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A HYDROLOGIC ASSESSMENT OF SURFACE PONDING IN A DRAINED PRAIRIE POTHOLE WETLAND

by

Stephanie Rose Then

A thesis submitted in partial fulfillment
of the requirements for the Master of Science
degree in Civil and Environmental Engineering in the
Graduate College of
The University of Iowa

August 2016

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

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Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

Stephanie Rose Then

has been approved by the Examining Committee for
the thesis requirement for the Master of Science degree
in Civil and Environmental Engineering at the August 2016 graduation.

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ABSTRACT

This thesis evaluates the surface water hydrology in an artificially drained and farmed prairie pothole wetland located in north-central Iowa as part of the Iowa DNR Wetland Program Development (WPD) project. The purpose of the WPD project was to begin documentation of basic hydrology, wildlife value, and water quality to improve understanding of ecosystem services provided by drained prairie pothole wetlands. The surface water hydrology was evaluated using a daily water balance (PPWB) model. The model development, validation, and applications are described in detail in this thesis.

The PPWB model estimates the water depth and duration in the drained wetland. Several sensitivity analyses were performed to evaluate how site-specific factors affect the frequency, depth, and duration of surface ponding in the drained wetland. In the absence of surface inlets, infiltration was found to have a significant impact on ponding, second only to the amount of precipitation in importance. The topography also plays an important role in surface water ponding, with higher ponding durations occurring for larger catchment-to-pothole area ratios. However, the presence of a surface inlet in a drained prairie pothole wetland significantly alters the hydrology and all other ponding factors become negligible. In addition, long-term ponding was evaluated for historic and future hydrologic trends. The long-term simulation showed increasing trends for precipitation and ponding duration.

The possible implications of continued farming of drained wetlands were explored using PPWB model sensitivity analysis and long-term simulation results. Agricultural implications include mitigation strategies to balance ecosystem needs with crop production and impacts of the projected future outlook with regards to climate. Environmental implications include insight on impacts of wetland restoration.

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PUBLIC ABSTRACT

The widespread use of artificial drainage (i.e. tile drainage, surface inlets, and drainage ditches) to improve agriculture in north-central Iowa has resulted in natural wetland losses of more than 90% (Bishop et al., 1981). Even though these now drained and farmed wetlands are a major component of the north-central Iowa landscape, relatively little is known about how artificial drainage has impacted their basic hydrology, wildlife value, and water quality. The purpose of this thesis project was to develop a model that estimates depth and duration of surface ponding in a drained and farmed wetland. The daily water depth and duration was calculated using a water balance equation that included the following parameters: precipitation, runoff, evapotranspiration, infiltration, and artificial drainage capacity.

Evaluation of the parameters included in the water balance equation showed that infiltration, topography (used in the runoff calculation), and artificial drainage capacity have a significant impact on surface ponding. A long-term simulation, which evaluated ponding for a 200 year period, showed increasing trends in annual precipitation and ponding duration. These increasing trends are expected to impact agriculture production in future years. In some cases, when ponding results in a high impact on agricultural production, wetland restoration should be considered.

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CHAPTER 1: INTRODUCTION

1.1 Overview of the Iowa DNR Wetland Program Development Project

Prior to European settlement, the Des Moines Lobe (DML) of north-central Iowa was a vast prairie ecosystem inter-spread with millions of prairie pothole wetlands and marshes. An estimated 1.4 million hectares (ha) of prairie pothole wetlands covered the DML (Miller et. al., 2009). The introduction of artificial drainage over the last century for agricultural purposes, however, has reduced the wetland acreage to a mere 12,140 ha (Bishop et al., 1981). Even though these now drained wetlands are a recurrent component of the landscape, relatively little is known about their basic hydrology, wildlife value, and water quality. The purpose of the Iowa DNR Wetland Program Development (WPD) project was to begin documentation of basic hydrology, wildlife value, and water quality to improve understanding of ecosystem services provided by drained wetlands. Documentation of this information will be useful to several government agencies, as well as conservation and agricultural groups interested in the environmental implications of policy decisions related to agriculture and water quality.

The WPD project involved eight randomly chosen townships in the DML. One or two drained wetlands in each township were selected for groundwater monitoring (Figure 1.1) to assess groundwater hydrology. The wildlife and water quality components of the WPD project evaluated multiple drained wetlands in each township (see Murphy and Dinsmore (2015) and Schilling et. al. (2016) for additional site selection details). The drained wetlands monitored in the WPD project share many common characteristics: they have similar soil types and stratigraphy, most have sub-surface drainage and are in organized agricultural districts, and they are typically farmed in a corn-soybean crop rotation. The drained wetlands vary in size, from 0.6 ha to more than 23 ha, and experience ponding for weeks-months every spring/summer.

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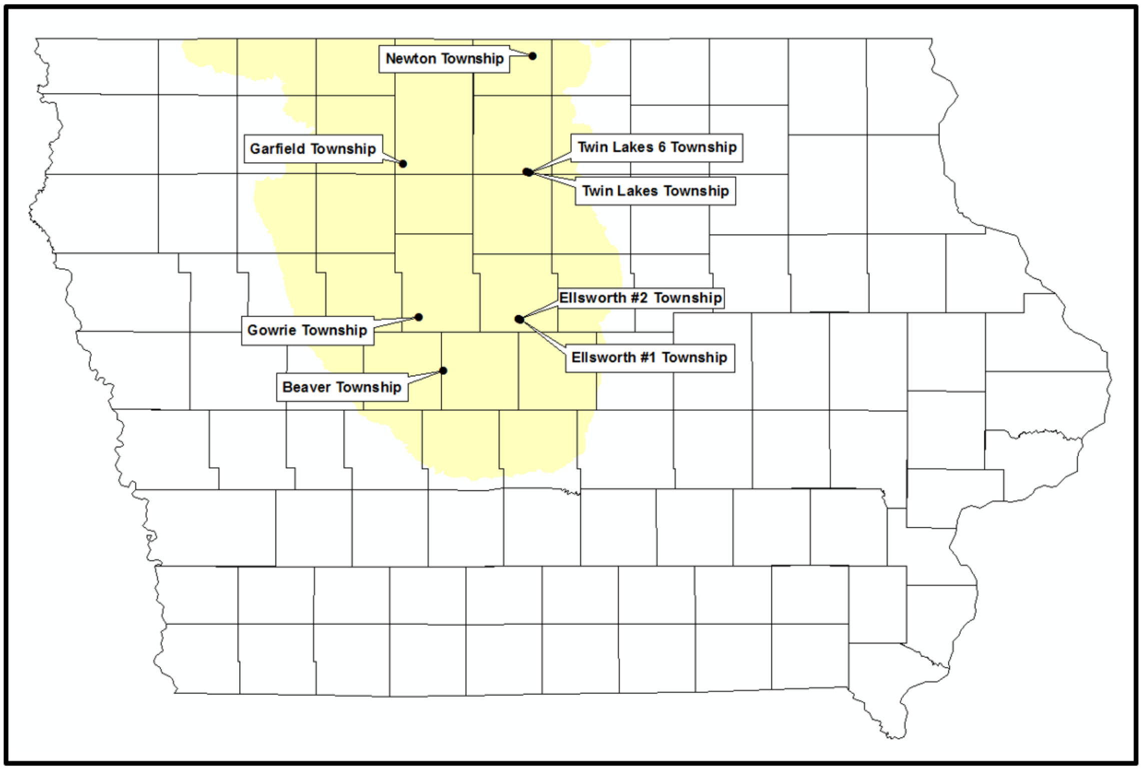

Figure 1.1. Eight townships were chosen as part of the Iowa DNR Wetland Program Development Project.

1.1.1 Basic Hydrology

Shallow groundwater monitoring wells were installed at eight drained wetland sites to improve basic understanding of groundwater hydrology. Depth of the wells ranged from 6 to 7.5 feet below the ground surface. Transducers in the wells monitored hourly groundwater fluctuations from 2011-2013. The water table fluctuated considerably at all the sites. In 2013, the water table rose above the surface on at least one occasion in every well except Ellsworth #2. In all years, the water table dropped below monitoring capabilities in late fall or winter. See Schilling et. al. (2016) for additional installation and monitoring information.

