	0.00	0.38	0.24	0.29	0.25	1.22	0.65

Table A-2. Chloride concentrations collected from field samples from June 2016 to April 2017 sampling period.

	Chloride Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	44.39	9.14	47.43	6.52	6.76	1.55	12.72	7.71	27.12	6.97
7/13/2016	36.75	6.64	43.07	5.75	5.62	14.31	13.67	—	27.25	—
7/28/2016	42.50	3.97	42.57	5.62	5.56	12.06	12.56	6.48	27.48	—
8/16/2016	28.25	5.06	44.67	5.47	6.00	—	4.98	5.22	26.16	6.13
9/12/2016	37.80	44.39	44.39	5.83	6.97	9.57	8.31	3.77	30.60	7.32
9/26/2016	37.40	4.67	41.32	5.80	7.43	11.90	6.50	5.24	25.12	6.52
10/12/2016	45.74	3.73	42.07	5.02	6.86	10.10	6.91	—	24.02	5.94
4/13/2017	63.04	69.59	65.91	38.07	9.93	11.61	61.90	—	19.15	12.00
mean	41.98	18.40	46.43	9.76	6.89	10.16	15.94	5.68	25.86	7.48
St. dev	9.48	23.21	7.57	10.71	1.31	3.79	17.64	1.33	3.11	2.08

Table A-3. Specific Conductivity concentrations collected from field samples from June 2016 to April 2017 sampling period.

	Specific Conductivity (μS cm^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	896	995	771	756	530	524	577	731	510	461
7/13/2016	1359	1189	785	845	565	603	621	696	550	—
7/28/2016	1090	1181	839	844	622	595	700	839	567	—
8/16/2016	1401	1223	853	887	585	562	525	645	343	461
9/12/2016	1242	1060	844	1251	496	582	636	826	228	597
9/26/2016	920	914	815	882	491	538	786	526	546	228
10/12/2016	914	1172	831	1077	391	639	683	580	249	536
4/13/2017	1430	953	822	863	367	514	688	847	545	316
mean	1157	1086	820	926	506	570	652	711	442	433
St. dev	215	113	27	149	84	40	75	114	135	126

Table A-4. Dissolved oxygen concentrations collected from field samples from June 2016 to April 2017 sampling period.

	DO Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	1.72	1.33	1.18	0.93	1.6	3.64	2.41	4.49	8.17	0.92
7/13/2016	—	—	—	—	—	—	—	—	—	—
7/28/2016	—	—	0.73	0.57	1.09	1.22	2.31	1.85	9.11	
8/16/2016	—	1.83	1.08	0.71	1.21	4.49	1.43	1.33	6.71	5.16
9/12/2016	0.95	2.00	1.14	0.94	0.96	1.33	1.66	1.68	6.36	8.48
9/26/2016	2.52	1.08	1.24	0.9	1.47	4.9	3	1.13	7.53	3.48
10/12/2016	1.21	1.08	1.18	1.44	1.62	1.28	1.74	3.51	9.4	8.31
4/13/2017	1.32	2.12	2.4	2.34	5.09	3.8	5.71	7.7	12.13	10.68
mean	1.54	1.56	1.28	1.12	1.86	2.95	2.61	3.10	8.49	6.17
St. dev	0.55	0.44	0.48	0.56	1.34	1.50	1.36	2.20	1.82	3.32

Table A-5. Oxidative reduction potential concentrations collected from field samples during June 2016 to April 2017 sampling period.

	ORP (mV)									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	-65.80	-80.60	-57.50	-121.60	-31.90	32.60	5.50	-74.60	-92.00	-147.00
7/13/2016	-104.80	-117.90	-55.70	-106.00	41.00	2.00	-5.70	-33.10	-21.50	—
7/28/2016	-13.20	-100.90	-50.30	-114.00	-16.30	-9.00	0.30	-17.60	-16.60	—
8/16/2016	-59.80	-70.00	-66.50	-76.20	-55.90	-12.40	-33.50	-62.70	-35.60	-31.50
9/12/2016	41.80	38.10	32.70	23.20	20.90	18.80	32.40	32.60	23.40	23.70
9/26/2016	54.80	20.00	13.40	4.30	-7.00	7.90	7.00	-7.50	-3.50	3.00
10/12/2016	30.30	28.10	29.20	36.80	81.90	88.20	94.80	27.50	86.40	88.00
4/13/2017	38.00	38.50	51.30	46.20	25.10	11.20	34.20	36.30	18.50	0.00
mean	-9.84	-30.6	-12.9	-38.4	7.23	17.41	16.88	-12.4	-5.11	-10.63
St. dev	56.35	63.36	45.77	68.07	41.07	29.99	35.64	40.10	48.25	70.99

Table A-6. Sulfate concentrations collected from field samples from June 2016 to April 2017 sampling period.

