2015

# Hydrological impacts of microwatersheds in the Des Moines Lobe

Ligia De Oliveira Serrano
*Iowa State University*

# Hydrological impacts of microwatersheds in the Des Moines Lobe

by

**Ligia De Oliveira Serrano**

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Agricultural and Biosystems Engineering

Program of Study Committee:

Amy Kaleita, Major Professor

Michelle Soupir

Michael Castellano

Iowa State University

Ames, Iowa

2015

# TABLE OF CONTENTS

Page

# ACKNOWLEDGEMENTS

Many thanks to Dr. Amy Kaleita, for giving me the amazing opportunity of doing my Masters at Iowa State University, and for guiding me in through this project. I am well aware of the challenges of advising international students, and I am truly grateful for her trust. Also, thanks for the support of all the ABE family that were always very welcoming and made my time at ISU very special.

Thanks to Ron Bingner for helping me with AnnAGNPS watershed model, and for receiving me in Oxford to receive training.

I am also very thankful to friends and family I have made in Ames, for giving me support and being patience with me through difficult times; and for helping me to enjoy my time the most.

I am also thankful for my Brazilian friends, for bring a bit of my country to Ames, and for my family in Brazil, for the immense faith in my potential. You guys made everything possible.

Finally, thanks to the Iowa Department of Natural Resources (IDNR) for the financial support for this project.

# ABSTRACT

Potholes are features with no evident natural outlet, formed in hydric landscapes, such as the Prairie Pothole Region (PPR). Potholes are commonly under cropland management, which is not consistent with their hydrological patterns since periodic flooding during the growing season is frequent. Although there are studies investigating undisturbed and/or restored potholes, there is limited information about the hydrology of features that are farmed and artificially drained, a common situation in the Des Moines Lobe, the Iowan part of the PPR. The estimation of pothole hydroperiod and water balance variations would allow their hydrological classification and estimation of their potential environmental impacts. To estimate pothole hydrology, Annualized Agricultural Non-Point Source model (AnnAGNPS), was used in this project to model two potholes located in Story County, IA, for which we had two years of periodic measurements of inundation depth. For a better understanding of the features, a high-resolution DEM was used to study their potential volume storage, before overflowing. A conserved scenario, in which the potholes were consider to be retired from cropland production and from artificial tile drainage was also simulated to estimate potential hydrological impacts of pothole conservation. After model calibration, AnnAGNPS was used to estimate pothole water volume and depth variations in the features under both current and conserved conditions, for 23 years of historical weather data. It was proved that AnnAGNPS can provide reliable representations of the observed data, particularly for water depth variations. Results include pothole hydroperiod, consecutive days of inundation, average water depth during ponding events, and frequency of overflow. In the current condition, the potholes water regimen suggests that these potholes are classified as semipermanent. Most ponding occurred in early stages of the growing season, and mostly lasted from one to two days, barely overwhelming their storage capacity. Nevertheless, crop failure is common within their extent, which indicates that their management does not agree with their hydrological patterns. In the conserved condition, potholes flooded more often, held water for longer periods, and exceed their maximum storage capacity more frequently than in the current scenario. Further research includes the assessment of potholes under different management conditions, improvement of AnnAGNPS tools to address wetland features, and investigation of the reliability of the results of pothole conservation.

# CHAPTER 1: GENERAL INTRODUCTION

## 1.1. Motivation for Prairie Pothole Assessment

Prairie potholes consist of common features in the Des Moines Lobe landscape, in Iowa (Roth and Capel 2012; Logsdon 2015). This landscape, which is a part of the Prairie Pothole Region (PPR), was recently glaciated, and is characterized by an undulating topography with enclosed depressions that induce depressional infiltration and groundwater recharge (Rosenberry and Hayashi 2013; Hayashi et al. 2009; Sloan 1972). In Iowa, since most of the landscape is drained in order to allow agricultural production, little is known about the hydrology of drained and farmed potholes, their volume storage capacity, or their role in the watershed hydrology (Schilling and Drobney 2014; Schilling and Helmers 2008; Du et al. 2005).

One of the reasons to study pothole hydrology is that even with the use of subsurface drainage, potholes provide temporary water storage after high intensity rainfall events, commonly during the growing season, which compromise management operations, and crop yields (Logsdon 2015; Westbrook et al. 2011). Another motivation for the study is the fact that Iowa is one of the main responsible for the hypoxia in the Gulf of Mexico (Schilling and Spooner 2006; Schilling and Helmers 2008), and the potential ecological benefits of the potholes in the improvement of water quality. Therefore, the conservation of some features can be justified as a conservation practice, to increase water quality. For instance, isolated depressions can perform as nutrient sinks, and have other ecological benefits (Whigham and Jordan 2003). Nevertheless, the main focus of this thesis is to study pothole hydrology, while their potential impacts in water quality are left for further research because the lack of data.

Most of the information available about potholes investigate restored and/or features in their natural state, or about their impact in the watershed. For instance, potholes were previously attempted to be simulated with SWAT watershed model, with little success. SWAT was used to model systems with potholes and surface inlets in Walnut Creek watershed, and it performed poorly in the assessment of daily flows, which indicate a difficulty in the assessment of these feature with hydrological models, and a need for improvement (Du et al. 2005). Here, we will attempt to simulate the hydrology of individual features, with a model that can be delineated for small scale watersheds, and leave for further research their impact in larger ones.

To increase the knowledge about pothole hydrology, the Iowa Department of Natural Resources (IDNR) invested in the study of this feature, in partnership with Iowa State University (ISU). Here, two potholes located in Walnut and Worrell Creek (HUC 12) watersheds, in the de Des Moines Lobe were assessed (figure 1-1) in order to simulate their hydrology. Both watersheds have a high density of prairie potholes, and are broadly farmed and drained (Schilling and Spooner 2006).

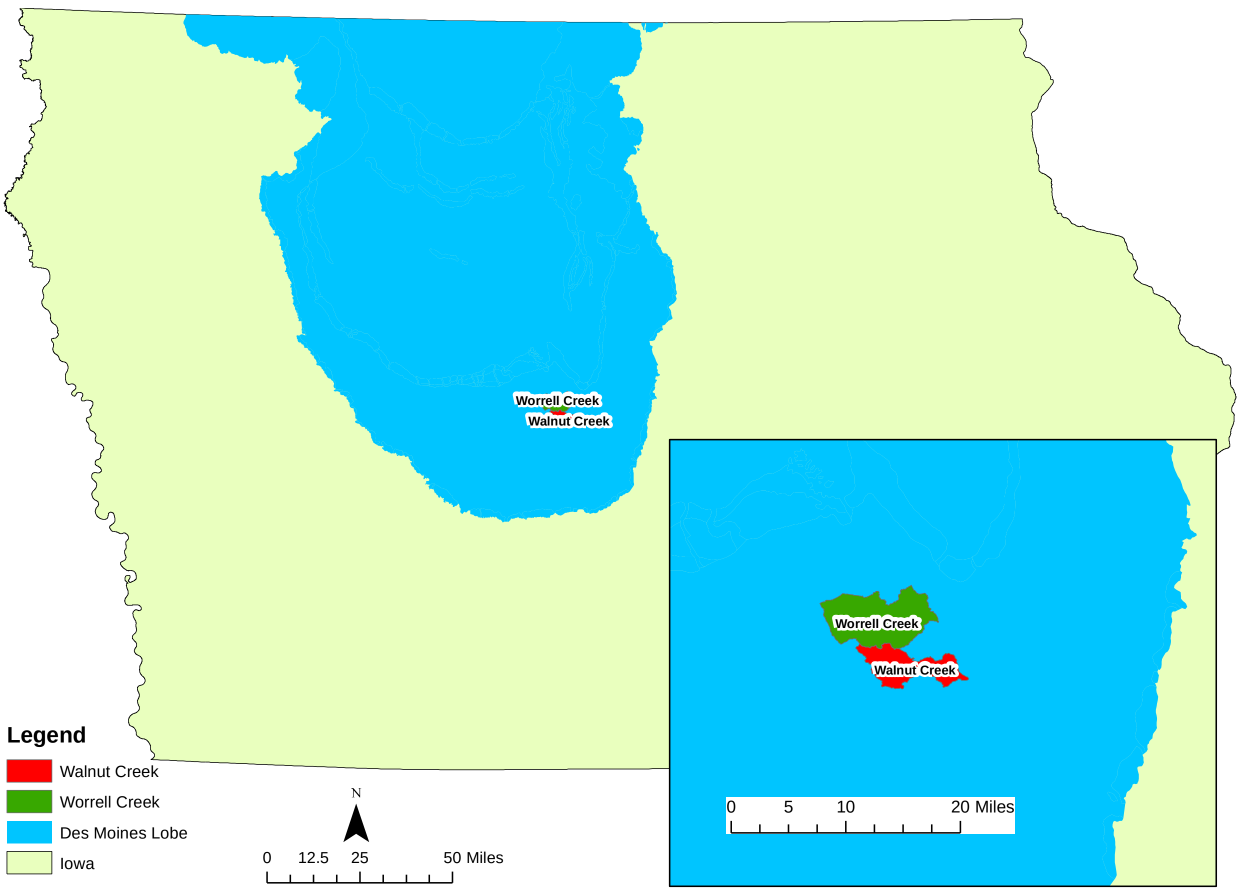



Figure 1-1: HUC-12 Walnut and Worrell Creek watershed locations in relation to the Des Moines Lobe.

Figure 1-1 illustrates the location of Walnut and Worrell HUC-12 watersheds in relation to the Des Moines Lobe, and figure 1-2 illustrates the location of the potholes in relation to the HUC-12 watersheds.

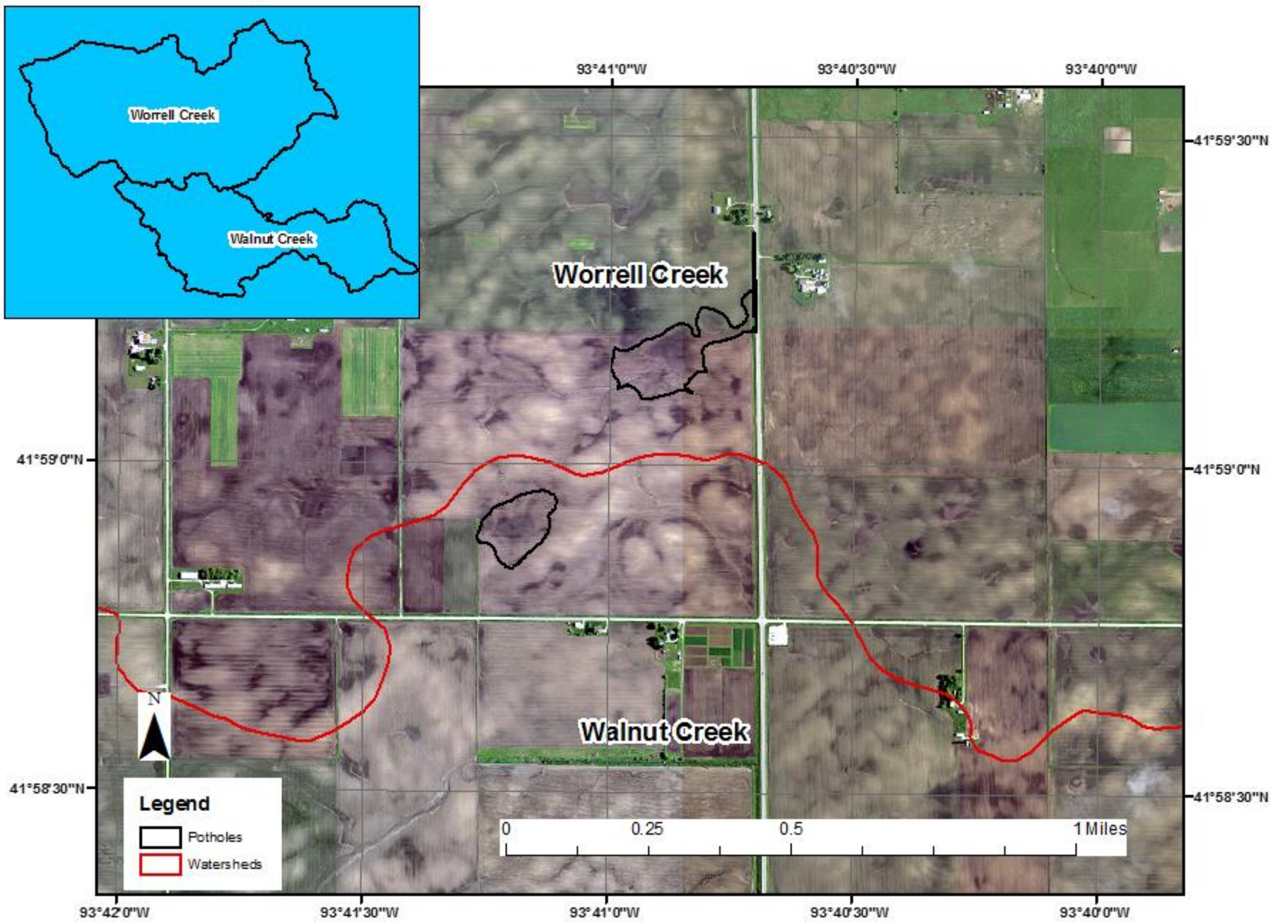



Figure 1-2: Potholes location in relation to Walnut and Worrell Creek watersheds.

The two features illustrated in figure 1-2 were selected due the existence of water depth variation data, used for calibration of the hydrological model. The hydrological model is used to determine if it is possible to simulate pothole hydrological patterns. This information can be used to estimate the pothole hydrology of some features in the Des Moines Lobe, and in the prairie pothole region, with more study. Then, if the model is able to simulate observed conditions, it is used to study different conservation scenarios, and the potential impacts in pothole hydrology. This information is useful to increase the knowledge about the feature, and for the estimation management and land cover modifications in the hydrology.

This report is divided into different sections. First, data about watershed characteristics were collected and processed to allow characterization of the drainage areas of the potholes. Because of their small size, drainage areas of potholes are referred as microwatersheds in this document. Second, based in model characteristics, assumptions are made to represent hydrological conditions observed. Third, model performance is estimated with the comparison of observed and simulated data, collected in the years of 2010 and 2011 (Logsdon 2015), and in 2014, collected for the scope of this project. For last, if the model is able to simulate observed conditions with a certain level of accuracy, it will be used to estimate the hydrological impacts of the retirement of the potholes. The hydrology associated with the potholes is discussed in the last two sections.

The focus at this point is to study pothole hydrology, which correspond to the hydroperiod and the water balance within these features for the period weather data is available for the area, the consecutive days the features are flooded for, and the investigation of the average water depth in the features during inundation events. Their frequency of inundation will be estimated once it gives insights of their nexus with the watershed outlet, and whether their current management is consistent with their use.

### 1.2. Objectives

The specific objectives of this project were to:

a) To determine the maximum surface storage associated with two potholes after runoff events, before the features overflow;
b) To investigate hydrology patterns of two prairie potholes through several years of agricultural production with the use of AnnAGNPS. Results include the determination of:
    i) frequency of inundation during the growing seasons from 1992 through 2014;
    ii) frequencies of consecutive days of inundation;
    iii) intensity of inundation, or how often water reaches different depths in the potholes;
    iv) frequency the potholes exceed their maximum storage capacity.
c) To simulate prairie potholes hydrology patterns in current and conserved conditions, to estimate the potential effects of the conversion of these features.

## 1.3. Structure of the Thesis

First, general information about potholes, such as definitions, history, among other information, is available in Chapter 2 as a literature review. Then, the potholes under study are discussed, as well as the way data was collected, in Chapter 3. Chapter 4 and 5 will provide information about AnnAGNPS, and how the data was collected and organized to characterize the watersheds of the potholes. The topography assessment of the potholes is discussed in Chapter 6, and the calibration and performance of the model are discussed in Chapter 7. The results are available in Chapters 8 and 9, and the conclusion of the thesis in Chapter 10. The Annexes A and B discuss data collected about soil and water quality during the year of 2014.

## 1.4. Summary

The introductory chapter provides general information about prairie potholes and the motivation for their assessment, which is the focus of this Master's thesis. The potholes assessed in this thesis are located in the Des Moines lobe, in Walnut and Worrell watersheds, and were selected once there water balance data available for these features, which is essential for hydrological model calibration and performance assessment.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Introduction

Enclosed depressions are commonly observed features throughout the landscapes of Iowa (Roth and Capel 2012; Gleason et al. 2011; Richardson and Arndt 1989). Particular characteristics of these features are their disconnection from the stream flow, and their lower elevation in comparison to the surroundings, that enables water to be stored under wet conditions and during precipitation events (Winter and Rosenberry 1995; Brunet and Westbrook 2012; Frei and Fleckenstein 2014).

These depressions are formed in hydric landscapes, especially in the Upper Midwestern United States, where the Prairie Pothole Region (PPR) is located. This region is known by its hydric soils, grass prairie as original land cover, river systems, and isolated wetlands or potholes in undisturbed conditions (Gleason et al. 2008). It extends from Alberta, in Canada, to United Stated, in a total of 700,000 $km^2$. In the US it is observed in five stated, North Dakota, South Dakota, Nebraska, Minnesota, and Iowa (Wright and Wimberly 2013). In Iowa, this region is denominated Des Moines Lobe, which is located in the upper and central part of the state, is the southern extent of the PPR (Roth and Capel 2012; Creed et al. 2013).

Potholes commonly represent an issue for farmers in the PPR, because to their frequency of inundation and difficulty to use machinery in its surroundings (Brunet and Westbrook 2012). A current practice to deal with this situation is to install subsurface drainage, and sometimes surface intakes, devices designed to promotes the removal of water ponded in specific areas in the surface (Blann et al. 2009; Schilling 2005).

Hydric soils are formed under conditions of saturation, flooding, and when there is ponding until anaerobic conditions develop in the soil upper part (63 Federal Register 133, 1994, Vepraskas 2013). The presence of hydric soils is one of the factors analyzed in order to identify wetlands in the field (Vepraskas 2013; Collins et al. 2014; Gusman, Voigt, and Forman 2001; Galatowitsch and Valk 1996). In the Midwest, however, because the soils were largely drained, some are no longer considered to be hydric, and it is unclear how well, and how long it takes for potholes to revert to hydric conditions and full function if left to return to their natural state. If hydric soils show to perform the same way before drainage was installed, it would be an important argument for conservation and restoration of farmed potholes, especially if their conservation is proven to be beneficial to water quality in the watershed.

The majority of these features have no evident inlet or outlet, in other words, the main sources of water recharge and discharge cannot be easily identified. For this reason, it has been discussed whether these are disconnected from the rest of the stream in a watershed or not (Winter and Rosenberry 1998). Nevertheless, under wet conditions these features were observed to connect to each other (Marton, Fennessy, and Craft 2014). There is minor groundwater communication for a great amount of them once these features are underlain by glacial till (Winter and Rosenberry 1995). As a result, the water balance in their natural state mainly happens through the atmosphere, by evaporation and precipitation (Winter and LaBaugh 2003), and sporadically shallow, in some situations where wetlands have been noted to receive groundwater discharge or contribute with water recharge (Winter and Rosenberry 1995).

Pothole hydroperiod vary according the length of time water is stored in the depression during the growing season (Galatowitsch and Valk 1996). For example, temporary, seasonal, and semi-permanent potholes are defined as those that are ponded with rain from one to three weeks, three weeks to ninety days, and throughout the complete growing season or more, respectively, depending on weather conditions. During wet periods, temporary potholes can look and perform as seasonal ones. On the other hand, during dry years, semi-permanent potholes can dry out and function as seasonal or temporary drainage areas. Temporary potholes correspond to 60, seasonal to 35 and around 5% of the potholes present in the PPR are permanent (Johnson, Oslund, and Hertel 2008).

Even though potholes are considered to be separated from main flow in the watershed (Sloan 1972), the behavior of these features play a role in its hydrology. Especially after the occurrence of intense precipitation events, many potholes exceed their storage capacity and the connectivity between them is established (Roth and Capel 2012). Potholes provide storage during precipitation events, and habitat for bird species. They are also recognized as “wet spots,” problematical geographies that drain without a sophisticated drainage system. Potholes flood frequency favors the occurrence of a unique habitat, with a high agricultural potential when the excess of water is removed from the system (Johnson, Oslund, and Hertel 2008).

However, the practice of drainage can compromise the environment balance, or the habitat characteristics. This circumstance represents a significant conflict between farmers, whose aim to drain these depressions in order to optimize yield, and wild life protectors, that wish to protect these features (Winter and Rosenberry 1995). The dilemma is aggravated with the fact that the impacts of the drainage in pothole dynamics in the watershed, and its impacts in the downstream flow are not well known yet in the larger scale (Schilling and Drobney 2014).

Because a significant quantity of these features was drained, little is known about their hydrological impact in the watersheds, especially in agricultural areas (Schilling and Drobney 2014). However, some research has been done. For example, according to Richardson & Arndt (1989), the physical and chemical characteristics of enclosed depressions are very similar to the hydrology of a wetland. In fact, according the USGS, potholes are considered seasonal inland wetlands, that can hard to identify because of their seasonality (National Wetland Research Center, 2014).

For this reason, some wetland characteristics must be discussed in order to predict impacts of pothole management. For example, conserved wetlands provide some hydrological services, such as: abating floods, improving water quality, and enhancing biodiversity (Zedler 2003;Gleason et al. 2008; Euliss, Mushet, and Johnson 2001; Gleason et al. 2011). Considering these facts, if potholes are proven to behave the same way, their preservation will be considered beneficial for the environment. From a regulatory standpoint, however, wetlands are protected by Section 404 of the Clean Water Act, and isolated topographies such as prairie potholes, that are already being drained, are not (Ross 2009).

As a consequence of the intense drainage in the hydric soils of Iowa, some consequences of landscape transformation has been observed, such as in wildlife community (Schilling and Drobney 2014); increase in the baseflow in some rivers in the state; increase in the nitrate flux reaching the Gulf of Mexico (Whigham and Jordan 2003); and consequently, a higher cost in the water treatment because excessive quantities of nitrate are some examples of the impacts (Johnson, Oslund, and Hertel 2008; Schilling 2005).

Given these circumstances, research is needed to determine the impact of management practices in the pothole region in the downstream flow, and the most appropriated approach, such as farming practices, to deal with these features (Brunet and Westbrook 2012). More information is needed about the detention time in these depressions, the water quality flowing into and from them, and the impact of these features on the water balance.

For a future scenario, equilibrium must be set between conservation and agriculture before any management decision (Johnson, Oslund, and Hertel 2008). To achieve this balance, government tools, such as the Iowa Nutrient Reduction Strategy were created in order to increase the number of conservational practices implanted in a more effective way (Iowa Nutrient Reduction Strategy, 2014).

## 2.2. Prairie Pothole Region

The Prairie Pothole Region (PPR) is an unique ecosystem, that is placed in the United Stated and Canada in the states of Montana, Minnesota, Iowa, North and South Dakota, Alberta, Saskatchewan and Manitoba (Sloan 1972). In Iowa, the PPR corresponds to the landform region denominated Des Moines Lobe, with silty and loamy soils formed in glacial till in an area of 3.5 million hectares (Miller, Crumpton, and van der Valk 2009; Schilling, Jones, and Seeman 2013). Other landforms observed in Iowa, are the Northwest Iowa Plains, the Southern Iowa Drifty Plain, and the Iowan surface, that surround the lobe, among others (Department of Natural Resources, 2014).

The dominant geomorphic surface of the region is hummocky, formed by knolls and depressions, shaped after ice mass melt of the Winsconsinan ice sheet (Pennock et al. 2010). Since glaciation, around 12,000 years BCE, the region has primarily had arid to sub-humid climates, and is characterized by undeveloped natural drainage networks (Sloan 1972; Winter and Rosenberry 1995). That is consequence of insufficient runoff, low energy or reduced time for fluvial erosion to develop a system that is similar to that in more temperate regions, as less intense weathering and relatively young landscape formations are observed (Hayashi et al., 1998; Johnson et al., 2008; Schilling et al., 2013). However, its hydrology varies according to the season, climatic conditions, and with the agricultural management of the area (Winter and Rosenberry 1995; Winter and Rosenberry 1998).

Much of the prairies in the PPR are internally drained to small ‘prairie potholes’, features that consist of seasonal wetlands, where ponding is sometimes observed in just part of the year. The great majority were formed by melting glacial ice (Sloan 1972). The behavior of the potholes is strongly related with the landscape delineation, in this case, the Western Glaciate Plains. This region was covered by lacustrine sediment or till, and, if not fractured or biologically modified, presents lower hydraulic activity (Lennox, Maathuis, and Pederson 1988).This landscape has low permeability, which favors runoff when field capacity is exceeded, and leads to limited aquifer recharge rate (van der Kamp and Hayashi 1998; Shaw, Pietroniro, and Martz 2012; Winter and Rosenberry 1995). Some examples of glacial formations located in the PPR are the Missouri and the Prairie Coteau (Gleason et al. 2011).

The composition of the glacial deposit undelaying the PPR will have some impacts in water dynamics, since flow patterns will vary according rock and soil formations, and its structure. In situations in which a high quantity of clay is observed, the till behaves in a plastic way in the presence of water. On the other hand, in the absence of it the behavior is the opposite (Sloan 1972). Therefore, the content of water and consequent impact in the glacial deposit have impacts of the depressional storage, as well as in the water quality, and volume on the downstream flow. To predict downstream flow water patterns, the pothole role in the watershed must be assessed. This topic is relevant especially after the floods of 2008, which caused a significant amount of destruction in the state of Iowa (Buchmiller and Eash 2010).

Pothole shape will vary according to the glacial processes responsible for its formation, and weathering will continue to affect it. Their length can vary from less than an acre up to 40 acres, in which they are denominated lakes. On the other hand, the depth tends to be shallow; most are less than two feet deep (Sloan 1972; W. C. Johnson et al. 2010). For this reason, we hypothesize that potholes have the characteristic of providing temporary hydrological storage for small to moderate precipitations and minimal storage to the more intense ones, since they will tend to overflow, and therefore to connect with each other (Winter and Rosenberry 1995; Winter and LaBaugh 2003). Additionally, it is likely that over time, accumulation of sediments changes the depth and volume of farmed wetlands (Preston, Sojda, and Gleason 2013; Robert A Gleason and Euliss 1998; Lenhart et al. 2012; Gleason et al. 2011). In this situation, apart from the water that will infiltrate, most of the water will overflow and reach the outlet of the watershed.

The soils in the PPR are generally characterized by humid conditions combined with high organic matter. As a consequence, anaerobic conditions transform this habitat in ways important in the N cycles, enabling denitrification, and reducing available nitrogen of the soil solution (Brunet and Westbrook 2012). According to a conservation program held by the United States Department of Agriculture (USDA), in the year of 2011, just the areas in the PPR involved in the Conservation Reserve Program were responsible for the reduction of 24, 117 and 12 million tons of sediment, nitrogen, and phosphorus, respectively (USDA 2011).

The hydrological dynamics of potholes depends weather patterns, which is extremely variable in the PPR, because its extent (W. C. Johnson et al. 2010; Millett, Johnson, and Guntenspergen 2009). The climate is divided into ecoregions, areas in which specific biotic and abiotic characteristics are observed, and has influence of three air masses: Continental Polar, Maritime Tropical and Maritime Polar. Complex interactions of these masses proportionate an extreme and dynamic environment is characterized, with temperatures ranging from 40 to -40 ◦C (Millett, Johnson, and Guntenspergen 2009; Niemuth, Wangler, and Reynolds 2010). For this reason, analyses of potholes in one ecoregion may not be directly transferrable to potholes in another ecoregion; therefore, a close assessment of the characteristics of individual sites must be taken into consideration.

## 2.3. Hydrology

Pothole hydrology has impacts in the water chemistry, biodiversity, and crop productivity in a watershed in the watershed (Gleason et al. 2011), which justifies the investigation of these features. The PPR has a different behavior in relation to its surroundings. Its characteristics include a comparatively flat landscape, marked by the presence of features such as moraines, flutings, drumlins, outwash plains, glacial outburst valleys, sand dunes and glacially dammed lake beds that were formed though ice age conditions of the Pleistocene (Sloan 1972). These consist of glacial and post- glacial characteristics of landscape formation (Shook et al. 2013). Potholes are glaciogenic landforms that can provide an idea of ice movement and when deposition occurred. For instance, flutings and drumlins are composed of till, and bedrock core (Heikkinen and Tikkanen 1989).

In most watersheds, water flows from higher to lower altitudes. However, in the PPR, it is commonly observed a lack of integrated drainage, in other words, the lack of rivers or an evident water path, which causes water to be stored in upper areas in the watershed (Sloan 1972; Johnson, Oslund, and Hertel 2008). This enables the occurrence of ponding in depressions, the potholes (Winter and Rosenberry 1995; Winter and LaBaugh 2003; Oslund, Johnson, and Hertel 2010; van der Kamp and Hayashi 1998). The presence of these features is a consequence of the combination of the cold-semiarid climate, that is a characteristic of most the PPR, with the clay-rich glacial deposits, that cover most of the region (van der Kamp and Hayashi 2008). However, connections between potholes can exist when events of spillage occur, when the features exceed their maximum storage capacity (Leibowitz and Vining 2003; Rosenberry and Winter 1997; Winter 1999; van der Kamp and Hayashi 2008). Once their volume is filled, a stream is created, and a wetland connection can be formed. This allows the water to travel through the watershed, and as a consequence, the contributing area downstream, and the load of some pollutants, is likely to be higher (Schilling, 2005; Shook et al., 2013).

In regards to pothole characteristics, van der Kamp and Hayashi (2008) stated that these features can be divided into segments that can be classified as hydrological units, as seen in Figure 2-1. The wetland is the variable area in which the soil is saturated most of the year; the riparian zone, usually counting with dense vegetation, is the transaction between upland and wetland; and the upland is the rest of the basin, located in a higher altitude in comparison with the other units. However, this classification is likely to be directly applied to potholes in their natural state, since most studies were undertaken in conservation areas.

It is possible to observe that the water balance is mainly composed by the sum of the evaporation and lateral subsurface flows, when overflow is not observed (Nachshon et al. , 2013; van der Kamp & Hayashi, 1998, 2008).

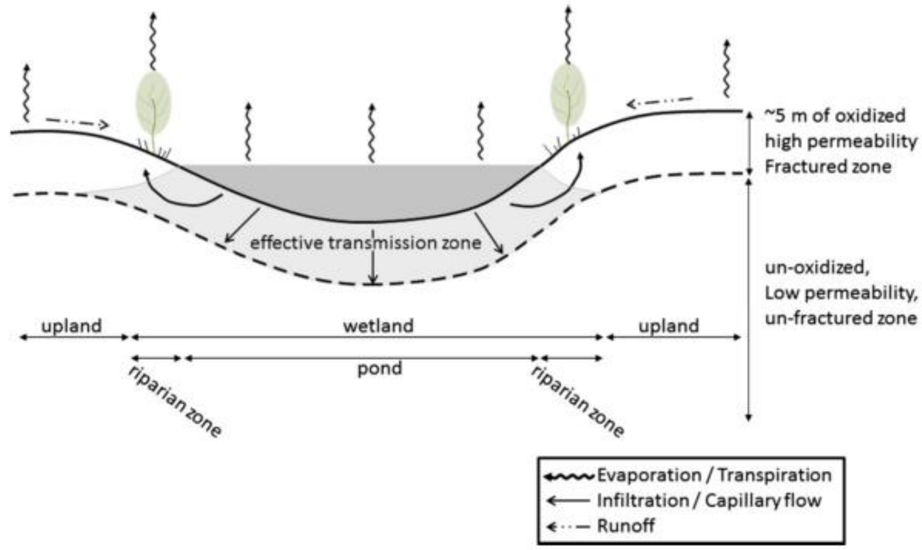



Figure 2-1: Major hydrologic units in a pothole (after Nachshon et. al. 2013).

Water can remain ponded in the wetland in different time scales. During the growing season, when generally higher density of rainfall events is observed, water can be stored from weeks to years, and this specific characteristic determines pothole regime classification (Miller, Crumpton, and van der Valk 2009; Rover et al. 2011). Temporary potholes are not able to store water for more than 3 weeks; the ones that can hold water for up to three months are seasonal; and the ones that keep surface water for years are semipermanent (Euliss and Mushet 1996). Size may be related with water retention, in which larger potholes can store water for longer periods (Johnson, Oslund, and Hertel 2008).

As discussed, most hydrological processes are related with variations in climate, position of the feature in the landscape, water table, and type of underlying material. Some potholes are highly ephemeral, and others only dry up after years of drought (Winter and Rosenberry, 1995). The water balance in the pothole was described by Du et al. (2005) in Equation 2-1 (Du et al. 2005):

$$V = V_{pcp} + V_{flowin} + V_{stored} - V_{evap} - V_{seep} - V_{flowout} \qquad \text{Equation 2-1}$$

In which V: volume of water in the impoundment in a given day ($m^3$); $V_{pcp}$: volume of precipitation ($m^3$); $V_{flowin}$: surface runoff and lateral soil flow in the pothole ($m^3$); $V_{stored}$: volume of water stored in the water body at the beginning of the measurement ($m^3$); $V_{evap}$: water volume removed by evaporation ($m^3$); $V_{seep}$: volume of water lost by seepage ($m^3$), and $V_{flowout}$: volume of water flowing out of the water body during the day ($m^3$).

In the paper in which this equation was proposed, the aim was to model potholes with the non-point source model Soil and Water Assessment Tool (SWAT), used to estimate nutrient and sediment load in water resources. However, their conclusion was that further work was needed in order to model this feature with a higher level of precision (Du et al. 2005).

The riparian zone, or the intermitent area between the bottom of the pothole and upland, plays a role in the water loss and infiltration. In a study developed in North Dakota, seepage loss was higher in vegetated wetlands in comparisson to bare ones, even with a smaller evapotranspiration (Sloan 1972). The riparian zone also can have an effect in groudwater recharge patterns. Van der Kamp and Hayashi (1998) pointed out that local groundwater recharge in the PPR likely depends on the maintanance of the vegetation in this area, even though wetland drainage as a whole has a minimal impact on regional groundwater recharge (van der Kamp and Hayashi 1998). Pothole plant communty provide an idea of the length in which water is stored in the wetland. Whereas the water ponds for more time, more stable plant communities are usually observed (Aronson et al. 2008). It happens since a great positive fluctuation can be fatal for plant community (Gleason et al., 2011).

In farmed potholes it varies as a funtion of landscape disturbance, and dynamic change in cover (Schilling and Drobney 2014). In a study of pothole classification, it was observed that some small wetlands that were worked on for several years might have lost a great store of their storage capacity (Gusman, Voigt, and Forman 2001). Therefore, the small depressions are more vulnerable to effects of agricultural activities because of their shallow depth and typically dry conditions in part of the year (Niemuth et. al. 2010). Figure 2-2 illustrates an example of ground water dynamics of small depressions a in the landspace.

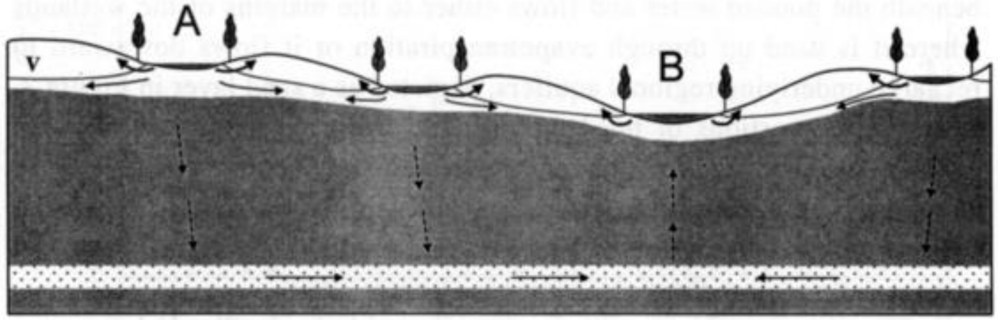



Figure 2-2: Groundwater flow systems with prairie wetlands. The arrows indicate the direction of the groundwater flow. The symbol V, located in the left, stands for the avarage position of the water table. The shaded area indicates the glacial till and the dots layer the aquifer. Lastly, the non-shaded region indicates the oxidized and fractured till or clay (van der Kamp and Hayashi 1998).

Pothole location in relation to other features has some influence in the groundwater hydrologic function, i.e. recharge, discharge, and flow-through. As seen in Figure 2-2, in which A is considered a recharge and B a discharge wetland, as the water table varies, the water flux in the potholes A and B are different. In depressions located in higher landscapes, like in A, once water infiltrates, it can flow either to the boarder of the wetland, where it will likely be evaporated; or it can flow down, until it reaches an impervious layer. On the other hand, in lower elevation B, groundwater tends to follow the opposite direction, in the direction of the impoundment, recharging the wetland. Apart from this movement, in this wetland water can also flow to the margins, alike the behavior observed in A (Gleason et al., 2011; van der Kamp & Hayashi, 1998; Winter & Rosenberry, 1995).

Flux directions determine the water table of the region, and as a consequence, help govern the lifespan of the pond in the depression (Roth and Capel 2012). This information refer back to the nexus of potholes in the relation to watershed hydrology and water quality in the outlet. If these features have impact in their surroundings, they might as well impact watershed hydrology as a hole, in particular in wetlands with a high density of these fearures.

Since pothole location influence their hydrology, the best management to be adopted when these features are observed in the landscapes vary. Potholes located inner in the watershed can be used as sedimentation basins and to hold water (Tomer, Crumpton, et al. 2013; Tomer et al. 2015), while potholes in the surroundings can be used for a different purpose.

Wetland interaction with the watershed hydrology can happen through two ways. First, through shallow flux, as in case of overflow or increase of water table, and through deep vertical fluxes with the aquifers, when a connection is observed, i.e. the presence of fracturing (Frei and Fleckenstein 2014). When artificial drainage is observed, the interaction can also take place through ditches formed in the construction of the drainage system (Westbrook et al. 2011).

Frei & Fleckenstein (2014) summarize the behavior and effects of depressional features in terms of surface, surface/ subsurface couplings, and subsurface effects. Some of these are listed below.

- Surface:
  - Buffering of incoming rainfall;
  - Attenuates and delays surface flow;
  - Threshold controlled surface flow activation (storage up to a point, and outflow above that threshold);
  - Surface flow networks and micro-channeling effects (usually designated by the interconnection of smaller depressional features).
- Surface/ Subsurface Couplings:
  - Non-linear and hysteretic feedback mechanisms;
  - Shifts between surface and subsurface flow dominance for wetlands.
- Subsurface:
  - Small scale variations of the water table - reported for wetlands;
  - Small scale variations of biochemical transformation processes – reported for wetlands;
  - Complex hydraulic head distributions – reported for wetlands and streambed topographies.

Since micro-topographies involve a high range of sizes, some of this effects might not represent the actual effect of the potholes. Because of that, studies have to be developed in order to evaluate these potential effects.

A classifying model designed by Gray, 1984 for the PPR in Canada, determined infiltration potential of frozen soils, and divided them into three groups, according to their infiltration pattern. The groups were: (1) Restricted: low infiltration and high runoff potential; (2) Limited: Infiltration governed by ice content of soil layer from 0 to 30 centimeters during melt; (3) Unlimited: soil with a relatively high content of large, air-filled, noncapillary pores, therefore, increasing chances of infiltration.

## 2.4. Water Quality

Runoff flow can reach the streams through different paths in the landscape, which have direct impact in the water quality of a watershed. Figure 2-3 illustrates some of the potential water paths.