1.1.2 Wildlife Value

The wildlife value of drained wetlands was evaluated through observational surveys of waterbirds (shorebirds and waterfowl), as well as, amphibian and reptile species. The waterbird survey included documenting the frequency and abundance of species observed at the temporarily ponded wetlands. Surveys were conducted during spring migration from 2011-2014. Fifty-three species of waterbirds were documented

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with 3,661 total observations. The 2011, 2012, 2013, and 2014 observation totals were 1025, 168, 1350, and 1284, respectively. The most common species observed were Mallards (*Anas platyrhynchos*), Blue-winged Teal (*Anas discors*), and Killdeer (*Charadrius vociferous*). More details of the waterbird component of the WPD project are discussed in Murphy (2013) and Murphy and Dinsmore (2015).

The amphibian and reptile surveys were conducted using Visual Encounter Surveys (EVS) in 2011 and 2013 and Nocturnal Calling Surveys (NCS) in 2012. The change in survey technique was due to severe drought in 2012 which resulted in little surface ponding among many drained wetlands. No reptiles were found in 2011 and 2013 and only one garter snake was observed in 2012. American toads and boreal chorus frogs were seen every year, but only at 60% of the site visits. The amphibian and reptile survey concluded that drained wetlands did not appear to have functional habitat for amphibian breeding (Kinkead, 2014). See Samson and Knopf (1996) and Mushet et al. (2015) for more information on amphibian and reptile response in prairie pothole wetlands.

1.1.3 Wetland and Groundwater Quality

A total of 103 surface water samples were taken at various drained wetlands in the study area. Only one sample was taken in 2011, 54 samples were taken in 2012, and 48 samples in 2013. Sampling occurred from April/May to late June in all years. A total of 62-69 analytes were tested per sample and included five nutrient analytes. Total Kjeldahl Nitrogen (TKN) and Nitrate (NO_3-N) were the predominant nutrients found in the drained wetlands. The ortho-phosphate and total phosphate were present in all samples but in smaller concentrations. In 2012, nutrient concentrations were highest in samples taken in late May-early June. In 2013, however, nutrient concentrations were consistently low throughout the sampling period.

Multiple groundwater water samples were collected from each well during the study period. Samples were tested for pH, specific conductance, dissolved oxygen, oxidation-reduction potential, temperature, NH_4-N, NO_3-N, dissolved phosphorus, and dissolved organic carbon. NO_3-N concentrations fluctuated throughout the monitoring period, with NO_3-N concentrations ranging from <0.1 mg/L to 102 mg/L; however, there was a clear relation between groundwater rise and increased concentration in 2013.

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Dissolved phosphorus concentrations were considerably less variable; nonetheless, concentrations still ranged from 0.01 mg/L to 3.9 mg/L.

1.2 Goals and Objectives

The only documentation of hydrology currently in the WPD project is the groundwater hydrology assessment from well monitoring. The purpose of this thesis is to expand the basic hydrology component of the project to include surface water hydrology. The main goals for this thesis are:

1. Develop a water budget model for a drained wetland located in Ellsworth, IA.
2. Use the water budget model to evaluate how site-specific controls affect the frequency, depth, and duration of surface ponding in the drained wetland.
3. Discuss implications for agriculture and wildlife value based on historic and future climate projection trends.

1.3 Chapter Summary

This introductory chapter provides an overview of the Iowa DNR Wetland Program Development (WPD) project and outlines the goals of this Master’s thesis. The Iowa DNR WPD project aimed to improve understanding and documentation of ecological functions of drained wetlands in the Des Moines Lobe. The project was organized into three components; basic hydrology, wildlife value, and water quality. Shallow groundwater monitoring wells were installed and hourly groundwater fluctuations were recorded for three years to evaluate groundwater hydrology. Wildlife usage from waterbirds, amphibians, and reptiles was documented by frequency and abundance of species in each drained wetland. Water quality was evaluated for both surface water and groundwater.

This thesis focuses on the augmentation of the hydrology component, specifically the surface water hydrology, of the WPD project. The goal of this research is to evaluate how site-specific controls affect surface ponding using a water budget model. Results of this research can provide insight to the environmental implications of continued farming and potential restoration of drained wetlands in the DML.

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CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The prairie pothole region (PPR) of central North America is a result of the Wisconsin glacier retreat that occurred around 12,000 years ago (McAndrews, 1967; Tiner, 2003). Encompassing three southern Canadian provinces and five upper Midwest states, the PPR extends as far south as north-central Iowa (Figure 2.1) (Miller, et. al., 2009). The portion of the PPR in Iowa is known as the Des Moines Lobe (DML). Prior to European settlement, the PPR landscape was composed of an extensive prairie ecosystem interspersed with many wetlands and marshes (Urban, 2005). It has been estimated that 12.6 million pothole wetlands once covered the PPR (van der Valk and Pederson, 2003). However, in the late 1880's to early 1900's, artificial drainage was introduced in the region, and much of these pothole areas were drained for agricultural purposes (Kanwar et al., 1983; Zucker and Brown, 1998). It has been estimated that wetland losses on the DML range from 95 to 99%, and only 12,140 ha of wetland areas remain (Bishop et al., 1981). It is important to understand the hydrologic and ecologic changes that have occurred because of artificial drainage in prairie pothole wetlands over the last century. The following literature review sections provide some background information on the impact artificial drainage has on hydrology and wildlife value as well as several examples of similar water budget modeling studies.

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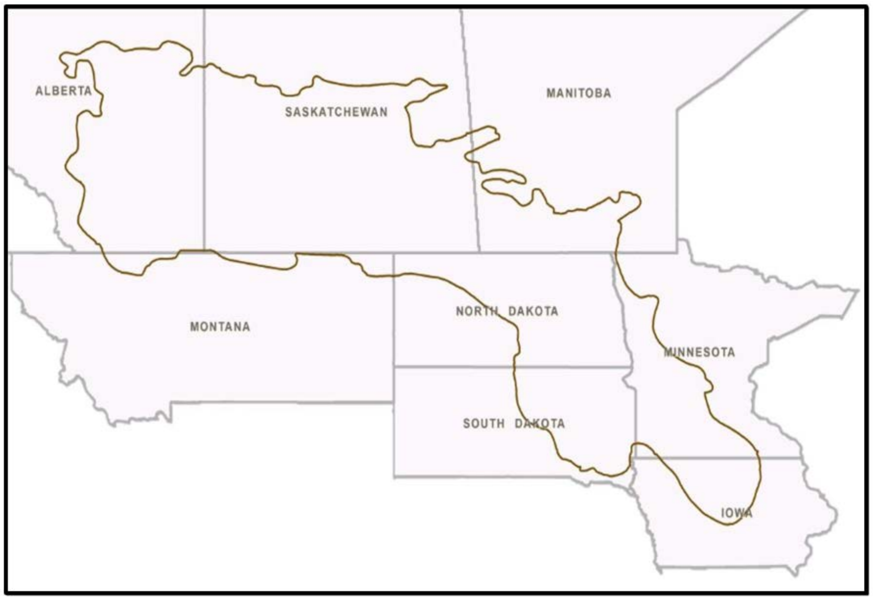

Figure 2.1. The Prairie Pothole Region of central North America.

2.2 Impacts of Artificial Drainage on the Hydrology in Drained Wetlands

Despite the fact that artificial drainage hydrology has been studied for more than a century, many questions regarding its actual hydrologic impact remain unanswered (Robinson, 1990; Sloan, 2013). It is generally agreed upon that the degree of impact on hydrology is influenced by both physical pothole characteristics (soil type, land use, topography, etc.) and artificial drainage characteristics (size, depth, and spacing). There is no clear understanding of which characteristic(s) cause the largest degree of impact. Other impacts on hydrology from artificial drainage include reducing prolonged saturation in the root zone, which benefits agriculture by increasing planting and harvest windows during typically wet spring and fall seasons (Fipps and Skaggs, 1991; Hatfield et al., 1998).