	SO_4^- Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	79.57	126.21	126.21	6.94	14.12	1.95	17.93	153.93	21.31	5.99
7/13/2016	71.13	172.29	172.29	42.01	11.84	23.43	20.01	—	21.62	—
7/28/2016	70.67	117.71	117.71	10.10	12.78	18.97	19.49	156.77	25.49	—
8/16/2016	68.70	123.82	123.82	54.46	14.00	—	23.57	91.62	23.22	7.04
9/12/2016	37.48	80.80	80.80	175.90	10.44	16.85	14.35	142.00	22.85	8.07
9/26/2016	80.07	133.19	133.19	41.37	11.17	26.29	92.63	40.44	20.68	6.33
10/12/2016	62.96	46.67	46.67	82.53	7.43	12.81	11.29	—	24.02	5.81
4/13/2017	17.70	4.50	4.50	4.63	7.51	9.74	7.24	5.62	29.12	7.69
mean	61.04	100.65	100.65	52.24	11.16	15.72	25.81	98.40	23.54	6.82
St. dev	20.60	50.28	50.28	53.07	2.44	7.72	25.72	58.32	2.56	0.85

Table A-7. Dissolved reactive phosphorous concentrations collected from field samples during June 2016 to April 2017 sampling period.

	DRP Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
6/29/2016	0.07	0.08	0.08	0.12	0.13	0.11	0.08	0.24	0.18	2.61
7/13/2016	—	0.07	0.80	0.07	0.10	0.10	0.07	0.10	0.13	—
7/28/2016	0.05	0.06	0.07	0.06	0.07	0.09	0.11	0.35	0.10	—
8/16/2016	0.07	0.07	0.09	0.06	0.15	—	0.38	0.70	0.21	0.94
9/12/2016	0.10	0.08	0.08	0.23	0.14	0.09	0.13	0.79	0.17	0.38
9/26/2016	0.08	0.10	0.08	0.03	0.18	0.10	0.40	0.48	0.163	0.98
10/12/2016	0.05	0.27	0.05	0.05	0.09	0.10	0.09	NA	0.347	0.09
4/13/2017	0.53	0.42	0.03	0.13	0.06	0.08	0.07	0.13	0.06	0.08
mean	0.14	0.15	0.16	0.09	0.11	0.10	0.17	0.40	0.17	0.85
St. dev	0.16	0.13	0.24	0.06	0.04	0.01	0.13	0.25	0.08	0.87

Appendix B: Water quality and chemistry after April, 2017 flood

Table B-1. Nitrate field sample concentrations collected from April 2017 to June 2017.

	NO3-N Concentration (mg l-1)									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	0.9	1	2.2	0.8	1.1	0.9	0.8	—	9.5	1.8
5/12/2017	0.38	1.21	1.98	0.41	0.44	0.37	1.71	0.54	12.93	0.4
5/23/2017	0.4	1.87	2.71	0.26	0.27	0.28	1.44	0.44	12.13	0.31
6/2/2017	0.47	0.1	3.41	0.1	0.1	0.1	0.1	0.48	11.06	0.1
mean	0.56	1.04	2.57	0.39	0.48	0.4	1.03	0.49	11.41	0.66
st dev	0.22	0.63	0.56	0.26	0.37	0.28	0.62	0.04	1.27	0.69

Table B-2. Chloride field sample concentrations collected from April 2017 to June 2017.

	Chloride Concentration (mg l-1)									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	65.48	67.54	50.86	44.29	15.42	17.73	17.71	—	16.45	8.88
5/12/2017	14.69	28.53	45.29	4.53	7.89	9.16	8.2	3.29	24.17	7.7
5/23/2017	18.1	41.21	43.61	4.71	6.91	7.63	7.83	3	21.73	6.77
6/2/2017	14.96	6.54	38.52	6.9	8.51	8.84	7.15	5.18	19.65	8.24
mean	28.31	35.96	44.57	15.11	9.68	10.84	10.22	3.82	20.5	7.9
st dev	21.5	22.06	4.41	16.87	3.36	4.02	4.34	0.97	2.83	0.77

Table B-3. Specific conductivity field sample concentrations collected from 2017 to June 2017.