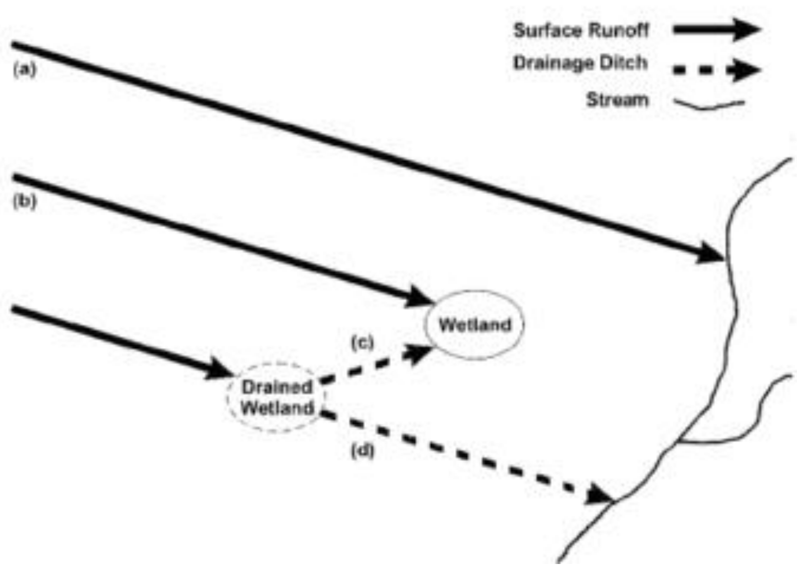



Figure 2-3: Potential pathways of surface runoff: A) surface runoff, B) wetland storage, C) drainage of wetlands D) drainage of runoff flow (Source: Westbrook et al. 2011).

In most situations, tile drainage water reaches the streams with low or no processing, the runoff water quality reaches the depressions with surface intakes has a direct impact on the quality of the streams (Smith and Livingston 2013). In addition, depending on the management of the area, surface runoff can as well contribute with high nutrient loads.

Enclosed depressions are known as nutrient sinks (Whigham and Jordan 2003), and also can trap bacteria and salt from runoff flow (Johnson, Oslund, and Hertel 2008). It is known that oxygen availability, nutrient cycling, biochemical transformations, as well as chemical variances in water can be observed in prairies wetlands (Winter and Rosenberry 1995; Frei, Lischeid, and Fleckenstein 2010; Westbrook et al. 2011; Pennock et al. 2010). However, the relation between downstream water quality and the hydrology of these features, the duration in which water is accumulated, and their density within the watershed is still not completely understood (van der Kamp and Hayashi 1998; Schilling and Drobney 2014).

Since the PPR is generally rich in sulfate, the dynamics of this salt can influence water quality and soil acidification (Nachshon et al. 2013). Salts are highly soluble, being transported by surface and subsurface fluxes (Nachshon et al. 2013; Hayashi, van der Kamp, and Rudolph 1998), and salinity is a measure of the quantity of total dissolved solids in water (Sloan 1972). Therefore, despite limited exchanges between wetland and groundwater as a whole, the nature and direction of flow determines whether salts accumulate in the wetland or are leached out (Westbrook et al. 2011). Salinity is directly related to the ponding dynamics. When stored water is not renewed for long periods, it can have a higher salt concentration (Sloan 1972). However, impacts of salinity in water quality downstream were not commonly investigated in depth in the literature. Generally, this parameter is measured in order to estimate the amount of time water is kept in the depression.

Hydroperiod, the number of days potholes flood during the growing season, has shown to have impacts in pollutant dynamics. Seasonal wetlands have been shown to have higher phosphorus concentrations in relation to other wetland types because of leaching from riparian zones surrounding the potholes (Westbrook et al. 2011). Therefore, an alternative to reduce the phosphorus load from drained wetlands might be to replace surface inlet installation by blind inlets, which filters the water before it reaches the stream network, as stated previously (Smith and Livingston 2013).

In Iowa, where most of the landscape is now agricultural, the effect of the pothole in the water quality deserves special attention since agriculture is considered the main source of nutrient loads to water bodies, especially in the Mississippi/Ohio River watersheds (Singh, et al., 2009). This fact is especially relevant considering the recommendations of the Watershed Nutrient Task Force, in which the states would have to reduce their nutrient load in order to reduce the size, duration and severity of hypoxia in the Gulf (Iowa Nutrient Reduction Strategy, 2014).

The recent Iowa Nutrient Reduction Strategy framework was created as an attempt to direct the efforts to reduce nutrient load in a scientific, reasonable and cost effective way in the state. Conservation practices such as implantation of wetlands are proposed to reduce the load (Tomer, Porter, et al. 2013). However, the challenge is to identify areas that should be assessed, and which other conservation practices should be offered to the farmers in order to achieve this goal. Potholes were not specifically addressed in the Nutrient Reduction Strategy.

## 2.5. Drainage

Drainage is an important component in the hydrology of potholes since it is a common practice in North America prairies, where the natural habitat was replaced by croplands (Blann et al., 2009; Johnson et al., 2008; Millett et al., 2009). The ecological and downstream economic impacts of this practice in potholes were not yet known by the agricultural community (Westbrook et al. 2011; Schilling and Drobney 2014). However, studies show that in permanent wetlands, drainage modifies water dynamics, structure, function, quantity, among other characteristics (Blann et al. 2009).

This practice modifies original hydrologic conditions, and causes habitat loss (Westbrook et al. 2011; Blann et al. 2009). However, it is adopted because of the agricultural potential of the PPR, and their seasonality (Gleason et al. 2011; Blann et al. 2009). To farm, to prevent delay in seeding rates, and to allow optimal agricultural production in the potholes, drainage is used in some areas of the PPR (Du et al. 2005). In the state of Iowa, the state of higher prairie conversion to cropland within the PPR extent, wetland loss is estimated to be around 89 % (Drum et al. 2015; Gleason et al. 2011; Schilling and Drobney 2014).

Figure 2-4 illustrates an example of how artificial drainage can be applied to potholes. To remove ponded water, inlets, or vertical surface intakes, are commonly installed. These structures are usually an extension from the subsurface pipes (Blann et al. 2009). Drainage can occur from the surface of the soil, or below it. In the Midwest, where subsurface drainage systems started to be installed in the early 1800s, the main objective was to drain ponded areas. However, nowadays the systems are also designed to decrease the water table of agricultural areas (Blann et al. 2009). The installation of a surface inlet usually assumes that the water within the depression arrived as runoff, however, the water table has been shown to increase during wet periods (Roth and Capel 2012).

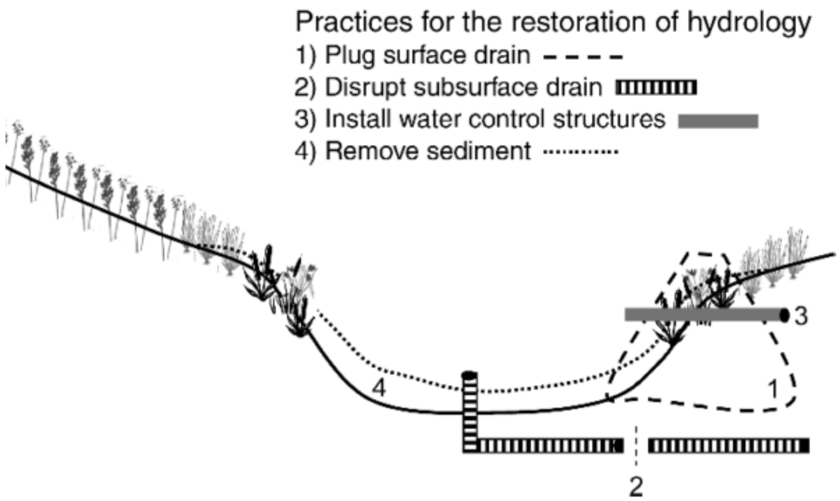



Figure 2-4: Example of a drainage system in a pothole (Gleason et al. 2011).

As discussed, since the use of these inlets in enclosed depressions are considered to be a contributor to water quality problems downstream, the adoption of blind inlets can be an alternative to reduce the nutrient loads into the streams. Blind inlets, also known as French drains, allow water to filtrate before reaching the drainage system (Smith and Livingston 2013).

The effects of drainage on the environment involve a large number of factors, connected through complex interactions. For instance, these relevant factors include hydrological condition, chemical properties, cycling of nutrients, organic matter content, among others (Blann et al. 2009). An example of drainage impacts is documented in Smith Creek, Canada. In this location, an increase in the flow contributing area is being observed as a consequence of the increase in agricultural land area. Additionally to the increase in downstream flow, eutrophication is being observed in the lake into which Smith Creek drains (Westbrook et al. 2011).

This phenomenon results in low oxygen content in the region it is observed because of high algae growth as a consequence of high nutrient availability, in particular nitrogen and phosphorus (Turner, Rabalais, and Justic 2008). When drainage systems are installed, continuous inundations in the field are observed less frequently (Roth and Capel 2012; Logsdon 2015), however the peak runoff in the outlet of the watershed tends to be higher. We believe that the most realistic scenario for Iowa would be the use of artificial drainage systems in the fields, but in the pothole extent. This management would potentially allow agricultural production and enhancement of environmental benefits, such as water quality improvement and flood control (Drake 2014; Manale 1997).

As wetland drainage connects stored pothole water to the drainage network and hastens its arrival to downstream water bodies, the excessive nutrient load, in particular dissolved nitrogen, can compromise the water quality. Likewise, as reported in Smith Creek watershed, eutrophication took place once there was less chance for nutrient reduction in the soil solution (Westbrook et al. 2011; Leibowitz and Nadeau 2003; Whigham and Jordan 2003). Moreover, conservation programs in which cropland is replaced by perennial vegetation, has shown a significant reduction in nutrient transport as well as nutrient loss for upland zones. Nevertheless, the downstream benefits were not yet accurately evaluated (Gleason et al. 2011).

The hypoxia in the Gulf of Mexico is another example of the impacts of the nutrients flowing from drainage systems in a bigger scale (Blann et al. 2009). As an attempt to reduce the hypoxia in this area, programs such as 'Mississippi River/ Gulf of Mexico Watershed Nutrient Task Force' were created in order to involve the main contributing states in the development of potential solutions to improve water quality of the Mississippi river. In Iowa, the 'Iowa Nutrient Reduction Strategy' was created (Iowa State University of Science and Technology 2014).

As stated, the intense adoption of this practice compromised the wetland habitat in the United Stated. To revert some of the negative impacts, some initiatives were taken in order to minimize the consequences. For instance, the Wetland Reserve Program (WRP) was created in 1992 as an attempt to provide conservation and protection of the environment and create a balance between social benefits related to the environment in relation to private ones (USDA). Landowners can voluntary enroll in the program through different contracts that can be permanent or with a settled length. Before the implantation of this program, in 1985, the Food Security Act included a provision that determined that farmers would not have some Farm Bill benefits if wetlands were drained or filled (Aronson et al. 2008). However, there is still economic pressure to increase corn acreage in order to produce ethanol, and consequently, the use of drainage to optimize corn production (Voldseth et al. 2009).

The conservation of the original landscape, and as consequence, drainage control, is important since wetlands are among the most biologically productive ecosystem in the world. For instance, in the United States, around five percent of the landscape consist of wetlands, while more than half of North American birds nest in these areas. In addition, one-third of the endangered and threatened species rely on them (USDA). Apart from these facts, some ecological functions, such as water quality improvement, flood prevention, fish and wildlife habitat, can be attributed to these sites.

Consequently, as potholes are usually located in areas where agrochemical residues and eroded soils are deposited, drainage is likely to have impacts in the water quality and regime in the watershed downstream, since it will impact in their capacity to trap nutrients, ions, and bacteria (Westbrook et al. 2011). The regime might change with combination of management practices, such as drainage and tillage.

Research shows that land use has a significant effect on sedimentation of wetlands in the PPR. In a study developed in Montana, soil erosion was observed in higher rates in the upland catchments of wetlands surrounded by cropland in relation to native prairie. Also, recent land use change in the Western Corn Belt threatens grasslands and wetlands (Wright and Wimberly 2013). Thus, potholes in agricultural areas can be expected to have different sediment loading compared to those in prairie or grassland areas.

Because of agricultural conversion, drainage practices are broadly used in the PPR. It has shown positive effects, such as increase in agricultural production, and negative ones, like loss of habitat, compaction, lower water table, and decrease in water quality (Galatowitsch and Valk 1996). For better understanding in the impacts of potholes, more research is needed to determine the consequences of drainage in field and watershed scale, the management that would be most suitable for these areas, and if conservation is suitable.

## 2.6. Restoration

Different wetland types have specific benefits, and because of it, restoration of a range of wetlands is considered as a way to revert the negative impacts of drained areas and wetland loss. Because pothole short hydroperiod for the majority of years, these features cannot sustain predators as fish, and for the same reason are nests for amphibian reproduction, they might not allow water to pound enough time to permit nutrient uptake, and represent medium change in the landscape hydrology (Fennessy 2011). Therefore, one of the major objectives of restoration would be to increase the number of days the features stay inundated in order to allow chemical and sediment transformation, which will provide environmental benefits. Some benefits are the settlement of sediments and denitrification, the transformation of dissolved nitrogen (nitrate) in water into nitrogen gas. Phosphorus transformations in wetland environment consist of sorption onto soil particles, incorporation into organic matter and plant uptake (Marton, Fennessy, and Craft 2014).

Apart from hydroperiod, water balance dynamics and disturbance regimes will play a role in the wetland capacity to provide environmental benefits (Marton, Fennessy, and Craft 2014). For instance, in a study developed by Marton et. al. (2014), it was observed that surface soils, from 5- to 10-year-old restored wetlands provided less water quality benefits, such as N and P removal by denitrification and sorption, respectively, in comparison to natural features.

Wetlands with higher hydrological connectivity, that overflow more frequently, will have a higher change to provide environmental benefits, and a higher change to influence the hydrology downstream than features that are more hydrologically disconnected (Marton, Fennessy, and Craft 2014). With the use of artificial drainage, small temporal depression such as pothole tend to be considered hydrologically disconnected once the water load is removed from the depressions before these have the chance to overflow.

Research in restored prairie has shown that the impacts of potholes in the environment are better observed in field, rather than large scale. Results of conservation of prairie landscape in the Neal Smith National Wildlife Park (NSNWP), Iowa, have shown progress in the understanding of infiltration, reduced nitrate and P concentration, and decrease in sediment transport in plot scale

(Schilling and Drobney 2014). However, more research is necessary in the assessment of watershed scale.

Restored native grassland has shown to have a higher capacity to mineralize carbon and perform denitrification in relation to corn-soybeans vegetation, according with a study in the NSNWP (Iqbal et al. 2014). In the study, denitrification and carbon fixation of a 19-year restored grassland was compared with scenarios corn-soybeans rotation with and without buffers.

## 2.7. Hydrological Models

Hydrological models are important tools to improve the quantitative understanding of the hydrological cycle in different scales and scenarios (Yuan, Bingner, and Rebich 2003; Taguas et al. 2012; Que et al. 2015). These generally simulate observed conditions with the use of empirical equations, but some aspects vary from model to model (Moriasi and Wilson 2012). There are several models available, and the selection of one is a function of the application, data availability, scale of analysis, ability to model special features (i.e. buffers, wetlands), level of complexity, the watershed under assessment, among others.

Calibration and validation consist of important steps to test whether models are able to generate consistent data, in other words, if their results that replicate conditions observed in the reality. In these two steps, observed data is compared with simulated, and some inputs of the models are changed to until the best fit is observed. There is not an universally accepted method of calibration and validation, these vary according with the quality and extent of observed data, hydrological model used, among other factors (Moriasi and Wilson 2012).

For this project AnnAGNPS was selected. More information about the model is available in Chapter 4.

## 2.8. References

Aronson, Myla F J, Susan Galatowitsch, Alderman Hall, and St Paul. 2008. "Long-Term Vegetation Development Of Restored Prairie Pothole Wetlands Long-Term Vegetation Development of Restored Prairie Pothole Wetlands" 28 (4): 883–895.

Blann, Kristen L., James L. Anderson, Gary R. Sands, and Bruce Vondracek. 2009. "Effects of Agricultural Drainage on Aquatic Ecosystems: A Review." *Critical Reviews in Environmental Science and Technology* 39 (November 2): 909–1001. doi:10.1080/10643380801977966. http://www.tandfonline.com/doi/abs/10.1080/10643380801977966.

Brunet, Nathalie N., and Cherie J. Westbrook. 2012. "Wetland Drainage in the Canadian Prairies: Nutrient, Salt and Bacteria Characteristics." *Agriculture, Ecosystems & Environment* 146 (1) (January): 1–12. doi:10.1016/j.agee.2011.09.010. http://linkinghub.elsevier.com/retrieve/pii/S0167880911003410.

Buchmiller, Robert C., and David A. Eash. 2010. "Floods of May and June 2008 in Iowa: U.S. Geological Survey Open-File Report."

Creed, Irena F., Johnston Miller, David Aldred, Jennifer K. Adams, Salvatore Spitale, and Rick a. Bourbonniere. 2013. "Hydrologic Profiling for Greenhouse Gas Effluxes from Natural Grasslands in the Prairie Pothole Region of Canada." *Journal of Geophysical Research: Biogeosciences* 118 (2) (June 13): 680–697. doi:10.1002/jgrg.20050. http://doi.wiley.com/10.1002/jgrg.20050.

Du, B, J G Arnold, A Saleh, and D B Jaynes. 2005. "Development and Application of Swat to Landscapes with Tiles and Potholes" 48 (3).

Fennessy, S Iobhan F. 2011. "Agricultural Conservation Practices Increase Wetland Ecosystem Services in the Glaciated Interior Plains" 21 (3): 49–64.

Frei, S, and J H Fleckenstein. 2014. "Environmental Modelling & Software Representing Effects of Micro-Topography on Runoff Generation and Sub-Surface Fl Ow Patterns by Using Super Fi Cial Rill / Depression Storage Height Variations" 52: 5–18.

Frei, S., G. Lischeid, and J.H. Fleckenstein. 2010. "Effects of Micro-Topography on Surface–subsurface Exchange and Runoff Generation in a Virtual Riparian Wetland — A Modeling Study." *Advances in Water Resources* 33 (11) (November): 1388–1401. doi:10.1016/j.advwatres.2010.07.006. http://linkinghub.elsevier.com/retrieve/pii/S0309170810001417.

Gleason, R. A., N. H. E. Uliss, B. A. T. Angen, and M. K. L. Aubhan. 2011. "USDA Conservation Program and Practice Effects on Wetland Ecosystem Services in the Prairie Pothole Region." *Ecological Applications* 21 (3): S65–S81.

Gleason, RA, MK Laubhan, BA Tangen, and KE Kermes. 2008. "Ecosystem Services Derived from Wetland Conservation Practices in the United States Prairie Pothole Region with an Emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs." http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1111&context=usgsnpwrc.

Gray, D. M., P. G. Landine, and R. J. Granger. 1984. "Simulating Infiltration into Frozen Prairie Soils in Streamflow Model." Saskatoon, Sask., Canada S7N OW. http://www.nrcresearchpress.com/doi/pdf/10.1139/e85-045.

Gusman, A. Jake ., Richard L. Jr. Voigt, and Selena M. Forman. 2001. "Delineation and Classification of Prairie Pothole Wetlands Using GIS and Aerial Photos." *Wetlands Engineering & River Restoration* (1): 1–12.

Hayashi, Masaki, Garth van der Kamp, and Dave L. Rudolph. 1998. "Water and Solute Transfer between a Prairie Wetland and Adjacent Uplands, 1. Water Balance." *Journal of Hydrology* 207 (1-2) (June): 42–55. doi:10.1016/S0022-1694(98)00098-5. http://linkinghub.elsevier.com/retrieve/pii/S0022169498000985.

Heikkinen, Olavi, and Matti Tikkanen. 1989. "Drumlins and Flutings in Finland: Their Relationships to Ice Movement and to Each Other." *Sedimentary Geology* 62: 349–355.

Iowa State University of Science and Technology, ISU. 2014. "Iowa Nutrient Reduction Strategy." http://www.nutrientstrategy.iastate.edu/.

Iqbal, Javed, Timothy B. Parkin, Matthew J. Helmers, Xiaobo Zhou, and Michael J. Castellano. 2014. "Denitrification and Nitrous Oxide Emissions in Annual Croplands, Perennial Grass Buffers, and Restored Perennial Grasslands." *Soil Science Society of America Journal* 79 (1): 239. doi:10.2136/sssaj2014.05.0221. https://dl.sciencesocieties.org/publications/sssaj/abstracts/79/1/239.

Johnson, Rex R., Fred T. Oslund, and Dan R. Hertel. 2008. "The Past, Present, and Future of Prairie Potholes in the United States." *Journal of Soil and Water …* 63 (3): 84–87. http://www.jswconline.org/content/63/3/84A.short.

Leibowitz, Scott G., and Tracie -Lynn Nadeau. 2003. "Isolated Wetlands: State-of-the-Science and Future Directions." *Wetlands* 23 (3) (September): 663–684. doi:10.1672/0277-5212(2003)023[0663:IWSAFD]2.0.CO;2. http://link.springer.com/10.1672/0277-5212(2003)023%5B0663%3AIWSAFD%5D2.0.CO%3B2.

Leibowitz, Scott G., and Kevin C. Vining. 2003. "Temporal Connectivity in a Prairie Pothole Complex." *Wetlands* 23 (1) (March): 13–25. doi:10.1672/0277-5212(2003)023[0013:TCIAPP]2.0.CO;2. http://link.springer.com/10.1672/0277-5212(2003)023%5B0013%3ATCIAPP%5D2.0.CO%3B2.

Lennox, D. H., H. Maathuis, and D. Pederson. 1988. "Region 13, Western Glaciated Plains." *Hydrogeology Journal* 0-2: 115–128.

Marton, John M., M. Siobhan. Fennessy, and Christopher B. Craft. 2014. "Functional Differences between Natural and Restored Wetlands in the Glaciated Interior Plains." *Journal of*

*Environment Quality* 43 (1): 409. doi:10.2134/jeq2013.04.0118. https://www.agronomy.org/publications/jeq/abstracts/43/1/409.

Miller, Bradley A., William G. Crumpton, and Arnold G. van der Valk. 2009. "Spatial Distribution of Historical Wetland Classes on the Des Moines Lobe, Iowa." *Wetlands* 29 (4): 1146–1152.

Millett, Bruce, W. Carter Johnson, and Glenn Guntenspergen. 2009. "Climate Trends of the North American Prairie Pothole Region 1906–2000." *Climatic Change* 93 (1-2) (February 19): 243–267. doi:10.1007/s10584-008-9543-5. http://link.springer.com/10.1007/s10584-008-9543-5.

Moriasi, Dn, and Bn Wilson. 2012. "Hydrologic and Water Quality Models: Use, Calibration, and Validation." *Transactions of the …* 55 (4): 1241–1247. doi:10.13031/2013.42265. http://swat.tamu.edu/media/63553/asabe55(4).asp.pdf.

Nachshon, Uri, Andrew Ireson, Garth van der Kamp, and Howard Wheater. 2013. "Sulfate Salt Dynamics in the Glaciated Plains of North America." *Journal of Hydrology* 499 (August): 188–199. doi:10.1016/j.jhydrol.2013.07.001. http://linkinghub.elsevier.com/retrieve/pii/S002216941300509X.

Niemuth, Neal D., Brian Wangler, and Ronald E. Reynolds. 2010. "Spatial and Temporal Variation in Wet Area of Wetlands in the Prairie Pothole Region of North Dakota and South Dakota." *Wetlands* 30 (6) (November 6): 1053–1064. doi:10.1007/s13157-010-0111-1. http://link.springer.com/10.1007/s13157-010-0111-1.

Oslund, Fred T., Rex R. Johnson, and Dan R. Hertel. 2010. "Assessing Wetland Changes in the Prairie Pothole Region of Minnesota From 1980 to 2007." *Journal of Fish and Wildlife Management* 1 (2) (November): 131–135. doi:10.3996/122009-JFWM-027. http://www.fwspubs.org/doi/abs/10.3996/122009-JFWM-027.

Pennock, A Dan, Thomas Yates, Angela Bedard-Haughna, Kim Phipps, Richard Farrell, and Rhonda McDougal. 2010. "Landscape Controls on N2O and CH4 Emissions from Freshwater Mineral Soil Wetlands of the Canadian Prairie Pothole Region." *Geoderma* 105: 308–319.

Rosenberry, Donald O., and Thomas C. Winter. 1997. "Dynamics of Water-Table Fluctuations in an Upland between Two Prairie-Pothole Wetlands in North Dakota." *Journal of Hydrology* 191 (1-4) (April): 266–289. doi:10.1016/S0022-1694(96)03050-8. http://linkinghub.elsevier.com/retrieve/pii/S0022169496030508.

Roth, J L, and P D Capel. 2012. "The Hydrology of a Drained Topographical Depression within an Agricultural Field in North-Central Iowa" 55 (5): 1801–1814.

Schilling, K.E. 2005. "Relation of Baseflow to Row Crop Intensity in Iowa." *Agriculture, Ecosystems & Environment* 105 (1-2) (January): 433–438. doi:10.1016/j.agee.2004.02.008. http://linkinghub.elsevier.com/retrieve/pii/S0167880904001227.

Schilling, Keith E., Christopher S. Jones, and Anthony Seeman. 2013. “How Paired Is Paired? Comparing Nitrate Concentrations in Three Iowa Drainage Districts.” *Journal of Environmental Quality* 42 (1412-1421).

Shaw, Dean a., Al Pietroniro, and L.W. Martz. 2012. “Topographic Analysis for the Prairie Pothole Region of Western Canada.” *Hydrological Processes* 3114 (June 2012) (June 28): n/a–n/a. doi:10.1002/hyp.9409. http://doi.wiley.com/10.1002/hyp.9409.

Shook, Kevin, John W. Pomeroy, Christopher Spence, and Lyle Boychuk. 2013. “Storage Dynamics Simulations in Prairie Wetland Hydrology Models: Evaluation and Parameterization.” *Hydrological Processes* 27 (13) (June 30): 1875–1889. doi:10.1002/hyp.9867. http://doi.wiley.com/10.1002/hyp.9867.

Sloan, Charles E. 1972. “Ground-Water Hydrology of Prairie Potholes in North Dakota:” 1–29.

Smith, D. R., and S. J. Livingston. 2013. “Managing Farmed Closed Depressional Areas Using Blind Inlets to Minimize Phosphorus and Nitrogen Losses.” *Soil Use and Management* 29 (March) (March 5): 94–102. doi:10.1111/j.1475-2743.2012.00441.x. http://doi.wiley.com/10.1111/j.1475-2743.2012.00441.x.

Tomer, M. D., S. a. Porter, D. E. James, K. M. B. Boomer, J. a. Kostel, and E. McLellan. 2013. “Combining Precision Conservation Technologies into a Flexible Framework to Facilitate Agricultural Watershed Planning.” *Journal of Soil and Water Conservation* 68 (5) (August 23): 113A–120A. doi:10.2489/jswc.68.5.113A. http://www.jswconline.org/cgi/doi/10.2489/jswc.68.5.113A.

Turner, R Eugene, Nancy N Rabalais, and Dubravko Justic. 2008. “Gulf of Mexico Hypoxia: Alternate States and a Legacy.” *Environmental Science & Technology* 42 (7) (April 1): 2323–7. http://www.ncbi.nlm.nih.gov/pubmed/18504960.

USDA. “Restoring America’s Wetlands : A Private Lands Conservation Success Story.”

USDA, U.S. Department of Agriculture. 2011. “Conservation Reserve Program.” Washington D.C.

Van der Kamp, Garth, and Masaki Hayashi. 1998. “The Groundwater Recharge Function of Small Wetlands in the Semi-Arid Northern Prairies.” *Great Plains Research* 8 ((Spring 1998)): 39–56.

van der Kamp, G. and Masaki, M. 2008. “Groundwater-Wetland Ecosystem Interaction in the Semiarid Glaciated Plains of North America.” *Hydrogeology Journal* 17 (1) (October 23): 203–214. doi:10.1007/s10040-008-0367-1. http://link.springer.com/10.1007/s10040-008-0367-1.

Vepraskas, M J. 2013. “Morphological Methods to Characterize Hydric Soils.” In *Methods in Biogeochemistry of Wetlands*, edited by R.D. DeLaune, K.R. Reddy, C.J. Richardson, and J.P.

Megonigal, 7619:117–136. Madison, WI: Soil Science Society of America. doi:10.2136/sssabookser10.c8.

Voldseth, Richard A, W Carter Johnson, Glenn R Guntenspergen, Tagir Gilmanov, and Bruce V Millett. 2009. "Adaptation of Farming Practices Could Buffer Effects of Climate Change on Northern Prairie Wetlands" 29 (2): 635–647.

Westbrook, Cherie J, Nathalie Brunet, Iain Phillips, and John-mark Davies. 2011. "Wetland Drainage Effects on Prairie Water Quality Final Report."

Whigham, Dennis F., and Thomas E. Jordan. 2003. "Isolated Wetlands and Water Quality." *Wetlands* 23 (3) (September): 541–549. doi:10.1672/0277-5212(2003)023[0541:IWAWQ]2.0.CO;2. http://link.springer.com/10.1672/0277-5212(2003)023%5B0541%3AIWAWQ%5D2.0.CO%3B2.

Winter, Thomas C. 1999. "Relation of Streams , Lakes , and Wetlands to Groundwater Flow Systems" (September 1998): 28–45.

Winter, Thomas C, and Donald O. Rosenberry. 1995a. "The Interaction of Ground Water with Prairie Pothole Wetlands in the Cottonwood Lake Area, East-Central North Dakota, 1979-1990" 15 (3): 193–211.

Winter, Thomas C. and Rosenberry Donald O. (1998). 1998. "Hydrology of Prairie Pothole Wetlands During Drought and Deluge." *Climatic Change* 40: 189–209.

Winter, Thomas C., and James W. LaBaugh. 2003. "Hydrologic Considerations in Defining Isolated Wetlands." *Wetlands* 23 (3): 532–540. http://download.springer.com/static/pdf/7/art%3A10.1672%2F0277-5212%282003%29023%5B0532%3AHCIDIW%5D2.0.CO%3B2.pdf?auth66=1384202000_ef62f8fa61fbabfe6312ee4595f251ee&ext=.pdf.

Winter, Thomas C., and Donald O. Rosenberry. 1995b. "The Interactio of Ground Water With Prairie Pothole Wetlands in the Cottonwood Lake Area, East-Central North Dakota, 1979-1990." *Wetlands* 153: 193–211.

Wright, Christopher K, and Michael C Wimberly. 2013. "Recent Land Use Change in the Western Corn Belt Threatens Grasslands and Wetlands." *Proceedings of the National Academy of Sciences of the United States of America* 110 (10) (March 5): 4134–9. doi:10.1073/pnas.1215404110. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3593829&tool=pmcentrez&rendertype=abstract.

Zedler, Joy B. 2003. "Wetlands at Your Service : Reducing Impacts of Agriculture at the Watershed Scale" 53706.

# CHAPTER 3: SITE MONITORING AND DEM ANALYSIS

## 3.1. Objectives

In this chapter site investigations and data collection developed will be discussed, in prior to pothole modeling. The objective is to describe the study-area, to illustrate how the observed data of water depth variations were collected during 2014; and to describe the methodology used to compute pothole volume and area as a function of pothole depth-elevation. In 2014, data was collected to generate more information about pothole hydrology, to potentially be used in the calibration of the hydrological model used in pothole assessment. The methodology developed to estimate the volume-area-depth relationship required the assessment of a high-resolution DEM, which its source is also discussed here, and the results will be discussed in chapter 6.

## 3.2. Site Monitoring

Two potholes located in a single farm field straddling adjacent watersheds just outside of Ames, IA were assessed to quantify their surface water storage potential. The field site is located in the Des Moines lobe region, located in Story County, and is conventionally managed in a corn-soybeans rotation. The original vegetation consists of prairie, a vegetation with a higher biomass production in relation to corn and soybeans. There is no accurate record of the date of conversion from prairie to agricultural systems of the field, but records suggests that Story County was one of the first counties to be converted to agriculture land (Hewes and Frandson 1952). It suggests that this region is far from its original conditions, with several decades without a diverse vegetation, and through intense soil disturbance and compaction. Potholes might me one of the few components of the pre-settlement PPR region that are still present in the field.

The location of the Walnut and Worrell Creek HUC-12 watersheds in relation to the Des Moines Lobe is available in figure 1-1. For reference in this project, we named the potholes according the watersheds in which these are located. These two watersheds were selected for the study because their high concentration of potholes, and the existence of observed data of water depth variation for the years of 2010 and 2011 in two potholes in the area. This data will be used for the validation of the model, more information is available in Chapter 4.

As illustrated in figure 1-2, the potholes are located near the boundaries of their respective HUC-12 watersheds. Because of the flat landscape, the drainage area of potholes tend to merge as their distance of the watershed boundary increases, which is expected once the drainage area of a pothole located downstream may include other potholes upstream, and their respective drainage area. This is related with the “fill and spill” mechanisms of in the PPR (Winter and LaBaugh 2003; Huang et al. 2011), caused by the subtle variatons in the DEM. Furthermore, potholes near the boundaries of the watershed are likely to receive water from precipitation and runoff, while features towards the center will probably be more prone to changes in ground water fluctuations (Whigham and Jordan 2003; Sloan 1972; Leibowitz 2003).

In the 2010 and 2011 growing seasons, a pressure transducer was installed at or near the bottom of each pothole, and the depth of ponded water was derived from the transducer data on an hourly basis (Logsdon 2015).  In 2014, the features were visited from April to August of 2014, following rainfall.  When observable standing water was present, the perimeter of the flooded area was walked with a GPS unit (Magellan 210), and translated to an inundation map with ArcGIS (ESRI 2015). The inundation map was used to estimated volume storage and surface area of the collected data.  Later than August, data collection was compromised by the dense vegetation in the field.

The data collected in the years 2010 and 2011 were on a continuous basis, whereas the 2014 data was collected at a single time at a daily frequency when ponded, if possible. Because of consecutive days of rainfall, it was not possible to collect data in the following day of the precipitation event in some situations. The great advantage of the transducer dataset is that it was possible to capture the maximum water storage of each ponding event, since the transducers measured hourly water variation. In the GPS data, since observations were collected after rainfall events, it is likely that some volume was lost by evapotranspiration and drainage before the site was visited. Observed data collected during 2010 and 2011 were converted from hourly to daily to allow comparison with data generated by the model, which has a daily timestep. Figure 3-1 illustrates a picture of when these are filled with water, taken in 2014. In all the three years in which observed data was collected, standing water was observed in the features at some point during the growing season.

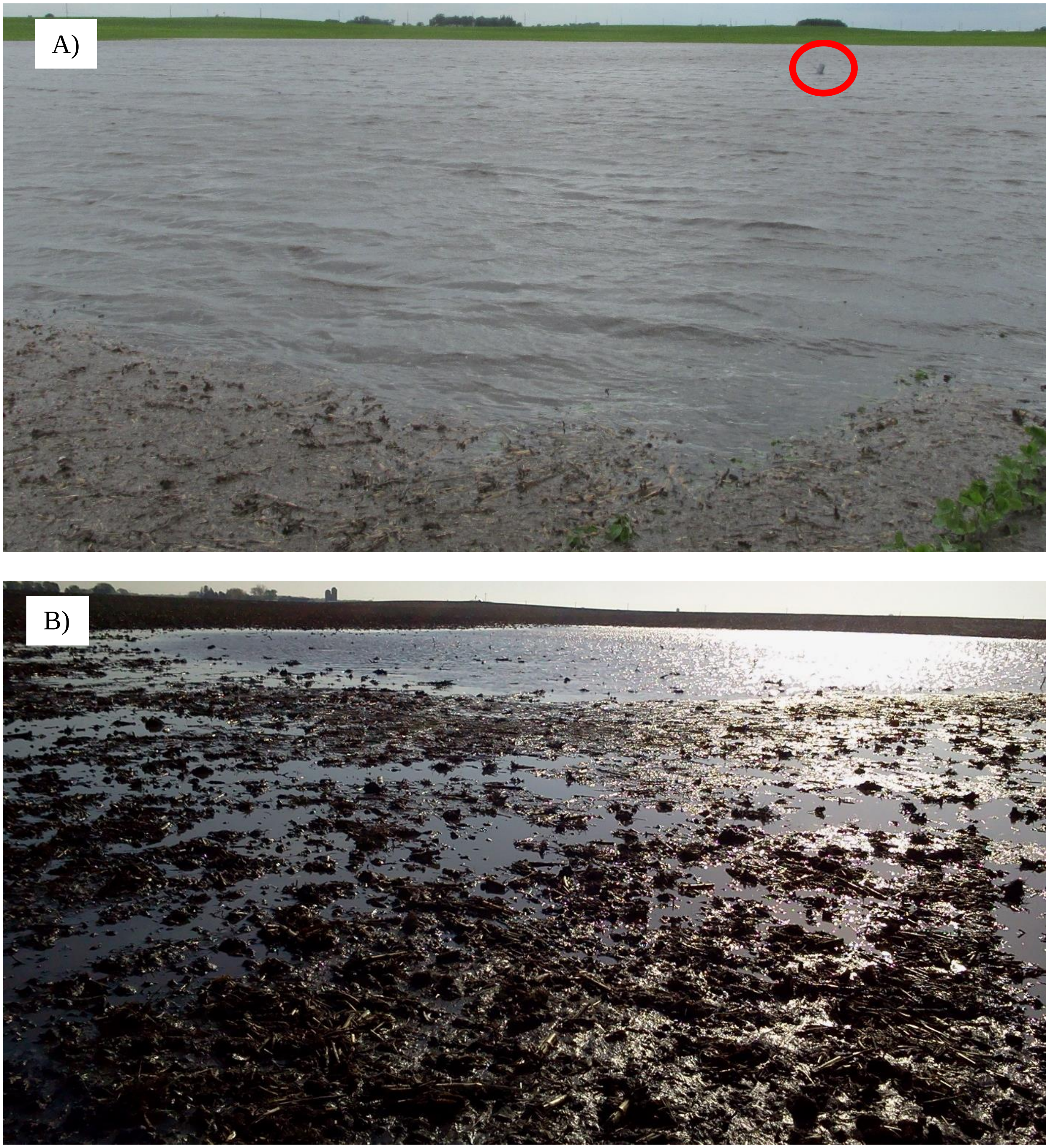



Figure 3-1: Example of potholes surface water storage after intense rainfall events. A) Worrell and B) Walnut potholes. The red circle notes the surface inlet in the Worrell pothole.

Figure 3-1 illustrates Walnut and Worrell potholes in two different stages of plant development. Figure 3-1A illustrates Worrell pothole in early July, when the plants had already started to grow. In this image, it is possible to see the surface inlet in the Worrell pothole, with detail in the surface intake, represented by the red circle. In figure 3-1A, it is possible to affirm that the drainage system was not able to maintain high rates of infiltration, since surface water was observed in the pothole for consecutive days. In figure 3-1B, Walnut is shown in late May, when the plants had been planted in the field not long before this inundation event.