Although the hydrology and vegetative conditions of prairie pothole wetlands have been altered by drainage and cultivation of annual crops, they frequently hold water during wet periods. Temporary ponding in pothole depressions has value for retention of surface water and reduction of runoff (Kreymborg and Forman, 2001; Huang et al., 2013).

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2.3 Impacts of Artificial Drainage on the Waterbird Use in Drained Wetlands

The PPR is considered to be the most important breeding ground for North American waterfowl species (Smith et al., 1964). According to Klett et al. (1998), the PPR covers only 10% of the North American duck breeding grounds, but it normally produces more than 50% of the ducks. Shorebirds are renowned for bi-annual long distance migrations as they move between temperate or tropical wintering sites and extreme northern latitudes for breeding purposes. There are many shorebird species that migrate through mid-continental areas of North America and utilize a network of stopover sites along migratory routes (Skagen and knopf, 1993; Haig et al., 1998; Skagen et al., 1999; Skagen, 2006).

The DML hosts many shorebird species during migration; 34 species of shorebirds are regularly observed in Iowa (Kent and Dinsmore, 1996), and eight species of shorebirds in the PPR and 21 species nationally are listed as species of conservation concern (Brown et al., 2001; U.S. Fish and Wildlife Service, 2008). During a four year study, Murphy and Dinsmore (2015) documented 53 species of waterbirds from a total of 3,661 observations (see Section 1.1.2). Waterfowl diversity was greatest in March with an expected initial surge in migrants due to spring melt of ice and snow cover. Diversity in shorebird species was greatest in late April and early May with the expected arrival of spring migrants.

Even though 95%-99% of wetlands in the DML have been drained, studies have shown that temporarily ponded water in drained wetlands can host large concentrations of migratory waterfowl and shorebirds (LaGrange and Dinsmore, 1989; Kenne, 2006). Waterfowl and shorebirds have been observed using drained wetlands with only moist soils during the non-breeding season (Murphy and Dinsmore, 2015). This suggests that artificial drainage may have less of an impact on waterbird usage outside of the breeding season.

2.4 Similar Studies

The Roth and Capel (2012) field-based study assessed the hydrology of a drained wetland using a water balance for 11 ponding events during the 2008 growing season. The drained wetland is in a 39.5 ha agricultural field located in northern Hamilton

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County, IA. There is a surface inlet that connects to subsurface tiling located in the center of the pothole. A stilling well was installed to monitor surface ponding at 15-minute intervals. Two piezometers were installed at the center and edge of the pothole to monitor shallow groundwater fluctuations every 15 minutes. Water balances for each ponding event were determined using the continuity equation discussed in Chow et al. (1988) and using the ponded volume as a dynamic control volume. The potential inflows included in the water balance are overland flow (surface runoff), groundwater discharge, and precipitation. The overland and groundwater flow are calculated as a combined inflow and not explicitly quantified in the water balance calculations. The potential outflows are surface inlet capacity, evaporation, and infiltration.

The ponding duration was much longer during the early growing season (prior to June 6th) than later in the growing season. The drained wetland infiltration rate was estimated at 8.7 mm d^{-1} and was determined from deficits in water balance calculations. Overall, the surface inlet accounted for 95% of outflow of ponded water. Ninety-six percent of the inflows came from the combined overland and groundwater flows.

Huang et al. (2013) used a daily water balance of individual wetlands that form a wetland complex to model the surface and groundwater dynamics of wetland complexes. Surface hydrology of wetland complexes has been described in various studies (Liebowitz and Vining, 2003; Shaw et al., 2012, 2013; Huang et al., 2013) using the “fill-spill” concept. To evaluate “fill-spill” surface water connections, a topographic threshold for impounding runoff in a pothole must be established and once the storage requirements are met (i.e. filled), water overtops the pothole storage (i.e., spills) and is released downstream (Shaw et al., 2012).

The wetland complex in the Huang et al. 2013 study was located in North Dakota and included five individual wetlands that had water volumes ranging from less than 450 m^3 to >45,000 m^3 during the 29 year study period. Hydrological processes built into the water balance model include rainfall, snowfall, snowmelt, rainfall runoff, evapotranspiration, shallow groundwater losses, and fill-and-spill mechanisms. Evapotranspiration and surface runoff were calculated using the Penman-Monteith method and NRCS Curve Number method, respectively. Shallow groundwater loss was estimated using equation (1).

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$$SGW = 0.9 * RS_{ref} * \frac{ET_t}{ET_{ref}} * ratio * PA_t \tag{1}$$

Where RS_{ref} and ET_{ref} are reference recession slope and average evaporation constants, respectively. ET_t is evaporation on day t and PA_t is the ponded area on day t. The ratio component is ratio of pond shoreline length to the ponded area. The observed and modeled water volumes were compared for each of the five wetlands. Results revealed that the model performed well, in both trends and magnitudes, for wetlands with sizes greater than thousands of cubic meters. The model failed to accurately estimate water volume in wetlands smaller than 450 m^3.

Politano et al. (2016) used a fully integrated, physically-based HydroGeoSphere model to evaluate the connectivity of surface ponded water and groundwater in wetland complexes. The drained wetland complex, located in Ellsworth, Hamilton County, IA, used the “fill-spill” concept discussed in Shaw et al. (2012, 2013) and Huang et al. (2013) to model surface connectivity of drained wetland complexes. Panday and Huyakorn (2004) has an in-depth description of the HydroGeoSphere model. The major parameters of the annual water balance included in the HydroGeoSphere model are precipitation, evapotranspiration (ET), subsurface tiling, infiltration, and exfiltration (groundwater flow into the drained wetland).

During the six year study duration, the tile subsurface tile discharge accounted for 52.4% of the precipitation input and ET accounted for 47.5% of the precipitation input. Results showed that during wet years, subsurface tile drainage was the primary factor in the release of ponded water. Whereas, in dry years, the release of ponded water was controlled by ET (Politano et al., 2016). Surface ponding was primarily influenced by infiltration in the drained wetland complex. However, groundwater contribution had a significant impact on ponding during wet years. In 2010, the wettest of the six year study period, groundwater contributed to surface ponding by more than 20% of the precipitation input.

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CHAPTER 3: ELLSWORTH DRAINED WETLAND SITE DESCRIPTION

3.1 Introduction

This chapter reviews the hydrologic and physical characteristics of the Ellsworth drained wetland. Current watershed conditions relating to geology, soil, topography, land use and instrumentation are provided, as well as annual and monthly hydrologic patterns. This information was used to develop the model described in Chapter 4.

3.2 Physical Description of Watershed

This study focuses on a small, drained prairie pothole wetland located in Hamilton County, Iowa, referred to as the Ellsworth drained wetland (Figure 3.1). It is a 0.6 ha pothole depression with a total catchment area of 3.7 ha. The Ellsworth drained wetland is located within the Keigley Branch of the South Skunk River watershed; however, it is topographically isolated and only contributes direct runoff into the river system during exceptionally rare events. Physical features of the pothole must be considered when developing a hydrologic model because they play an important role in watershed hydrodynamics.

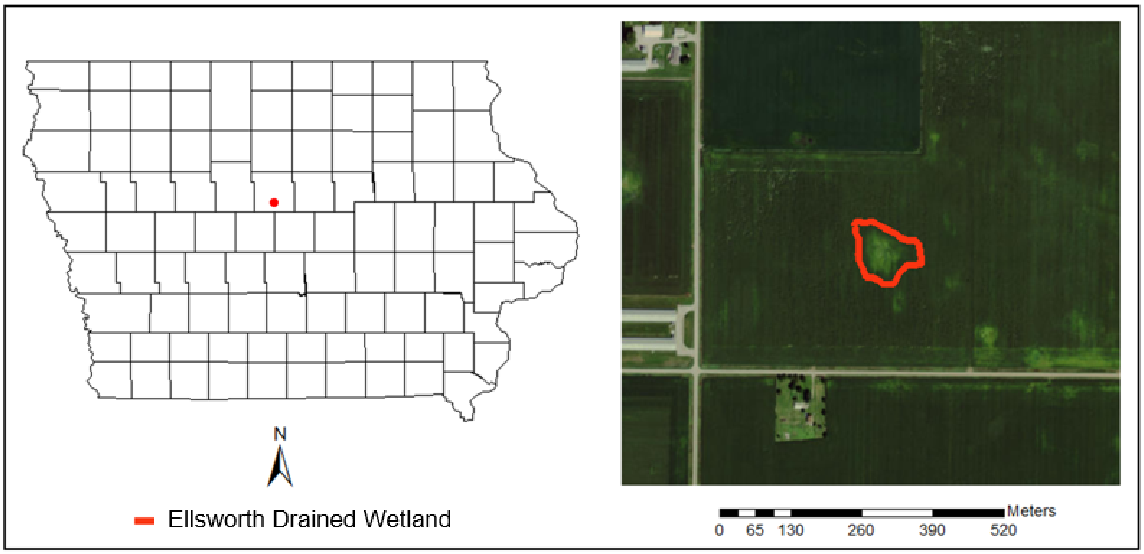

Figure 3.1. The Ellsworth drained wetland is located in north-central Iowa. It has a total catchment area of 3.7 ha.