	Specific Conductivity (µS cm^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	1054	706	639	607	353	392	518	438	428	214
5/12/2017	1424	859	777	784	461	476	620	614	481	202
5/23/2017	1550	616	811	903	424	490	647	726	453	236
6/2/2017	1551	929	808	971	442	507	697	809	531	299
mean	1395	778	759	816	420	466	621	647	473	238
st dev	235	142	81	159	47	51	75	160	44	43

Table B-4. Dissolved oxygen field sample concentrations collected from April 2017 to June 2017.

	DO Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	1.05	1.3	1.24	1.16	3.12	6.03	4.41	7.3	10.17	14.5
5/12/2017	1.06	1.46	1.66	1.54	2.29	2.23	3.64	6.23	10.42	10.66
5/23/2017	1.14	1.7	1.2	1.41	1.66	2.5	3.23	5.8	9.4	10.91
6/2/2017	0.66	1.1	1.41	1.1	1.48	1.34	2.67	2.52	8.18	9.8
mean	0.98	1.39	1.38	1.3	2.14	3.03	3.49	5.46	9.54	11.47
st dev	0.22	0.25	0.21	0.21	0.74	2.06	0.73	2.06	1.01	2.08

Table B-5. Oxidative Reduction Potential field sample concentrations collected from April 2017 to June 2017.

	ORP (mV)									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	37.6	44.8	39.2	40.2	69.4	73.6	75.7	38	58.4	-8
5/12/2017	75.9	70.1	78.6	95.1	66.9	65.5	62.1	65.9	48	-48.2
5/23/2017	51.8	43.5	47.9	61.7	41.5	61.6	58.7	54.7	34.9	-24.4
6/2/2017	25.5	33.5	5.2	16.4	-14.6	11.8	8.4	-2.5	-20.7	-51.4
mean	47.7	47.98	42.73	53.35	40.8	53.13	51.23	39.03	30.15	-33
st dev	21.66	15.59	30.19	33.42	39.02	28	29.48	29.96	35.24	20.56

Table B-6. Sulfate field sample concentrations collected from April 2017 to June 2017.

	SO_4^- Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	14.7	6.4	32.8	4.9	7.6	8.8	9.2	—	20.5	7.2
5/12/2017	57.47	80.48	68.51	42.32	15.86	13.79	15.34	80.06	17.56	7.25
5/23/2017	51.2	67.65	78.44	20.91	14.24	10.62	13.28	92.97	16.36	7.56
6/2/2017	32.97	40.5	80.3	19.3	10.8	10.1	7.8	104.3	18.2	7
mean	39.06	48.74	65.03	21.85	12.14	10.81	11.39	92.45	18.16	7.25
st dev	16.71	28.42	19.12	13.35	3.18	1.85	3.05	9.91	1.51	0.21

Table B-7. Dissolved Reactive Phosphorous field sample concentrations collected from April 2017 to June 2017.

	DRP Concentration (mg l^{-1})									
Well	1	2	3	4	5	6	7	8	Stream	Oxbow
5/3/2017	—	0.59	0.05	0.04	0.09	0.08	0.18	—	0.11	0.87
5/12/2017	0.19	0.06	0.04	0.15	0.09	0.07	0.13	0.52	0.11	0.18
5/23/2017	1.98	0.07	0.06	0.31	0.11	0.09	0.14	0.56	0.12	0.55
6/2/2017	1.6	0.5	0.13	0.46	0.16	0.16	0.21	0.76	0.19	0.54
mean	1.26	0.3	0.07	0.24	0.11	0.1	0.16	0.61	0.13	0.53
st dev	0.77	0.24	0.03	0.16	0.03	0.04	0.03	0.1	0.03	0.25

Appendix C: Soil composition and classification

Table C-1. Soil texture classification and notes during installation for well 1.

Depth (m)	Classification	Color	Notes
0 – .30	Sandy Loam	10 YR 2-1	Some fine to medium gravel, roots, dry, crumbles
.30 – 1.06	Loam	10 YR 2-1	"Slicken sides" red 7.5 YR 3/8 iron coating, fine to coarse gravel, fine sand
1.06 – 2.90	Sandy Loam	10 YR 2-1	Rounded fine to coarse gravel, moist to wet at around 5', sand in small thin layers, major roots 1.21 - 2.9 m

Table C-2. Soil texture classification and notes during installation for well 2.