The Worrell pothole is comprised of two depressions, referred to as "Worrell-Road", and "Worrell-Field", as shown in figure 3-2. These are frequently distinct, but merge under high ponded depth. Two surface inlets connected to the drainage system are presented in the Worrell-Field pothole. During data collection, it was observed that Worrell-Road would constantly be inundated for longer periods in relation to Worrell-Field, probably as a consequence of the inlets in Worrell-Field. The Worrell-Road pothole does not have a surface inlet, nor does the Walnut pothole, but both are known to be underlain by subsurface drainage lines.


Figure 3-2: Location of Worrell-Field (W-F), Worrell-Road (W-R).

Subsurface tile drainage systems are installed to keep soil moisture below field capacity and consequently enable a better plant development. The use of tile drainage can decrease the time it takes for water to leave the field, reducing field-scale inundation problems but potentially increasing flood problems in the drainage districts, because water from different locations are drained there. There was no record of subsurface tile lines location in the field, therefore, aerial photos were investigated to infer their potential location, and to understand and estimate the potential impacts of artificial drainage in the potholes. Figure 3-3 illustrates the potential location of the tiles according to aerial photo interpretation.

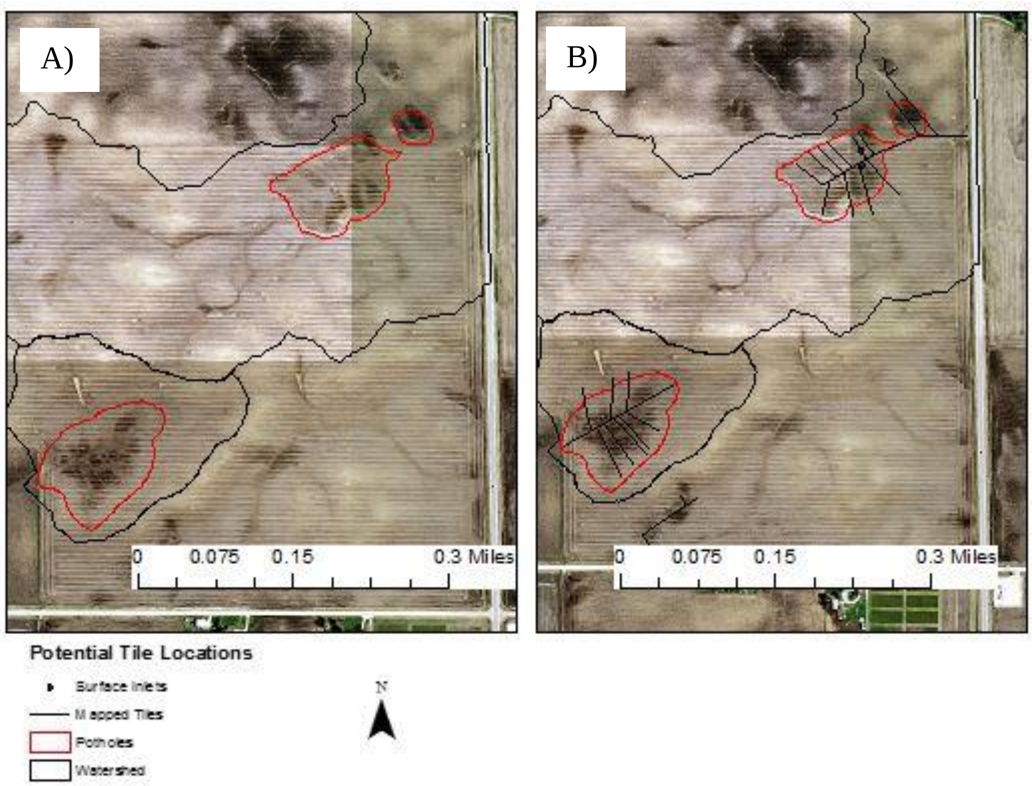



Figure 3-3: Potential tile locations. A) Aerial photo taken in 2014 as a part of a project in which the objective was the identification of tile drains with the use of aerial photos; B) mapped potential position of the tiles in the field.

In figures 3-2 and 3-3, the potholes are visible in aerial photos taken near the beginning of the growing season of the years of 2014 and 2013, respectively, before significant development of the plants. In the pictures, it is possible to observe darker areas in the middle of the features, which indicate higher moisture content in the soils. In the volume storage assessment, Worrell Field and Worrell Road will be assessed separately and together, since these tend to start storing water separately, but shortly connect in the case of higher runoff generation.

In addition to water depth in the potholes, soil and water quality data were collected, to estimate potential soil detachment and deposition, and water quality effects in the potholes. Soil samples were collected in different locations in the microwatersheds (Appendix B). Water quality data was collected when water was accumulated in the surface, which results in the collection of water quality data was collected for multiple days in a row, after some intense rainfall events (Appendix A).

## 3.3. Observed Pothole Hydrology

In this section, the number of inundation days, or hydroperiod, during the growing season of 2014 will be discussed. This data was collected for potential model calibration or validation, and to collect more information about pothole hydrology. The features were constantly visited, in particular after rainfall events of different intensities and durations. Generally, the potholes accumulated water after intense rainfall events. However, during wet conditions, water ponded with less intense precipitation, as discussed in previous papers (Roth and Capel 2012; Sloan 1972).

In the observed data collected for this project, there were 18 and 13 days of inundation for Walnut and Worrell potholes respectively, occurring at different growth stages of the plants within the pothole. For instance, some of the main events observed happened in early May, and late June. Figure 3-4 show the water extent in early May.

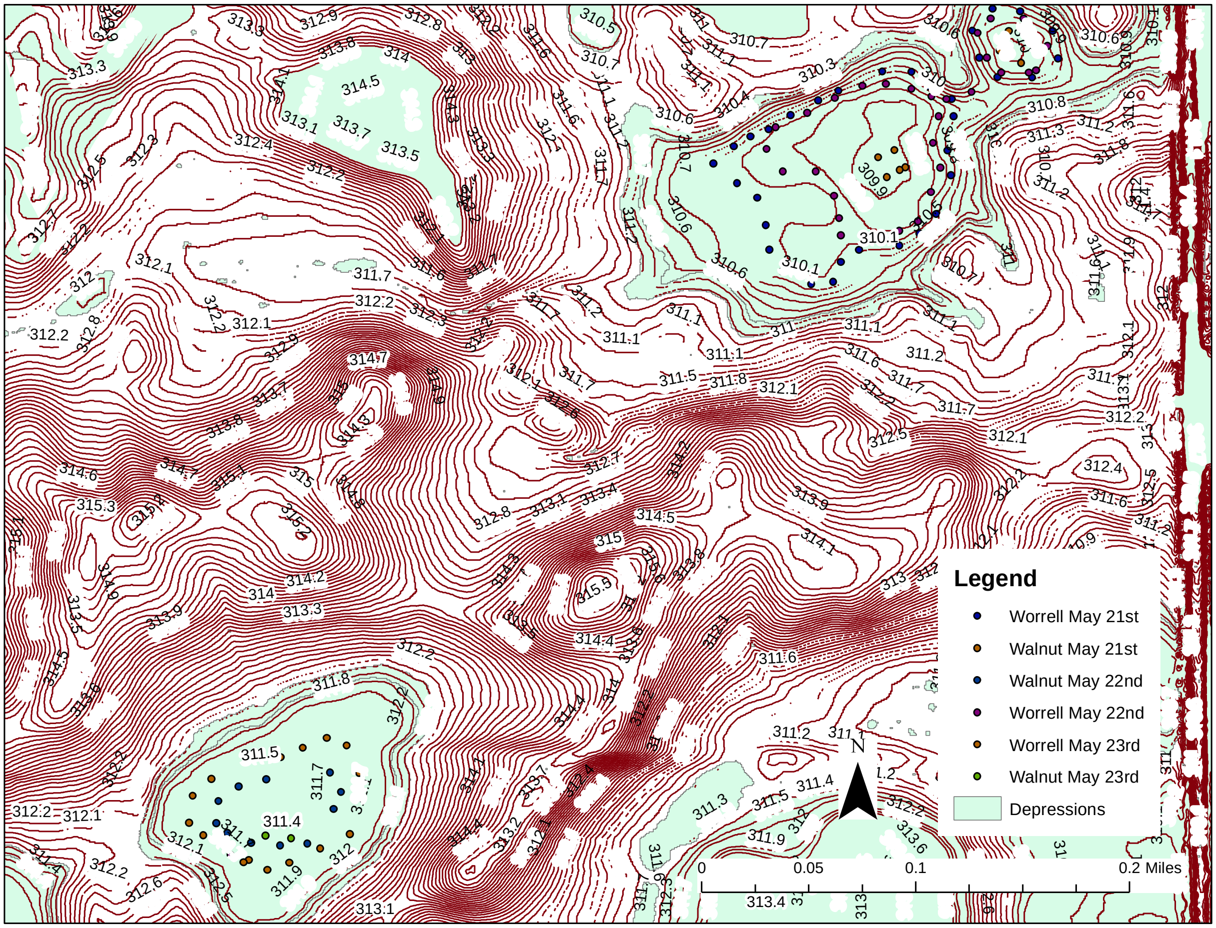



Figure 3-4: Example of consecutive inundations in the potholes collected in the days 21-23 May 2014.

As illustrated in Figure 3-4, in some of the events water would stay ponded for multiple days. For instance, in the Walnut pothole, from the 18 days in which water was observed in the feature, 9 represented the first visit, 4 the second, and the rest for the third, fourth and fifth visit. It indicates that the potholes held water for consecutive days, but for most times it would infiltrate/ evaporate within one day.

For the Worrell pothole, from the 18 days in which water was observed in the feature, 6 represented the first visit, 3 the second, and the rest for the third, fourth and fifth visit. There was one event that water lasted for more than 3 days in both potholes, following the July 30$^{th}$ rainfall of about 40 mm. After this event, water stayed in the same elevation for two days, which indicates that the tile lines were overloaded, and the drainage system was not effective. As discussed previously, the Worrell pothole is expected to drain faster due the presence of the surface inlet, which explains the fewer days of ponding in this feature despite of a higher drainage area. Regarding water depth variation, water elevation reached 0.4 and 0.6 meters in Walnut and Worrell pothole, respectively. Table 3-1 gives the number of days of ponding, as well as the maximum depth and volume stored in the growing season of 2014.

Table 3-1: Summary of data collected in 2014.

| | **Inundated days** | **Maximum elevation in m (in)** |
|---|---|---|
| **Walnut** | 18 | 0.6 (23.6) |
| **Worrell** | 13 | 0.4 (15.7) |

In respect of the observation collected in 2014, it is possible to say that the potholes inundated enough time to compromise plant development in the area (according with site visits it was possible to confirm that no crops were harvested in the area). Inundation usually starts in March and can occur in December, depending of the year. However, the illustration of the collected data is available from May to July. Later in the year, it was not possible to collect points with the GPS due the development of the plants.

As discussed, points were collected with a GPS by walking in the surroundings of the potholes. Based in the elevation of the points in relation to the topography, the depth of water was visually estimated according the location of the points, and the volume computed. The following section gives explanation of the procedures involved in the computation of elevation depth, surface water, and volume accumulated in the potholes.

Information about the data collected in 2010 and 2011 will be discussed during the calibration of the model, in Chapter 8.

## 3.4. DEM-based assessment of maximum storage volume:

Pothole connectivity is observed when potholes exceed their maximum storage capacity and overflow (Marton, Fennessy, and Craft 2014). To address the maximum storage capacity of potholes before overflow, a high-resolution Digital Elevation Model (DEM) was assessed. This information gives insights about the volume potholes can retain, which is not part of the volume loaded into the outlet or part of the peak flow rate. Retained water can be released at lower rates (Drake 2014), or infiltrated. Ideally, maximum storage capacity should be assessed frequently because of DEM changes caused by sedimentation (Euliss and Mushet 1996; R. A. Gleason et al. 2007; R. A. Gleason and Euliss 1998).

The topography of the area is relatively flat, with mean slopes of 2.1 and 2.2% for the Walnut and Worrell drainage areas respectively. The elevation varied from 309.8 to 315.8 for both microwatersheds, indicating a 6 meters variation. More detail about the generation of the DEM and the microwatersheds by the model is discussed in Chapters 4 and 6 respectively.

## 3.5. Summary

In this section, the site in which the potholes are located, and the procedures used for 2014 data collection were described. Three important components of the assessment were discussed, site description, data collection, and DEM assessment, used to estimate pothole maximum volume storage capacity, and discussed in further chapters. This information is useful for a better understanding of the site, and will be used for the calibration of the model.

# CHAPTER 4: MODELING WITH ANNAGNPS

## 4.1. Objective

The objective of this section is to describe and to discuss some relevant components of the AnnAGNPS hydrological model, as well as some particular considerations for the study of prairie potholes. The first step of the hydrological assessment, which consists of the DEM analysis by AnnAGNPS and generation of hydrological units and reaches, consists of the most important output of this section. This created data will represent the input with the topography information in the modeling process. The description of the inputs required are available here, however, accurate information will be described in further sections (Chapter 5).

## 4.2. AnnAGNPS Model

The model selected for this project was Annualized Agriculture Non-Point Source (AnnAGNPS). This watershed evaluation tool was developed through a collaboration between the USDA Agriculture Research Service (ARS), and the USDA Natural Resources Conservation Services (NRCS) (Yuan et al., 2003). AnnAGNPS is a watershed scale, continuous simulation, daily time step model, and was selected for this project because its applicability to small scale watersheds, and for being able to produce satisfactory results for the Midwest United States (Yuan et al. 2011).

In this project, the model is used to estimate the hydrology associated with the potholes. Some of the generated information include: pothole hydroperiod, water balance, depth variation, water volume storage, and connectivity analysis.

## 4.3. AnnAGNPS Assessment

The first step of the modeling process consists in the assessment of the DEM of the microwatersheds, and the generation of the hydrological units, also referred as cells. For this step, the model uses the Topographic ParameteriZation program (TOPAZ), which is run by an application called TOPAGNPS. Apart from the generation of the cells, this model will generate geographical files, useful for hydrological assessments. These include the study of runoff flow representation, flow accumulation, etc. These files are generated in the ".ascii" extension, which can be opened in ArcGIS. Nevertheless, AnnAGNPS has a GIS interface in which it is possible to open the files generated by TOPAZ, and to add information about soil, land use and weather of the study area. Figure 4-1 illustrates the AGNPS input graphical editor provided by the model. In this figure, it is possible to observe an example of the cells file generated by the model for Walnut and Worrell microwatersheds.

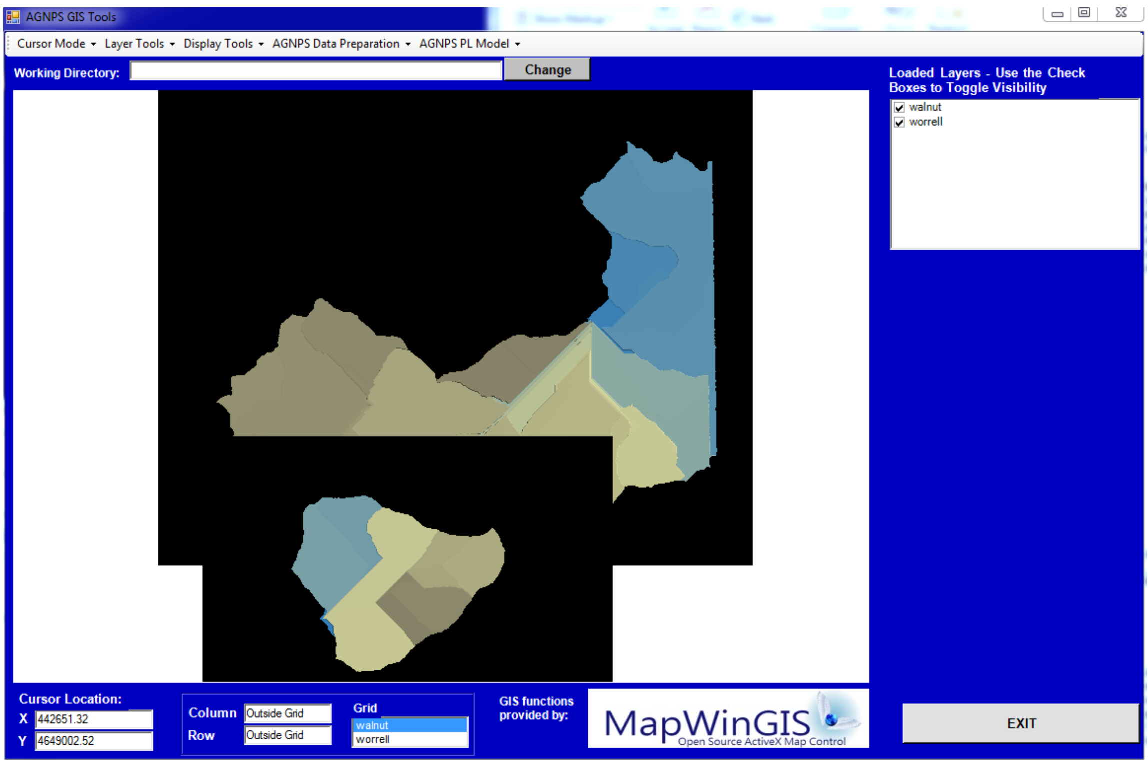



Figure 4-1: AGNPS GIS tool representation of the files generated in Walnut and Worrell watersheds, with TOPAZ, the program in AnnAGNPS responsible to process the DEM.

In figure 4-1 the DEMs overlap because the AGNPS GIS tool created the files based in the DEM uploaded into the model, therefore, all the files created will have the same extent as the DEM. Other files created include flow network of the entire DEM, and within the microwatersheds. Then, once the hydrological units are generated, it is possible to import soil and management layers, which the model will overlap with the geographical information of the cells, and update the inputs in an automated way into the folder describing the generated cells. More detain about the

To capture the detail of these microwatersheds, the model allows the user to enter the maximum AnnAGNPS cell area, which will be treated as a homogeneous unit by the model, and maximum reach length for uniform surface flow. These are denoted “Critical Source Area” (CSA) and “Minimum Source Channel Length” (MSCL). The division of the cells by the model happens according the DEM hydrological patterns suggested by AnnAGNPS, and the user enters CSA and MSCL values according the size of the watershed, and the level of spatial detail desired. The selection of these thresholds are important once all water load is produced by the cells, and is transported by the reaches.

Here, the CSA was 1 hectare (2.5 acres), or the maximum cell generated had 1 ha, and the MSCL was 10 meters (33 feet). Higher CSA and MSCL values would not generate cells/reaches, and smaller values would produce a high number of them, which would not add much in the characterization of the area, since the microwatersheds are within field boundaries, with little variability. In larger watersheds, cells can amount to several acres, and the reaches will often correspond to the rivers or continuously flowing channels. For this project, however, all the cells are within field boundaries and the reaches will indicate the preferential paths of surface water flow. The objective of the division of the drainage area into cells is to represent the runoff spatial variability, since different sections in the watershed will have different runoff patterns. For each cell, parameter values describing soil, land cover and weather are attributed according to input data to be described in further sections.

The model will generate different drainage areas depending on the selected outlet. Because the outlet of the pothole is not obvious, we used an iterative process to select the final outlet, having AnnAGNPS generate different drainage areas, and then visually assessing whether or not this was reasonable for our application. The criteria for outlet selection was microwatershed size and pothole location, since the objective was to create the minimum drainage area, in which all the pothole was included. Figure 4-2 illustrates the watersheds generated by TOPAZ. These were converted into a shapefile, to be opened in the ArcGIS software. In this figure, it is possible to observe the hydrological units associated with the microwatersheds of each pothole.

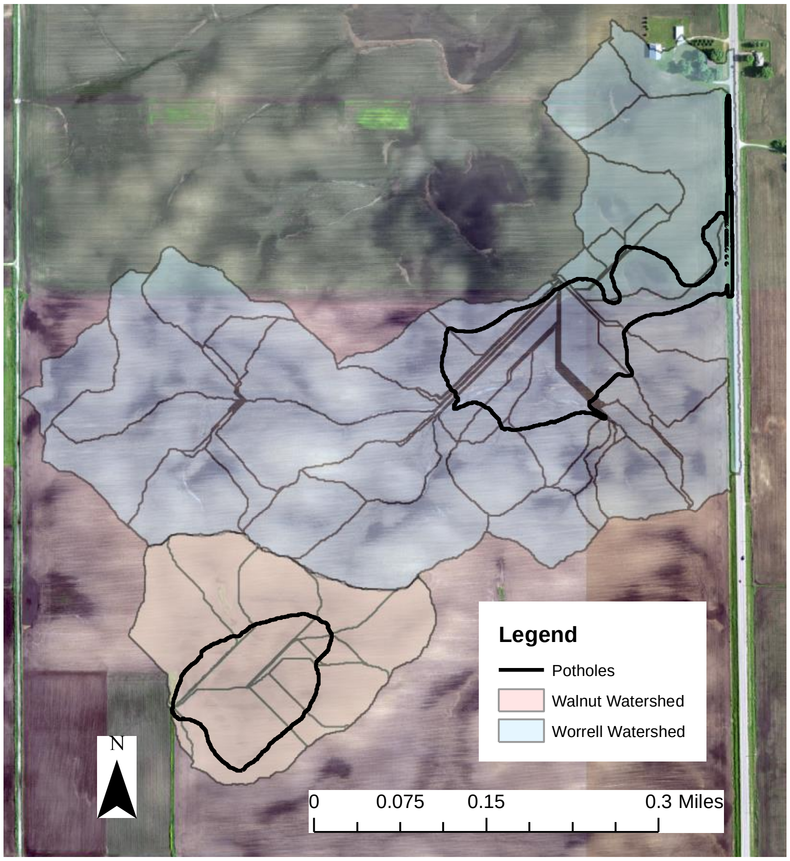



Figure 4-2: Microwatersheds generated by AnnAGNPS. Grey lines represent the cells within the microwatersheds.

Eleven and 49 cells were generated for Walnut and Worrell potholes respectively. As discussed, the drainage areas computed by AnnAGNPS for Walnut and Worrell potholes correspond to about to 9.5 and 40 hectares (24 and 100 acres) respectively. AnnAGNPS generated 6 and 22 reaches for Walnut and Worrell, respectively. The output generated consists of comma-separate-values (csv) files, one for the cells and one for the reaches. The csv files containing the cells generated, will have the attributes about the topography of each cell (i.e. area, slope, average elevation, etc), information about the reach in which the generated runoff will be loaded, and with no information about soil and management. These will be filled by the model in a further step, based in the information about soil and land cover. In relation reach csv files, these will mainly contain topography information, and will not be required to be updated by the user.

The cell and reach files will be responsible for accounting for the topography in the runoff estimation by AnnAGNPS. After this point, it is possible to start the characterization of other aspects of the microwatersheds. More information about the inputs is available in Chapter 5.

The model requires inputs such as runoff curve values, and management. Some input samples are available when the model is downloaded and can be used in case the user does not have access to data of his/hers area of study. Figure 4-3 presents the necessary inputs for AnnAGNPS.

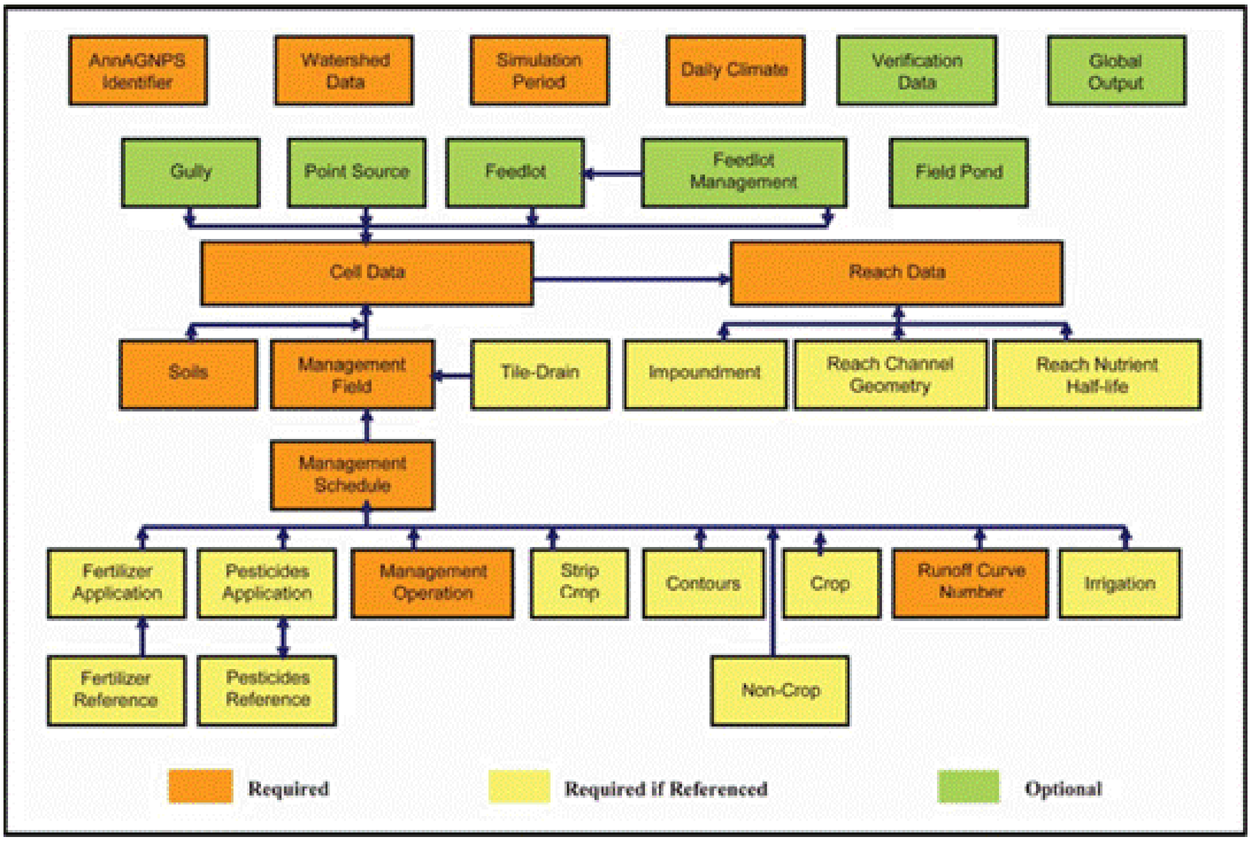



Figure 4-3: AnnAGNPS input data (Yuan et al. 2011).

Figure 4-3 illustrates some options of inputs that are required in the simulation, and some that can be simulated by AnnAGNPS if observed in the site, such as feedlots and gullies. For this project, the only optional featured discussed is the wetland. More information about AnnAGNPS inputs and computations is available in Bingner, 2011.

## 4.4. Hydrological Components

Runoff generation happens through an algorithm based in the SCS curve number model ("Urban Hydrology for Small Watersheds TR-55" 1986), with an extension in relation to its original application, once it is computed in a continuous basis, and accounts for a variable soil moisture content in AnnAGNPS simulation. The mathematics and quantitative effects can vary somehow, but the estimation of water retention after runoff initiation (S), and runoff (Q) are internally computed by the model. AnnAGNPS computes runoff, percolation, evapotranspiration, lateral subsurface flow, and tile drainage flow separately, then updates daily soil moisture estimates using a water balance approach, as given in equation 4-1.

$$SM_{t+1} = SM_t + \frac{WI_t - Q_t - PERC_t - ET_t - Q_{lat} - Q_{tile}}{Z} \qquad \text{Equation 4-1}$$

where $SM_{t+1}$ = moisture content for each soil layer at end of time period (fraction); $WI_t$ = water input, consisting of precipitation or snowmelt plus irrigation water (mm); $Q_t$ = surface runoff (mm); $PERC_t$ = percolation of water out of each soil layer (mm); $ET_t$ = potential evapotranspiration (mm); $Q_{lat}$ = subsurface lateral flow (mm); $Q_{tile}$ = tile drainage flow (mm); Z = thickness for soil layer (mm); and $SM_t$ = moisture content for each soil layer at the beginning of time period (fraction).

Surface runoff consists of the amount of soil moisture leaving the soil in a given day, and remaining soil moisture can be lost by ET or be added to soil moisture for the next day computation. Soil moisture of a given day determines the effect of curve number (CN) values in the area; therefore, it is directly related with surface and subsurface runoff patterns. The CN is adjusted every day, based in soil fraction of saturation. The CN for average conditions ($CN_2$) is defined by the user, and, based in soil moisture conditions, the one for dry ($CN_1$) and wet ($CN_3$) conditions is computed internally by the model according soil moisture values of a given day. For each moisture condition, the model will compute different retention values. CN values will vary in two different situations, when i) a new value is given in the management schedule, and ii) newly planted vegetation is in its active growth phase.

The main difference is that adaptations were included to account for the fraction of saturation of the soil top two layers, as well as their wilting point. Then, the variation from a higher water retention ($S_1$) varies smoothly to lower retention values ($S_3$). The retention is considered the minimum when the soil is frozen ($S_3$). After the estimation of S for a given day, the runoff will be computed according equation 4-2.

$$Q = \frac{(WI - 0.2S)^2}{\mathrm{WI} + 0.8S} \qquad \text{Equation 4-2}$$

where Q = runoff (mm); S = water retention in the soil (mm); and WI = water input to soil (mm). Case WI < 0.2S, runoff will be considered zero. Runoff volume generated by the cell is then computed by multiplying the computed Q to the cell area.

Subsurface flow consists of the lateral subsurface flow and tile drain flow. It will only occur when either an impervious layer, or a subsurface tile drainage system is indicated by the user. AnnAGNPS assumes that surface runoff and subsurface flow produced by the cells will merge in prior to be loaded into the features. It consist of a limitation because it was not possible to simulate scenarios in which the cells are artificially drained, once the load in the outlet would be higher, since annAGNPS assumes that the water load produced by the watershed will be drained to the outlet of the watersheds. It can be true for larger watersheds, but is not consistent with the assessment of pothole microwatersheds, in which drained water flows to the drainage districs, outside the extent of the microwatersheds.

Reference evapotranspiration ($ET_O$) is computed on a daily basis with the Penman-Monteith equation, and is then adjusted for crop evapotranspiration (ET) through a crop coefficient procedure. More information about equations used in the computation ET parameters can be found in the model documentation included in the model download, and in FAO (1998).

## 4.5. Scenarios

In this thesis, two scenarios were assessed: the current condition, corresponding to the actual conditions observed in the field, and a conserved scenario investigating the potential effects of the potholes if tiles were removed, and crops replaced by grass vegetation. Calibration and model efficiency are discussed for the current condition, since there is observed data for comparison. The calibration parameters (discussed in Chapter 6) were retained in the conserved scenario. In this field, the known subsurface drainage is within or near the potholes, therefore in the conserved condition, there is no drainage system in the field.

Ideally, other scenarios including drainage in the microwatersheds were proposed, however, since the model considers drained water produced by the cells to merge with surface runoff, it does not capture the real impact of microwatershed drainage, a reduction in the load into the potholes.

## 4.6. Summary

In this section, the aim was to describe relevant aspects of the modeling process with AnnAGNPS, list some of the assumptions used in the first phase of the simulation, and to briefly describe the scenarios proposed in the pothole modeling process. Here, the microwatershed topographies were assessed to generate cells and reaches of each microwatershed. Until this point, the only input analyzed was the DEM.

Runoff volume is generated by the cells, and its flow path on the watershed is determined by the location of the reaches. It is estimated by the model based in the water content of the soil, and the CN method is used to for the estimation of runoff of areas of different runoff generation patterns. Two scenarios were investigated: current, for which the model was calibrated, and conserved, to estimate the impact of landscape conversion from crop land to wetland vegetation in pothole hydrology.

# CHAPTER 5: DEVELOPMENT OF MODEL PARAMETERS FOR THIS STUDY

## 5.1. Objectives

The objective of this section is to provide an overview of the inputs and assumptions used in the watershed characterization to investigate pothole hydrology. Some relevant calculations computed by the model in the pothole assessment will be discussed, for a better understanding of the results generated by AnnAGNPS, and discussed in Chapter 7. Detailed information about the model procedures can be found in the Technical Documentation file, downloaded with the program.

## 5.2. Climate

Complete daily climate data is necessary to perform the simulations, and the quality of this data will determine the reliability of model results, since it is the main driven force of the hydrological cycle. The detailed weather data was obtained from the USDA ARS for most years, from station IAWC702, located within 5 kilometers from the site, as illustrated in Figure 5-1.

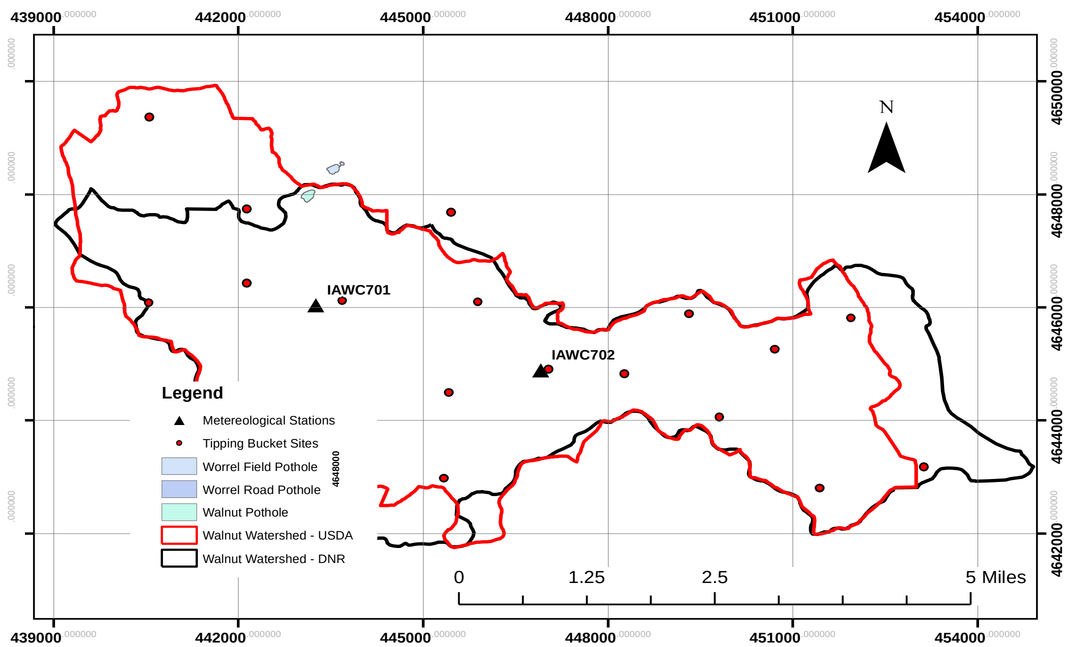



Figure 5-1: Location of weather stations surrounding the site.

Though station IAWC701 is closer to the field site, as seen in figure 5-1, this station logs rainfall and temperature only, whereas IAWC702 includes the full set of meteorological data required for the model. There was 25 years with complete data, from 1992 to 2014 (USDA 2014). Table 5-1 illustrates the weather data required by the model, and its respective unit.

Table 5-1: AnnAGNPS weather data required for simulation.

| **Parameter** | **Unit** |
|---|---|
| **Maximum Temperature** | Celsius |
| **Minimum Temperature** | Celsius |
| **Precipitation** | mm |
| **Dew Point (Td)** | Celsius |
| **Sky Cover** | % |
| **Wind Velocity** | m/s |
| **Wind Direction** | degrees |
| **Solar Radiation at ground level** | J/sec/$m^2$ |
| **Storm Type** | TR-55 - vary according location |

For 2010, the precipitation data used was collected at the field site through another project on which Amy Kaleita was a co-PI (Logsdon 2015). Overall, the precipitation records between the stations on site and 702 were similar, but usually with a lag in the beginning of the rainfall, probably because of the distance between stations. The 2010 weather was useful in the comparison of observed and simulated water-balance. No rainfall data in the field station was available for 2011. Figure 5-2 illustrates the precipitation variation for the assessed years.

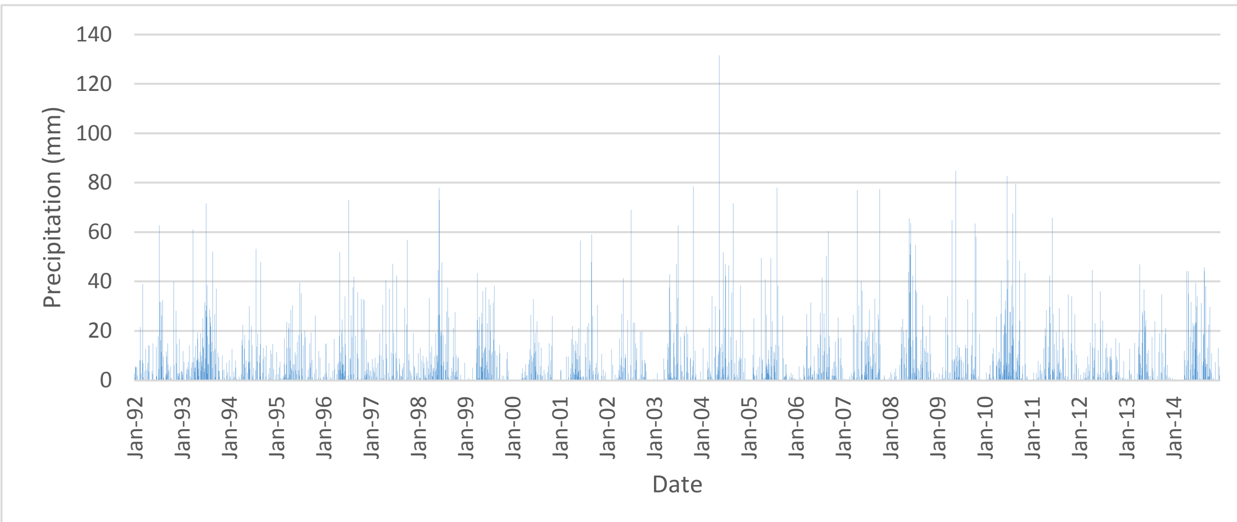



Figure 5-2: Precipitation variation data from 1992 to 2004.

None of the available weather data included sky cover, required by the model. Sky cover information was therefore generated by a weather generator included in the AnnAGNPS (agGEM). This impacts the ET computed by the model, and is one source of potential errors in the results.

## 5.3. Soils

As discussed in Chapter 4, soil information was downloaded from the SSURGO website, and updated into AnnAGNPS GIS interface for determination soil variability in the microwatersheds. Soil properties influence the water volume stored in the landscape, and therefore, the runoff generation. Here, we discuss the hydrologic soil group, and the percentage of each soil observed in the microwatersheds, in relation to the soil distribution according AnnAGNPS. Hydrologic soil group is related with the runoff potential of the soils, which is divided into four groups, A, B, C, and D. Soils classified as "A" will tend to have a high infiltration rate, and low runoff potential, while “D” soils will likely have a very slow infiltration rate, with a potential high of runoff generation. Table 5-1 illustrates the soils observed in Walnut microwatersheds, their hydrologic soil group, and the comparison between the actual watershed soil characterization in relation to the interpolation computed by the model.