3.2.1 Geology

The Ellsworth drained wetland is located in the Des Moines Lobe (DML) region of north-central Iowa. The DML is the southernmost reach of the Prairie Pothole Region

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(PPR). The PPR covers an estimated 700,000 square kilometers of central North America. It extends over three southern Canadian provinces and five upper Midwest states (Miller, et. al., 2009). The PPR is a result of the most recent glacial episode, the Wisconsin glacial retreat, which occurred around 12,000 years ago. During the glacial retreat isolated ice blocks lingered in the PPR and when they melted, millions of water-filled topographic depressions, termed prairie potholes, were formed (Tiner, 2003). The potholes developed into thriving wetland and marsh ecosystems (Urban, 2005). An estimated 12.6 million prairie pothole wetlands once covered the PPR and they were surrounded by an extensive prairie ecosystem (van der Valk and Pederson, 2003).

3.2.2 Soils

The DML is primarily oxidized glacial till that is typically overlain by a layer of rich, organic silt. Layers of gravel, sand, sandy loam, and/or silt loam are also often found in prairie pothole wetlands (Schilling et. al., 2016). The Ellsworth drained wetland lies in an Okoboji soil, which is common in prairie pothole wetlands. Surrounding soil series include Brownton and Kossuth. These soil series are all poorly-drained and often lead to temporary or semi-permanent wetland and marshes. The Natural Resources Conservation Service (NRCS) classifies these soils in Hydrologic Soil Group B.

3.2.3 Topography

Generally characterized as a low relief region, the DML has a landscape comprised of moraines, till plains, shallow channels, and prairie potholes (van der Valk and Pederson, 2003). The size and depth of prairie potholes varies from square meters to hectares and centimeters to meters, respectively (Schilling et. al., 2016). The Ellsworth drained wetland is relatively small with a pothole area of 0.6 ha and total catchment area of 3.7 ha. The occurrence of Okoboji soils was used to delineate the pothole area. The drained wetland has a depth of 0.7 m and volume of approximately 1,512 m^3.

3.2.4 Land Use

The Ellsworth site is a privately-owned drained wetland that lies in an organized agricultural drainage district and is farmed in a corn-soybean crop rotation. There is not a surface inlet present in the drained wetland, but there is subsurface tiling approximately

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1.2 m beneath the ground surface to improve drainage. The drained wetland experiences periodic ponding that constrains planting and harvest times and limits agricultural yields.

3.2.5 Hydrologic and Meteorologic Instrumentation

The Ellsworth drained wetland had a shallow monitoring well installed for 3 years as part of the WPD project (Schilling et al., 2016). The well was installed to a depth of approximately 2 m using a 152 mm diameter hand auger. A 1.5 m long factory-slotted PVC well screen and 1.5 m long PVC riser were installed in the borehole, with approximately 1 m of the riser sticking up above the land surface. A silica sand filter pack was poured around the screen, bentonite chips were added to provide a seal and drill cuttings were backfilled in the rest of the borehole. A water level transducer (In-situ TROLL) was placed in the well to record hourly water level fluctuations from 2011 to 2013.

There are no instruments located at the site to measure precipitation, temperature, wind speed, soil temperature, or solar radiation. The closest weather station is at the Ames Municipal Airport Weather Station and located 20 miles south of the Ellsworth drained wetland in Ames, IA (Figure 3.2). Weather information data was downloaded from multiple databases via the Iowa Environmental Mesonet. The periods of record for each database and parameter used in water balance modeling are listed in Table 3.1. The Automated Surface Observing System (ASOS) is controlled by National Weather Service (NWS) (NWS, 2014a). The primary function of ASOS is to provide minute-by-minute observations and generate weather reports that are used by aviation groups and organizations (Nadolski, 1998). The Global Surface Summary of Day (GSOD) is a National Oceanic and Atmospheric Administration (NOAA) controlled database that exchanges weather data with countries involved with the World Meteorological Organization (WMO) (Lott, 2010) The AgClimate database (ISU AgClimate Network, 2005) is operated by Iowa State University and is one of the nation’s oldest automated weather observation networks.

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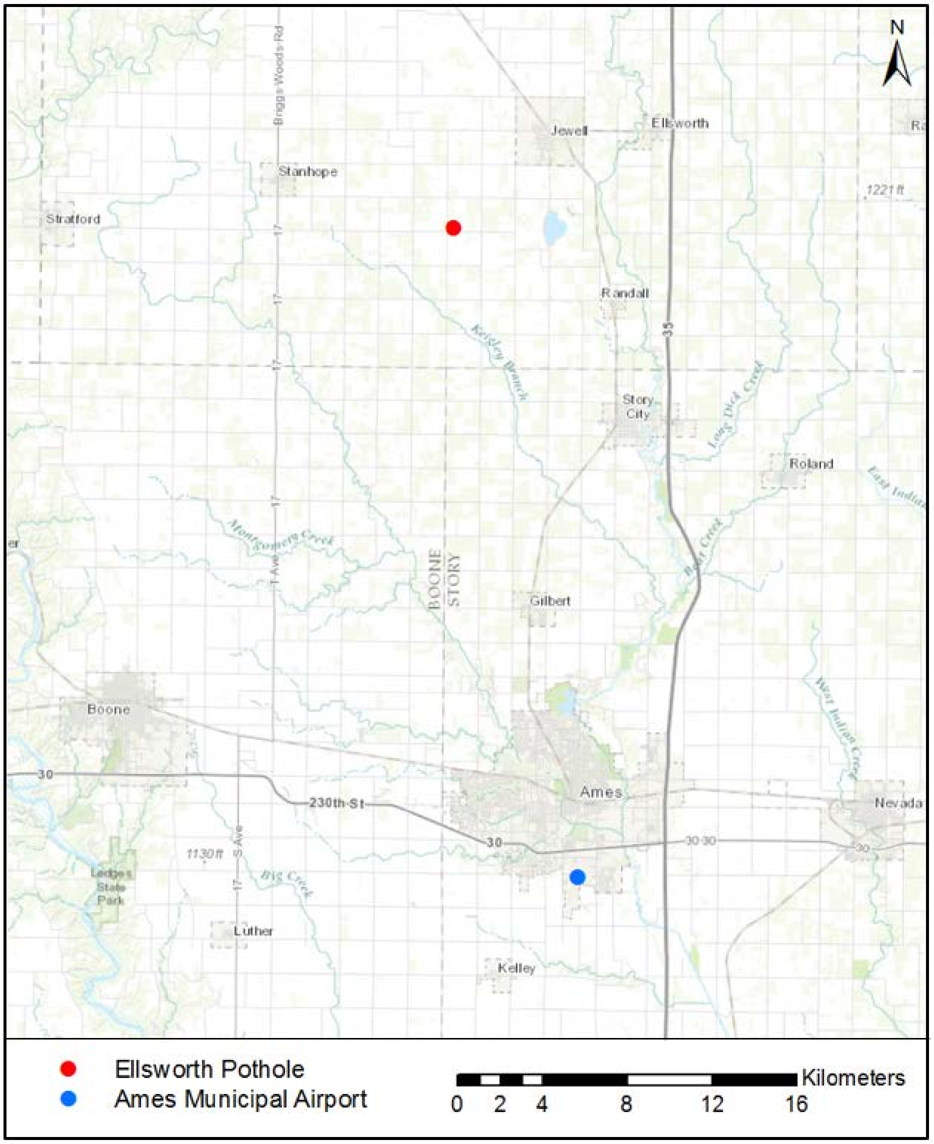

Figure 3.2. Location of site and weather station in Ames, IA.