Depth (m)	Classification	Color	Notes
0 - .30	Sandy clay Loam	10 YR 3_1	Medium angular gravel, roots, dry crumble
.30 - .75	Sandy loam	10 YR 3_1	Fine to medium gravel, crumble, roots
.75 - 1.21	Sandy Loam	10 YR 2_1	Iron Coating, trace of fine to small gravel
1.21 - 1.52	Sandy Loam	10 YR 2_1	Iron coating, moist, trace of small gravel
1.52 - 2.13	Loamy Sand	10 YR 2_1	Few medium coarse of rounded sub gravel
2.13 - 2.60	Sandy clay loam	10 YR 2_1	Trace medium gravel
2.60 - 3.04	Sandy loam	10 YR 2_1	
3.04 - 3.20	Loamy sand	10 YR 2_1	Sub rounded

Table C-3. Soil texture classification and notes during installation for well 3.

Depth (m)	Classification	Color	Notes
0 - .45	Silt loam	10 YR 3_2	Roots, dry, crumbles
.45 - .91	Clay loam	10 YR 2_1	Dense, dry
.91 - 1.52	Sand	10 YR 5_4	Mostly medium to coarse, wet
1.52 - 2.60	Loamy sand	10 YR 2_1	Coarser than above, darker Color, mostly coarse, wet
2.13 - 2.44	coarse sand		Fine to medium gravel
2.44 - 2.50	silt/sandy loam		
2.50 - 2.60	coarse sand		Fine to coarse gravel

Table C-4. Soil texture classification and notes during installation for well 4.

Depth (m)	Classification	Color	Notes
0 -.30	Clay loam	10 YR 3_1	Roots, crumble
.30 - .61	Sandy clay loam	10 YR 3_1	Roots, some fine sand
.61 - 1.1	Clay loam	10 YR 3_1	Very saturated
1.1 - 1.37	Sandy clay loam	10 YR 3_1	Iron with color of 7.5 YR 3_8
1.37 - 1.68	Sandy loam	10 YR 7_6	Fine to medium sand, some angular gravel
1.68 - 2.60	sandy loam	10 YR 7_6	Fine sand, few small gravel, cohesive
2.60 - 3.05	clay loam		

Table C-5. Soil texture classification and notes during installation for well 5.

Depth (m)	Classification	Color	Notes
0 - .30	Clay loam	10 YR 3_1	Roots, crumble
.30 - .61	Sandy clay loam	10 YR 3_1	Roots, some fine sand
.61 - 1.1	Clay loam	10 YR 3_1	Very saturated
1.1 - 1.37	Sandy clay loam	10 YR 3_1	Iron with color of 7.5 YR 3_8
1.37 - 1.68	Sandy loam	10 YR 7_6	Fine to medium sand, some angular gravel
1.68 - 2.60	sandy loam	10 YR 7_6	Fine sand, few small gravel, cohesive
2.60 - 3.05	clay loam		

Table C-6. Soil texture classification and notes during installation for well 6.

Depth (m)	Classification	Color	Notes
0 - .76	Sandy clay loam	10 YR 2_1	Roots, crumble, dry
.76 - 1.06	Clay loam	10 YR 2_1	Crumble, Iron with color of 7.5 YR 3_8
1.06 -1.22	Sandy clay loam	10 YR 2_1	Some fine sand
1.22 - 1.52	Sandy clay loam	10 YR 3_1	Super saturated
1.53 - 2.44	Loamy sand	10 YR 3_4	Sub angular fine to medium gravel

Table C-7. Soil texture classification and notes during installation for well 7.

Depth (m)	Classification	Color	Notes
0 -.61	Loam	10 YR 2_1	Top soil, roots, crumble
.61 -1.06	Loamy sand	10 YR 3_1	
1.06 - 1.22	Loamy sand	10 YR 3_1	Iron deposits, fine to medium sand
1.22 - 1.52	Sandy clay loam	10 YR 3_1	Fine sand, some silt layered
1.52 - 1.98	Sandy loam	10 YR 2_1	Some medium gavel
1.98 - 2.29	Loamy sand	10 YR 2_1	Fine to medium gravel, some rounded angular cobble
2.29 - 2.43	Clay loam	10 YR 7_6	Coarse sand, angular fine to medium gravel

Table C-8. Soil texture classification and notes during installation for well 8.