Table 5-2: Walnut microwatershed soils current condition. Source: Web Soil Survey website (http://websoilsurvey.sc.egov.usda.gov/).

| Map Symbol | Soil | Hydrologic Soil Group | AnnAGNPS Percentage Area (%) | Actual Percent Area (%) |
|---|---|---|---|---|
| **6** | Okoboji silt clay loam, 0 to 1 percent slopes | B | 4.5 | 14.6 |
| **55** | Nicollet loam, 1 to 3 percent slopes | C | 39.7 | 25.7 |
| **95** | Harps loam, 1 to 3 percent slopes | B | 2.8 | 7.3 |
| **138C2** | Clariom loam, 5 to 9 percent slopes, moderately eroded | B | 10.5 | 7.4 |
| **507** | Canisteo clay loam, 0 to 2 percent slopes | C | 27.9 | 27.2 |
| **L138B** | Clarion loam, Bemis moraine, 2 to 6 percent slopes | B | 14.7 | 17.7 |

In comparison to the actual soil distribution in the watershed, there are more areas classified as Nicollet, and less areas classified as Okoboji. It might cause a higher volume generation by the model, since a higher fraction of the area will be classified with “C” hydrological group instead of “B”, which has a higher runoff generation potential. Soils of Worrell microwatersheds are available in table 5-3.

Table 5-3: Worrell microwatersheds soils current condition. Source: Web Soil Survey website (http://websoilsurvey.sc.egov.usda.gov/).

| Map Symbol | Soil | Hydrologic Soil Group | AnnAGNPS Percentage Area (%) | Observed Percent Area (%) |
|---|---|---|---|---|
| **6** | Okoboji silt clay loam, 0 to 1 percent slopes | B | 5.6 | 5.2 |
| **55** | Nicollet loam, 1 to 3 percent slopes | C | 27.1 | 23.8 |
| **95** | Harps loam, 1 to 3 percent slopes | B | 6.2 | 6.6 |
| **107** | Webster clay loam, 0 to 2 percent slopes | B | 3.2 | 6.3 |
| **138C2** | Clariom loam, 5 to 9 percent slopes, moderately eroded | B | 19.9 | 11.2 |
| **507** | Canisteo clay loam, 0 to 2 percent slopes | C | 14.8 | 22.1 |
| **L138B** | Clarion loam, Bemis moraine, 2 to 6 percent slopes | B | 23.2 | 24.9 |

The main differences between observed and simulated in Worrell pothole is the Clariom soil, in which the model practically doubles its size; and in Canisteo, that is missrepresented. It indicates that the model will consider more areas classified as “B” hydrological soil group than the reality, therefore, the microwatershed simulation results might indicate the generation of less runoff in relation to the reality. The actual percentage of each soil in each of the microwatersheds was determined by uploading the shapefiles of the microwatersheds, in the Web Soil Survey website. Figure 5-3 illustrates the soil characterization of Walnut and Worrell microwatersheds by the model.

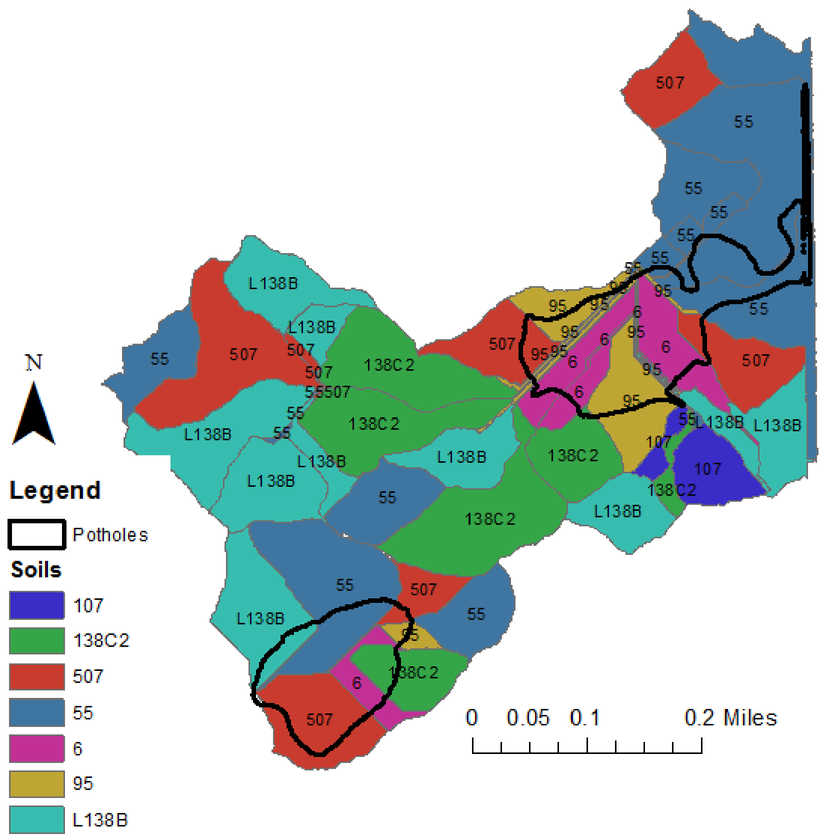



Figure 5-3: Soil characterization by AnnAGNPS. In the figure it is possible to observe the soil attributed to each in the microwatersheds.

Overall, AnnAGNPS was able to characterize the soils of microwatersheds at this scale, which can be seen by similar percentages of soils observed in the basin, and the soils determined by AnnAGNPS. Nevertheless, potential misrepresentations can be addressed in the calibration process, to improve basin characterizations.

## 5.4. Management

This field site is owned and operated by Iowa State University, so field boundaries and crop rotations are known. Detailed management schedule records were not promptly available, so we consulted the State Agronomist of Iowa, who shared the usual schedule of Story County, which we then assumed for this project. For the study area, while the entire area is under a corn-soybeans management, there are two portions of the field; when one is in corn the other is in soybeans (the divide can be seen in figure 4-2).

Each operation listed in the schedule must be detailed in an additional management file. In this file, the potential effects in the soil caused by each operation was listed. Ten types of effects can be selected, some examples are disturbance of the soil, and removal of residue from the field. AnnAGNPS has a default file available regarding the impacts of the operations, which can be changed by the user according observed conditions. In this project, we used the default operations file. This information is not listed in this thesis, but can be found in the AnnAGNPS documentation. Table 5-4 gives the land management schedule we assumed for this project. The year listed in the date refers to the year within the rotation, spanning a total period of three years.

Table 5-4: Management schedule used in the watershed characterization.

| Year | Date (m/d/y) | Operation | Vegetation | Yield (bushels/acre) |
|---|---|---|---|---|
| **1** | Nov. 1 | Fertilizer application | | |
| **2** | May 1 | Cultivator | | |
| **2** | May 2 | Sprayer pre-emergence | | |
| **2** | May 3 | Planter | Corn, grain | 125 |
| **2** | Jun. 7 | Sprayer; post emergence | | |
| **2** | Oct. 20 | Harvest | | |
| **2** | Nov. 1 | Chisel plow; disk | | |
| **3** | Apr. 28 | Disk; tandem light | | |
| **3** | May 1 | Cultivator | | |
| **3** | May 10 | Sprayer; pre-emergence | | |
| **3** | May 11 | Planter; double disk | Soybeans | 25 |
| **3** | Jun. 7 | Sprayer; post emergence | | |
| **3** | Aug. 1 | Sprayer; insecticide | | |
| **3** | Oct. 10 | Harvest | | |

Table 5-2 begins with a corn year. Some sections of the field began with a soybean year, for which the schedule is adjusted accordingly. Because the model considers the cells to have homogeneous properties, management and soils of the microwatersheds can be missrepresented. For instance, a cell with 20% corn, 20% soybeans, and 40% retire will be considered 100% retire by AnnAGNPS, since it is the predominant condition. Therefore, in project, we tried to attribute in AnnAGNPS similar areas for each management, in relation to the observed condition. Table 5-5 illustrates the percentage attributed to each different schedules in the study area according with AnnAGNPS, and to the observed conditions.

Table 5-5: Area corresponding to different managements in the field for the current condition.

| Management | Area in $m^2$ (acres) | AnnAGNPS Percentage Area (%) | Observed Percentage Area (%) |
|---|---|---|---|
| **CSCS** | 64409 (15.9) | 12.9 | 17.13 |
| **SCSC** | 433213 (107.0) | 87.1 | 80.46 |

In the simulation of the current conditions, the cell management classificarion was simpler, which was not the same in the assessment of the conserved scenario. For the conserved conditions, the potholes are considered to "retire", in other words, to be taken out of production. In this scenario, no agricultural crop is planted within the extent of the potholes, and no field operations take place in that area. Instead, potholes are considered to have a weedy wetland vegetation, and subsurface tiles are considered to be disconnected. The area of the potholes are 3 and 5 hectares, respectively for Walnut and Worrell potholes. In AnnAGNPS, we attempted to consider the pothole area as conserve. Table 5-6 illustrates the percentage of the microwatershed area attributed to each management of Walnut and Worrell for the conserved condition.

Table 5-6: Walnut and Worrell Management distribution for the conserved condition.

| Pothole | Management | Area (acres) | AnnAGNPS Percentage Area (%) |
|---|---|---|---|
| **Walnut** | Retire | 33189 (8.2) | 34.6 |
| | SCSC | 62866 (15.5) | 65.4 |
| | Total | 96055 (23.7) | 100 |
| **Worrell** | CSCS | 64409 (15.9) | 16.1 |
| | Retire | 52957 (13.1) | 13.2 |
| | SCSC | 283773 (70.1) | 70.7 |
| | Total | 401139 (99.1) | 100 |

In table 5-5 the observed percentage area is not represented, because the conserved condition consists of a proposed scenario for the estimation of pothole conservation. It was not possible to retire the exact area of the potholes because the cells have fixed format, which not allowed taking in consideration the shape and size of the potholes. Figure 5-4 illustrates the spatial distribution of the management in the field in the current and conserved management condition.

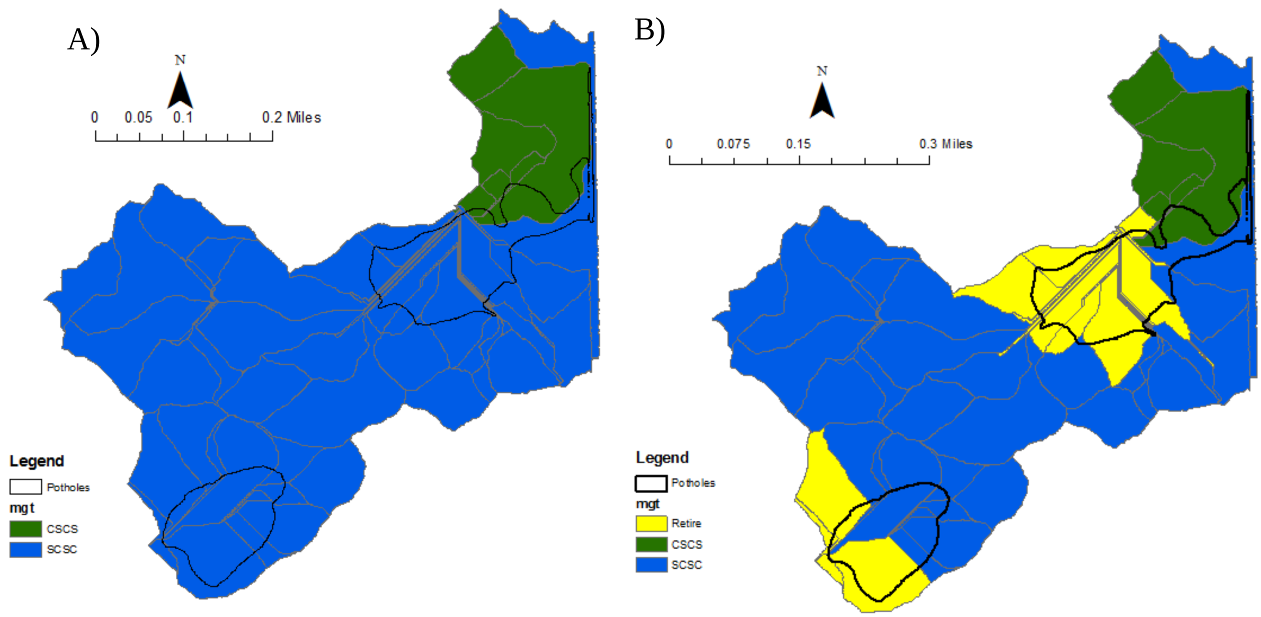



Figure 5-4: Spatial distribution of the management in A) current and B) conserved conditions for both potholes.

In figure 5-4B, it is possible to observe that in the Walnut conserved scenario, the retired cells are distant from the actual location of the pothole. Because of the shape of the cells of this microwatershed, it was not possible to classify cells in the middle as retire, without losing a consistent proportion of the pothole area and the retired cells. Unlike in Worrell microwatershed, there are fewer cells, and these commonly extent from the boundary of the watershed to its center. Therefore, it was assumed that the converted cells would be located toward the outlet, where soil moisture is likely higher than in upper areas.

The assumption of the retirement of the potholes is more realistic, once the natural vegetation would likely need several years to re-stablish in the area (Brown and Bedford 1997). For instance, in study of pothole restoration, it was observed a low colonization from the native species in comparison with invasive perennials. In this study, the main challenges of prairie vegetation recovery was isolation from other wetlands, infrequent flooding, and invasive species (Aronson et al. 2008). As observed in site visits in October of 2014, agricultural crop did not survive the flood frequencies, and the area was invaded by invasive plants. Here, a wetland vegetation was simulated, but it is possible to simulate pothole hydrology with other types of grass.

Additionally to modification in the management, we changed the infiltration rate in the AmmAGNPS wetland feature, as well as the curve number for the pothole extent. These modifications aim to account for the natural condition, without artificial subsurface tile drainage. More information about the wetland feature in current and conserved conditions are discussed in the following section of the thesis.

## 5.5. Wetland and Runoff Volume Generation

In this project, we considered the potholes to be wetlands, so the simulation in AnnAGNPS would be possible. The model, however, does not account for common features of farmed pothole wetlands, such as subsurface drainage systems nor their associated surface inlets. The wetland component operates at a point in a specific reach, intercepting upland, and shallow subsurface flow. A water balance will be computed according with wetland characteristics entered in the model. There is no relationship between the wetland and the cells in which the wetland is located. In other words, the cells will generate the same runoff with or without the wetland. Figure 5-5 illustrates the interpretation of the wetland features by the model, along with examples of how other types of features can be accounted for. Note that this figure describes the model structure generally, rather than specifically for our study site, which does not have gullies, feedlots, or point sources.

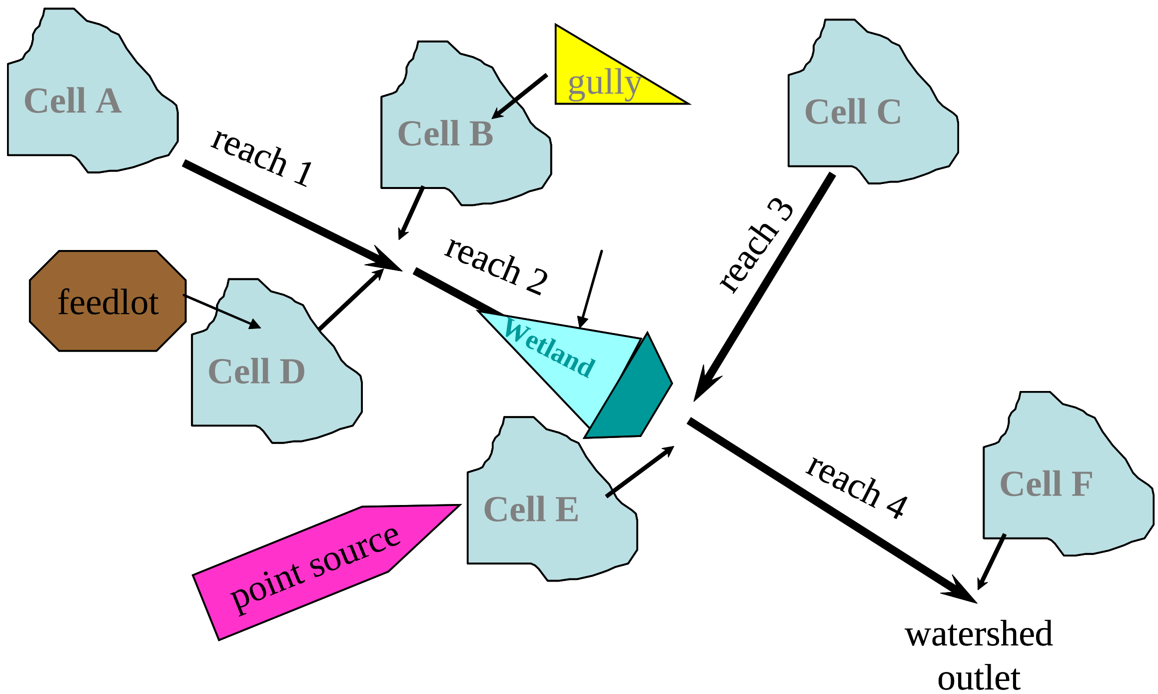



Figure 5-5: Wetland simulation in AnnAGNPS. Wetlands are located on AnnAGNPS reaches, and the effluent from wetland goes back to the same AnnAGNPS reach where the wetland is constructed. For the simulation of pothole microwatersheds, the wetlands are located in the reach before the outlet (Bingner, 2011).

AnnAGNPS considers the wetland to behave as a rectangular pool, assuming fixed surface area and weir (outlet) height, as well as constant infiltration throughout its extent, as shown in figure 5-6.

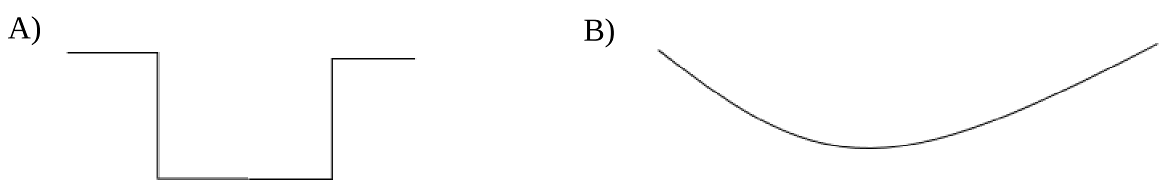



Figure 5-6: Example of wetland topography according to A) AnnAGNPS, and to B) the reality, in which the surface area of water varies according its elevation depth within the pothole.

As observed in figure 5-6, AnnAGNPS does not model a realistic representation of potholes, since their area and infiltration rates vary according the elevation depth. Furthermore, in the case of a surface inlet, the corresponding outlet height is non-constant. AnnAGNPS uses a mass balance approach to simulate both hydrologic and water quality process. The wetland water balance is presented in Equation 5-1.

$$V_i = V_{(i-1)} + Q_{inflow} - Q_{outflow} + P - ET - I \qquad \text{Equation 5-1}$$

where $V_i$ = volume of the water per unit area of wetland at the end of the day, [mm]; $V_{(i-1)}$ = volume of the water per unit area of wetland at the beginning of the day, [mm]; $Q_{inflow}$ = volume of the water generated by the cells as runoff flow and added to the wetland during the day per unit area of wetland [mm],; $Q_{outflow}$ = volume of the water released from the wetland per unit area of wetland, case its maximum storage capacity is exceeded [mm]; P = precipitation, from climate data information a user supplied, [mm]; ET = daily evaporation or evapotranspiration, calculated by the model based on the climate data and vegetation a user supplied, [mm]; and I = daily infiltration, by the model based on the soil properties a user. [mm/day].

Water depth reaching the wetland after rainfall events is a function of the upland area, supplied in the cells file. There are some precipitation events for which no water will be accumulated in the depression. First, because ET and infiltration rate will be subtracted from the water depth loaded into the features, and there will be no water in the wetland by the end of the day; and second because some events are not intense or long enough to produce runoff. It is consistent with the reality, since just some of the rainfall events would generate surface water to be held in the potholes. The inflow reaching the wetland can be computed as the equation 5-2.

$$Q_{inflow} = \frac{1000 * Q_{volume\_inflow}}{A_{wetland}} \qquad \text{Equation 5-2}$$

where: $Q_{inflow}$ = depth of the water added to the wetland during the day per unit area of wetland, [mm]; $Q_{volume\_inflow}$ = total depth of the water added to the wetland, [$m^3$]; and $A_{wetland}$ = wetland surface area, [$m^2$].

Weir properties simulate the natural outlet of the features. In the potholes, the outlet is large and shallow because of the subtle terrain in which these are located. The calculations used in the computation of the water behavior in the wetland and its relation with weir properties are listed in Equations 5-2 and 5-4.

$$Q_{outflow} = B_c \text{ x } L \text{ x } H^{B_e}$$ Equation 5-3

where $B_c$ = Weir coefficient, determined by user; L = Width of opening (m); H = Head (m); and $B_e$ = Weir exponent, determined by user.

$$H = \frac{V}{1000} - H_{weir}$$ Equation 5-4

where H = Hydraulic head on a given day (m); V = Volume of the water per unit area of the wetland on a given day (m); and $H_{weir}$ = Height of weir (m).

We first attempted to account for the surface inlet in the Worrell pothole by setting an appropriate elevation for the weir that the model assumes is the wetland outlet. However, by assuming that the pothole outlet was the inlet, the maximum depth water would reach was the inlet's height, which is not representative of the observed water depth variation, since water would reach higher depths then the height of the surface inlet, which corresponds to about 30 cm. When the surface inlet was considered the outlet of Worrel pothole, the maximum water-depth height would be the height of the inlet, which is about 30 cm. For this reason, the inlet was accounted mainly through the calibration of infiltration rate in this pothole. There was no surface inlet in Walnut, however, the existence of artificial tile drainage was accounted by the infiltration rate.

Ideally, the "weir" of Worrell-field pothole in the model should operate as the surface inlet, since part of the water that reaches the Worrell wetland will flow through the inlet before reaching the actual outlet of the microwatershed. However, not only is the model incapable of having a variable-height weir outlet, but also, the surface inlet is not capable of draining all water above it in reality, and water reaches high depths into the feature. Thus as mentioned earlier, the surface inlet component will instead be accounted as infiltration. That is, we set an infiltration rate for the wetland that incorporates both the natural and subsurface drainage, and the surface flow into the inlet to the subsurface drainage system. On the other hand, for the conserved condition, only natural infiltration of the soils is considered, assumed to be12.5 mm/day, which corresponds to the default infiltration rate in the model for wetland systems, in AnnAGNPS 5.42 version. On the other hand, in the recently new version, when no infiltration rate is indicated by the user, the default rate will be considered the mean infiltration of the soils in the watershed. This scenario will not be discussed in this thesis.

As discussed, the water balance computed by the model does not account for subsurface tile drainage within the pothole. Thus, we have the model compute it as infiltration. All of the potholes at this site, and indeed many farmed potholes in the Des Moines Lobe, have subsurface drainage underneath or very nearby. For this reason, in the assessment of current conditions, the infiltration will be considered high. Water balance of potholes under current and conserved scenarios will be simulated.

The outflow consist of the water leaving the wetland though a weir, going to the downstream reaches. The user specifies the properties of the weir, such as height in relation to the bottom of the wetland and width. Water flowing from the cells of the watershed will continue in the system through the reaches until it reaches the outlet, as observed in figure 5-5. Hence, we considered the potholes to be located in the reach that leads into the outlet because there will not be outflow most times, since water from their microwatersheds impounds in the potholes. Outflow will be simulated when the potholes exceed their storage capacity.

## 5.6. Summary

Two phases of the modeling were completed.  In the first phase, weather data from 2010 and 2011 were used to drive the model, conventional land management as described above were assumed, and model output of ponded water volume in each pothole was generated.  These output data were compared to the observed inundation data in order to confirm that the model is capable of generating satisfactorily realistic hydrology output.  More information about model validation is available in “Model Performance Assessment” section.

In the second phase of modeling, once the performance of the model was determined to be acceptable, a longer record of weather data (1992-2014) was used in the model to simulate the microwatershed and pothole hydrology under a larger range of conditions.  In this phase, we also simulated a conservation scenario in order to assess the potential hydrology effects of different pothole management.

Table 5-7 illustrates a summary of the data required by AnnAGNPS, as well as driving data type and our sources.

Table 5-7: AnnAGNPS data sources used for this project.

| Data layer | Type | Source |
|---|---|---|
| **Digital Elevation Model (DEM)** | Raster 1 x 1 m resolution | Iowa Lidar Mapping Project (http://www.geotree.uni.edu/lidar/) |
| **Soils** | Vector – polygon | SSURGO (USDA NRCS)<br>The soils were downloaded according AnnAGNPS documentation (Justice and Bingner 2015). |
| **Vegetation** | Raster 30 x 30 m resolution | CropScape (ARS project): http://nassgeodata.gmu.edu/CropScape/<br>aerial photo; USDA/ ARS personnel; State Agronomist advice |
| **Weather Station** | Vector – point | USDA ARS, USDA Stewards<br>http://www.nrrig.mwa.ars.usda.gov/stewards/stewards.html<br>Data from 702 station, in the Walnut watershed was used. This station is located 5 km from the site. |

# CHAPTER 6: TOPOGRAPHY ASSESSMENT

## 6.1. Objectives

In this section we illustrate the results of the DEM assessment necessary to estimate the volume and surface area related to each 0.1 m depth in elevation of Walnut and Worrell pothole. This assessment is important for a better understand of the pothole storage, which is then used for the pothole calibration with AnnAGNPS. Here we illustrate the relationship between depth-area-volume of Walnut and Worrell potholes through graphs and tables. First Walnut is described, then Worrell.

## 6.2. DEM Generation and Pothole Identification

To generate a high resolution DEM, Light Detection and Ranging (LiDAR) data with a 1-m horizontal resolution was downloaded, and processed in ArcGIS 10.1 (ESRI, 2014). The DEM available by Iowa GIS Library is a 3-m DEM, however, is not appropriate for the assessment of surface depressions such as potholes for its associate error, that can vary from 7 to 15 meters (Liu and Wang 2008). The conversion from LiDAR points to the DEM requires several operations; the final DEM used in this project was provided by ISU staff, Dr. Brian Gelder. The methodology he used can be found in Gelder (2015), the difference is that here a 1-m DEM was used, instead of a 3-m one (Gelder 2015).

The exact location and extent of the potholes was estimated by subtracting the raw DEM from the filled DEM. A filled DEM consists of a DEM without the depressions. The process of filling the DEM is generally done to eliminate sinks and imperfections in the data for use in hydrologic modeling, to guarantee the water will flow from the top of the watershed to the outlet. In most hydrological models, water flow is considered to stop every time a depression is observed in the flow path, and there are a limited number of computational tools for routing the flow from the depression. Consequently, the most common practice is to fill the depressions in the DEM and thus ignore them, which is a misrepresentation of the runoff generated by a watershed (Fennessy and Craft 2011). By running the filling procedure then subtracting the bare DEM from the filled one, the reminder is the depressions. The location representing the bottom of each pothole was then identified, and the area and volume of the pothole were computed in 10 centimeter elevation increments using ArcGIS, until the top of the depression.

For the computation of the ponded volume and surface area associated with each elevation within the potholes, the extension tools “Spatial Analyst”, and “3D Analyst” were used in ArcGIS. After this step a file with the information of the DEM of the potholes is created, and the area and volume of each feature is calculated based in the created file with the “Area and Volume Statistics” tool. This tool will calculate volume and area based in the perpendicular reference plane in relation to the DEM file, and estimation of the volume above or below the plane can be studied. The result consist of a text file containing the information of depth, area, volume, and location of the plane is generated by ArcGIS.

After the DEMs are generated, the extent of the potholes is determined by the subtraction of the filled DEM by the bare (generated with Lidar data) one. The filled DEM corresponds to the representation of the landscape without the depressions, such as potholes. Therefore, when we subtract the filled DEM by the bare one, the result will be the DEM of the depressions, or potholes. Then, we generate shapefiles that correspond to the extent of the DEM generated by the operation of subtraction. We suspect that shapefile generated to Walnut and Worrell is overestimated in relation to the actual extent of the feature. However, since there is not a documented approach to determine pothole area, this was the approach adopted for this project. With this assessment, Walnut and Worrell will have respectively approximately 5 and 3 ha in area.

The volume associate with each depth will be valuable for the estimation of the volume of water in the potholes from the data collected in 2014, and for the conversion of the observed data, collected in depth, to volume. A script in Python was used to compute the area and volume for each 10 centimeters above the bottom of the DEM of each of the potholes. More information is available in further sections of this chapter.

## 6.3. Walnut Pothole Depressional Storage

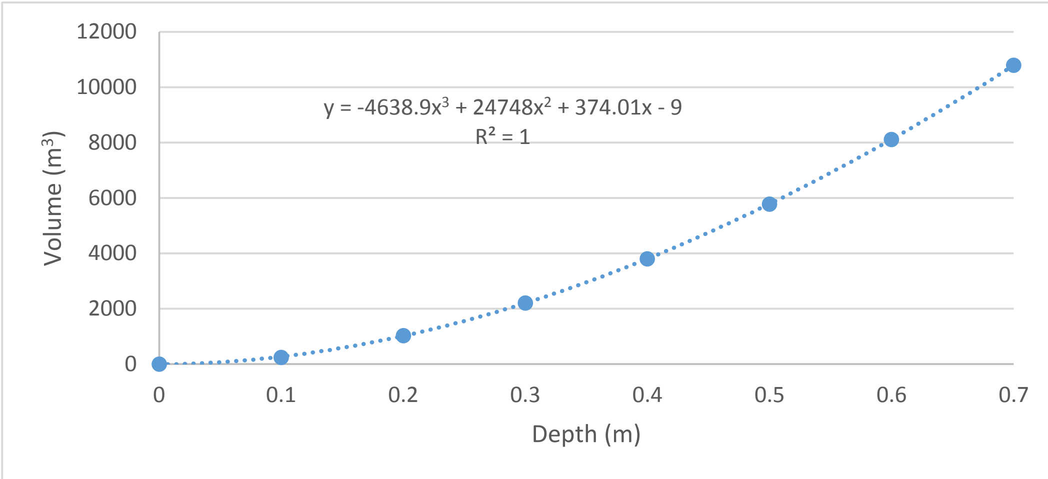
Walnut pothole is the single depression, located in the Walnut Creek side of the site. It is smaller in size in relation to the union of the depressions of Worrell pothole, and has 0.7 meters in depth, ranging from 311.4 to 312.2 meters in elevation. Table 6-1 shows the elevation-volume-surface area data for the Walnut pothole.

Table 6-1: Walnut volume variation.

| **Plane Height (m)** | **Pothole Depth (m)** | **Area ($m^2$)** | **Volume ($m^3$)** |
|---|---|---|---|
| **311.4** | 0 | 46 | 0 |
| **311.5** | 0.1 | 5458 | 250 |
| **311.6** | 0.2 | 9764 | 1027 |
| **311.7** | 0.3 | 14022 | 2210 |
| **311.8** | 0.4 | 17881 | 3810 |
| **311.9** | 0.5 | 21545 | 5782 |
| **312.0** | 0.6 | 25067 | 8112 |
| **312.1** | 0.7 | 28572 | 10794 |

The information available in figure 6-1 is illustrated graphically in figure 6-1. The equations generated from the relationship between volume and elevation will be used to convert observed depth data to volume, in order to allow volume storage calibration in the potholes.

A)




B)

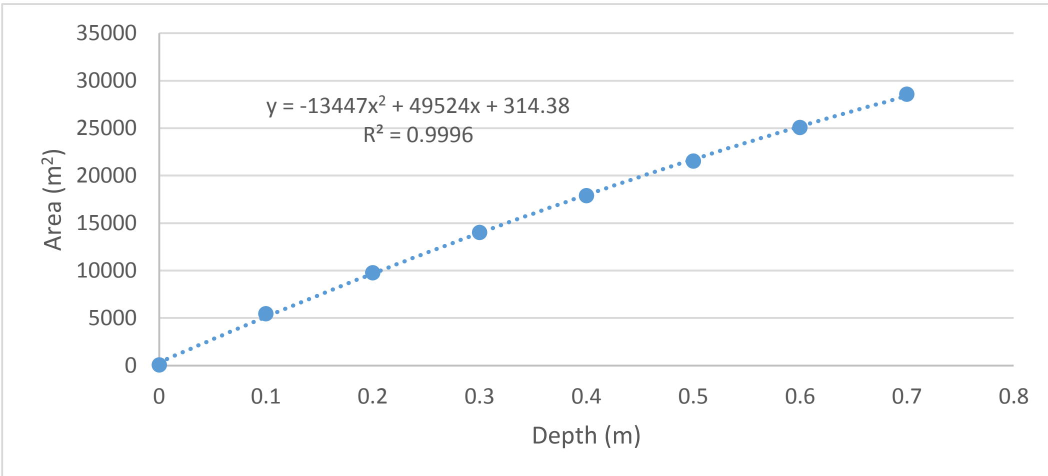



Figure 6-1: Graphical representation of A) volume storage and B) surface area of Walnut pothole as a function of the elevation depth.

## 6.4. Worrell Pothole Depressional Storage

Worrell pothole is composed by two depressions that frequently inundate concomitantly. For this reason, the volume associated with the pothole considering the union of both depression is estimated, as well as the volume of them individually. The assessment of the union of the depressions is important for the computation of the equation relating water depth and volume in the Worrell pothole. Table 6-2 illustrates the volume and area variation for different depths for the Worrell field, that corresponds to the larger depression within the Worrell pothole.

Table 6-2: Worrell Field volume variation.

| Plane Height (m) | Pothole Depth (m) | Area (m2) | Volume (m3) |
|---|---|---|---|
| **309.8** | 0 | 204 | 0 |
| **309.9** | 0.1 | 6482 | 386 |
| **310.0** | 0.2 | 11988 | 1282 |
| **310.1** | 0.3 | 18774 | 2840 |
| **310.2** | 0.4 | 22639 | 4913 |

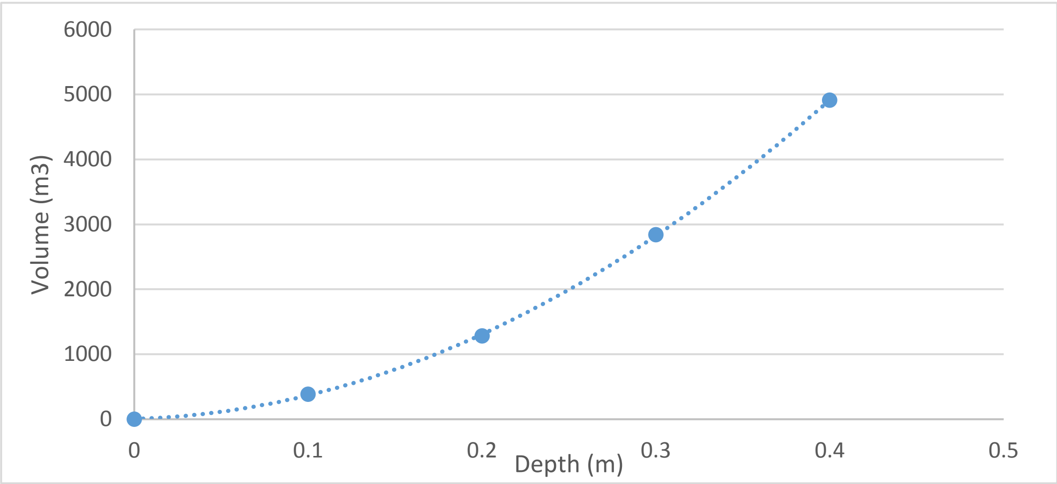
The illustration of the volume and area variation for different depths for the Worrell road pothole is presented in table 6-3.

Table 6-3: Worrell Road volume variation.

| Plane Height (m) | Pothole Depth (m) | Area (m2) | Volume (m3) |
|---|---|---|---|
| **309.9** | 0 | 0 | 0 |
| **310** | 0.1 | 1277 | 76 |
| **310.1** | 0.2 | 2115 | 245 |
| **310.2** | 0.3 | 2960 | 504 |

Figure 6-2 illustrates the volume storage in both depressions of Worrell pothole, field and road. Polynomial equation is not available because is not used for volume assessment.

A)




B)

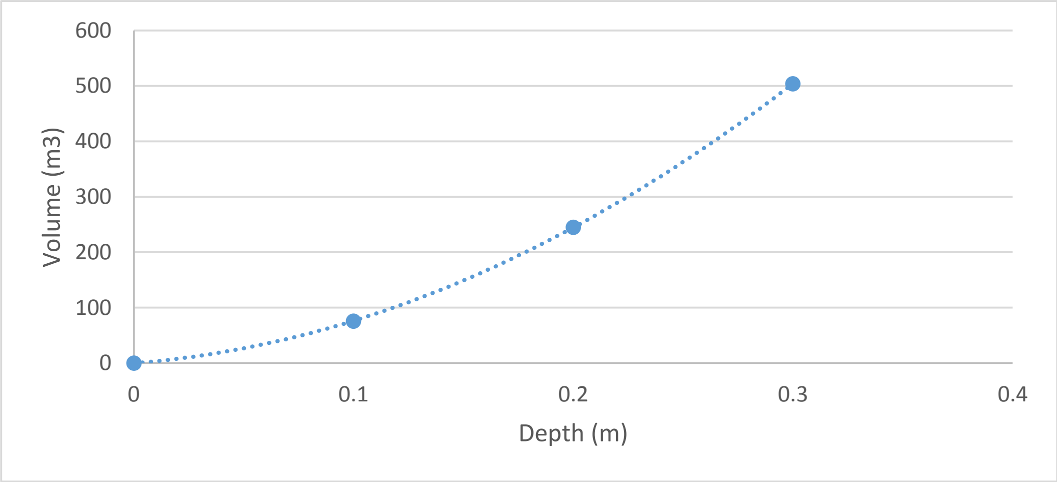



Figure 6-2: Graphical representation of volume storage of A) Worrell road B) Worrell field potholes.

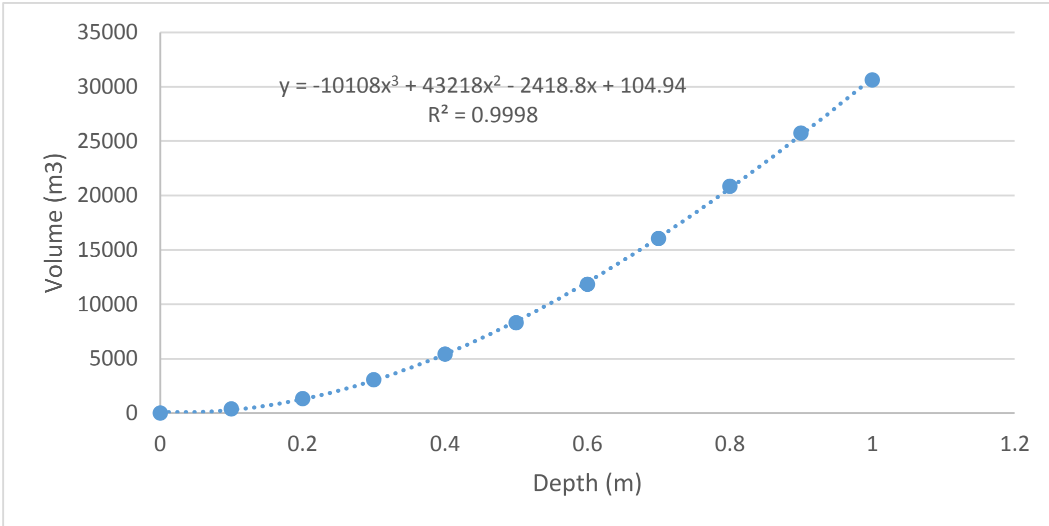
As it is possible to observe in tables 6-2 and 6-3, Worrell-Field is deeper, with the bottom depth around 309.8, which causes water will to accumulate there first. Nevertheless, considering that the lower depth of Worrell-Road is 309.9, it will start filling almost simultaneously, and merge when surface water rises more. Table 6-4 illustrates the volume and area variation for different depths for the Worrell pothole, which represents the union of road and field depressions.