Table 3.1. Database and parameters needed for water budget modeling.

Database	Parameter		Period of Record
ASOS	Maximum Air Temperature	(°F)	2005-2016
	Minimum Air Temperature	(°F)	
	Maximum Dew Point	(°F)	
	Minimum Dew Point	(°F)	
	Precipitation	(inch)	
GSOD	Mean Station Pressure	(millibar)	1997-2016
	Mean Wind Speed	(knot)	
ISU AgClimate	Mean 4 inch Soil Temperature	(°F)	1986-2014

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3.3 Hydrology

Iowa is located in a humid continental climate zone which typically experiences hot and humid summers, cold winters, and wet springs (Richardson, 1994). The average annual precipitation from 1981-2014 is 894 mm (PRISM Climate Group and Oregon State University (2004) and ASOS). Precipitation varies seasonally. Typically, nearly half of the annual precipitation occurs during April, May, and June, with averages exceeding 140 mm/month (Figure 3.3). During winter (December, January, and February), precipitation often falls in the form of snow which produces snowmelt runoff when temperatures rise in the spring. The daily average temperature is lowest in the winter months, dropping to more than 5°C below zero in January. The temperature steadily rises throughout spring and generally reaches highs close to 25°C in July.

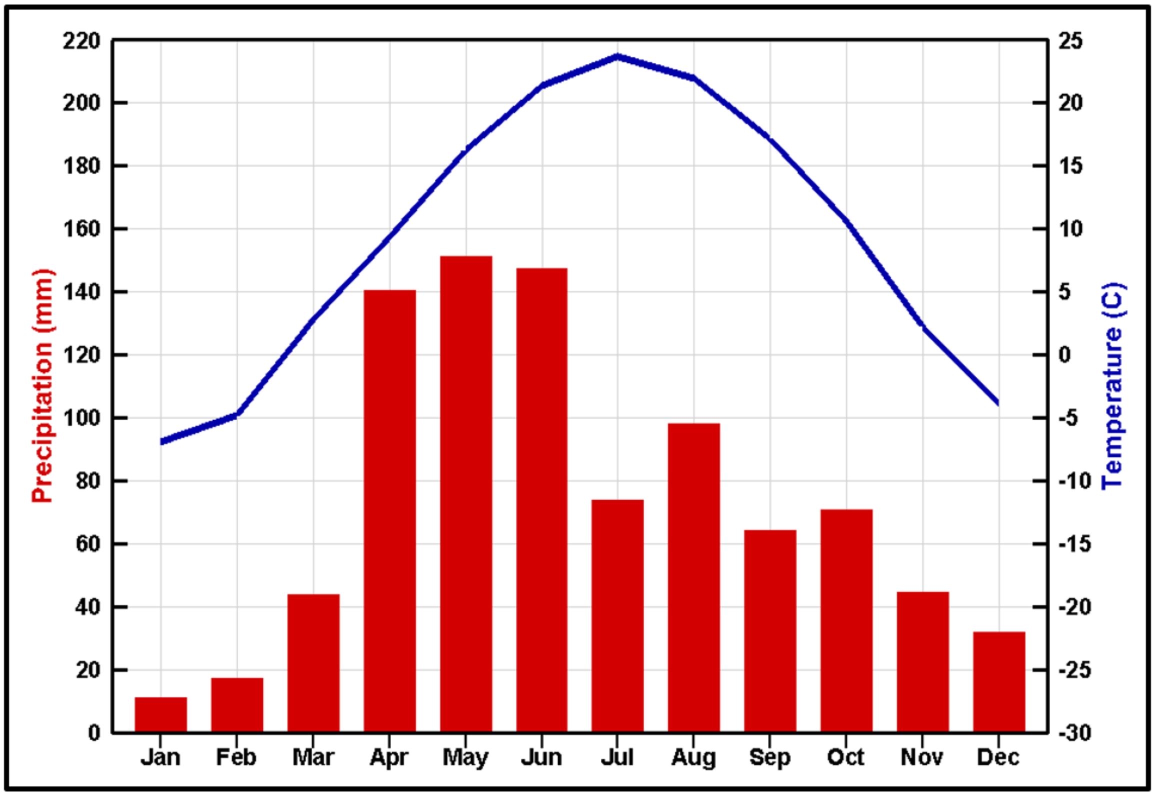

Figure 3.3. Average monthly precipitation and temperature for 1981-2014.

3.4 Chapter Summary

Chapter 3 describes the hydrologic and physical characteristics of the Ellsworth drained wetland. The site is located in the DML; more specifically, within the Keigley Branch of the South Skunk River. The average annual precipitation for the area (1981-

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2014) is 894 mm with a majority (nearly 50%) occurring from April-June. Like many drained wetlands in the DML, the Ellsworth site is characterized as low relief with poorly drained soils overlying glacial till.

The Ellsworth drained wetland has a pothole area of 0.6 ha and a total drainage area of 3.7 ha. There is not a surface inlet present but it has subsurface tile drainage to improve drainage. The site is located on private property, is in an organized agricultural drainage district, and is farmed in a corn-soybean crop rotation. The only instrumentation in the drained wetland was a shallow well that monitored groundwater levels for 3 years (2011-2013). Other hydrologic and meterologic measurements used in this thesis project were taken from a weather station located at the Ames Municipal Airport in Ames, IA.

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CHAPTER 4: ELLSWORTH DRAINED WETLAND HYDROLOGIC MODEL DEVELOPMENT AND CALIBRATION

4.1 Introduction

This chapter summarizes the development and calibration of the Ellsworth drained wetland hydrologic model. This is a water balance model that predicts daily water depth in the Ellsworth drained wetland. The general procedure for the development and calibration of the model was to determine which methods provided the best estimate for runoff, infiltration rate, evapotranspiration rate, and surface inlet capacity. The following sections provide in depth background information on water balance components and methods used to solve each parameter.

4.2 Spreadsheet Model

A prairie pothole daily water balance (PPWB) model was developed to predict ponded water depth in the Ellsworth drained wetland using equation (2) and is conceptualized in Figure 4.1. The PPWB model is a spreadsheet model and Excel was used for its development; screenshots of the Excel document are shown in APPENDIX A.

$$D_i = D_{i-1} + P_i + RO_i - I_i - ET_i - SI_i \tag{2}$$

D_i = ponded depth on day i (mm)
D_{i-1} = ponded depth on day i-1 (mm)
P_i = precipitation on day i (mm)
RO_i = surface runoff on day i (mm)
I_i = infiltration on day i (mm)
ET_i = Evapotranspiration on day i (mm)
SI_i = water lost via surface inlet on day i (mm)

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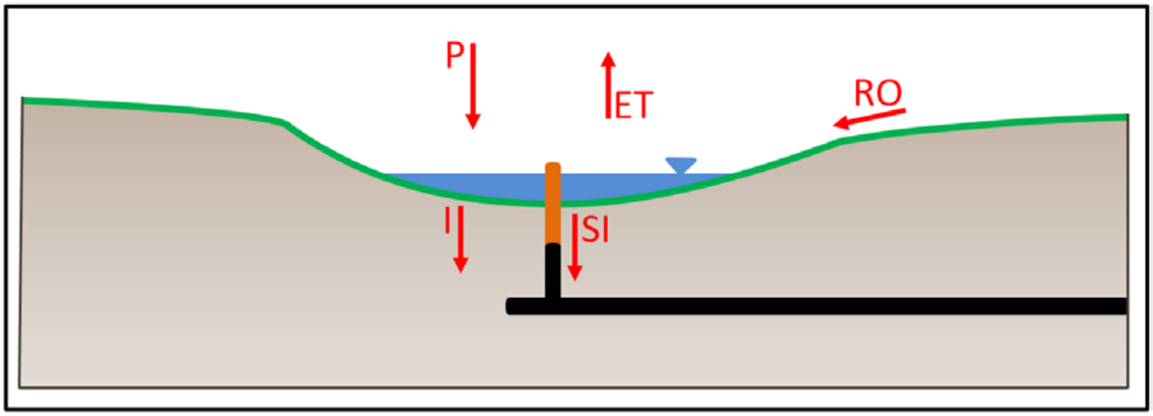

Figure 4.1. Conceptual image for PPWB model parameter inputs.