Depth (m)	Classification	Color	Notes
0 - .46	Clay	10 YR 2_1	Crumble, roots, top soil
.46 - .61	Sandy loam	10 YR 2_1	fine sand
.61 - .76	Sandy loam	10 YR 2_1	
.76 - .91	Sandy loam	10 YR 2_1	Clay
.91 - 1.52	Sand	10 YR 2_1	Coarse

Appendix D: Hydraulic conductivity

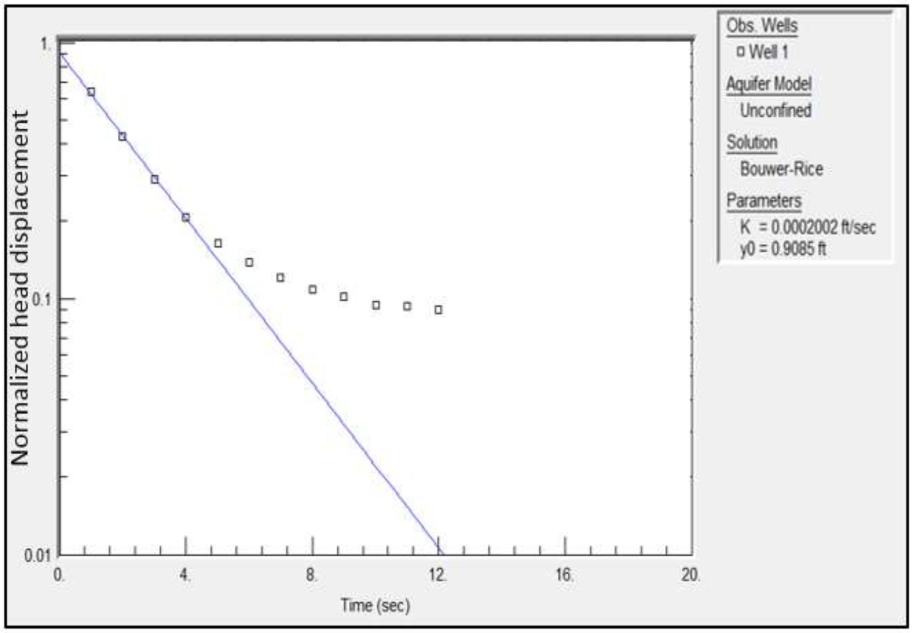

Figure D-1. Hydrualic conductivity estimated using the Bower and Rice method for well 1.

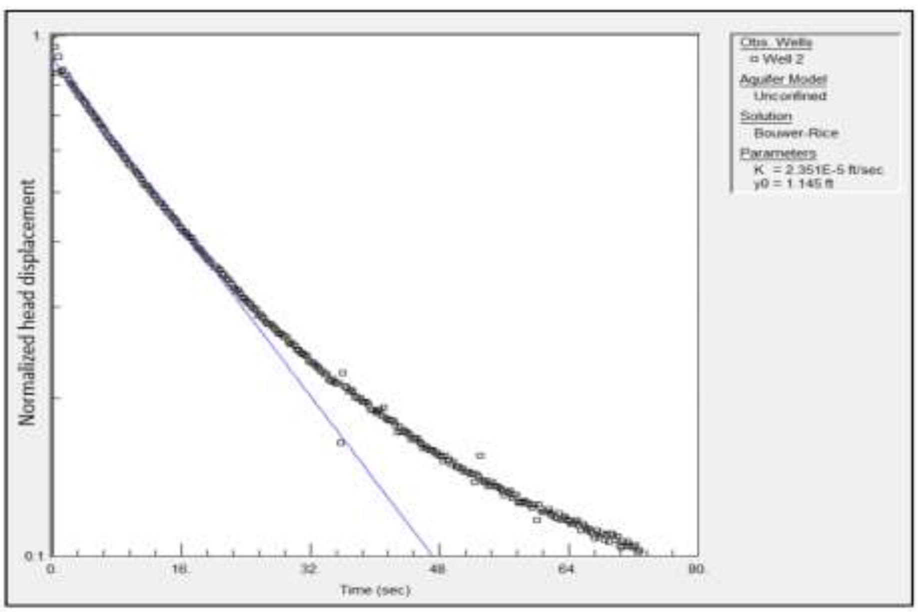

Figure D-2. Hydrualic conductivity estimated using the Bower and Rice method for well 2.