Table 6-4: Volume Variation of the Union of Worrell Road and Field.

| Plane Height (m) | Pothole Depth (m) | Area (m2) | Volume (m3) |
|---|---|---|---|
| **309.8** | 0 | 204 | 0 |
| **309.9** | 0.1 | 6481 | 386 |
| **310.0** | 0.2 | 13131 | 1334 |
| **310.1** | 0.3 | 21016 | 3058 |
| **310.2** | 0.4 | 26274 | 5420 |
| **310.3** | 0.5 | 31967 | 8319 |
| **310.4** | 0.6 | 38707 | 11841 |
| **310.5** | 0.7 | 45517 | 16071 |
| **310.6** | 0.8 | 48810 | 20861 |
| **310.7** | 0.9 | 48845 | 25744 |
| **310.8** | 1 | 48857 | 30630 |

With table 6-4 it is possible to observe that the pothole considering the union of both depressions will have a higher depth, in relation to the individual depressions. It is consistent with the reality, in which Worrell pothole reached depths higher than one meter. More information about the observed data is discussed in further sections. Figure 6-3 illustrates the volume storage and surface area related to each elevation in depth in the Worrell pothole.

A)




B)

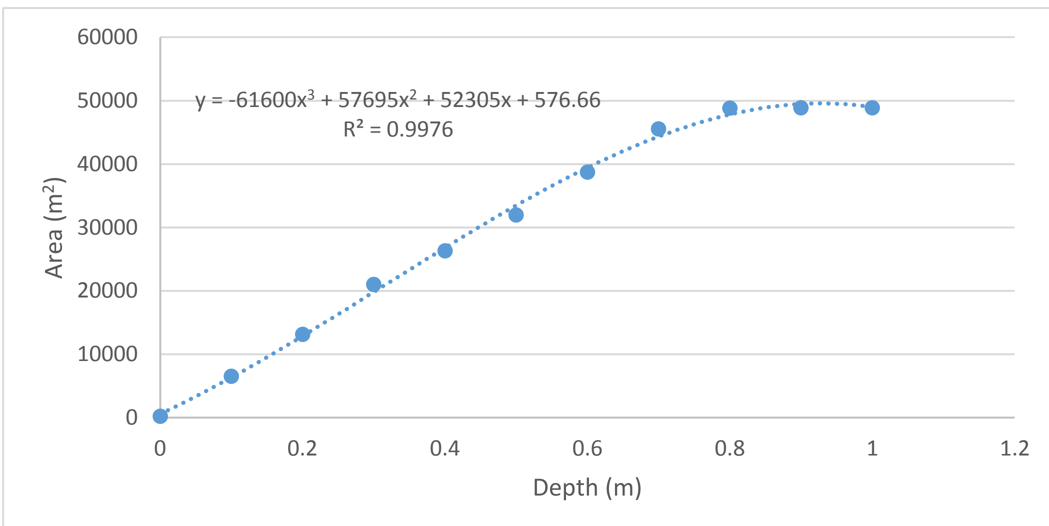



Figure 6-3: Graphical representation of A) volume storage and B) surface area of Worrell pothole as a function of the elevation depth.

## 6.5. Summary

Here, the storage volume capacity of the features were computed through the assessment of a high resolution DEM. Walnut and Worrell potholes, can store 10793 (8.8 acre-ft), and 34461 $m^3$ (27.9 acre-ft), of water respectively, before overflowing. Also, in their maximum storage, their surface area will correspond to approximatelly 28 and 49 thousand $m^2$, respectively. Later, the information of surface area and depth will be used to investigate the intensity of ponding.

# CHAPTER 7: MODEL CALIBRATION AND PERFORMANCE

## 7.1. Objectives

In this section, the objective was to analyze the data generated by AnnAGNPS for the simulation of the water balance in Walnut and Worrell potholes, and compare with the observed data, from the growing seasons of 2010 and 2011 for model calibration. The calibration process and statistical analysis were described for better understanding of the steps used in pothole calibration for this project. Then, the efficiency of the model in the simulation of data was estimated for both potholes, with the use of different efficiency models, according the best-fit calibration. The results indicate the level of reliability of the model to simulate pothole hydrology.

Additionally, elevation depth data collected during 2014, which was supposed to be used in the calibration, is available to illustrate how it is different from the dataset collected in 2010 and 2011.

## 7.2. Calibration Process

There is not a specific procedure for watershed model calibration (D. Moriasi and Wilson 2012). It depends on the quality and extent of observed data, hydrological model used, among other factors. Ideally, good model performance assessment accounts with observed data in wet, average, and dry years, which generally varies from 3 to 5 years of data for calibration, which is not the case for this project, since there were just two years of observed data, 2010 and 2011, for a short span, the growing season of both years, Additionally, these years were considerably different among themselves, since more rainfall was observed in 2010, in relation to 2011, as illustrated further.

Here, CN values and pothole infiltration rate were modified in order to find the calibration in which the model would generate the best results, according the Nash-Sutcliffe Efficiency (NSE) index model. CN and infiltration rate were the selected parameters for the calibration because the CN has direct effect in the runoff generation, therefore, in the volume load into the features; and the infiltration rate controls the rate in which water leaves the system. As a result, the user would be able to control the main sources, in and out, within the wetland system. The NSE model was selected due its broad use in the assessment of model efficiency. Nevertheless, other efficiency models are also tested for an estimation of the reliability of the model in estimating observed conditions.

However, AnnAGNPS was not able to generate consistent results for pothole hydrology in elevation depth and volume load variations with the same calibrations because the model considers the wetland feature to be flat, and therefore to have a linear relationship between volume storage and water depth elevation, as discussed in section 5.5. For this reason, the model was calibrated for volume and depth differently, as discussed in further sections of this chapter. First, the depth was calibrated, then the volume variations in the pothole. In each of the calibrations, the volume stored in the potholes is discussed and compared with the volume computed in the topography assessment, for a better understanding of the differences between the volume stored in the features with AnnAGNPS, and according with the reality. The Efficiency of the model in the simulation of both calibrations is discussed after the calibration process is explained.

In both depth and volume analysis, the CN was calibrated first, to identify its effects in the elevation depth and volume rise in the potholes. Then, once the CN selected was able to generate consistent water rise in the potholes, the infiltration rate would be calibrated to identify the rate in which water leaves the potholes. Because the infiltration of Worrell is likely higher because of the existence of the surface inlet, Walnut was calibrated first, and once the most suitable infiltration was observed, Worrell would be calibrated, starting from the value adopter for Walnut.

The comparison between observed and simulated datasets started on the 10$^{th}$ of June in 2010, and on the 9$^{th}$ of June in 2011, and lasted until September 10$^{th}$ in 2010, and June 27$^{th}$ in 2011, according the span in which there is observe data. The limited window of comparison between observed and simulated data is reduced to the span in which observed data was collected because the exact date in which the pressure transducers were installed or removed from the fields is not known. The device had to be installed after the field was planted, and removed before harvest or any other field operations, once these could be destroyed by farming machinery, during field operations. Additionally, field conditions had to be dry enough to allow the installation of the devices, which could have caused more delay in the installation of the pressure transducers, shortening the span of comparison between observed and simulated.

There were some variations in the simulation length of depth and volume analysis, since the events starting before the last day in which ponding was observed, and lasting to over the date the last observed data was recorded to last until the water depth or volume in the simulated dataset was zero. The calibration length corresponds to about 110 days of comparison, including both years.

### 7.3. Statistical Analysis

In this section, the evaluation metrics used to measure AnnAGNPS performance in the simulation of observed data are discussed. The performance assessment was based on the water balance in the potholes during the growing season of 2010 and 2011. Data were also collected in 2008 and 2009, but because of the delay in the installation of the pressure transducers, or problems with the reliability of the data, these were discarded. For comparison, observed data, collected hourly, was converted into daily data by considering the last hourly record in the day to be the water depth of the assessed day. This approach is more compatible with the simulated data, which computes the water into the features by the end of the day, after accounting for all water balance components of a given day.

Two comparisons between observed and simulated were made: one in which all days in the simulation period were considered, and another in which only days in which there was inundation in either the observed or simulated data. Performance analysis considering all length of observed data were named GS, and the one considering just days in which runoff was observed in any of the datasets, observed or simulated, were named VS. Just values greater than 0.05 m in the simulated data were considered in the calibration process because the pressure transducer would barely read values smaller than 0.05 m because water showed to rise fast. Therefore, we assumed 0.05 m to be the threshold of the values generated by AnnAGNPS. Nevertheless, if a value smaller than the threshold was observed as a part of consecutive days of ponding, it would be included in the calibration analysis.

There are several efficiency criteria that can be used in hydrological model studies. The selection of the criteria to be used depends on its sensitivity and on the assessed data (Krause, Boyle, and Bäse 2005). For this project, the Nash-Sutcliffe Efficiency index method (NSE) is used for calibration of the model, and percentage bias (PBIAS), root mean square error observations standard deviation ratio (RSE), and $R^2$ were be also computed after the determination of the best-fit calibration. These were selected because of their broad use in model evaluations.

The Nash-Sutcliffe efficiency (NSE) method consists of an empirical index used to estimate the agreement between observations and predictions, for a given day. It is widely used in hydrology studies and in related sciences to evaluate model outputs such as discharge flow and evapotranspiration estimates (Nash and Sutcliffe 1970; Meek, Howell, and Phene 2009). Equation 7-1 illustrates the equation of the Nash-Sutcliffe efficiency.

$$\mathrm{NSE} = 1 - \left[\frac{\left(\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2\right)}{\left(\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean-obs}\right)^2\right)}\right] \qquad \text{Equation 7-1}$$

Where $Y_i^{obs}$ = observed data, $Y_i^{sim}$ = simulated data, and $Y_i^{mean\text{-}obs}$ = mean of observed data. NSE values can vary from $-\infty$ to 1, in which reasonable models will have a NSE higher than zero, and perfect models will have a NSE equal to one. One limitation of NSE models is that it measures the difference between observed and simulated data in squared values, then, it over estimates of high values and neglects smaller ones (Parajuli et al. 2009). When we assess depth variations, it is mainly composed by smaller values, and for this reason, it is important to evaluate the results of the other tests, described below.

PBIAS is an error index that measures the average tendency of the model to simulate higher or smaller values in relation to the observed data on a given day (Moriasi et al. 2007). Perfect estimates would give a PBIAS of 0.0, and it can measure positive and negative values. Positive values indicate an underestimation, and negative values an overestimation of the observed data (Parajuli et al. 2009). PBIAS computation is illustrated in equation 7-2.

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \times 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \qquad \text{Equation 7-2}$$

Similar to PBIAS, RSR is an error index, and consists of the ratio between the average error between observed and predicted variables and the standard deviation of the measured data. It was generated from the Root Mean Square Error (RMSE) index, in which the RMSE is divided by the standard deviation of the observed data. The better the model, the closer it will be from 0. The RSR computation is illustrated in equation 7-3.

$$RSR = \frac{\sqrt{\frac{\sum_{i=1}^{n}(Y_i^{sim} - Y_i^{obs})^2}{n}}}{STDEV_{obs}}$$ Equation 7-3

Where $Y_i^{obs}$ = observed data, $Y_i^{sim}$ = simulated data, $Y_i^{mean\text{-}obs}$ = mean of observed data, n = number of events; $STDEV_{obs}$ = standard deviation of observed data.

Lastly, $R^2$ values describes how much the observed dispersion is captured by the predicted values. Because this model does not predict the amount of error or difference, it should not be used alone in the decision of the best-fit calibration (Parajuli et al. 2009; Krause, Boyle, and Bäse 2005). Visual comparison between observed and simulated data is crucial for a good judgment in the calibration process (Moriasi et al. 2007), and was also used in the calibration process.

After the final calibration is defined with NSE, other efficiency indexes are used to evaluate the data. Table 7-1 illustrates the quality class range associated with the NSE, $R^2$, PBIAS, and RSR, the efficiency models used to evaluate the performance and patters of the model. The performance range of the models vary according the parameter in study, like runoff flow, sediment or nutrient transport and load. Here, the model ranges were classified according runoff flow generation because water in the depressions is directly related with runoff generated by the cells.

Table 7-1: Classification of model efficiencies for streamflow.

| Class | NSE and $R^2$ | PBIAS | RSR |
|---|---|---|---|
| **Excellent** | < 0.9 | < ±10 | 0.0 – 0.25 |
| **Very Good** | 0.75 – 0.89 | ± 11 ≤ ± 15 | 0.26 – 0.50 |
| **Good** | 0.50 – 0.74 | ± 16 ≤ ± 25 | 0.51 – 0.60 |
| **Fair** | 0.25 – 0.49 | ± 26 ≤ ± 30 | 0.61 – 0.70 |
| **Poor** | 0.00 – 0.24 | ± 31 ≤ ± 35 | 0.71 - 0.89 |
| **Unsatisfactory** | < 0.0 | ≥ ± 36 | > 0.90 |

Source: Parajuli et. al. 2009, Table III, classification of model efficiencies considering flow (Parajuli et al. 2009).

## 7.4. Pothole Depth Calibration Process

The calibration assessment started by assuming that the entire watershed was under one CN, and the potholes were considered to have the area computed with ArcGIS, as the subtraction of the bare DEM from the filled one. This assessment provides an overestimation of the area of the potholes. The first step was to regulate the water load generated by the microwatersheds and therefore the rise in elevation depth in the potholes, by calibrating the CN value. Then, once a consistent water depth rise was observed, the infiltration rate would be calibrated to estimate the rate in which water was leaving the system.

The initial CN considered in the assessment was the “Straight Row Crop” for poor conditions. It was considered that the watershed would be prompt for less infiltration and more runoff generation because, during site visits, humid conditions were observed toward the potholes. Also, the approach was to simulate the most humid condition, and then decrease the CN until simulated values were consistent with observed. For both potholes, the default CN value in the SSURGO dataset was able to capture elevation depth dynamics in the potholes, in other words, water depth in simulated and observed data would be similar. Table 7-2 illustrates values for the final calibrations for depth analysis.

Table 7-2: CN values according depth calibration.

| **Curve Number Classification*** | **A** | **B** | **C** | **D** |
|---|---|---|---|---|
| **Row Crop – Poor Condition** | 72 | 81 | 88 | 91 |
| **Brush – Poor Condition** | 48 | 67 | 77 | 83 |

The brush condition represent the CN used in the areas converted to a grass vegetation, in the assessment of the conserved conditions. The term “Brush” is used because it is the nomenclature adopted in the CN dataset downloaded from the SSURGO website. Nevertheless, there will not be areas classified as “Brush” in the assessment of the current scenario. We also simulated the load with addition and reduction of one unit from the CN value. By decreasing one unit, NSE values would decrease, and by adding one, the results were almost the same, so we decided to keep the values available in the SSURGO dataset.

Before the regulation of the infiltration rate, the water depth would stay high for longer periods, therefore, the infiltration rate was calibrated to identify the rate that would cause a consistent drop in the water depth in the potholes, consistent with the reality. As discussed, Walnut infiltration was calibrated first, then Worrell calibration would start from the value assumed for Walnut because of the surface inlet. Here, we started the calibration with lower infiltration values and increased the values until the simulated dataset was representing the observed one. The final calibration for wetland properties according the depth analysis is illustrated in table 7-3.

Table 7-3: Wetland properties adopted for the calibrations of depth variations in the potholes.

| Wetland ID | Wetland Area (ha) | Daily infiltration (mm/day) | Max Water Depth (m) | Weir Width (m) | Weir Height (m) |
|---|---|---|---|---|---|
| **Walnut** | 3 | 25 | 1 | 20 | 0.7 |
| **Worrell** | 5 | 60 | 1.2 | 10 | 1.0 |

The constraint of simulating the pothole to have the area computed in the DEM assessment is the difference between the volume related with each elevation depth according to AnnAGNPS, in relation to the actual volume, computed with the DEM analysis. Figure 7-1 illustrates the difference between the volume estimated by the model, and the volume computed according the DEM assessment. It illustrates a graph of comparison between the volume stored in Walnut and Worrell potholes according AnnAGNPS computations (volume has a linear relationship with depth), and according the DEM computed with the assessment of the DEM, discussed in Chapter 6.

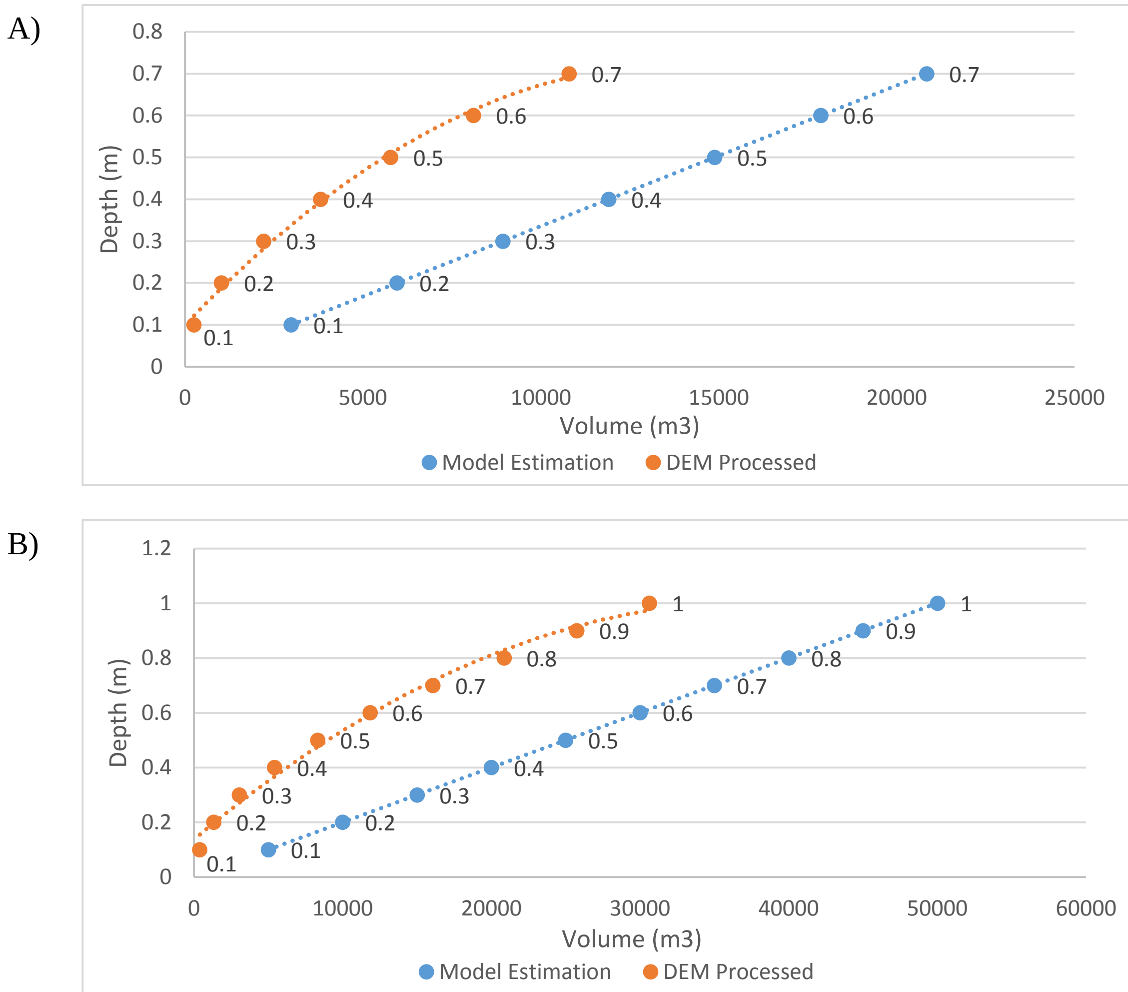
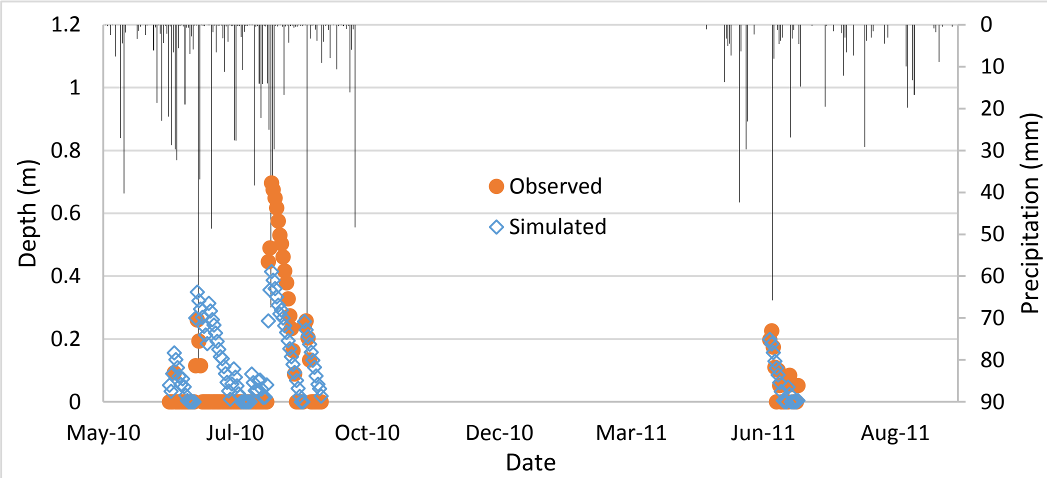



Figure 7-1: Volume Comparison Assessment for A) Walnut and B) Worrell potholes in the depth calibration.

With figure 7-1, it is possible to observe that for the same elevation depth, the volume estimated by the model is higher than the volume computed with the DEM. When we reduced the size of the potholes, keeping the same calibrations, the rise in depth would be higher, because all the water generated by the microwatersheds would be stored in smaller areas; which is not consistent with the reality. Figure 7-2 illustrates the results of depth calibrations for both potholes, according CN values and wetland properties available in tables 7-1 and 7-2.

A)




B)

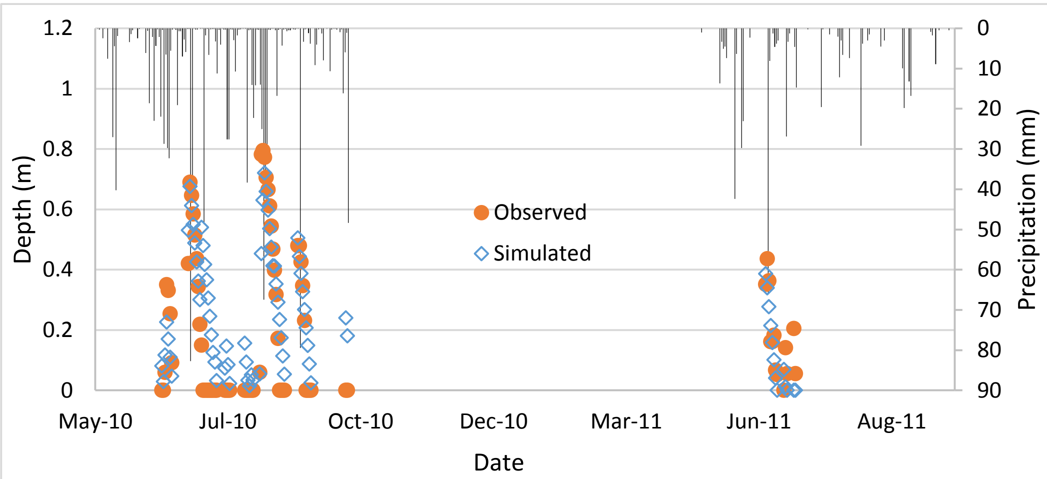



Figure 7-2: Total simulation of water depth variation, Walnut (A) and Worrell (B) potholes.

For depth calibrations, there were 111 and 110 days of simulation for Walnut and Worrell potholes considering the GS assessment. The comparison length was not the same because, in Walnut, one of the events started before the last day of observed data, and continued for few more days. Also, there was more observed data for Worrell in relation to Walnut. The number of days of the VS assessment was respectively 72 and 70 for Walnut and Worrell. In this calibration, the microwatersheds will generate more runoff, which will be stored in the potholes, which, here, are considered to store more water than the reality. More discussion about the performance of the model is available in the end of this chapter.

## 7.5. Pothole Volume Calibration Process

The observed data, collected in depth, was converted to volume by equations generated with the relationship between depth and volume, discussed in Chapter 6. The results simulated by AnnAGNPS will compute the depth in the potholes in mm, then this value will be converted to volume by multiplying the depth by the end of a given day by the area of the potholes. This extra step of conversion from depth to volume consist of another source of error in this assessment, which can impact the reliability of the model in simulating the observed data.

Here, the maximum volume stored according the topography was the same as the volume stored according AnnAGNPS representation of the wetland. In this assessment, Walnut and Worrell potholes were considered to have respectively 1.5 and 2.8 hectares in area. After this value is determined, the CN and then the infiltration rate of the potholes were calibrated. Figure 7-3 illustrates the relationship between elevation depth, and volume stored in the potholes according the assessment of the topography, and with AnnAGNPS.

A)

B)

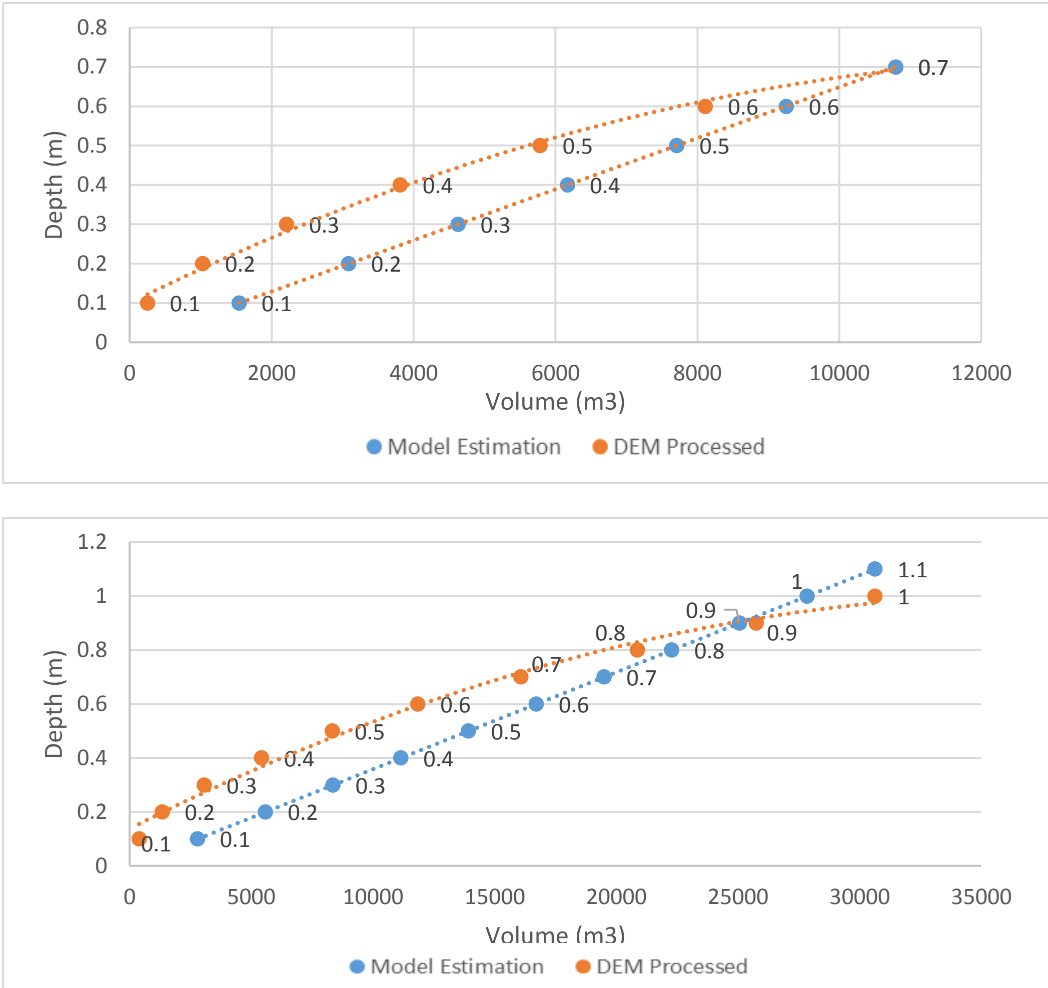



Figure 7-3: Volume Comparison Assessment for A) Walnut and B) Worrell potholes for volume calibration.

In the calibration of the volume loaded into the potholes, the calibration was started with the same infiltration rate as reported in the depth analysis, but we have changed the area in the potholes, so the volume capacity of the AnnAGNPS representation of the wetland would be similar to the volume stored according the DEM analysis, as illustrated in figure 7-3.

First, the same CN value assumed in the depth analysis were attributed for the volume analysis calibration. However, it was observed that in this simulation the potholes would exceed their volume storage capacity continuously, and the water level was higher than the observed for all the growing seasons of 2010 and 2011, which does not correspond to the reality. Therefore, it was decided to attribute different CN values for different sections in the microwatersheds, based in the position of the cells in relation to the potholes. The CN basis value was the “Row Crop”, as attributed for the depth analysis. The difference was that here, there was the “Row Crop” for poor, good and medium hydrological conditions, in which medium hydrological condition corresponds to the mean of the poor and good values of CN.

Therefore, for the volume variation analysis in the potholes, there was three values of CN, in which higher values were assumed for cells toward the potholes. It was assumed because a higher clay content was observed in the middle of the potholes, indicating transport of sediments in the watershed and potentially less infiltration in these areas. More information about soil samples is available in Appendix A. The CN classification cells is available in figure 7-4.

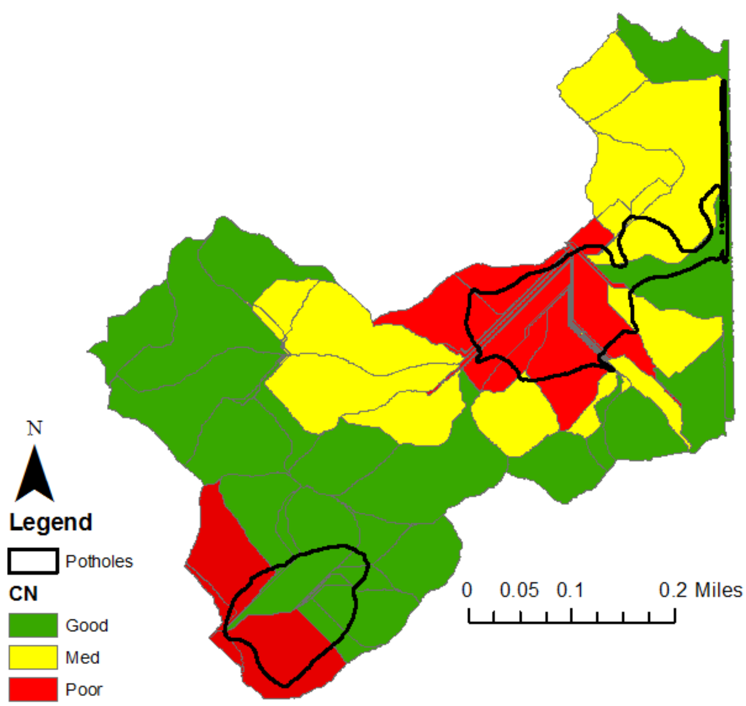



Figure 7-4: CN values for microwatershed cells according the volume calibration.

As observed in figure 7-4, and also illustrated in figure 5-2B, in the management distribution of the cells in the conserved condition, the cells classified as poor correspond to the cells to be considered to be conserved in the assessment of the conserved scenario. Table 7-4 illustrates the areas attributed to each CN for Walnut and Worrell for the volume calibration.

Table 7-4: Areas attributed to each CN according volume calibration.

| Pothole | CN | Area (m2) | Area (acres) | Area(ha) | Area (%) |
|---|---|---|---|---|---|
| **Walnut** | Good | 62866.00 | 15.53 | 6.29 | 64.44 |
| | Med | 0.00 | 0.00 | 0.00 | 0.00 |
| | Poor | 34691.00 | 8.57 | 3.47 | 35.56 |
| **Worrell** | Good | 190387 | 47.0 | 19.0 | 47.5 |
| | Med | 149399 | 36.9 | 14.9 | 37.2 |
| | Poor | 61353 | 15.2 | 6.1 | 15.3 |

After the determination of different CN values to different sections in the watershed, , however, the watershed was still generating great amounts of runoff, and the CN was reduced in order to identify the CN values that would replicate the volume variations in the microwatersheds. The CN values were decreased in 10, 25, 30, 35, and 40% of the real values.

As in the calibration of the depth, Walnut pothole was calibrated first, and then Worrell. With the calibrations, it was possible to observe that the most suitable CN values for this pothole corresponded to a reduction of 30% in the CN values, according poor and good hydrological conditions, since there was no cell classified as medium in Walnut microwatershed. Then, the calibration of infiltration rate started by assuming the same infiltration rate determined by the depth calibration.

Because the area of the potholes was smaller, the infiltration rate had to be higher, to compensate for the smaller volume infiltrated, in relation to the depth analysis. Once Walnut was calibrated, Worrell calibration started. As tested for Walnut, the CN values evaluated for Worrell corresponded to “Row Crop”, in good, medium, and poor hydrological conditions, and by decreasing 10, 25, 30, 35, and 40% of the real values. The CN values that represented better Worrell microwatershed were the CN values representing a decrease in 25% of the original values. The values attributed to CN classification for the volume analysis for Walnut and Worrell potholes is illustrated in table 7-5.

Table 7-5: CN values for Walnut and Worrell potholes according volume calibration.

| Pothole | Curve Number Classification* | A | B | C | D |
|---|---|---|---|---|---|
| **Walnut** | Row Crop – Straight Row – Good Condition | 46.9 | 54.6 | 59.5 | 62.3 |
| | Row Crop – Straight Row – Poor Condition | 50.4 | 56.7 | 61.6 | 63.7 |
| | Row Crop – Straight Row – Medium Condition | 48.3 | 55.3 | 60.2 | 63 |
| | Brush – Poor Condition | 33.6 | 46.9 | 53.9 | 58.1 |
| **Worrell** | Row Crop – Straight Row – Good Condition | 50.3 | 58.5 | 63.8 | 66.8 |
| | Row Crop – Straight Row – Poor Condition | 54 | 60.8 | 66 | 68.3 |
| | Row Crop – Straight Row – Medium Condition | 51.8 | 59.3 | 64.5 | 67.5 |
| | Brush – Poor Condition | 36 | 50.3 | 57.8 | 62.3 |

The CN values for Walnut and Worrell were slightly difference, since CN values for Walnut were smaller, indicating that this watershed will generate less runoff than Worrell watershed. The calibration of Worrell infiltration rate started by the value attributed in the depth analysis. For the calibration of the volume into the potholes, the watersheds are considered to generate less runoff, with the use of lower CN values in relation to the depth analysis, and the infiltration rates within the potholes were higher, to compensate smaller potholes. Additionally, it is important to emphasize that in the current assessment there will be no "Brush" classification, and in the conserved, there will be no CN in poor condition, since these will be replaced by the grassy vegetation ("Brush")

Values of Walnut and Worrell potholes for volume calibration are illustrated in table 7-6.

Table 7-6: Wetland properties adopted for the calibrations of volume variations in the potholes.

| Wetland ID | Wetland Area (ha) | Daily infiltration (mm/day) | Max Water Depth (mm) | Weir Width (m) | Weir Height (m) |
|---|---|---|---|---|---|
| **Walnut** | 1.54 | 55 | 1000 | 20 | 0.7 |
| **Worrell** | 2.8 | 70 | 1400 | 10 | 1.1 |

Figure 7-5 illustrated the results of depth calibrations, according CN values and wetland properties available in tables 7-5 and 7-6.

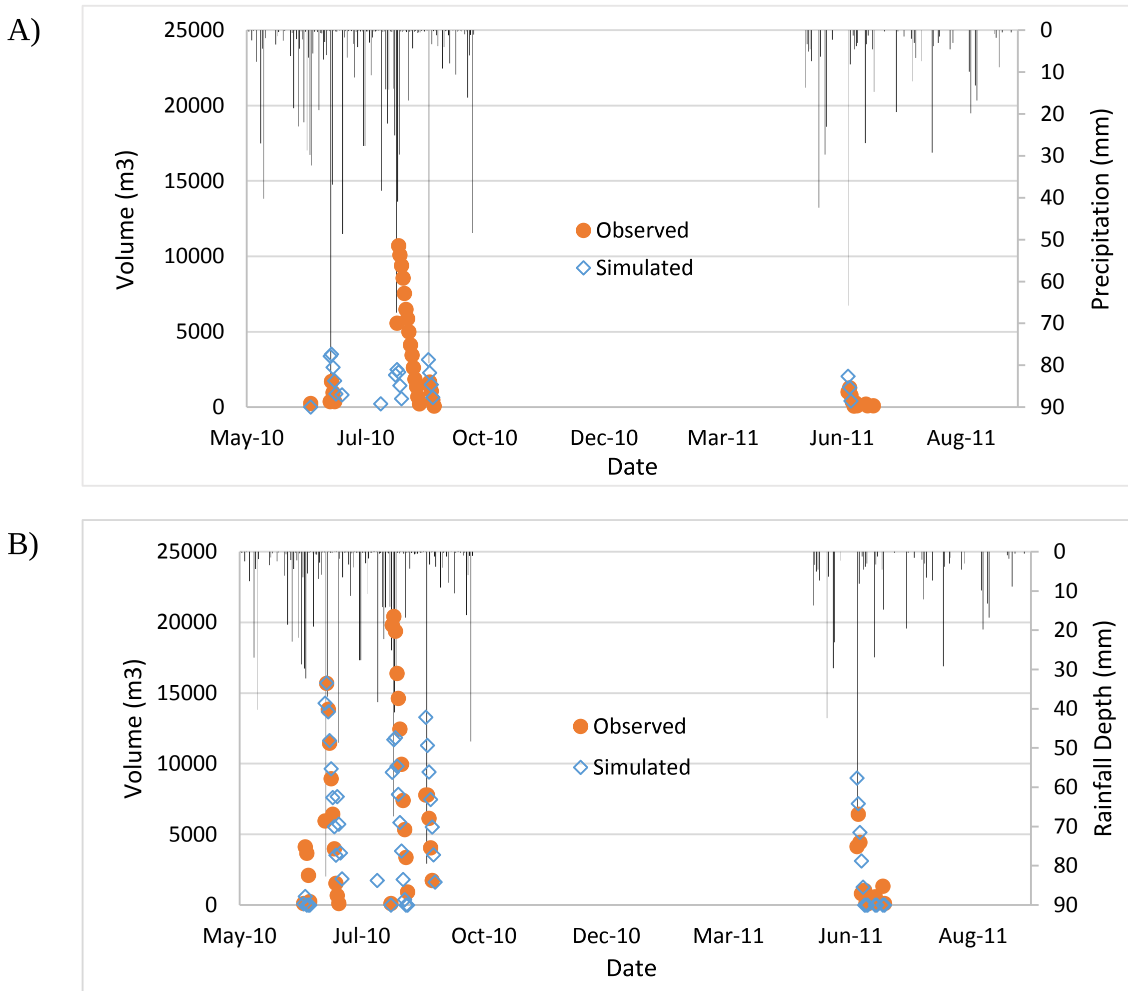



Figure 7-5: Total simulation of water volume variation, (A) Walnut and (B) Worrell potholes.