The simulated time period for the PPWB model is from 2011-2013 which coincides with the period of groundwater table monitoring. However, the groundwater contribution was not considered for ponding at the Ellsworth site because continuous monitoring for the study period indicated that groundwater rarely contributed to ponding (Schilling et al., 2016).

During the hydrologic monitoring period reported by Schilling et al. (2016), the groundwater hydraulic head was above the land surface <4% of the time. During this limited time, ponded water in the pothole was due to both surface water and groundwater contributions, but their relative contributions are difficult to separate. Hence this thesis focuses exclusively on modeling ponding due to surface water runoff. The modeling framework was used to assess how variations in the distinct water balance components affect the timing, duration and depth of ponding.

4.3 Model Construction

As explained in Chapter 3, the data used in the model came from the Automated Surface Observing System (ASOS), Global Surface Summary of Day (GSOD), and ISU AgClimate databases. Daily precipitation measurements came from the ASOS database and are reported as liquid or liquid-equivalent of frozen precipitation (LEFP) values (Nadolski, 1998).

4.3.1 Evapotranspiration

Evapotranspiration (ET) is the combined effect of evaporation of soil moisture, evaporation of ponded water, and transpiration from growing plants (Allen, 1998). Actual

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ET rates can be difficult to measure in the field; so ET rates are often estimated in the form of potential evapotranspiration (PET) using models (Lu, 2005). The numerous methods developed to estimate PET can be categorized as temperature based, radiation based, and temperature-radiation combination based methods. Seven PET methods were compared against each other to see which methods provided similar results. The PET models include three temperature based, three radiation based, and one temperature-radiation combination based model. The temperature based models are, Ivanov (Ivanov, 1954), Blaney-Criddle (Blaney, 1962), and Thornthwaite (Thornthwaite, 1948). The radiation based models are Hargreaves (Hargreaves, 1985), Makkink (Makkink, 1957) and Priestley-Taylor (Priestley, 1972). The temperature-radiation combination based model used is the Penman-Monteith (Monteith, 1965). See Table 4.1 for equations and parameters required for each method.

4.3.1.a. Ivanov Method

The Ivanov method was developed in 1954 by Russian scientist, Nikolai N. Ivanov. It is a modified Turc ET method (not used in this evaluation) that accounts for both positive and negative temperatures. The relatively simple Ivanov method was developed for estimating PET from grass canopies and requires only data for daily average air temperature and relative humidity.

4.3.1.b. Blaney-Criddle Method

The Blaney-Criddle method is used when only air temperature measurements are available. It was developed by American scientists for primary use in the western United States (Schappi, 2012). Previous studies using the Blaney-Criddle method have found that it typically produces a rough estimate of PET, but should not be used in extreme climatic environments. In windy, dry, sunny areas the Blaney-Criddle method may underestimates PET by up to 60%; and in calm, humid, clouded areas, the PET is overestimated by up to 40% (Brouwer, 1986).

4.3.1.c. Thornthwaite Method

The Thornthwaite method was developed for eastern United States; however, it is used in regions throughout the world that experience similar climate patterns (Thornthwaite, 1948). The Thornthwaite method uses daily air temperature and long-term monthly air temperature averages. It can only be calculated for positive temperatures –

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any negative temperatures must be set to zero before the calculation begins (Schappi, 2012).

4.3.1.d. Hargreaves

The Hargreaves method, first developed in 1985 by George Hargreaves, has been widely used to estimate PET in the United States for regional planning, reservoir operations, irrigation and drainage, and many other purposes (Hargreaves, 1985). Since its development in 1985, George Hargreaves has updated his method to provide more reliable and simple-to-use computations (Hargreaves, 2003). The most up-to-date Hargreaves method is shown in Table 4.1.

4.3.1.e. Priestley-Taylor Method

The Priestley-Taylor radiation based PET model provides accurate PET estimates through an energy based approach. The main input for the Priestley-Taylor method is net radiation, which is derived from the solar and extraterrestrial radiation. Daily average air temperature is also required (Stannard, 1993). C. Priestley and R. Taylor developed the method with an added parameter, α, called the calibration constant. The constant is derived from environmental aspects of the region where PET is being estimated. The calibration constant is usually taken as 1.26, which Priestley and Taylor recommend, but can be adjusted if necessary (Lu, 2005).

4.3.1.f. Makkink Method

The Makkink method is a simplification of Priestley-Taylor method. It is energy based in that its main input is radiation; however, the Makkink method only requires the incoming solar radiation and not the entire radiation balance (Schappi, 2012). The solar radiation can be calculated from extraterrestrial radiation. The method was developed for estimating PET from grass in humid regions.

4.3.1.g. Penman-Monteith Method

The Penman-Monteith method, which was developed by Howard Penman and John Monteith, is a more advanced version of the Priestley-Taylor method. Like Priestley-Taylor, the Penman-Monteith method includes both the net energy balance and temperature characteristics of ET. It also includes the effect of aerodynamic principles (Stannard, 1993) to calculate the total reference evapotranspiration (RET). The Penman-Monteith is the standard method used by the United Nations Food and Agriculture

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Organization (FAO), and a modified version is a used by engineers involved with the American Society of Civil Engineers (ASCE).

Table 4.1. Equations and parameters required for PET methods.

Method	**Equation**	**Inputs**		
		Temp	**Radiation**	**Others**
Ivanov	$PET = 0.000036 * (25 + T)^2 * (100 - RH)$	Mean Daily		Mean Daily Relative Humidity
Blaney-Criddle	$PET = (8.128 + 0.457 * T) * \frac{S_o * 100}{S_{year}}$	Mean Daily		Daily Sunshine Duration
Thorn-thwaite	$PET = 0.533 * \frac{S_o}{12} * \left(\frac{10 * T}{J}\right)^a$ $J = \sum_{JAN}^{DEC} \left(\frac{\bar{T}}{5}\right)^{1.514}$ $a = (0.0675 * J^3 - 7.71 * J^2 + 1792 * J + 49239) * 10^{-5}$	Mean Daily		Longtime Monthly Mean Temp
Priestley-Taylor	$PET = \alpha * \frac{\Delta}{\Delta + \gamma} * \frac{R_n - G}{0.0864(28.9 - 0.028 * T)}$	Mean Daily	Net	Parameter (1.26)
Makkink	$PET = \frac{\Delta}{\Delta + \gamma} * \left(c_1 * \frac{R_s}{L}\right) + c_1$	Mean Daily	Solar	Coefficients (0.61,-0.12)
Hargreaves	$PET = 0.0135 * R_s * \text{conv} * (\mathrm{T} + 17.8)$ $R_s = 0.16 * R_a * (T_{max} - T_{min})^{0.5}$	Max and Min Daily	Extra-terrestrial	
Penman-Monteith	$RET = \frac{0.408\Delta(R_n - G)}{\Delta + \gamma(1 + C_d u_2)} + \frac{\gamma\left(\frac{C_n}{(T + 273.16)}\right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)}$	Mean Daily	Net	Wind Speed, Grass Reference Constants

Evaluation of seven different ET models (Figure 4.2) showed that the temperature based models, Ivanov, Blaney-Criddle, and Thornthwaite, either extremely overestimated or underestimated PET when compared to the other models. Radiation based models produced better results with the Hargreaves and Priestley-Taylor models; however the Makkink model still underestimated PET. The Penman-Monteith had similar results as the Hargreaves and Priestley-Taylor (Figure 4.3).