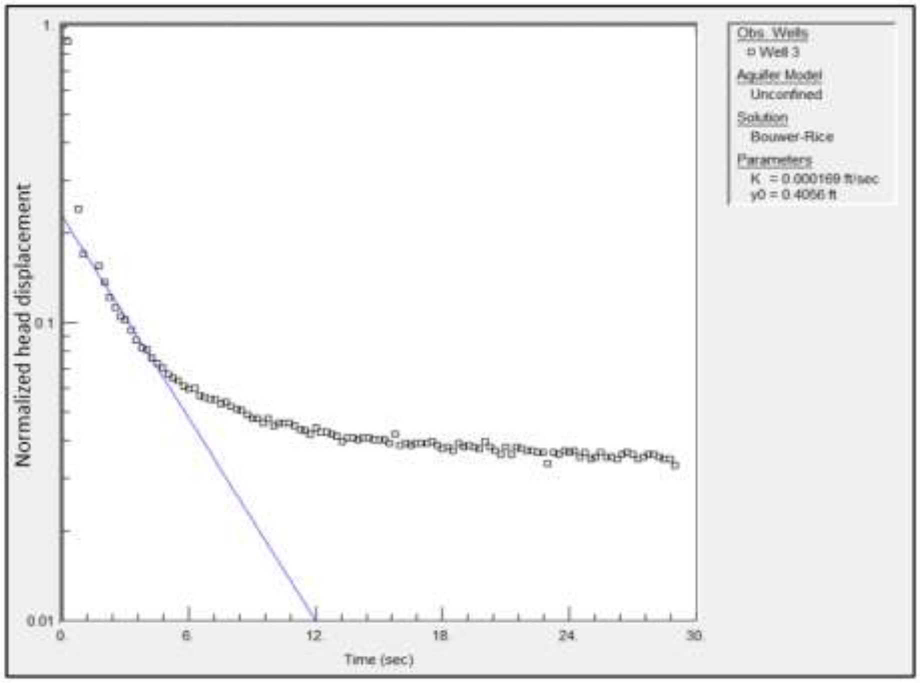

Figure D-3. Hydrualic conductivity estimated using the Bower and Rice method for well 3.

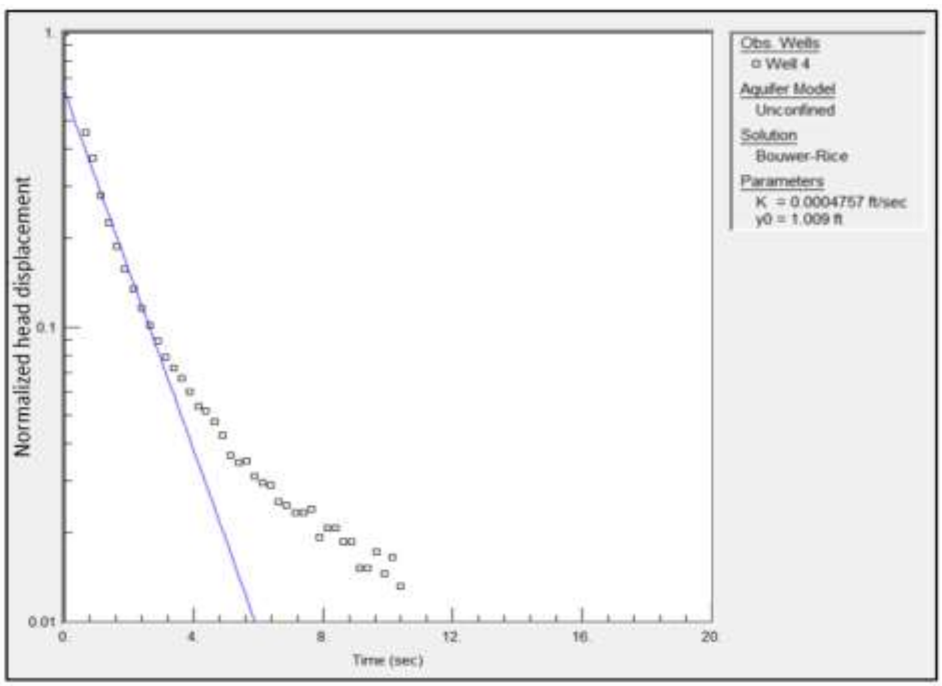

Figure D-4. Hydraulic conductivity estimated using the Bower and Rice method for well 4.