In for the volume calibrations there were 104 and 109 days of simulation for Walnut and Worrell potholes. It is a little less than the simulation of the depth because the microwatersheds calibrated for the volume analysis had a better hydrological condition, therefore, the last day in which data was recorded was the last day of the simulation. The number of days of the simulation considering just days in which there was water in the potholes was respectively 40 and 49 for Walnut and Worrell.

Several calibrations were tested in order to generate better results for Walnut simulation (figure 7-5A). Higher NSE values were observed by increasing the volume generation of the microwatershed, however, it would over-estimate the volume generated in most observed data, but the highest value of volume accumulated in this pothole. Visual comparison was also used in the calibration of Walnut pothole in the volume analysis because it was observed that when the CN was higher, the model would over estimate all volume fluctuations in the simulation, but one of the events observed in 2010, in which the potholes accumulated. Therefore, it was decided to calibrate the model according the most observed conditions. Model efficiency of both calibrations is presented and discussed in the following section of this chapter.

## 7.6. Model Efficiency Assessment

As discussed, the NSE efficiency index was used to calibrate the model. For a better analysis of its performance, the results of the NSE index approach were investigated considering the entire growing season (NSE-GS) of the years 2010 and 2011, and considering just the days in which there was volume stored in the potholes (NSE-VS), which number of days of comparison varied according with calibration pothole assessment. Both analysis were investigated once the efficiency of the model was directly dependent of the number of days in which runoff was observed in the potholes. Figures 7-2 and 7-5 illustrate observed and simulated data for the best performance of the model for Walnut and Worrell according depth and volume calibration, respectively. The results of the NSE-GS and NSE-VS index for the simulation of depth and volume are illustrated in table 7-6.

Table 7-6: Simulation performance by pothole considering the NSE efficiency model.

| **Analysis** | **Pothole - year** | **NSE - GS** | **Performance** | **NSE - VS** | **Performance** |
|---|---|---|---|---|---|
| **Depth** | Walnut | 0.50 | Good | 0.48 | Fair |
| | Worrell | 0.72 | Very Good | 0.64 | Good |
| **Volume** | Walnut | 0.02 | Poor | -0.33 | Unsatisfactory |
| | Worrell | 0.67 | Good | 0.56 | Good |

Models with NSE > 0.5 are considered to represent the observed data (Table 7-1). Using this standard, it is possible to affirm that AnnAGNPS results of depth and volume are acceptable for their respective calibrations, except for the runoff-only simulation of volume in the Walnut pothole.

As reported by the NSE index results, the model is more efficient in the estimation of the water depth variation of Worrell pothole than in Walnut, which is clear to observe when daily observed and simulated data are plotted together (figures 7-2 and 7-5). It was probably because the surface inlet in Worrell pothole, which allowed the user to have a higher control through the infiltration rate component in this pothole. On the other hand, in Walnut, the feature was subjected to more natural environmental variations. The higher values in the NSE-GS assessment were likely a consequence of a drier year in 2011, in which there were a number of days in which no runoff was observed nor simulated in the field.

By comparing figures 7-2 and 7-5, it is possible to observe that the depth analysis was able to represent better the hydrological variations in the potholes in relation to the volume analysis. For instance, in the simulation of the two consecutive events in which water reached higher elevation depths and volume stored into the potholes, after $10^{th}$ of August 2010, the depth simulation captured a higher elevation depth in the first event in relation to the second, as seen in the observed condition. It is possible to see that in 2010, the rise in water depth in the potholes was not directly related with rainfall depth, since the first large rainfall after the $10^{th}$ of August was smaller (67 mm) than the second (79 mm), that happened by the end of August. However, this pattern was not observed in the volume simulation, since the water load into the potholes was directly related with precipitation depth for the assessed days in 2010 and 2011. The differences between volume and depth calibrations were likely due a previous wet condition of the soil, which was captured by the depth, and not for the volume calibration.

Volume calibration required more critical thinking since the observed data was collected in extreme years (2010 being much wetter than 2011), which resulted in variations that could not be represented by the model. It would generate higher efficiency results for calibrations of a higher runoff generation, to account for the intense rainfall events, in particular the high peak in 2010. Given the better hydrological condition of the system created for the estimation of the volume in the potholes, the volume generated in the potholes by AnnAGNPS was directly related with the precipitation depth, which is not the case under wet conditions, according with the observed data.

As discussed before, other efficiency tests were also used to investigate the simulation performance of the model, for instance, to potentially infer if AnnAGNPS overestimates or underestimates observed data, PBIAS efficiency model is computed for both potholes, for both calibrations. Table 7-8 illustrates the efficiency of the model according the PBIAS efficiency models.

Table 7-7: Simulation performance by pothole considering the PBIAS efficiency model.

| **Analysis** | **Pothole - year** | **PBIAS - GS** | **Performance** | **PBIAS - VS** | **Performance** |
|---|---|---|---|---|---|
| **Depth** | Walnut | -29.3 | Poor | -33.6 | Poor |
| | Worrell | -18.2 | Good | -20.8 | Good |
| **Volume** | Walnut | 14.5 | Good | 65.2 | Unsatisfactory |
| | Worrell | 5.1 | Excellent | 5.16 | Excellent |

Walnut and Worrell presented different signs for PBIAS values for depth and volume analysis, which indicates that the model is overestimating depth values (negative PBIAS), and underestimating volume values (positive PBIAS) (D. N. Moriasi et al. 2007). For both analysis, AnnAGNPS performed better in the simulation of Worrell pothole than of Walnut, as observed in NSE results. Tables 7-8 illustrates the efficiency of the model according with the RSE, and $R^2$ tests.

Table 7-8: Simulation performance by pothole considering the RSE and $R^2$ efficiency models.

| **RSE** | **Pothole - year** | **RSE - GS** | **Performance** | **RSE - VS** | **Performance** |
|---|---|---|---|---|---|
| **Depth** | Walnut | 0.70 | Fair | 0.72 | Poor |
| | Worrell | 0.52 | Very Good | 0.62 | Fair |
| **Volume** | Walnut | 0.52 | Good | 1.13 | Unsatisfactory |
| | Worrell | 0.57 | Good | 0.56 | Good |
| **$R^2$** | **Pothole - year** | **$R^2$ - GS** | **Performance** | **$R^2$ - VS** | **Performance** |
| **Depth** | Walnut | 0.54 | Good | 0.54 | Good |
| | Worrell | 0.73 | Good | 0.67 | Good |
| **Volume** | Walnut | 0.10 | Poor | 0.0 | Unsatisfactory |
| | Worrell | 0.67 | Good | 0.51 | Good |

In the RSE, the root mean square error of the simulated data is divided by the standard deviation. The lower the root-mean square of the data, or the squared difference between predicted and observed, the lower the RSE and the best the model is. On the other hand, $R^2$ represents the percent of the variation explained by the model.

An example of AnnAGNPS performance is discussed in a 45-months simulation developed in two watersheds in the state of Kansas. It was observed that AnnAGNPS underestimated the extreme events of runoff generation in comparison to the observed data and other watershed model (Parajuli et al. 2009). This situation was also observed in another project, in Ontario, in the occurrence of high peaks of runoff generation (Das et al. 2008). Considering that 2010 amounted several peaks of runoff flow, AnnAGNPS probably would not be able to generate consistent results. Ideally, more data would be necessary in more “normal” years for calibrate and validation.

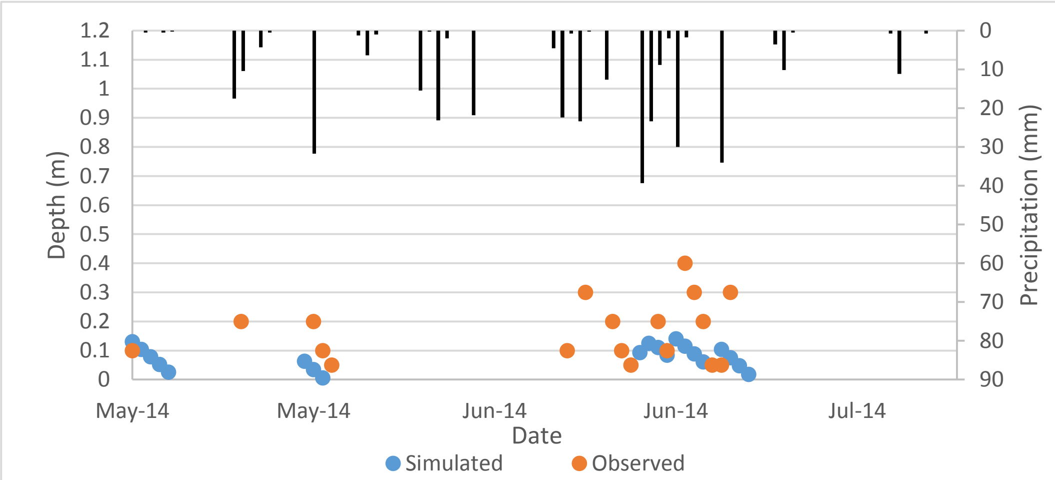
In general, the model was able to capture the occurrence of ponding, as well as the initial depth of ponding, though in a few events of deeper maximum depth than the model simulated were observed.  This is likely due to the observed data reflecting the influence of short-duration, high-intensity events, whereas the model operates on a daily basis and will assume less intense rainfall events over a 24-hour period, potentially dividing the rainfalls across multiple days when a single event spans midnight.  The model tends to simulate slower drainage or contraction of the ponding than was observed in reality, estimating longer duration of ponding for larger events than was observed. For the smaller rainfall events, AnnAGNPS was more likely to simulate ponded water in the pothole even when none was observed.  This could be due difficulties with the equipment, or the water depth was not high enough to be read by the equipment. Overall, potential reasons for lower performance in the assessment of Walnut pothole include (1) poor calibration of the model, (2) inaccurate measured data (3) more detailed inputs required (4) model is not able to accurately represent observed data.

The performance of the models tend to be better in the evaluation of the entire growing season than in the evaluation of only runoff-days, due to the inclusion of the days in which both the model and the observations show no water in the potholes.  This is especially true in the assessment of Walnut pothole. With the analysis of tables and graphs illustrated in this chapter, we concluded that AnnAGNPS is an efficient tool for the determination of water-depth in the potholes, but further research is necessary for a better estimation of the runoff generation in the microwatershed.

## 7.7. Model Efficiency with GPS collected data

As discussed in other sections of the thesis, data collected in 2014 was intended to be used for calibration of the model. However, it was observed that the data collected with the GPS was not as effective representing the observed data in comparison to the pressure transducers. In this section, observed data collected in 2014 was compared with simulated data, according to both depth and volume calibrations discussed in sections 7.4 and 7.5 to illustrate the difference between simulated values, and data collected with a GPS in 2014. Depth and volume observed in 2014 is compared with simulated data according with both depth and volume simulation. Figure 7-6 illustrates the results for Walnut pothole.

A)




B)

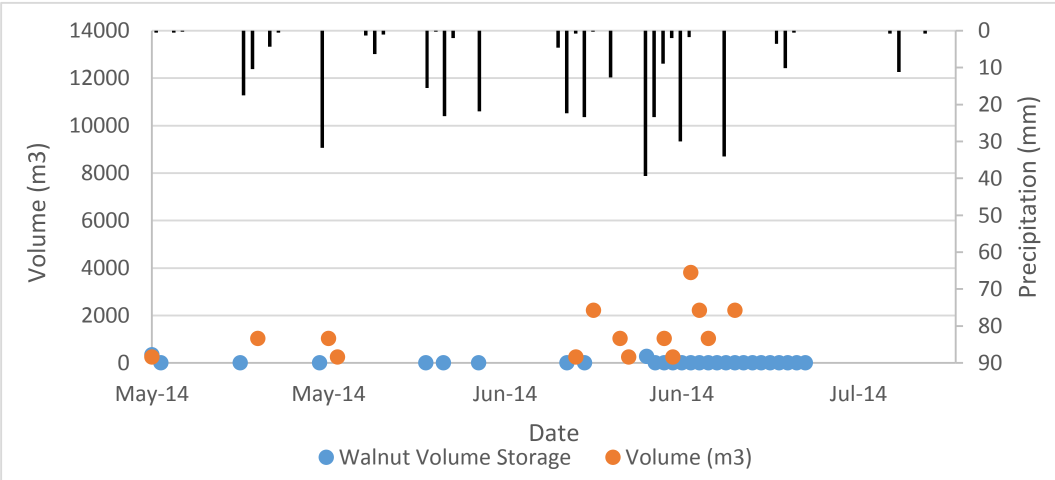



Figure 7-6: A) Walnut depth and B) volume analysis during 2014 data collection.

For the depth assessment, 20 days of flooding were simulated. On the other hand, for volume assessment, AnnAGNPS generated just two occasions in which volume is observed in the pothole, which does not correspond to the reality, 18 days of inundation. Figure 7-7 illustrates the results for Worrell pothole.

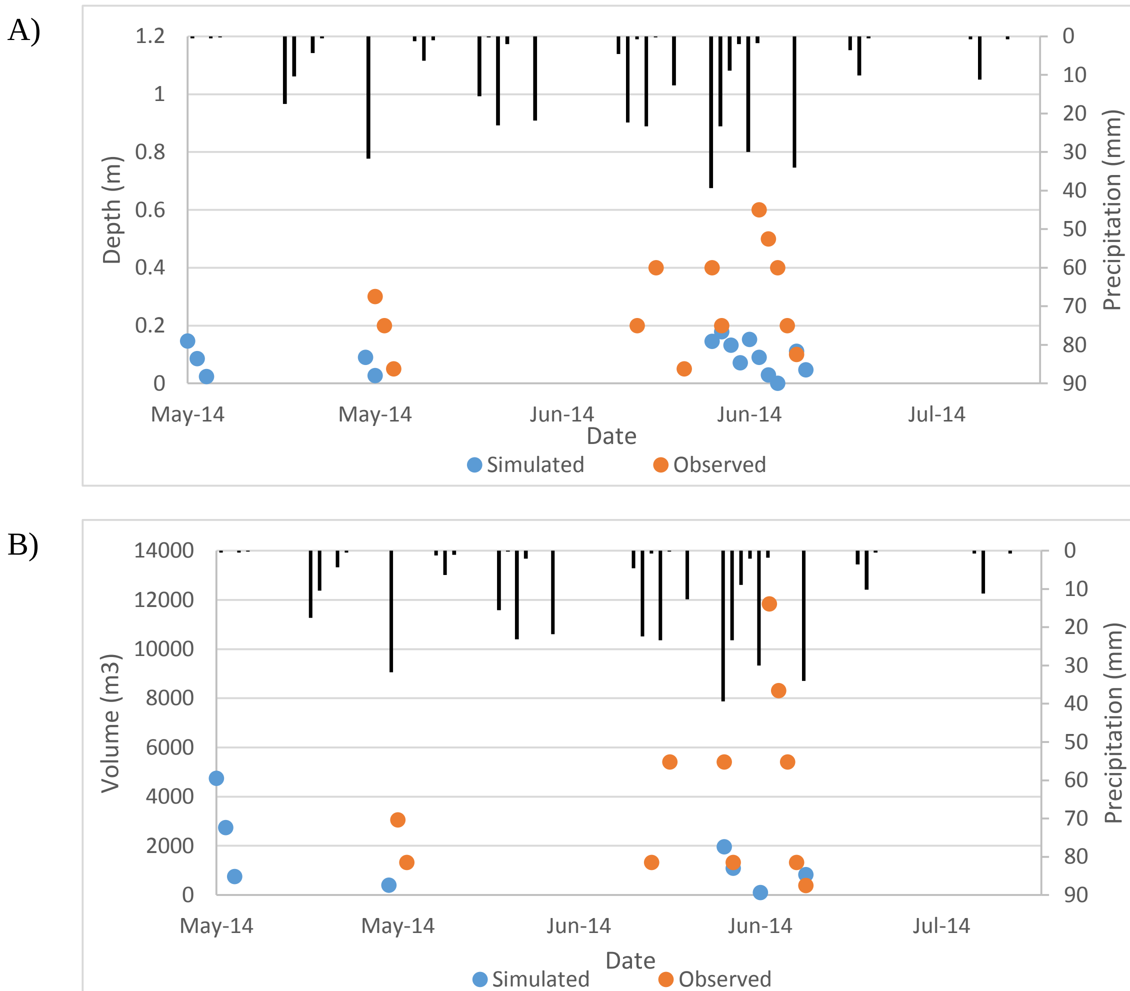



Figure 7-7: Worrell A) depth and B) volume during 2014 data collection.

There were eight days of inundation for the volume, and 19 days in the depth analysis, according with AnnAGNPS simulations, and 13 observed days of inundation in the observed data. Based in figures 7-6 and 7-7, it is possible to affirm that the GPS assessment did not generated suitable data for model calibration and validation due uncertainties related with the collection of data (surface water determined by the user was not consistent with the reality), GPS error, and visual determination of volume storage.

## 7.8. Summary

Here we have proved that AnnAGNPS is able to simulate pothole hydrology, however, was not able to simulate water depth and volume concomitantly because it considers a linear relationship between volume and elevation depth, not consistent with the reality. Therefore, AnnAGNPS was calibrated in different ways, to capture depth and volume variations in the potholes. CN values and pothole infiltration rate were the components used for model calibration because CN would influence water rise in the pothole, and the infiltration the rate in which water leaves the system.

The calibration process was significantly different for volume and depth analysis, in which the former required more critical thinking and assumptions than the latter. For depth calibration, just one CN was adopted for the entire microwatershed areas, and the model was able to represent observed data better. It has been reported that when data is collected in worst case conditions, model performance should be relaxed to reflex the limitation (D. N. Moriasi et al. 2007), which can be a justification for some of the low values of model efficiency in simulating the observed data.

For depth calibration, more runoff is generated by the microwatersheds, the infiltration rate is lower, and the potholes had a larger area. On the other hand, in the calibration of the volume storage into the features, the area of the potholes was changed, so the volume load computed by AnnAGNPS was consisted with the pothole topography. In this calibration less runoff is generated by the microwatersheds, and the infiltration rate was higher to compensate for the reduced size of the potholes.

# CHAPTER 8: DEPTH SIMULATION RESULTS

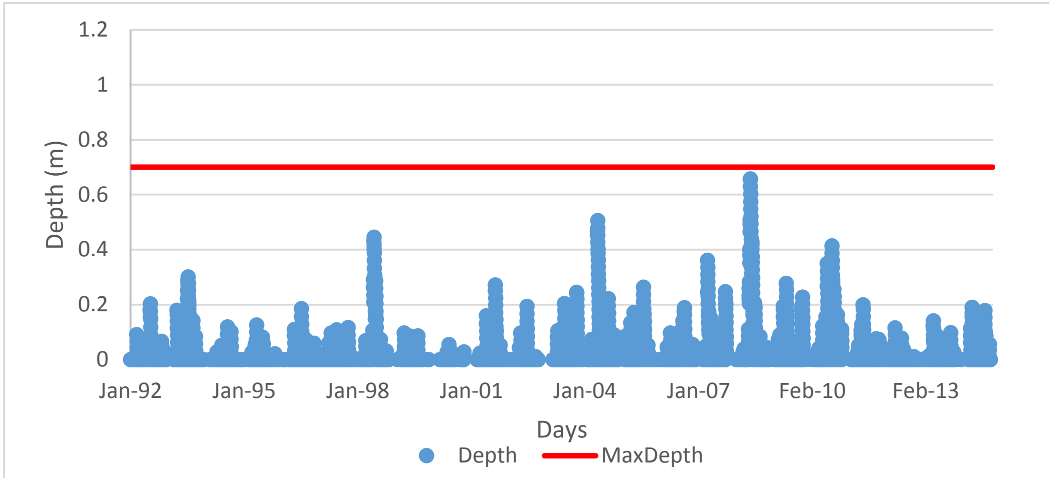
## 8.1. Objectives

In this section, the results of pothole hydrology according the depth calibration for current and conserved conditions are illustrated for both potholes. Discussions about frequency of inundations, consecutive days of inundations and its intensity are available in addition to the long-term results for pothole hydrology.

## 8.2. Simulated Long-Term Depth Variation under Current Conditions

After the calibration of the potholes discussed in Chapter 7, it is possible to simulate the long-term water depth variation of the potholes. Figure 8-3 presents the water depth variation in the current condition, for the all simulated years for Walnut and Worrell potholes.

A)




B)

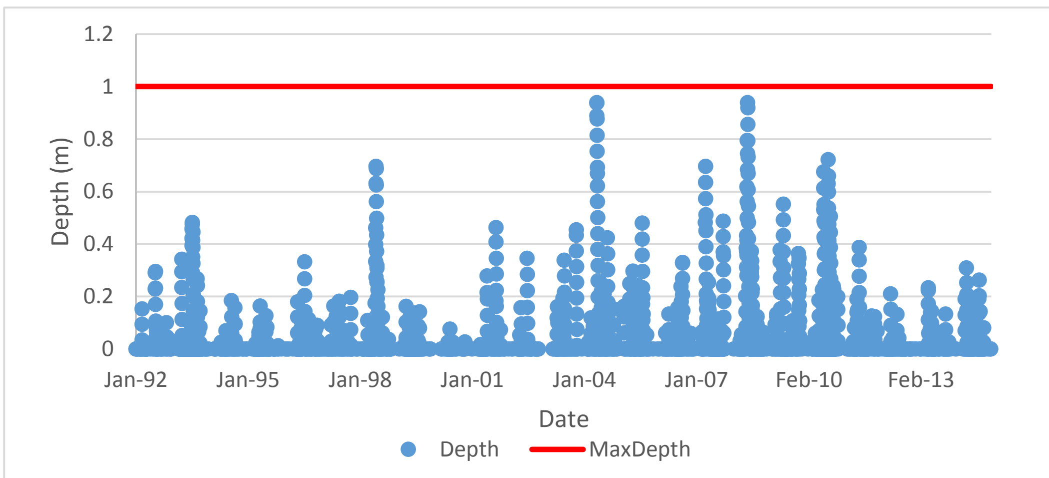



Figure 8-1: A) Walnut total depth simulation and B) Worrell total depth simulation.

In figure 8-1 it is possible to see that infiltration rate was higher in Worrell (8-1B) in relation to Walnut (8-1A) through the spacing of the dots; and also that Worrell reached higher depths than Walnut. Also, the potholes rarely reached their maximum storage capacity (overflowed), which is predicted, once these are under a corn-soybeans management, and are being artificially drained. Nevertheless, overflow caused by snowmelt was observed during the early season of 2014, which suggests that AnnAGNPS is not efficient in the estimation of runoff generated because of snowmelt, as discussed by other authors (Das et al. 2008)

Based in this assessment, it is possible to estimate the hydroperiod of the potholes, which will give us an idea of the frequency of inundation, the average number of consecutive days the features stay flooded, and the intensity of inundation. In following assessments, just the depths higher than 0.05 m were considered. Figure 8-2 shows the hydroperiod, or total number of inundated days for the simulated years, from 1992 to 2014, and the number of inundations during the growing season for both potholes.

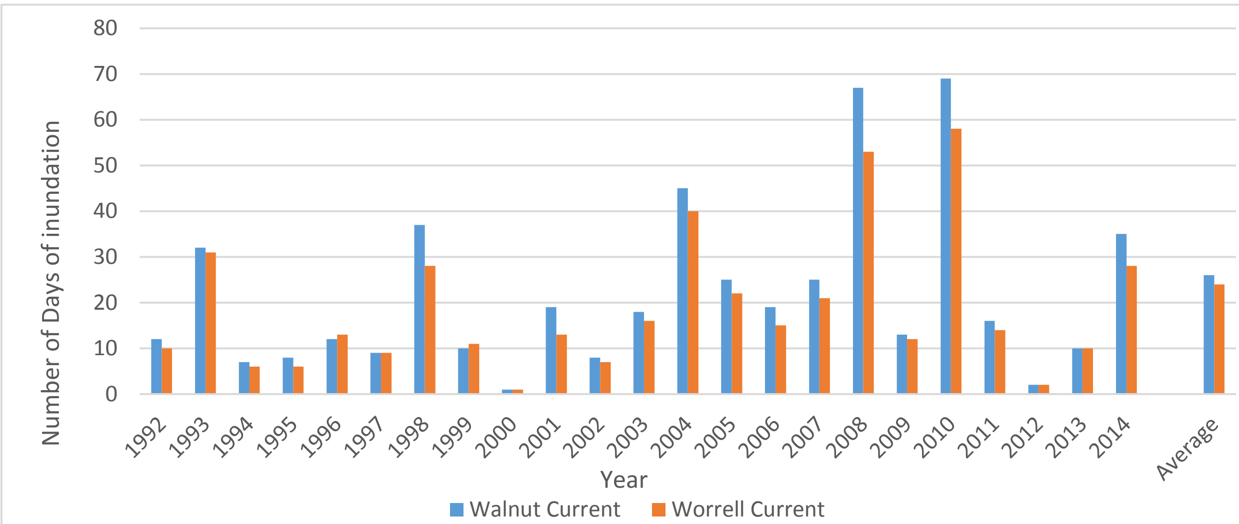



Figure 8-2: Simulated inundated days from 1992 to 2014 for current conditions in Walnut and Worrell potholes.

In the current condition, Walnut and Worrell potholes had similar patterns through the years, which is expected, due their proximity and similar management. Based on these simulations, the water regime of the potholes can be classified as semipermanent, since these tend to flood at least once a year (Galatowitsch and Valk 1996). The years of 2008 and 2010 had the higher number of inundations, whereas 2000 and 2012 had the fewest. The average number of inundations per year was 26 and 24 for Walnut and Worrell, respectively.

The number of consecutive days in which the potholes stay flooded is discussed because it also has a significant impact in crop development in the field, and in the efficiency of the potholes in the improvement of water quality, since, the longer water is stored by the potholes, the higher is the chance of nutrient absorption and sediment settlement. Table 8-1 gives the number of consecutive days the features stay flooded, and its frequency for all the simulated years.

Table 8-1: Worrell and Walnut frequencies of consecutive inundations in the current condition.

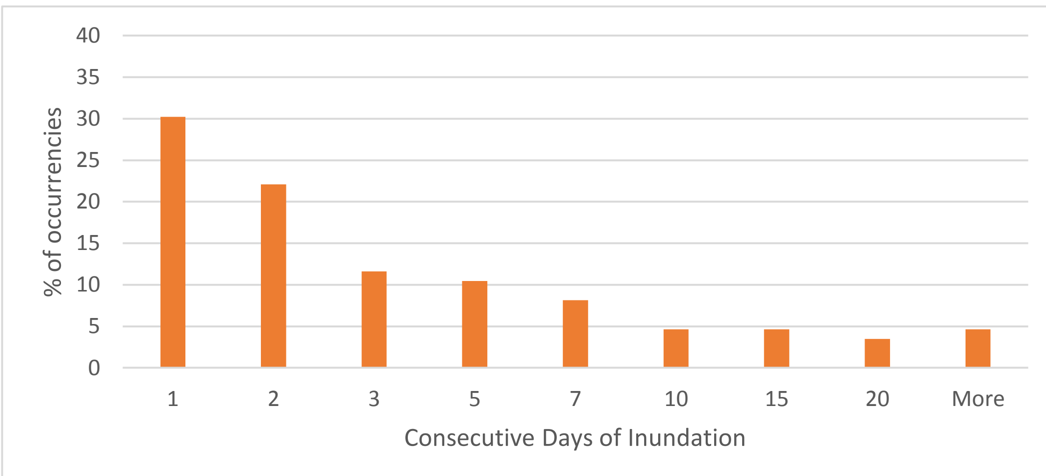
| | Walnut | | Worrell | |
|---|---|---|---|---|
| **Days of consecutive inundations** | | (%) | | (%) |
| **1** | 26 | 30.2 | 36 | 32.4 |
| **2** | 19 | 22.1 | 25 | 22.5 |
| **3** | 10 | 11.6 | 19 | 17.1 |
| **5** | 9 | 10.5 | 11 | 9.9 |
| **7** | 7 | 8.1 | 9 | 8.1 |
| **10** | 4 | 4.7 | 4 | 3.6 |
| **15** | 4 | 4.7 | 1 | 0.9 |
| **20** | 3 | 3.5 | 5 | 4.5 |
| **20 +** | 4 | 4.7 | 1 | 0.9 |
| **Sum** | 86 | 100 | 111 | 100 |
| **2 to 20+** | 60 | 69.8 | 75 | 67.6 |

In table 8-1 we have assessed all the inundation events simulated by AnnAGNPS. The length of the inundation event will last from the first day to the last day water is observed in the features. The number of days the potholes stayed flooded during the simulation can be computed by multiplying a specific number of consecutive inundations by its frequency. For instance, Walnut had 10 events of 3 days of consecutive inundations, which consists of 30 days of flooding in this pothole, for events lasting 3 days during the simulation. Percentage frequency corresponds to the number of events in which water stayed in the potholes during a specific consecutive number of inundations, in relation to all inundation events, from one to more than 20 days of consecutive inundation. According this table, over 30% of the events in which the potholes filled with water lasted for one day in the current condition.

In table 8-1 we have added the sum of the consecutive inundations lasting from two to more than 20 days because when the potholes hold water for more than two days, the higher the chance of negative impacts in the yields. With these results we have that almost 70% of the inundation will some negative impacts on the plants. The effect of consecutive days of inundation in the crops is also a function of the development stage of the plant. However, since the objective of the project was to address the water balance of the potholes; here we considered that any inundation event lasting more than two days will cause negative impacts for crops. Additionally, because this analysis was made considering the total simulation, some consecutive events might have happened outside the growing season, which would not impact the crops. Nevertheless, this study can provide a better understanding of pothole hydrology. The water quality impact as a consequence of multiple days of inundation is not discussed due the limitation of data.

Figure 8-2 illustrates the information of frequency percentage, available in table 8-1, in a histogram format, for the assessment of consecutive inundations in the current conditions.

A)




B)

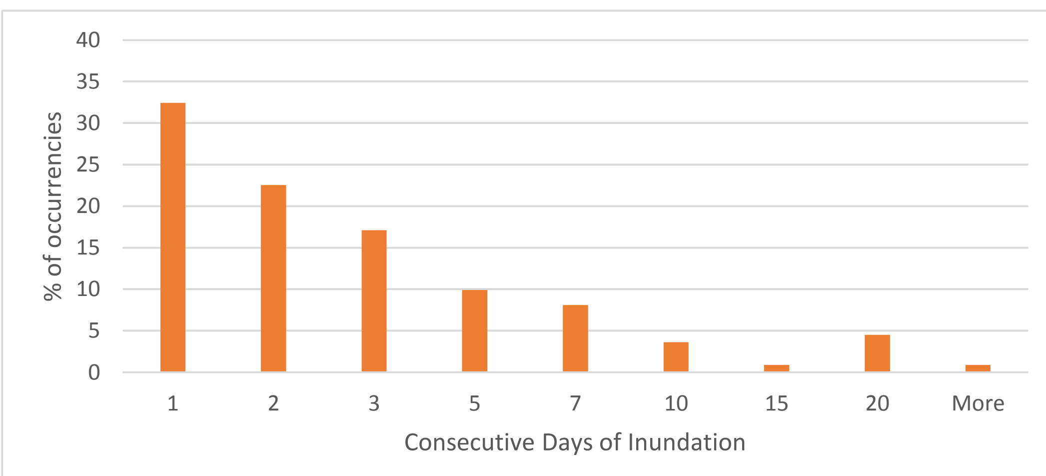



Figure 8-3: Consecutive inundations in the potholes A) Walnut and B) Worrell in the current condition.

In figure 8-2 and table 8-1, it is possible to observe that for most of the inundation events, water will stay flooded for fewer consecutive number of days, probably as a consequence of the high infiltration rate of the potholes in the current condition. According to the median of the results of consecutive inundations of both potholes, these will stay flooded for two days in a row in both potholes. The median was used instead of the average because the percentage of occurrences is higher for fewer consecutive days of inundation.

The average number of inundations per month for each pothole is shown in table 8-2 along with the corresponding estimated plant growth stage for corn and soybeans. The plant growth stages are: Initial, Development, Maturation, and Senescence, and correspond respectively to 15, 40, 30 and 5% of the growing season, according to FAO documentation (FAO, 1998).

Table 8-2: Inundation in the potholes in a monthly basis.

| **Plant Stage** | **Initial/Develop.** | **Develop.** | | **Develop. / Mat.** | **Mat.** | **Senesc.** | |
|---|---|---|---|---|---|---|---|
| **Month** | May | June | July | August | September | October | Total |
| **Walnut** | 5 | 6 | 6 | 4 | 3 | 1 | 25 |
| **Worrell** | 4 | 6 | 5 | 3 | 3 | 1 | 22 |

According the results available in table 8-2, it is possible to affirm that the simulations from 1992 to 2014 have shown that the potholes tend to flood more frequently in early stages of plant development, during May, June, and July, which can also represent a delay in operation dates.

The potholes are considered to overflow when water exceeds their maximum elevation depth, which corresponds to 0.7 and 1 meter for Walnut and Worrell, respectively. No events of overflow were observed in Walnut for the depth analysis in the current condition. On the other hand, Worrell exceeded its holding capacity once during the simulation period, in November of 2008. Nevertheless, in April of 2014, overflow was observed in the site as a consequence of snowmelt, which was not simulated by the model. Then, it is likely that AnnAGNPS will generate better results of pothole inundation for rainfall events, in relation to snowmelt.

Because of the few occurrences of overflow in both potholes in the depth calibration, it is likely that the water stored in the features is drained by tile inlets, and overflow will likely be generated only under limited circumstances of a combination of wet conditions and high intensity precipitation events.

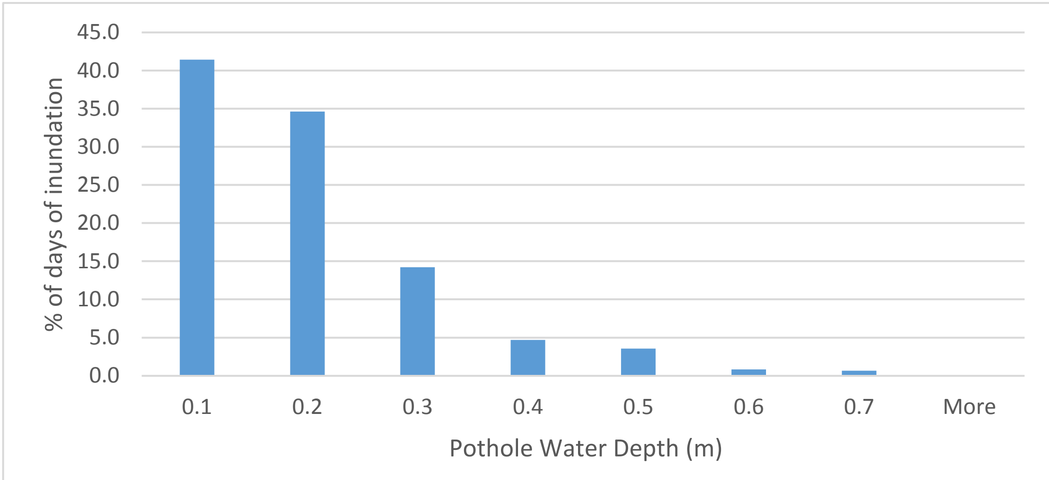
Intensity of inundation illustrates the average water depth during the simulation period, and the corresponding area ponded with water. This analysis will give an idea of the average area not suitable for agricultural purposes in the field as a function of the depth of water. Table 8-3 illustrates the frequency water was accumulated in each depth of the potholes, for a better understanding of the average depth of the inundations.

Table 8-3: Intensity of inundation in Walnut and Worrell potholes for the current condition.

| | **Walnut** | | | **Worrell** | | |
|---|---|---|---|---|---|---|
| **Depth** | Area (m2) | Frequency | Frequency (%) | Area (m2) | Frequency | Frequency (%) |
| **0.1** | 5458 | 256 | 41.4 | 6481 | 159 | 29.3 |
| **0.2** | 9764 | 214 | 34.6 | 13131 | 164 | 30.2 |
| **0.3** | 14022 | 88 | 14.2 | 21016 | 82 | 15.1 |
| **0.4** | 17881 | 29 | 4.7 | 26274 | 55 | 10.1 |
| **0.5** | 21545 | 22 | 3.6 | 31967 | 38 | 7.0 |
| **0.6** | 25067 | 5 | >1 | 38707 | 14 | 2.6 |
| **0.7** | 28572 | 4 | >1 | 45517 | 17 | 3.1 |
| **0.8** | | 0 | 0 | 48810 | 6 | 1.1 |
| **0.9** | | 0 | 0 | 48845 | 4 | >1 |
| **1** | | 0 | 0 | 48857 | 4 | >1 |
| **Total** | | 618 | 100 | | 543 | 100 |

Here, the frequency represents the number of days water was in the specific depth, occupying a specific surface area, computed in ArcGIS, and discussed in Chapter 6. With this assessment, it is possible to observe that Walnut and Worrell potholes have similar hydrology, and both of them will accumulate shallow depths of water, from 0 to 0.2 depth of surface water for most times. Worrell has a higher variation of frequencies within depths because it has a broader depth range. Figure 8-4 illustrates the representation of the results of table 8-3 in a histogram format.

A)




B)

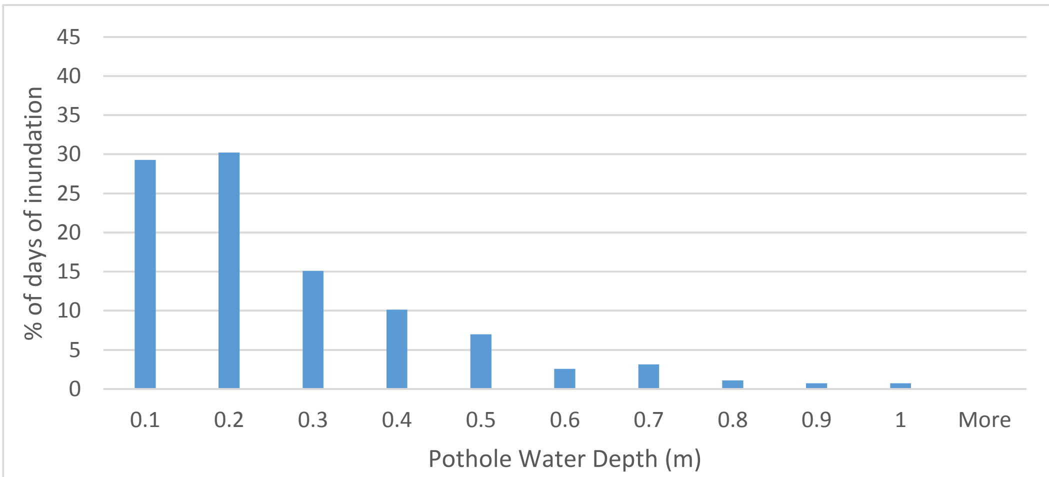


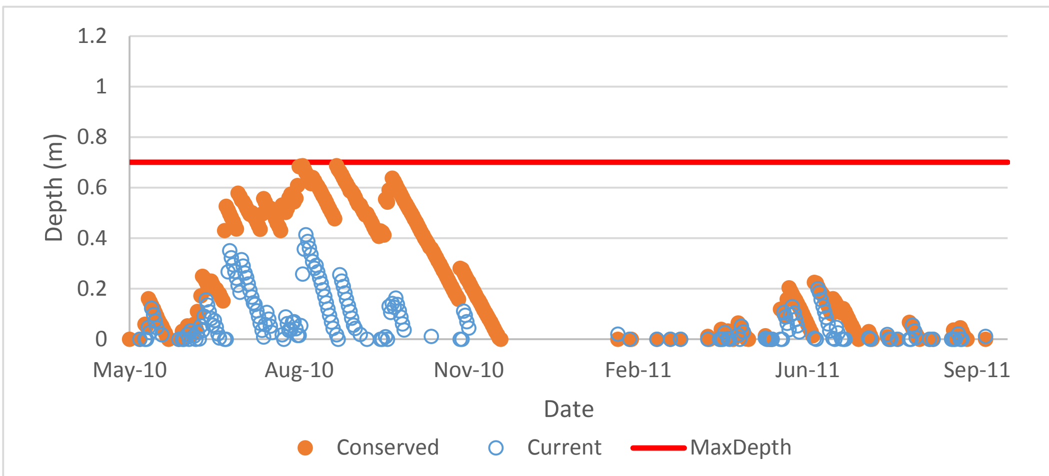

Figure 8-4: Intensity of inundation in the potholes A) Walnut and B) Worrell in the current condition.