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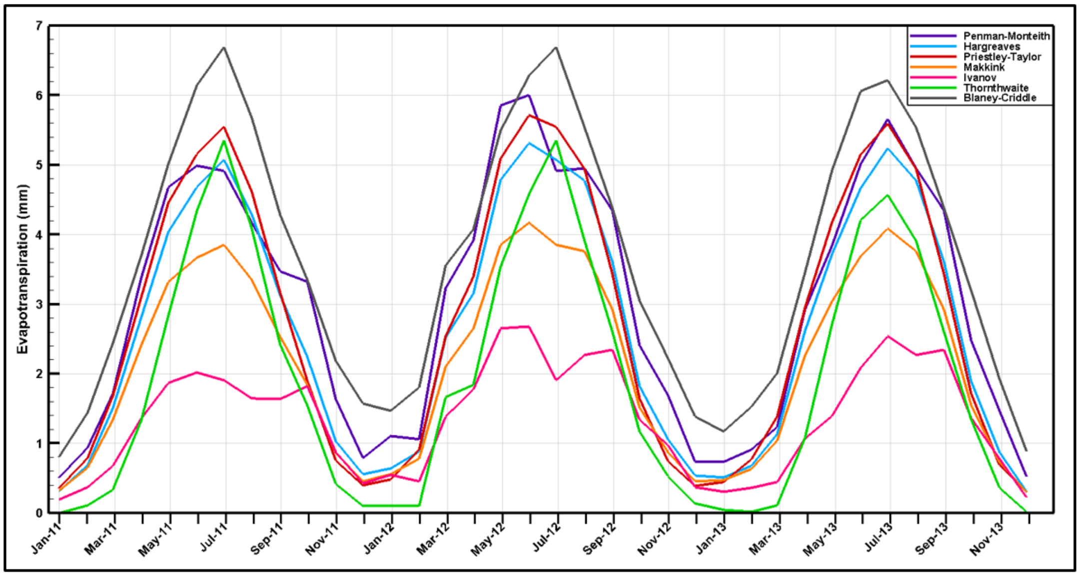

Figure 4.2. Monthly summaries of PET/RET for seven ET methods.

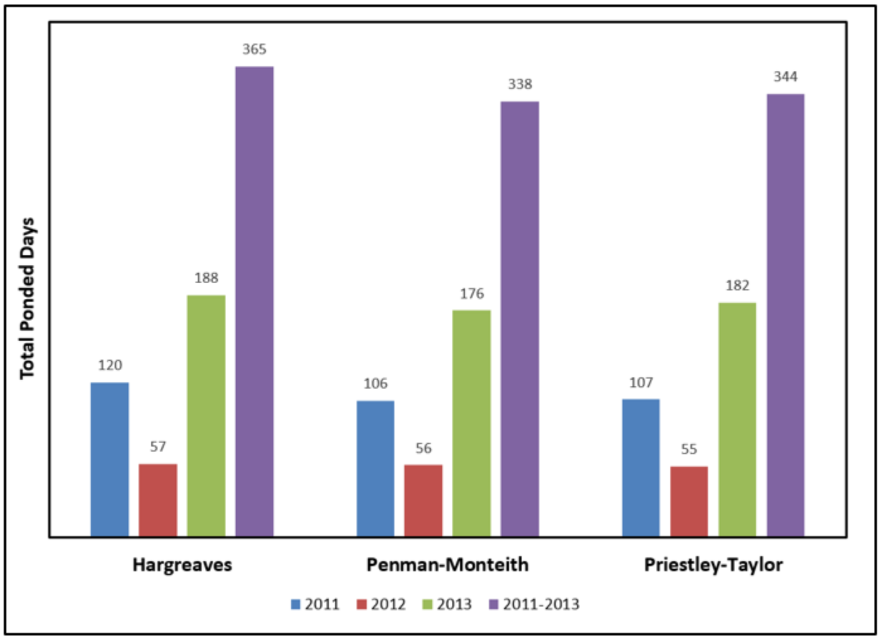

Figure 4.3. Simulated total ponding days for Hargreaves, Penman-Monteith, and Priestley-Taylor PET methods.

The Penman-Monteith method has been shown to provide more consistent estimates of actual ET over other methods (Chiew et al., 1995). Because of this, the Penman-Monteith was used to calculate RET in the PPWB model. The Penman-Monteith equation (3) requires maximum and minimum air temperature and dew point, average wind speed, pressure, and site location (for extraterrestrial radiation) to solve.

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$$RET = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{C_n}{(T+273.16)}\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{3}$$

RET=Reference ET (mm day^{-1})
Δ=Slope of vapor pressure curve (kPa °C^{-1})
R_n=Net radiation (MJ m^{-2} day^{-1})
G=Soil Heat Flux Density (MJ m^{-2} day^{-1})
γ=psychometric constant (kPa °C^{-1})
C_n, C_d=grass reference constants
T=Average air temperature (°C)
u_2=wind speed (m s^{-1})
e_s=Saturation vapor pressure at T_{avg} (kPa)
e_a=Actual vapor pressure (kPa)

Steps taken to solve the Penman-Monteith equation are explained in Huffman et al. (2011). A crop coefficient of 1.05, assumed for shallow, open water (Allen et al., 1998), was used to adjust RET to daily ET rates.

4.3.2 Surface Runoff

Runoff was predicted using the NRCS Curve Number (CN) method (SCS, 1986) for small watersheds. This method uses precipitation and a hydrologic CN. The CN is an index for potential runoff and can be estimated from local soil and land use information. Curve Numbers typically range from 30-100 with larger CN representing lower infiltration rates. The runoff depth equation is shown below (4).

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

Q = Runoff Depth (inches)
P = Precipitation (inches)
I_a = Initial Abstraction (inches)
S = Potential maximum soil retention (inches)

The potential maximum soil retention is inversely related to the CN and can be calculated using equation (5). The initial abstraction is the amount of precipitation losses that occur before runoff begins. Losses include water captured by vegetation and soil infiltration (SCS, 1986). Initial abstraction is assumed to be 20% of S.

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$$S = \frac{1000}{CN} - 10 \tag{5}$$

An initial CN of 78, which corresponds to row crops (straight rows), good conditions, and Hydrologic Soil Group B, was used (SCS, 1986). The CN was then adjusted on a daily basis for antecedent moisture conditions using a methodology documented by Huffman et al. (2011).

4.3.3 Infiltration

Infiltration is defined as the movement of surface water into the soil, and is commonly described as a rate (Chin, 2012), having units of depth of water per unit of time per unit area (e.g., millimeters per day). Varying soil types can have dramatically different infiltration rates. Coarse, sandy soils tend to have high infiltration rates; whereas fine clay and silty soils, like those in the PPR, typically have low rates of infiltration (SCS, 1986). Additionally, infiltration rates of soils are impacted by vegetation and animals, tillage practices, antecedent soil moisture, and many other factors (McGinty, 1979; Dunne, 1991; Meek, 1992). The PPWB model assumes a constant daily infiltration rate for days when the soil temperature (ISU AgClimate database) is above freezing.

A wide range of estimates have been published for infiltration rate in the Ellsworth area. At one end of the spectrum, the published NRCS soil survey for Hamilton County reports the infiltration rate in the Okoboji soils of the Ellsworth drained wetland to be 60.5 mm d^{-1} (Soil Survey Staff, 2013). In contrast, Roth (2010) and Roth and Capel (2012) reported on a field study of a drained wetland located in northern Hamilton county at a site with similar Okoboji soils. Through a detailed evaluation of the inflows and outflows in a water balance study of a drained and farmed prairie pothole wetland, Roth and Capel (2012) estimated the pothole infiltration rate to be 8.7 mm d^{-1} (see Chapter 2: Literature Review for more information on the Roth and Capel studies). Because of the wide range of published estimates for infiltration rate in Okoboji soil, another method using site specific data was explored.

The Hantush equation for groundwater mounding (Hantush, 1967), in conjunction with groundwater monitoring data, provided an estimate suitable for the Ellsworth drained wetland. The Hantush equation for groundwater rise describes the response of groundwater mounds from uniform percolation (Hantush, 1967). This method has been

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widely used for estimating groundwater mounding in infiltration basins and beneath septic systems (Carleton, 2010).