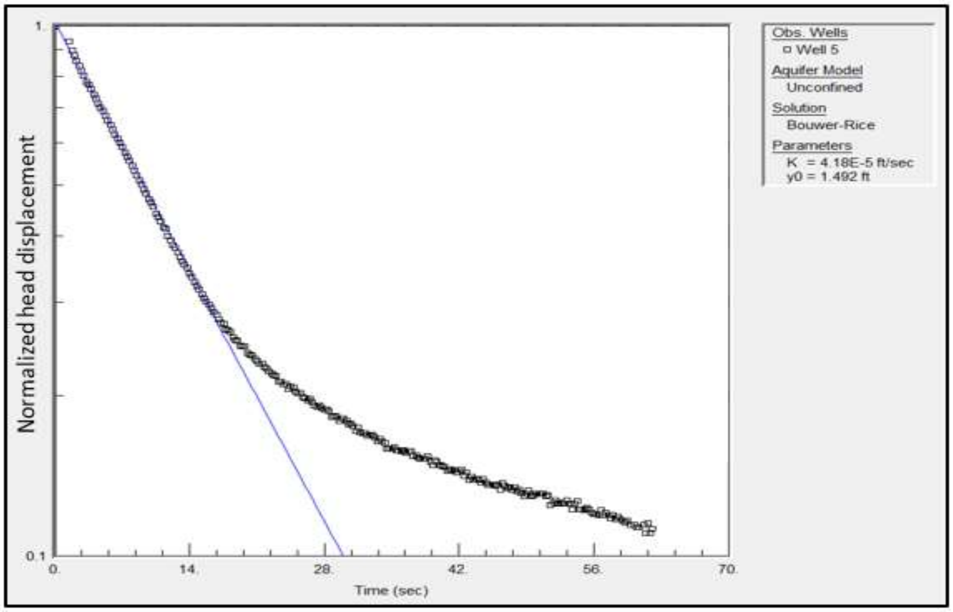

Figure D-5. Hydraulic conductivity estimated using the Bower and Rice method for well 5.

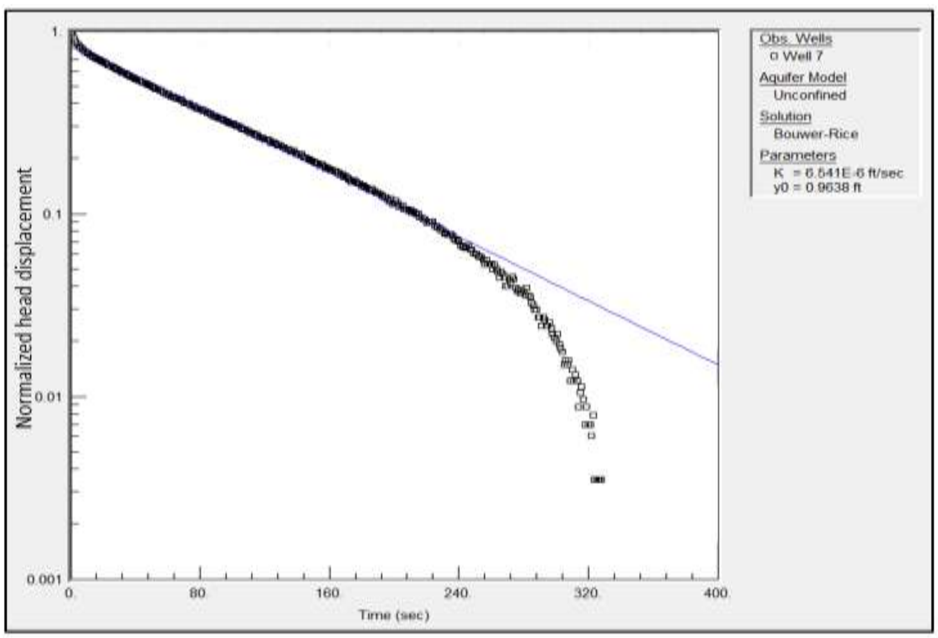

Figure D-6. Hydraulic conductivity estimated using the Bower and Rice method for well 7.

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