With figure 8-4, it is clear to observe that in the current condition, for most events in which water is observed in the potholes, water depth will mainly be around 0.1 and 0.2 m from the bottom of the potholes. Because of the higher frequency of the days in which water is in shallower in relation to higher depths, the median was also the measure chosen to give an idea of the center of distribution of the data. The median of the depth in elevation of the inundation for Walnut and Worrell potholes in the current condition is 0.11 and 0.16 m, that will occupy an area of 0.58 and 1.03 ha respectively, which corresponds to 20% of the surface area of both potholes when these are in their maximum storage capacity. It consists of an additional evidence of the hydrological similarities of the potholes in the current condition.

## 8.3. Simulated Long-Term Depth Variation under Conserved Conditions

Under conserved condition, pothole infiltration is considered to be reduced to 12.5 mm/day, which is considered the default wetland infiltration according AnnAGNPS documentation; and some extent of the microwatersheds converted to bushy vegetation, as discussed in section 5-4. Figure 8-5 illustrates the comparison between conserved and current conditions for Walnut and Worrell current and conserved variations according the depth analysis for the calibration period (2010 and 2011 growing seasons). Summary data for the longer record is presented afterwards.

A)




B)

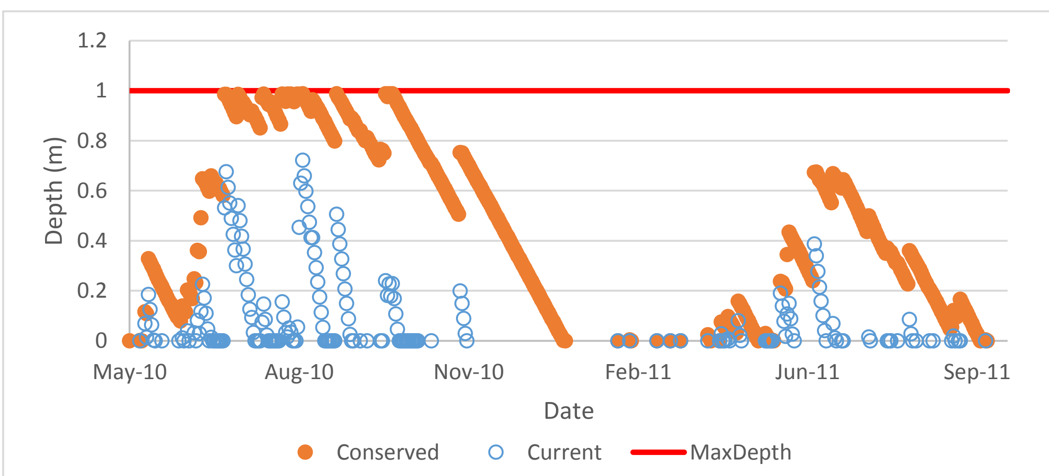
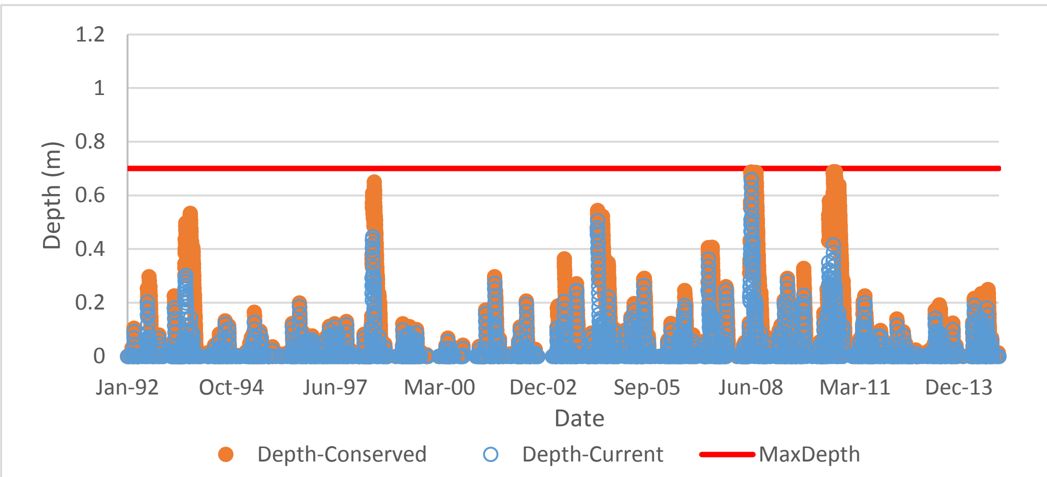



Figure 8-5: Pothole depth comparison in current and retired conditions for the calibration period for A) Walnut and B) Worrell potholes.

In figure 8-5 it is possible to see the differences between current and conserved conditions, in particular for wet years. In drier years, the difference between current and conserved is reduced, which is observed in the results of 2010 (wet) in relation to 2011 (dry). In Worrell (8-5B) the difference between current and conserved is higher because of the higher reduction in the infiltration rate, in relation to Walnut. Figure 8-6 illustrates the comparison between current and conserved for the entire simulation for both features.

A)




B)

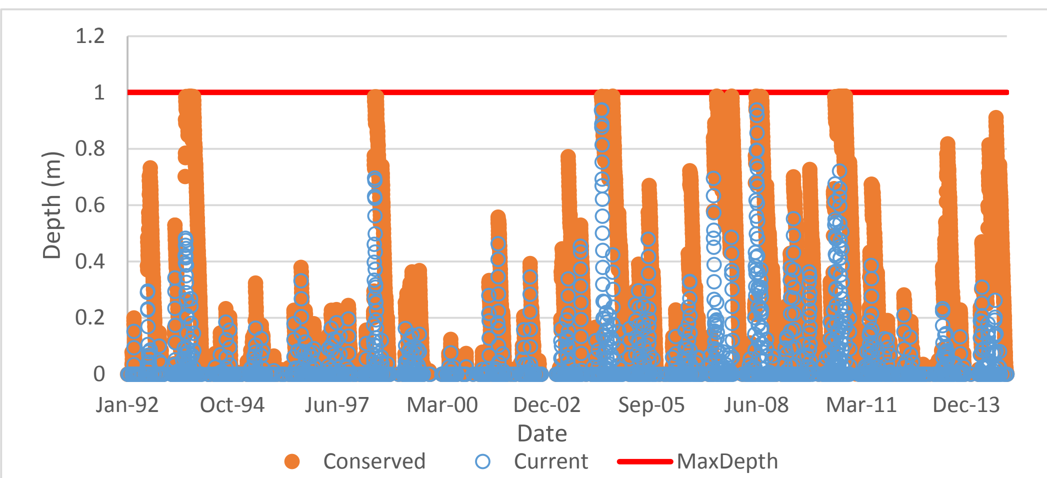



Figure 8-6: A) Walnut and B) Worrell total simulation comparison between current and conserved conditions.

The number of days of ponding is higher in the conserved condition in relation to the current, because of the modifications in the current management in relation to the conserved. The conversion had a higher impact in Worrell in relation to Walnut, probably due the higher drainage area, and a higher infiltration rate in the conserved condition. Figure 8-7 illustrates a comparison between the number of days of inundation in the current and conserved conditions for Walnut and Worrell potholes.

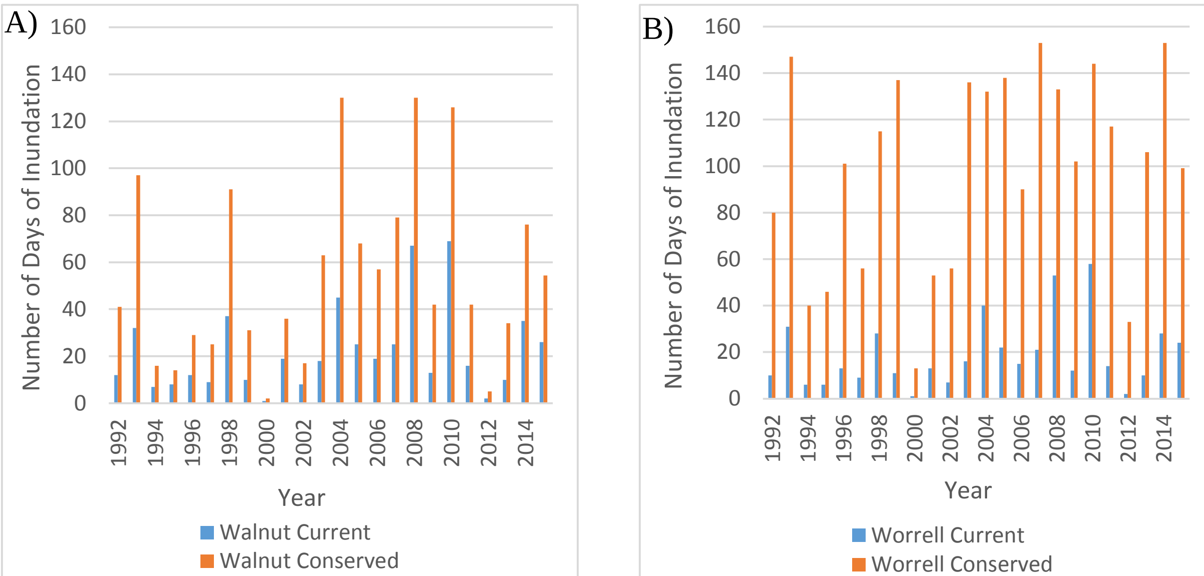



Figure 8-7: Comparison between the number of days of inundation between current and conserved conditions for A) Walnut and B) Worrell pothole.

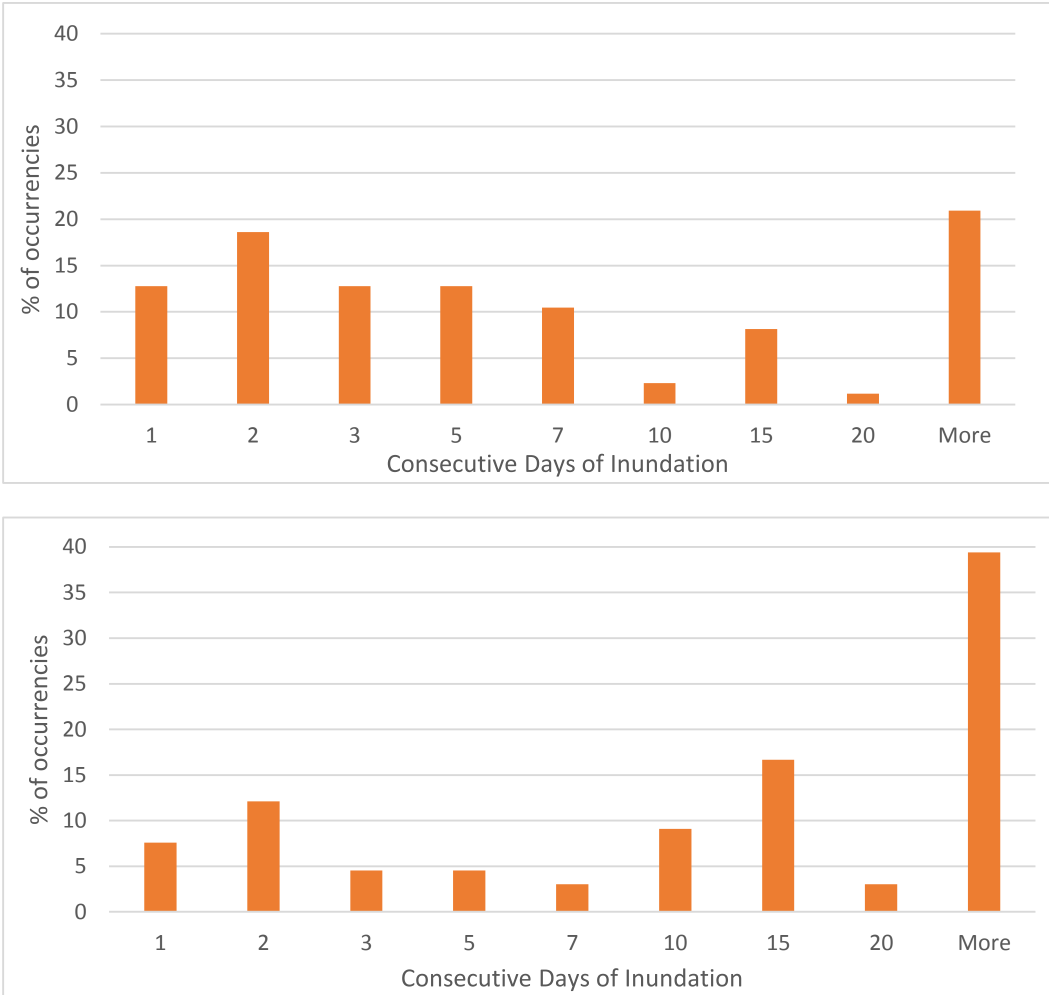
For all the simulation, the difference between current and conserved condition was higher in Worrell, which suggests that the conversion of this pothole to the conserved condition would have a higher impact in its hydrology. Nevertheless, the conserved scenario consists of a hypothetical condition, and more research is required to access whether it would be the real impact of conservation. The assessment of the number of days of consecutive days of flooding for the conserved condition is illustrated in table 8-4.

Table 8-4: Worrell and Walnut frequencies of consecutive inundations for the Conserved condition.

| | **Walnut** | | **Worrell** | |
|---|---|---|---|---|
| **Days of consecutive inundations** | | (%) | | (%) |
| **1** | 11 | 12.8 | 5 | 7.6 |
| **2** | 16 | 18.6 | 8 | 12.1 |
| **3** | 11 | 12.8 | 3 | 4.5 |
| **5** | 11 | 12.8 | 3 | 4.5 |
| **7** | 9 | 10.5 | 2 | 3.0 |
| **10** | 2 | 2.3 | 6 | 9.1 |
| **15** | 7 | 8.1 | 11 | 16.7 |
| **20** | 1 | 1.2 | 2 | 3.0 |
| **20 +** | 18 | 20.9 | 26 | 39.4 |
| **Sum** | 86 | 100 | 66 | 100 |

Differently from the current condition, in the conserved, the potholes will spend more consecutive days inundated. As observed in table 8-4, about 21 and 40% of the consecutive days of the inundation events will last for more than 20 days, for Walnut and Worrell, respectively. In the conserved condition, there will be fewer inundation events, but the features will hold water for longer periods. The number of inundation events lasting more than two days is not available in table 8-4 because in this scenario there will be no crops within the potholes. Figure 8-8 illustrates the histogram related with each of the potholes, in the assessment of consecutive inundations for the conserved condition for both potholes.

A)




B)



Figure 8-8: Consecutive inundations in the potholes A) Walnut and B) Worrell in the conserved condition.

In the comparison between the consecutive number of inundations in the current (figure 8-2), and conserved condition (figure 8-8), it is possible to observe a higher variation in the later in relation to the prior. In the conserved condition, the median will increase from two consecutive days of inundation to 5 and 14 consecutive days of inundation for Walnut and Worrell potholes. The number of consecutive days of inundation in Worrell in relation to Walnut can be a consequence of the higher drainage area of this pothole, and larger difference between the infiltration in the current and conserved conditions.

In the conserved condition, there were eight occurrences of overflow for Walnut pothole, all during 2008 and 2010. For Worrell, there were 34 events of overflow, in several years. It suggests that by retiring the potholes these will flood and inundate more frequently if no other conservational practice is used in the fields. Considering that the drainage system in the fields are located in the specific to the potholes, in other words, if the drainage systems are unplugged, there will not be any other system to drain the fields. Therefore, the drainage system is removed, it is very likely that the field would be under high humid conditions, which would impact crop yields. Therefore, some practices might be necessary in order to keep the pothole surrounds drier, and leave the potholes to store the extra volume generated by the microwatersheds. Table 8-5 illustrates the frequency water was accumulated in each depth of the potholes in the conserved conditions.

Table 8-5: Intensity of inundation in Walnut and Worrell potholes for the conserved condition.

| | **Walnut** | | | **Worrell** | | |
|---|---|---|---|---|---|---|
| **Depth** | Area (m2) | Frequency | Frequency (%) | Area (m2 | Frequency | Frequency (%) |
| **0.1** | 5458 | 453 | 28.3 | 6481 | 475 | 13.4 |
| **0.2** | 9764 | 457 | 28.5 | 13131 | 708 | 20.0 |
| **0.3** | 14022 | 227 | 14.2 | 21016 | 505 | 14.3 |
| **0.4** | 17881 | 154 | 9.6 | 26274 | 385 | 10.9 |
| **0.5** | 21545 | 132 | 8.2 | 31967 | 246 | 7.0 |
| **0.6** | 25067 | 120 | 7.5 | 38707 | 260 | 7.4 |
| **0.7** | 28572 | 58 | 3.6 | 45517 | 262 | 7.4 |
| **0.8** | | | | 48810 | 233 | 6.6 |
| **0.9** | | | | 48845 | 186 | 5.3 |
| **1** | | | | 48857 | 273 | 7.7 |
| **Total** | | 1601 | 100 | | 3533 | 100.0 |

As predicted, the conversion to conserved conditions had a higher impact in Worrell than in Walnut, because of the higher drainage area, and a higher infiltration rate in the conserved condition. Most times, in the occurrence of inundation, the water depth in Walnut will be around 0.1 and 0.2 m, and the frequency it reaches higher depths decrease as the elevation in the potholes increase, similarly to the current conditions. On the other hand, water depth varies more in the

Worrell pothole, since it spreads out more through the pothole profile. Figure 8-9 illustrates the information available in table 8-5 of each pothole in the conserved scenarios.

A)

B)

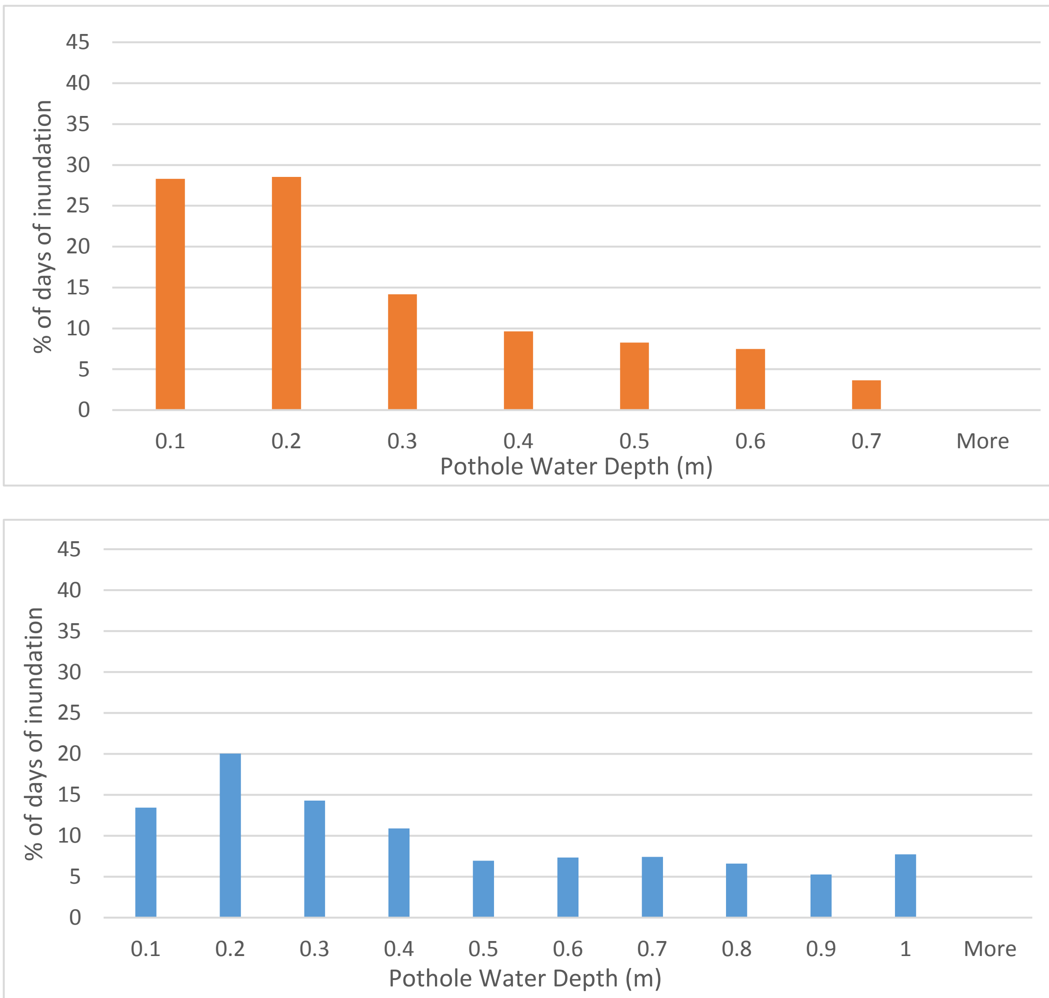



Figure 8-9: Intensity of inundation in the potholes A) Walnut and B) Worrell in the conserved condition.

By comparing the intensity of the inundation in the current and conserved conditions (figures 8-4 and 8-9), it is possible to observe that in the conserved conditions, the potholes will have a smoother variation in the surface water depth in the potholes, while in the current conditions, during an inundation events, the water in the potholes will be likely around 0.1 and 0.2 m. The median of the depth in elevation of the inundation for Walnut and Worrell potholes in the current condition is 0.23 and 0.40 m, that will occupy an area of 0.84 and 2.14 ha respectively, which corresponds to 30% and 44% of the surface area for Walnut and Worrell potholes when these are in their maximum storage capacity. In the conserved scenario, the hydrology of the potholes will no longer be similar, since Worrell will inundate for longer periods and water will reach higher depths in this pothole, in relation to Walnut.

### 8.4. Summary

In this chapter, the results of the depth calibration for the current and conserved conditions are available. With the results, it is possible to affirm that the potholes will inundate more during early stages of the growing season, and for more consecutive days in the conserved condition in relation to the current. Additionally, in the current condition, the surface water will mainly be around 0.1 and 0.2 m in the potholes, while, in the conserved condition, the water depth will have a higher variation in the profile of the potholes, which suggests that the surface water will be higher in the current condition in relation to the conserved, as expected.

# CHAPTER 9: VOLUME SIMULATION RESULTS

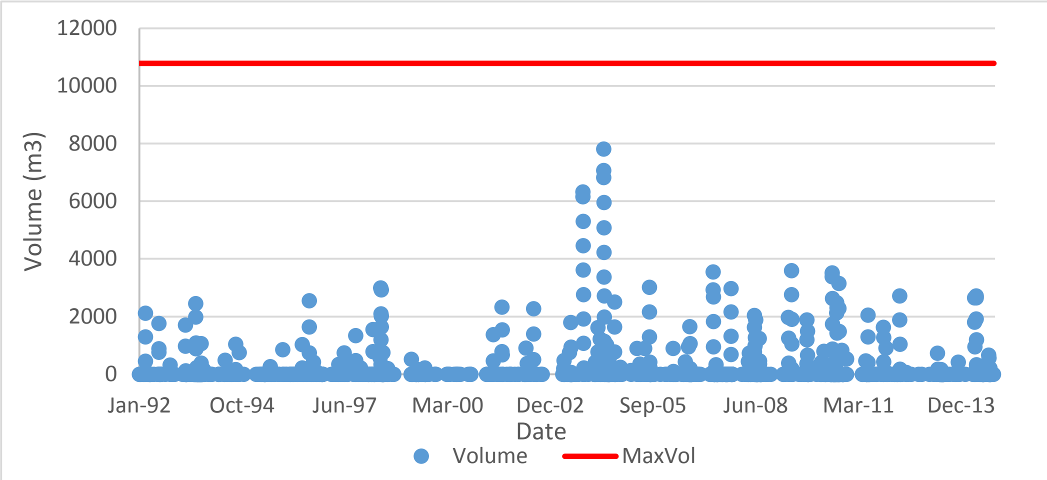
## 9.1. Objectives

Here, the objective is to discuss the results of AnnAGNPS simulations according the volume calibration for current and conserved conditions, and illustrate the differences in volume variations in the comparison of both scenarios. Because the objective of the project was to investigate water balance variations in the potholes, the results of this section do not include the assessment of the hydroperiod, as the results in the depth analysis. The results of both potholes are available, although AnnAGNPS had unsatisfactory results in the volume calibration.

## 9.2. Simulated Long-Term Volume Variation under Current Conditions

As discussed in previous sections, calibrations for the volume analysis were different, in which the microwatesheds had a better hydrological condition of in the volume analysis in relation to the depth, resulting in less water accumulation in the features. The objective of this analysis was to capture volume variations, when the objective of the depth analysis was to capture depth variations. Figure 9-1 illustrates the volume storage for the total simulation for Walnut pothole, for the current condition.

A)




B)

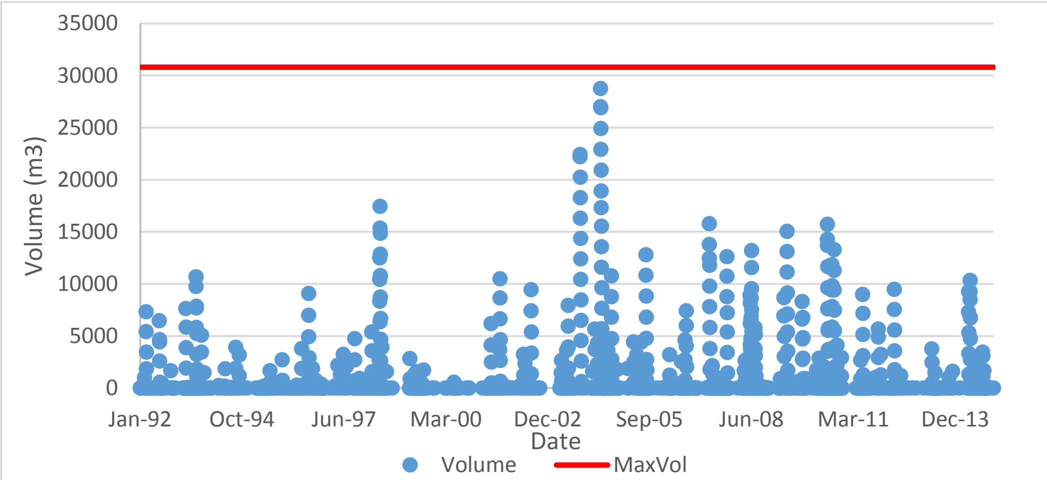



Figure 9-1: A) Walnut and B) Worrell volume variation for the total simulation.

Because of the different hydrological conditions between simulations, the graphs of the total simulation were different for depth and volume analysis. The number of days in which the features flooded in the growing season is not applicable in this analysis since calibration of Walnut pothole did not have satisfactory results.

The dynamics of volume were different from depth simulations. The potholes reached a higher volume storage in the year of 2004, not 2008 or 2010, in which the higher depth was observed in the previous calibration, probably due the high rainfall depth of 131.5 mm/day in 2004, the highest of the 23 years of data. For the volume analysis, the volume stored in the potholes was directly related with rainfall depth, while in the depth analysis, the moisture conditions played a big role in the dynamics of water table. Therefore, it is likely that the depth were higher in 2008 and 2010 in the depth analysis because of continuous rainfall events, while, in the volume analysis, the event itself has higher influence. For this calibration, the potholes did not overload in any circumstance of the growing season.

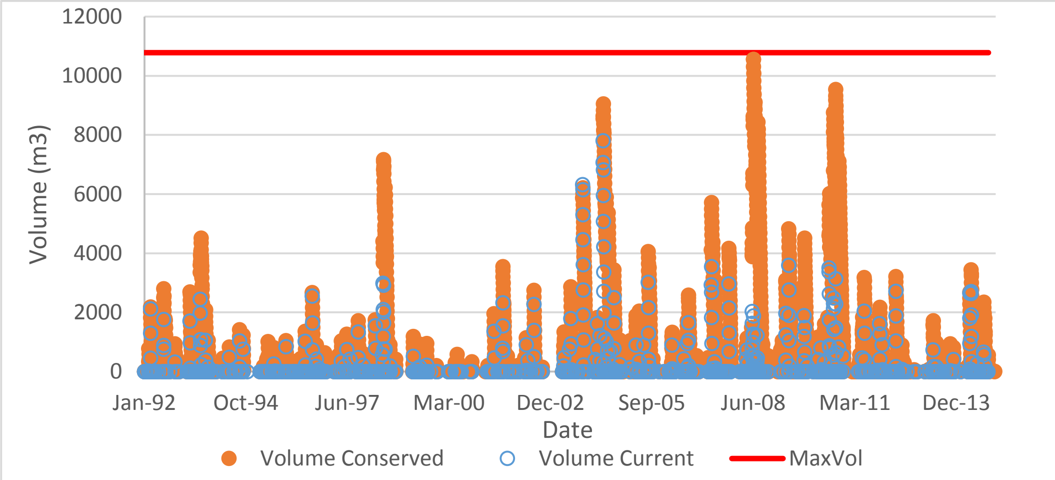
## 9.3. Simulated Long-Term Volume Variation under Conserved Conditions

In this section, the differences between the volume loaded in the microwatersheds in the conserved scenarios are discussed. As performed for the depth analysis, the conversion to conserved conditions happened through the conversion of a certain percentage of the watershed to bushy vegetation and the reduction of the infiltration in the wetland, from 55 and 70 mm/day for Walnut and Worrell, to 12.5 mm/day. The differences between current and conserved are expected to be smaller for the volume analysis since the microwatersheds are considered to generate less runoff, and discussed in Chapter 7.

In the estimation of the number of inundation events, the potholes exceed their volume capacity more often than in the current condition. Walnut and Worrell overflow one and eight times, during the entire simulation, mainly in the wet years of 2004, 2008, and 2010.

Graphical representation of volume loaded into the features in current and conserved conditions, as well as the volume difference are available in figure 9-2, for Walnut pothole.

A)




B)

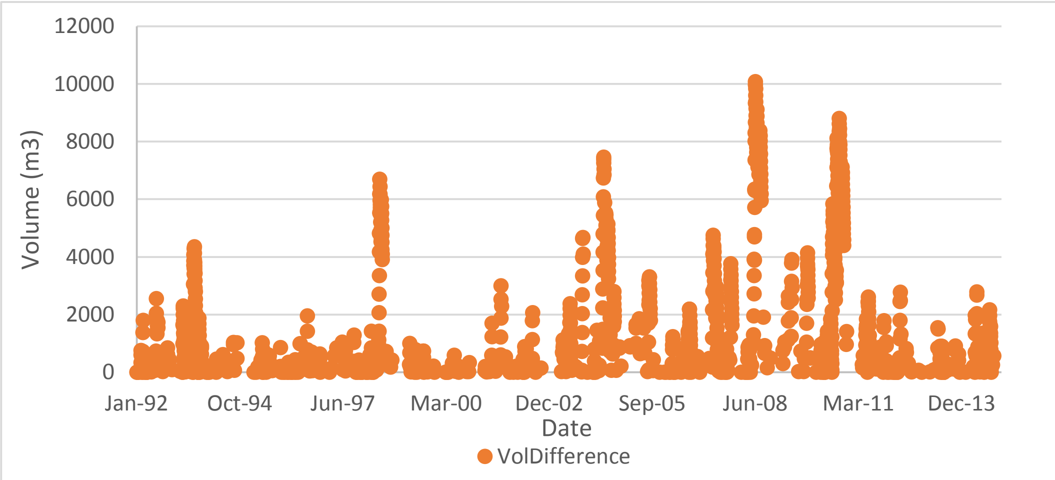
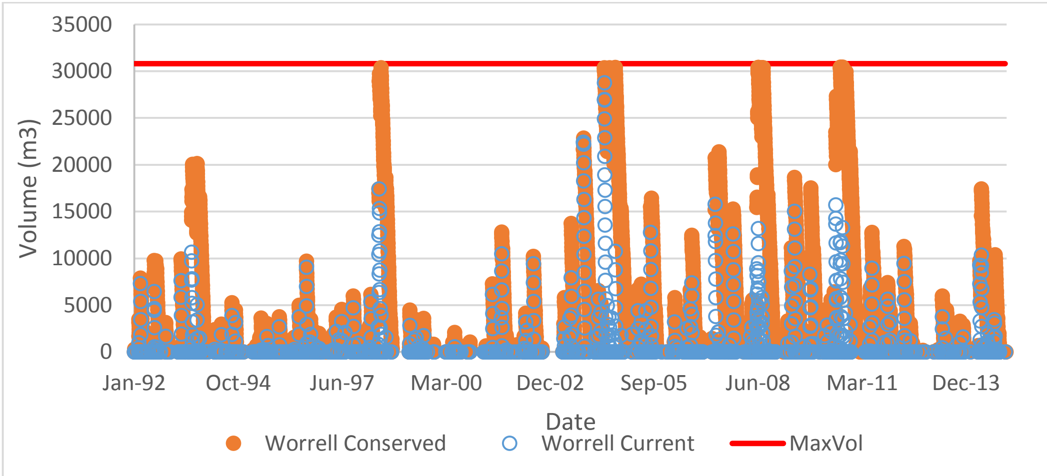



Figure 9-2: A) Current and conserved comparison and B) volume difference for Walnut pothole.

For Worrell, the graphical representation of volume loaded into the features in current and conserved conditions, and the volume difference are available in figure 9-3.

A)




B)

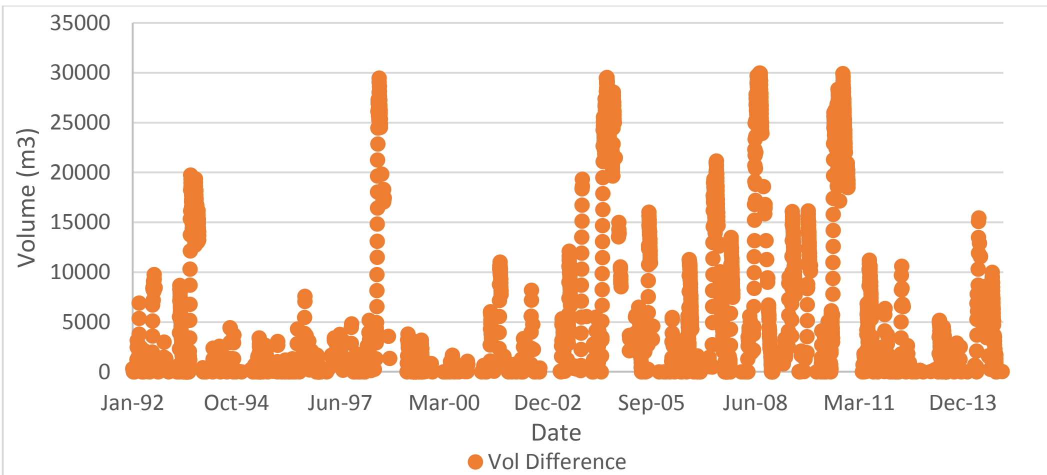



Figure 9-3: A) Current and conserved comparison and B) volume difference for Worrell pothole.

## 9.4. Summary

As observed in the results of the depth calibrations, in the conserved scenario, the potholes will store more water. Nevertheless, because the microwatershed generates less runoff under the volume calibration, here, the potholes will exceed their volume storage capacity fewer times in relation to the depth calibration.

More research is needed to identify better analysis in the volume storage variation in the potholes that can contribute for the understanding of their hydrological patterns, and therefore what would be their best use.

# CHAPTER 10: CONCLUSIONS AND FURTHER RESEARCH

## 10.1. Conclusions

The objective of this thesis was to increase the understanding of pothole hydrology in the Des Moines Lobe with the use AnnAGNPS watershed model. It estimates watershed runoff by the characterization of physical processes in the watershed, which required diverse inputs, such as topography, climate, soil, and land cover. Two features in Story County were investigated, and to improve their assessment with AnnAGNPS, pothole volume capacity was estimated with the a assessment of a high-resolution DEM, which allowed the estimation of the volume and surface area related with each 0.1 m in elevation depth of the features. Results of the potential volume holding capacity of the feature suggests that they can be used for other purposes apart from agriculture land, such as flood control structures. Also, the area of surface water was related with model results of water depth variations in the potholes, to estimate the area in the fields covered by water, when the potholes are flooded.

Two management conditions were investigated and simulated by AnnAGNPS. First current management, in which the potholes are under corn-soybeans rotation, was characterized; and the conserved condition, in which the artificial drainage was removed and no cropland was considered in the potholes extent. The model was calibrated with a limited number of observed data, which suggests that the results could be relaxed to account for the limitation of a reduced span of calibration. Because the model considers a linear relationship between the volume stored and water depth in the potholes, it was not able to simulate depth and volume variations in the potholes with the same calibration, and for this reason AnnAGNPS was calibrated twice, according depth and volume variations in the features. Through simulations and comparisons, it was observed that AnnAGNPS watershed model was able to assess the hydroperiod of prairie potholes in the current condition with a certain level of reliability according depth calibrations, with fair NSE indexes. Currently, the model was successfully able to capture water depth variations, not the same for volume storage assessment, because NSE values were smaller, and unsatisfactory in the assessment of Walnut pothole.

Simulations indicate that potholes will have similar hydrological patterns. Both will flood during the growing season, having a semipermanent water regime, which is contradictory with their current use, lands designated to agricultural production. In the occurrence of inundations, these will mostly stay flooded for two consecutive days, and will accumulate water in shallow depths, occupying about 20% of their surface area in their maximum storage. Results also show that these features commonly inundate early in the season, potentially causing problems to farmers by interfering in the dates of field operations, and also in crop yields.

Under the current condition, potholes were barely observed to overflow. When drained, potholes tend to flood less often, however, drained water merges with other sources of flow in the drainage districts, which suggests an indirect influence and nexus downstream. On the other hand, under the conserved scenario, the potholes will have different hydrological patterns, in which Worrell will flood more often, for a higher number of consecutive days, and for more consecutive days in relation to Walnut pothole. For instance, Walnut will mostly inundate for five consecutive days, and during the inundation will inundate about 30% of its surface area, while Worrell will inundate for 14 consecutive days, reaching 44% of its surface area. Both features will overflow more often, in particular Worrell, having direct effects downstream, but less indirect impact. The higher impact of in Worrell in relation to Walnut is because its higher reduction in the infiltration rate in relation to the current condition, and its larger drainage area. Therefore, the higher the pothole drainage area, the higher the impact in its hydrology.

With the disconnection of the tiles in the potholes, soils in the field will store more water, which has shown to cause flood in the fields for both depth and volume analysis. For this reason, with the disconnection of the tiles, it is important to consider the use of conservation practices to reduce runoff production by the watershed. Nevertheless, more research is necessary to affirm whether pothole conservation will provide significant storage for flood control and have similar effects to the simulated by the model.

The main contribution of this project is that it is possible to model farmed and drained pothole microwatersheds. Then, it is possible to simulate the hydrology of other features, in other places and with other models, to investigate if similar patterns are observed. Here, the hydrology of the potholes suggests that these are not being used according their potential, which might not be the pattern to other features in the PPR. Results of this project can be used as a justification to policy-makers in the new legislations to decide the future of this feature and its most suitable management, consistent with their hydrological patterns.

### 10.2. Further Research

Since it was proved that it is possible to model potholes, the next step is to improve modeling techniques to understand its hydrological dynamics. For instance, to improve AnnAGNPS model to account for the topography of the features, so it would not be necessary to calibrate the model according depth and volume variations. Additionally, if tiled water were not loaded into the reaches along with surface water, it would be possible to simulate the impact of tiled microwatersheds with AnnGNPS.

If drained water was not loaded into the features with surface water, it would be possible to simulate tilled microwatersheds, instead of potholes. This scenario would be more realistic for the state of Iowa, in relation to no artificial drainage, as simulated in the conserved condition. A further step in the improvement of the model would be the computation of the water balance in an hourly basis, to capture the maximum water level and volume in the potholes in a given day. Also, the model would generate better results if it was possible to simulate common features in potholes, such as artificial tile drainage, and surface intake.

Future research include the collection of observed data to be used in the calibration and validation of the model, and simulation of potholes under diverse scenarios in order to assess the most suitable management for potholes, compatible with their hydrology. Also, the assessment of the impacts of potholes in the transport of pollutants in the watershed, and assessment of their potential environmental services. Observed data of water quality must be collected to understand the dynamics of pollutants in the potholes, and whether watershed models are able to simulate their behavior.

During the development of this project, a new version of AnnAGNPS (Version 5.43) was released. In the newer version, instead of assuming infiltration rate in the potholes to be equal to 12.5 mm/day when the user does not include any infiltration rate value, it assumes that the infiltration will be equivalent to the average infiltration of the watershed, based in its soils. The results of this scenario for the depth calibration is shown in figure 10-1.

A)

B)

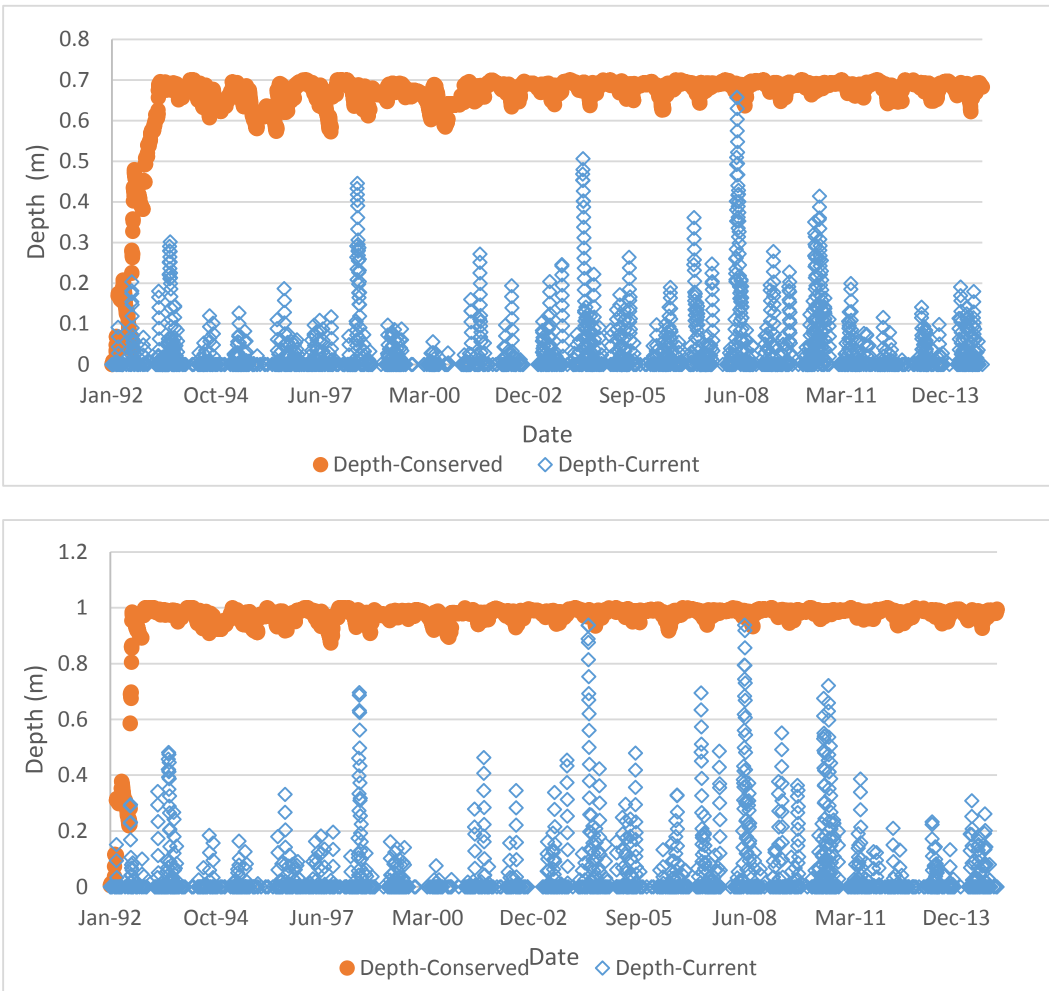



Figure 10-1: Comparison between current and conserved conditions considering average infiltration in the watersheds for A) Walnut and B) Worrell potholes.

In this simulation, the infiltration rate computed by the model was minimum for the watershed soils, which caused the potholes to flood all year long. It is probably not the case for the potholes investigated for this project, but was the case of some potholes in Story County in prior to settlement. This simulation arises the question of whether pothole conservation would cause some features to store water all year long, and what would be the impacts in the watershed.

For last, more research is necessary in the determination of the best approach to determine pothole extent, with DEM assessment. Here, we have determined the pothole extent according the subtraction of the original DEM by its filled version. It gives a good notion of the location of the feature, but not its actual extent. In this project we believe that the pothole area was overestimated.

# CHAPTER 11: REFERENCES

Allen, R.G, Pereira, L. S., Raes, D, Smith, M. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO – Food and Agriculture Organization of the United Nations Rome, ISBN 92-5104219-5, http://www.fao.org/docrep/X0490E/X0490E00.htm, FAO Irrigation and drainage paper 56. 565p.

Aronson, Myla F J, Susan Galatowitsch, Alderman Hall, and St Paul. 2008. "Long-Term Vegetation Development Of Restored Prairie Pothole Wetlands Long-Term Vegetation Development of Restored Prairie Pothole Wetlands" 28 (4): 883–895.

Bingner, R.L.; Theurer, F.D.; Yuan, Y. AnnAGNPS Technical Processes 2011. Available online: http://www.ars.usda.gov/Research/docs.htm?docid=5199 (accessed on 10 March 2015).

Brown, Stephen C., and Barbara L. Bedford. 1997. "Restoration of Wetland Vegetation with Transplanted Wetland Soil: An Experimental Study." *Wetlands* 17 (3): 424–437. doi:10.1007/BF03161432.

Das, S, R P Rudra, B Gharabaghi, S Gebremeskel, P K Goel, and W T Dickinson. 2008. "Applicability of AnnAGNPS for Ontario Conditions" 50: 1–11.

Drake, Chad Walter. 2014. "Assessment of Flood Mitigation Strategies for Reducing Peak Discharges in the Upper Cedar River Watershed." University of Iowa.

Du, B, J G Arnold, A Saleh, and D B Jaynes. 2005. "Development and Application of Swat to Landscapes with Tiles and Potholes" 48 (3).

Euliss, Ned H, and David M Mushet. 1996. "Water-Level Fluctuation in Wetlands as A Function of Landscape Condition in the Prairie Pothole Region" 16 (4): 587–593.

Fennessy, Siobhan, and Christopher B. Craft. 2011. "Agricultural Conservation Practices Increase Wetland Ecosystem Services in the Glaciated Interior Plains" 21 (3): 49–64.

Frei, S, and J H Fleckenstein. 2014. "Environmental Modelling & Software Representing Effects of Micro-Topography on Runoff Generation and Sub-Surface Fl Ow Patterns by Using Super Fi Cial Rill / Depression Storage Height Variations" 52: 5–18.

Galatowitsch, Susan M., and Arnold G. Valk. 1996. "Characteristics of Recently Restored Wetlands in the Prairie Pothole Region." *Wetlands* 16 (1) (March): 75–83. doi:10.1007/BF03160647. http://link.springer.com/10.1007/BF03160647.

Gelder, K. Brian. 2015. Automation of DEM Cutting for Hydrologic/Hydraulic Modeling. Iowa Highway Research Board Report No. TR-631.

Gleason, RA, MK Laubhan, BA Tangen, and KE Kermes. 2008. "Ecosystem Services Derived from Wetland Conservation Practices in the United States Prairie Pothole Region with an Emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs." http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1111&context=usgsnpwrc.

Gleason, Robert A, and Ned H Jr. Euliss. 1998. "Sedimentation of Prairie Wetlands." *Great Plains Research: A Journal of Natural and Social Sciences* 363.

Gleason, Robert A., Brian A. Tangen, Murray K. Laubhan, Kevin E. Kermes, and Ned H. Jr Euliss. 2007. "Estimating Water Storage Capacity of Existing and Potentially Restorable Wetland Depressions in a Subbasin of the Red River of the North." Virginia.

Huang, Shengli, Claudia Young, Min Feng, Karl Heidemann, Matthew Cushing, David M. Mushet, and Shuguang Liu. 2011. "Demonstration of a Conceptual Model for Using LiDAR to Improve the Estimation of Floodwater Mitigation Potential of Prairie Pothole Region Wetlands." *Journal of Hydrology* 405 (3-4) (August): 417–426. doi:10.1016/j.jhydrol.2011.05.040. http://linkinghub.elsevier.com/retrieve/pii/S0022169411003684.

Justice, Vance, and Ronald L Bingner. 2015. "AGNPS Input Data Preparation Model User ' S Guide" (February).

Karlen, Douglas L, Dana L Dinnes, and Jeremy W Singer. 2010. "Midwest Soil and Water Conservation: Past, Present, and Future." In *Soil and Water Conservation Advances in the United States*, edited by T.M. Zobeck and W.F. Schillinger, 131–162. Madison, WI: SSSA Special Publication 60.

Krause, P., D. P. Boyle, and F. Bäse. 2005. "Comparison of Different Efficiency Criteria for Hydrological Model Assessment." *Advances in Geosciences* 5: 89–97. doi:10.5194/adgeo-5-89-2005.

Leibowitz, Scott G. 2003. "Isolated Wetlands and Their Functions : An Ecological Perspective" 23 (3): 517–531.

Lenhart, C F, E S Verry, K N Brooks, and J A Magner. 2012. "Adjustment of Prairie Pothole Streams to Land - Use , Drainage And Climate Changes and Consequences for Turbidity Impairment" 1619 (July 2011): 1609–1619. doi:10.1002/rra.

Licciardello, F, D A Zema, S M Zimbone, and R L Bingner. 2007. "Runoff and Soil Erosion Evaluation by The Annagnps Model in a Small Mediterranean Watershed" 50 (5): 1585–1593.

Liu, Hongxing, and Lei Wang. 2008. "Mapping Detention Basins and Deriving Their Spatial Attributes from Airborne LiDAR Data for Hydrological Applications." *Hydrological*

*Processes* (22): 2358–2369. doi:10.1002/hyp. http://jamsb.austms.org.au/courses/CSC2408/semester3/resources/ldp/abs-guide.pdf.

Logsdon, S. D. 2015. “Relation of Depressional Flooding to Soil Water and Upstream Accumulated Flow.” *Transactions of the the ASABE* 58 (2): 1–10. doi:10.13031/trans.58.10625.

Marton, John M., M. Siobhan. Fennessy, and Christopher B. Craft. 2014. “Functional Differences between Natural and Restored Wetlands in the Glaciated Interior Plains.” *Journal of Environment Quality* 43 (1): 409. doi:10.2134/jeq2013.04.0118. https://www.agronomy.org/publications/jeq/abstracts/43/1/409.

Meek, David W., Terry a. Howell, and Claude J. Phene. 2009. “Concordance Correlation for Model Performance Assessment: An Example with Reference Evapotranspiration Observations.” *Agronomy Journal* 101 (4): 1012. doi:10.2134/agronj2008.0180x. https://www.agronomy.org/publications/aj/abstracts/101/4/1012.

Mello, Carlos R De, and Samuel Beskow. 2013. “Simulação Hidrológica Em Uma Bacia Hidrográfica Representativa Dos Latossolos Na Região Alto Rio Grande , MG Hydrological Simulation in a Watershed with Predominance of Oxisol in the Upper Grande River Region , MG - Brazil” (61): 69–76.

Miller, Bradley A., William G. Crumpton, and Arnold G. van der Valk. 2009. “Spatial Distribution of Historical Wetland Classes on the Des Moines Lobe, Iowa.” *Wetlands* 29 (4): 1146–1152.

Miller, Bradley A., William G. Crumpton, and Arnold G. van der Valk. 2012. “Wetland Hydrologic Class Change from prior to European Settlement to Present on the Des Moines Lobe, Iowa.” *Wetlands Ecology and Management* 20: 1–8. doi:10.1007/s11273-011-9237-z.

Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith. 2007. “Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations.” *Transactions of the the ASABE* 50 (3): 885–900. doi:10.13031/2013.23153. http://swat.tamu.edu/media/1312/moriasimodeleval.pdf.

Moriasi, Dn, and Bn Wilson. 2012. “Hydrologic and Water Quality Models: Use, Calibration, and Validation.” *Transactions of the …* 55 (4): 1241–1247. doi:10.13031/2013.42265. http://swat.tamu.edu/media/63553/asabe55(4).asp.pdf.

Nash, J E, and J V Sutcliffe. 1970. “River Flow Forecasting Through Conceptual Models, Part I.” *Journal of Hydrology* 10: 282–290. doi:10.1016/0022-1694(70)90255-6. http://linkinghub.elsevier.com/retrieve/pii/0022169470902556.

Parajuli, Prem B, Nathan O Nelson, Lyle D Frees, and Kyle R Mankin. 2009. “Comparison of AnnAGNPS and SWAT Model Simulation Results in USDA-CEAP Agricultural Watersheds in South-Central Kansas” 763 (December 2008): 748–763. doi:10.1002/hyp.

Que, Z., O. Seidou, R. L. Droste, G. Wilkes, M. Sunohara, E. Topp, and D. R. Lapen. 2015. “Using AnnAGNPS to Predict the Effects of Tile Drainage Control on Nutrient and Sediment Loads for a River Basin.” *Journal of Environment Quality* 44 (2): 629. doi:10.2134/jeq2014.06.0246. https://dl.sciencesocieties.org/publications/jeq/abstracts/44/2/629.

Que, Zhenyang. 2011. “Evaluation of the Impact of Controlled Tile Drainage on Surface Water Quality in the South.”

Roth, J L, and P D Capel. 2012. “The Hydrology of a Drained Topographical Depression within an Agricultural Field in North-Central Iowa” 55 (5): 1801–1814.

Schilling, Keith E, and Matthew Helmers. 2008. “Effects of Subsurface Drainage Tiles on Streamflow in Iowa Agricultural Watersheds : Exploratory Hydrograph Analysis” 4506 (May): 4497–4506. doi:10.1002/hyp.

Schilling, Keith E, and Jean Spooner. 2006. “Effects of Watershed-Scale Land Use Change on Stream Nitrate Concentrations.” *Journal of Environmental Quality* 35 (6): 2132–45. doi:10.2134/jeq2006.0157. http://www.ncbi.nlm.nih.gov/pubmed/17071882.

Schilling, Keith E., and Pauline Drobney. 2014. “Restoration of Prairie Hydrology at the Watershed Scale: Two Decades of Progress at Neal Smith National Wildlife Refuge, Iowa.” *Land* 3 (1) (March 6): 206–238. doi:10.3390/land3010206. http://www.mdpi.com/2073-445X/3/1/206/.

SCS. (1986). Technical Release 55: Urban hydrology for small watersheds. Soil Conservation Service, USDA.

Singh, R, and MJ Helmers. 2009. “Potential Impact of Climate Change on Subsurface Drainage in Iowa’s Subsurface Drained Landscapes.” *... of Irrigation and Drainage ...* (August): 459–466. http://ascelibrary.org/doi/abs/10.1061/(ASCE)IR.1943-4774.0000009.

Sloan, Charles E. 1972. “Ground-Water Hydrology of Prairie Potholes in North Dakota:” 1–29.

Tomer, M. D., S. a. Porter, K. M. B. Boomer, D. E. James, J. a. Kostel, M. J. Helmers, T. M. Isenhart, and E. McLellan. 2015. “Agricultural Conservation Planning Framework: 1. Developing Multipractice Watershed Planning Scenarios and Assessing Nutrient Reduction Potential.” *Journal of Environment Quality* 44 (3): 754. doi:10.2134/jeq2014.09.0386. https://dl.sciencesocieties.org/publications/jeq/abstracts/44/3/754.

Tomer, M. D., S. a. Porter, D. E. James, K. M. B. Boomer, J. a. Kostel, and E. McLellan. 2013. “Combining Precision Conservation Technologies into a Flexible Framework to Facilitate Agricultural Watershed Planning.” *Journal of Soil and Water Conservation* 68 (5) (August 23): 113A–120A. doi:10.2489/jswc.68.5.113A. http://www.jswconline.org/cgi/doi/10.2489/jswc.68.5.113A.

Tomer, M.D., W.G. Crumpton, R.L. Bingner, J.a. Kostel, and D.E. James. 2013. “Estimating Nitrate Load Reductions from Placing Constructed Wetlands in a HUC-12 Watershed Using LiDAR Data.” *Ecological Engineering* 56 (July): 69–78. doi:10.1016/j.ecoleng.2012.04.040. http://linkinghub.elsevier.com/retrieve/pii/S092585741200167X.

“Urban Hydrology for Small Watersheds TR-55.” 1986.

USDA, U.S. Department of Agriculture. 2014. “STEWARDS: Access to CEAP Data.” http://www.nrrig.mwa.ars.usda.gov/stewards/stewards.html.

Whigham, Dennis F., and Thomas E. Jordan. 2003. “Isolated Wetlands and Water Quality.” *Wetlands* 23 (3) (September): 541–549. doi:10.1672/0277-5212(2003)023[0541:IWAWQ]2.0.CO;2. http://link.springer.com/10.1672/0277-5212(2003)023%5B0541%3AIWAWQ%5D2.0.CO%3B2.

Winter, Thomas C, and Donald O. Rosenberry. 1995. “The Interaction of Ground Water with Prairie Pothole Wetlands in the Cottonwood Lake Area, East-Central North Dakota, 1979-1990” 15 (3): 193–211.

Winter, Thomas C, and Donald O. Rosenberry. 1998. “Hydrology of Prairie Pothole Wetlands During Drought and Deluge.” *Climatic Change* 40: 189–209.

Winter, Thomas C., and James W. LaBaugh. 2003. “Hydrologic Considerations in Defining Isolated Wetlands.” *Wetlands* 23 (3): 532–540. http://download.springer.com/static/pdf/7/art%3A10.1672%2F0277-5212%282003%29023%5B0532%3AHCIDIW%5D2.0.CO%3B2.pdf?auth66=1384202000_ef62f8fa61fbabfe6312ee4595f251ee&ext=.pdf.

Yuan, Y, R L Bingner, M A Locke, F D Theurer, and J Stafford. 2011. “Assessment of Subsurface Drainage Management Practices to Reduce Nitrogen Loadings Using AnnAGNPS” 27 (3): 335–344.

Yuan, Yongping, Ronald L Bingner, and Richard A Rebich. 2003. “Evaluation of AnnAGNPS Nitrogen Loading in an Agricultural Watershed” 6649: 457–466.

Yuan, Yongping, Megan Mehaffey, Ricardo Lopez, Ronald Bingner, Randy Bruins, Caroline Erickson, and Michael Jackson. 2011. “AnnAGNPS Model Application for Nitrogen Loading Assessment for the Future Midwest Landscape Study.” *Water* 3 (4) (February 17): 196–216. doi:10.3390/w3010196. http://www.mdpi.com/2073-4441/3/1/196/.

# A. APPENDIX: WATER QUALITY

## A.1. Data collection

Potholes were observed to have some impacts in water quality downstream, and undesirable water quality impacts when disturbed (Winter and Rosenberry 1995a; Winter and Rosenberry 1998; Winter and Rosenberry 1995b). For this project, water samples were collected after precipitation events, when water was accumulated by the surface of the potholes during the year of 2014. Information about Total N, P and sediments from the samples were investigated, as well as nitrate, nitrite, ammonia, and dissolved P. Tables A-1, A-2, and A-3 below illustrate the results found for Walnut, Worrell Field and Worrell Road potholes.

Table A-1: Water quality values for Walnut pothole

| Sample ID | Sample Date | Ammonia (mg/L N) | Nitrate + nitrite (mg/L N)* | Dissolved reactive P (mg/L P) | TSS (g/L) | TP (mg/L) | TN (mg/L)** |
|---|---|---|---|---|---|---|---|
| WAP | 5/1/2014 | 0.0514 | 4.2073 | 0.380 | 6.4900 | 32.5 | 33.7** |
| WAP | 5/21/2014 | 0.2374 | 0.9004 | 0.329 | 1.5750 | 9.3 | 14.3 |
| WAP | 5/22/2014 | 0.0270 | 0.7648 | 0.268 | 0.9000 | 5.3 | 8.2 |
| WAP | 5/23/2014 | 0.0546 | 2.3516 | 0.401 | 1.3867 | 6.0 | 12.7 |
| WAP | 6/17/2014 | 0.1563 | 0.623 | 0.299 | 0.1820 | 0.67 | 3.9 |
| WAP | 6/18/2014 | 0.0471 | 0.7241 | 0.357 | 0.3680 | 5.0 | 3.0 |
| WAP | 6/20/2014 | 0.0257 | 0.3657 | 0.213 | 0.4550 | 6.2 | 6.8 |
| WAP | 6/23/2014 | 0.3566 | 0.0478 | 0.363 | 0.0292 | 0.55 | 3.4 |
| WAP | 6/24/2014 | 0.4581 | 0.0770 | 0.348 | 0.0183 | 0.56 | 1.6 |
| WAP | 6/25/2014 | 1.3814 | 0.0288* | 0.590 | 0.3900 | 10.6 | 11.0 |
| WAP | 6/28/2014 | 0.0635 | 0.0741* | 0.109 | 0.1200 | | |
| WAP | 7/1/2014 | 0.0953 | 0.1313 | 0.044 | 0.0450 | 0.30 | 3.8 |
| WAP | 7/2/2014 | 0.1075 | -0.0085* | 0.068 | 0.0467 | | |
| WAP | 7/3/2014 | 0.1614 | 0.1268 | 0.055 | 0.0400 | 0.24 | 10.9 |
| WAP | 7/6/2014 | 0.2823 | -0.0708* | 0.109 | 0.0150 | | |

* values in red indicate results lower than the standard of 0.02 mg/L of N; **High range TP tests (1-33 mg/L P) are reported to the 1.0 mg/L P level; low range TP tests (0-1 mg/L P) are reported to the 0.01 mg/L P level.

To improve the visualization of the results, the values total P and N are presented in a graphical representation (figs A-1, A-2, and A-3). Sediment is not plotted in the graphs once values collected are in a different scale.

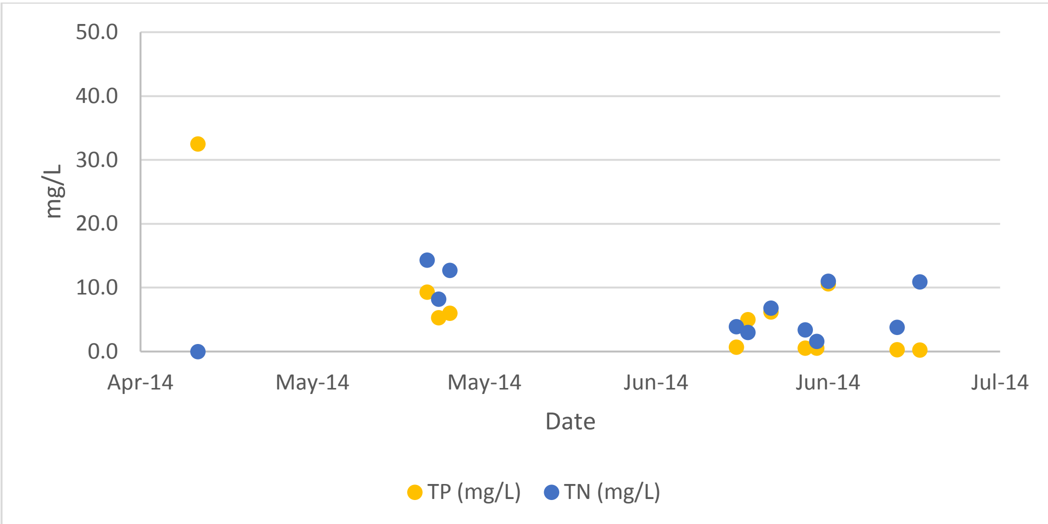



Figure A-1: Nutrient Load in the Walnut pothole.

Table A-2: Water quality values for Worrell Field pothole

| Sample ID | Sample Date | Ammonia (mg/L N) | Nitrate + nitrite (mg/L N)* | Dissolved reactive P (mg/L P) | TSS (g/L) | TP (mg/L)** | TN (mg/L)** |
|---|---|---|---|---|---|---|---|
| WOF | 5/22/2014 | 0.0391 | 1.8346 | 0.344 | 7.6143 | 79.4** | 44** |
| WOF | 5/23/2014 | 0.0545 | 1.4911 | 0.348 | 11.2200 | 45.6 | 50.2** |
| WOF | 6/17/2014 | 0.0955 | 0.7585 | 0.434 | 0.0875 | 0.93 | 4.6 |
| WOF | 6/20/2014 | 0.0622 | 0.3431 | 0.250 | 0.1538 | 1.9 | 1.0 |
| WOF | 6/23/2014 | 0.3480 | 0.4013 | 0.373 | 2.7000 | 26.0 | 3.0 |
| WOF | 6/28/2014 | 0.0467 | 0.4608 | 0.215 | 0.1067 | 2.3 | 3.0 |
| WOF | 6/29/2014 | 0.0946 | 0.1938 | 0.210 | 0.0333 | 0.43 | 6.8 |
| WOF | 7/1/2014 | 0.0380 | 0.3142 | 0.134 | 0.3567 | 4.4 | -1.1** |
| WOF | 7/2/2014 | 0.0502 | 0.0069* | 0.145 | 0.2133 | | |
| WOF | 7/3/2014 | 0.0430 | 0.2967 | 0.131 | 0.1420 | 0.55 | 4.9 |
| WOF | 7/6/2014 | 0.1272 | 0.6213 | 0.217 | 0.3900 | 4.7 | 8.3 |

* values in red indicate results lower than the standard of 0.02 mg/L of N; **High range TP tests (1-33 mg/L P) are reported to the 1.0 mg/L P level; low range TP tests (0-1 mg/L P) are reported to the 0.01 mg/L P level.

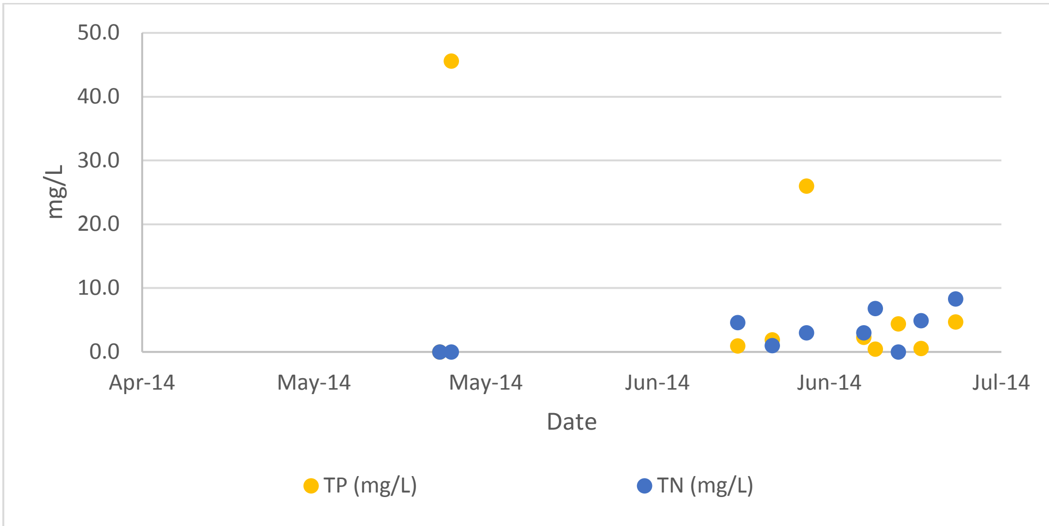



Figure A-2: Nutrient Load - Worrell Field pothole

Table A-3: Water quality values for Worrell Road pothole

| Sample ID | Sample Date | Ammonia (mg/L N)* | Nitrate + nitrite (mg/L N)* | Dissolved reactive P (mg/L P) | TSS (g/L) | TP (mg/L) | TN (mg/L) |
|---|---|---|---|---|---|---|---|
| WOR | 5/21/2014 | 0.0096* | 5.9621 | 0.641 | 1.6200 | 14.4 | 19.8 |
| WOR | 5/22/2014 | 0.0238 | 7.5371 | 0.594 | 0.4000 | 4.9 | 9.8 |
| WOR | 5/23/2014 | 0.0164* | 8.3939 | 0.612 | 0.3731 | 5.2 | 9.4 |
| WOR | 6/17/2014 | 0.0854 | 1.4207 | 0.319 | 0.4125 | 0.90 | 5.6 |
| WOR | 6/20/2014 | 0.0328 | 0.426 | 0.295 | 0.1867 | | |
| WOR | 6/23/2014 | 0.2208 | 0.3974 | 0.272 | 0.0333 | 0.43 | 1.0 |
| WOR | 6/28/2014 | 0.1642 | 0.0065* | 0.171 | 0.0250 | 0.33 | 2.6 |
| WOR | 7/1/2014 | 0.0393 | 0.14* | 0.227 | 0.0467 | | |
| WOR | 7/2/2014 | 0.0470 | 0.3199 | 0.233 | 0.7333 | 4.0 | 14.8 |
| WOR | 7/3/2014 | 0.0132* | 0.0665 | 0.223 | 0.0106 | 0.34 | 8.8 |
| WOR | 7/6/2014 | 0.1013 | -0.1066* | 0.204 | 0.0075 | | |

*values in red indicate results lower than the standard of 0.02 mg/L of N

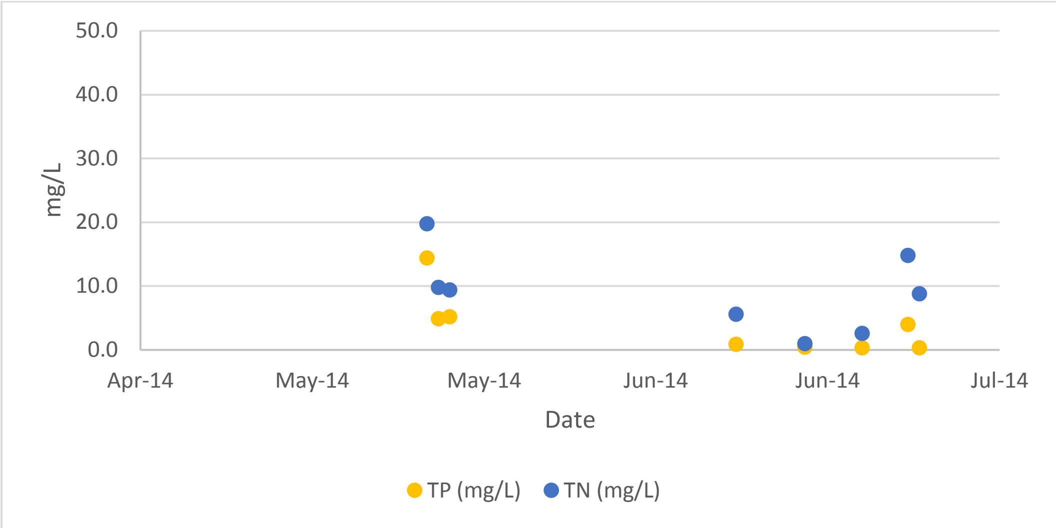



Figure A-3: Nutrient Load in the Worrell Road pothole.

More inundation events were observed in Walnut pothole, which justifies the higher number of water quality samples. It was expected larger pollutant loads just after high intensity rainfall events, and a reduction in the following days. This behavior was observed in some equations, but due the limited data, more research is needed in the topic.

Research has shown that the water quality aspect is largely variable through enclosed wetlands (Whigham and Jordan 2003). For this reason, considering there was not observed data for calibration of the model, water quality aspect was not broadly discussed in this thesis.

### A.2. Further Research

Water quality data was collected with the aim to monitor water quality aspect of the potholes. However, not enough data was available to calibrate the model, and assess nutrient load in the potholes, and therefore its dynamics. Further research include the collection of nutrient and sediment data in order to estimate the load of pollutants in the potholes. With more collection of this type of data, it will be possible to calibrate and validate the model to simulate these parameters, and understand more pothole role in water quality.

# B. APPENDIX: SOIL SAMPLES

## B.1. Data collection

Soil samples were analyzed for a better estimation of soil textures in pothole microwatersheds. The impact of intense use of drainage in the PPR has been related to soil erosion in the area (Karlen, Dinnes, and Singer 2010; Freeland, Richardson, and Foss 1999). Our hypothesis is that sail erosion also happens in a small scale, and will probably be observed in the assessment of microwatersheds. Therefore, sediments with smaller sizes would likely be found in the bottom of the potholes, once more energy is necessary to transport bigger particles, while upper areas in the potholes would have sandier soil. In figure B-1, it is possible to observe the distribution of the points collected for assessment of soil variability in the microwatersheds.

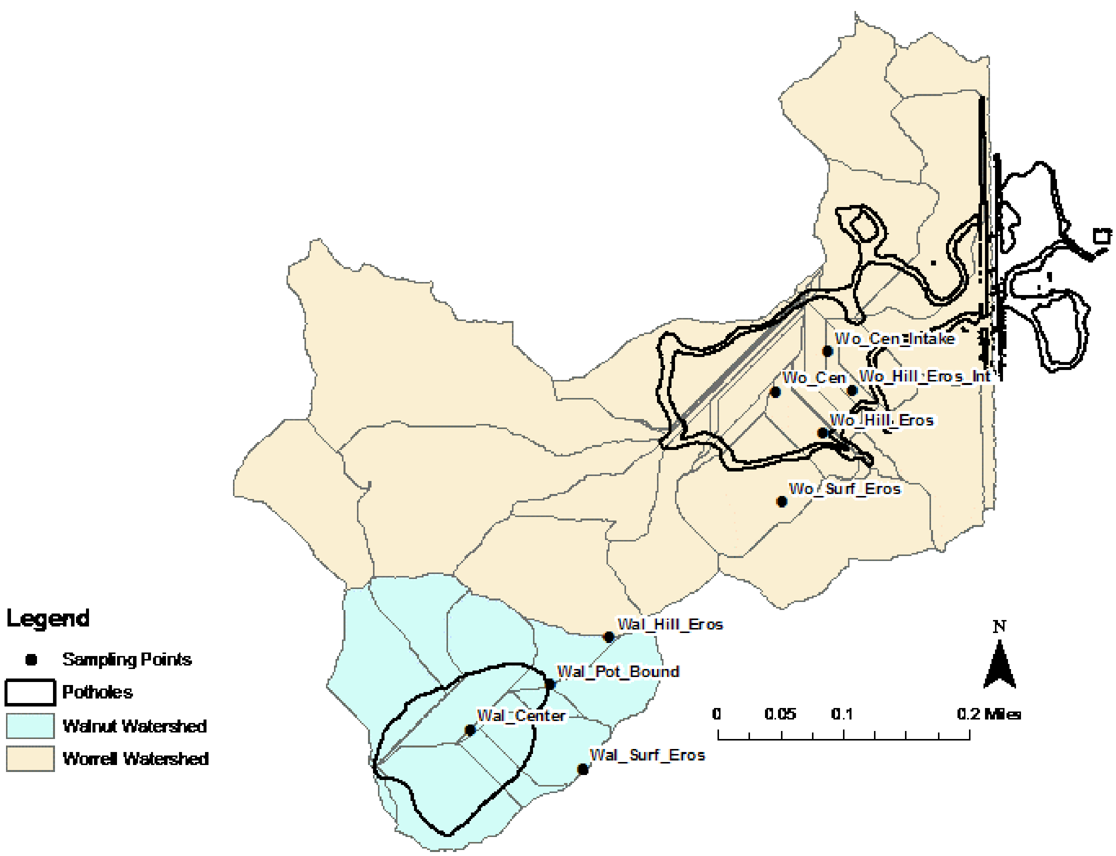



Figure B-1: Location of soil samples collected from Walnut and Worrell microwatersheds.

Our hypothesis was confirmed by higher contents of clay towards the center of the potholes, by the outlet of the watersheds. Table B-1 illustrates the results of texture for the collected points.

Table B-1: Results of soil texture in the watersheds

| **Message** | **pH** | **Sol Salts (mmho/cm)** | **Texture** | **P M3 (ppm)** | **Sand (%)** | **Silt (%)** | **Clay (%)** | **Texture (%)** |
|---|---|---|---|---|---|---|---|---|
| **Wal_Center** | 6.7 | 0.34 | Clay Loam | 66 | 25 | 38 | 37 | 25-38-37 |
| **Wal_Pot_Bound** | 7.9 | 0.49 | Loam | 14 | 39 | 36 | 25 | 39-36-25 |
| **Wal_Hill_Eros** | 6.5 | 0.16 | Sandy Clay Loam | 6 | 53 | 26 | 21 | 53-26-21 |
| **Wal_Surf_Eros** | 6.1 | 0.12 | Sandy Clay Loam | 6 | 54 | 26 | 20 | 54-26-20 |
| **Wo_Hill_Eros_Int** | 7.8 | 0.46 | Loam | 33 | 47 | 30 | 23 | 47-30-23 |
| **Wo_Hill_Eros** | 7.7 | 0.5 | Loam | 28 | 45 | 28 | 27 | 45-28-27 |
| **Wo_Surf_Eros** | 6.4 | 0.22 | Loam | 10 | 49 | 28 | 23 | 49-28-23 |
| **Wo_Cen** | 7.8 | 0.63 | Clay Loam | 66 | 27 | 38 | 35 | 27-38-35 |
| **Wo_Cen_Intake** | 7.2 | 0.75 | Clay | 102 | 17 | 32 | 51 | 17-32-51 |

### B.2. Further Research

For a better understanding of soil transport and deposition in prairie pothole microwatersheds, it is important collect more representative data points of soil in the microwatershed, and investigate other sites in the PPR, to confirm whether the patterns are repeated or not.