The Hantush equation is:

$$h^2 - {h_i}^2 = \left(\frac{w}{2K}\right)(vt) \cdot \left\{S^*\left(\frac{l+x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}}\right) + S^*\left(\frac{l+x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}}\right) + S^*\left(\frac{l-x}{\sqrt{4vt}}, \frac{a+y}{\sqrt{4vt}}\right) + S^*\left(\frac{l-x}{\sqrt{4vt}}, \frac{a-y}{\sqrt{4vt}}\right)\right\}$$

where, $S^*(\alpha, \beta) = \int_0^1 \mathrm{erf}\left(\frac{\alpha}{\sqrt{\tau}}\right) \cdot \mathrm{erf}\left(\frac{\beta}{\sqrt{\tau}}\right) d\tau$ and $\nu = K\bar{b}/\epsilon$ (6)

h = head at a given time after recharge starts
h_i = head before recharge starts
w = constant percolation (infiltration) rate
K = horizontal hydraulic conductivity
v = diffusivity
b = aquifer thickness
ϵ = specific yield
t = elapsed time
l = half-length of pothole
a = half-width of pothole
x = distance from center of pothole in the x-direction
y = distance from center of pothole in the y-direction
$\alpha = \frac{l+x}{\sqrt{4vt}}$ or $\frac{l-x}{\sqrt{4vt}}$
$\beta = \frac{a+y}{\sqrt{4vt}}$ or $\frac{a-y}{\sqrt{4vt}}$
τ = variable of integration
erf = error function

The equation was calibrated for the Ellsworth drained wetland specifically (Figure 4.4), using groundwater monitoring data and several assumptions. Infiltration rate is assumed to be one-tenth of the horizontal hydraulic conductivity and the specific yield, ϵ, is 0.08 (Logsdon et al., 2010). The aquifer thickness is assumed to be 1.4 m (Schilling et. al., 2016) with an initial saturated zone of 0.67m. The groundwater monitoring data (collected at the center of the pothole) was used to determine the head change during mounding.

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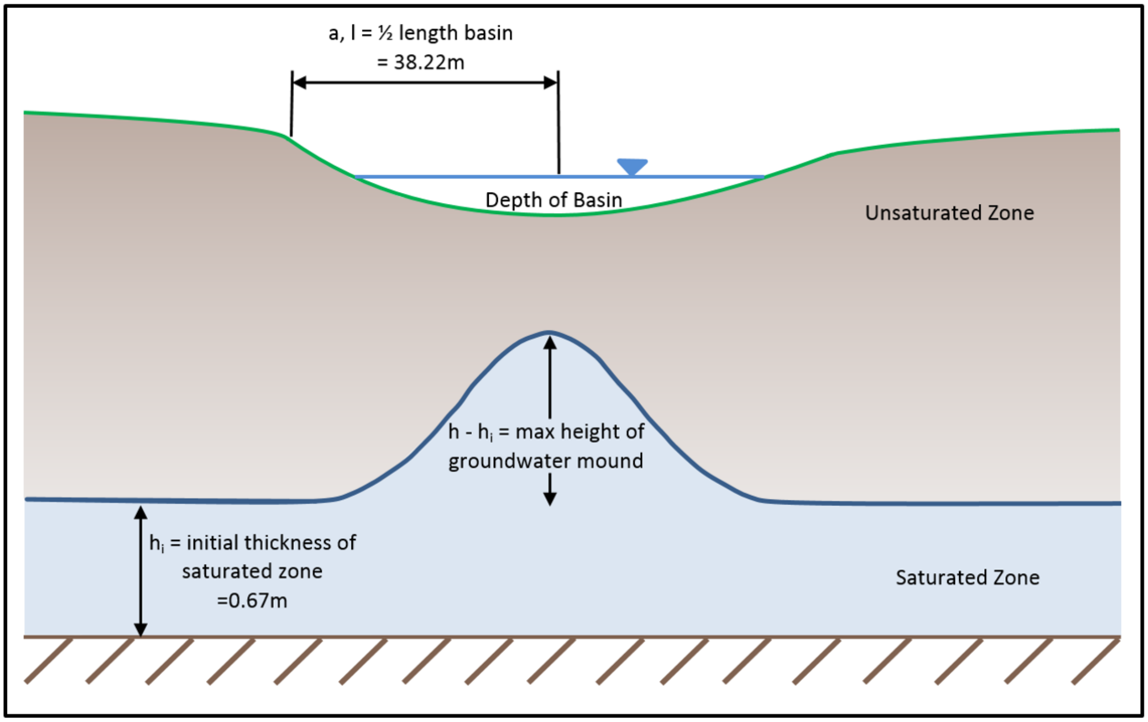

Figure 4.4. Hantush method for groundwater mounding from uniform percolation.

Groundwater levels fluctuated during the monitoring period and discrete periods of mounding were observed in all years (Figure 4.5). In 2011, mounding occurred from the well installation in early June to late July, in 2012, mounding was from late February to late July. In 2013 mounding occurred from March to August. During the annual mounding periods, rapid daily fluctuations in the water table produced mounding events at a smaller scale.

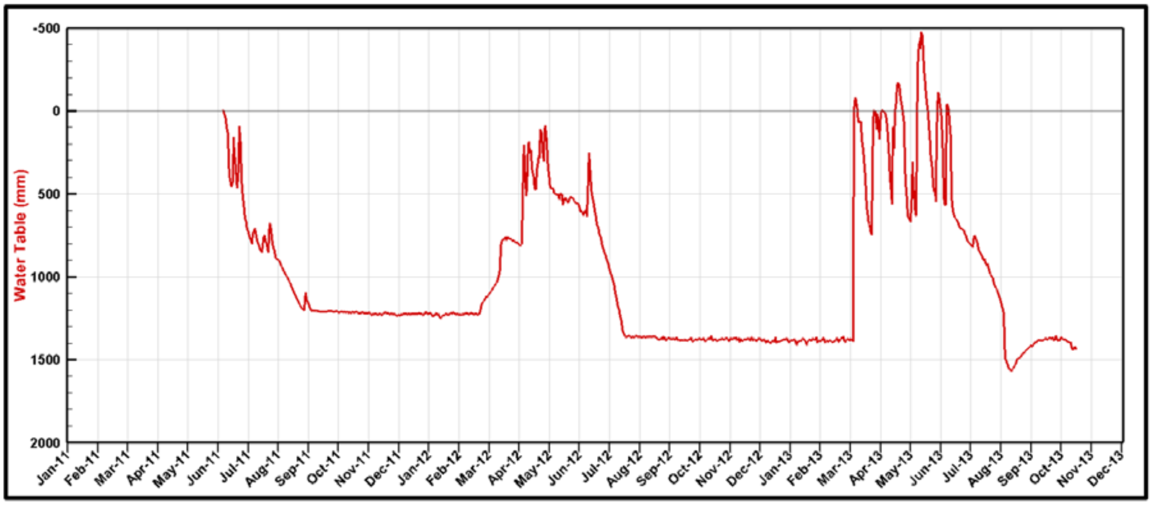

Figure 4.5. Groundwater table below the surface during a 3 year monitoring period.

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The smaller mounding events occurred in response to surface ponding periods. For each mounding event the elapsed time, t, was estimated for a range of infiltration rates, w. Substituting this information (elapsed time and infiltration) into the calibrated Hantush equation and solving, through iterations, for the infiltration rate and elapsed time corresponding to the observed groundwater head change, yielded an average infiltration rate for 2011, 2012, and 2013 of 7.25, 4.6, and 8.75 mm d^{-1}, respectively, and averaged 6.87 mm d^{-1} for the three years. This infiltration rate is close to the Roth and Capel (2012) estimate and 6.87 mm d^{-1} will be used for further data analyses.

4.3.4 Surface Inlet Capacity

Surface inlets are often placed in farmed prairie pothole wetlands to remove ponded water via the subsurface tile drainage system. Inlet capacity varies with both inlet size and type. Their efficiency in draining ponded water also depends heavily on proper maintenance of these structures. Although they are not considered a high maintenance agricultural practice, surface inlets occasionally fill with sediment and debris and become clogged until they are cleaned out. Three sizes of commonly used surface inlets were evaluated in this study. Manufacturing specifications (Hickenbottom, Inc.) were used to quantify the potential impact of three typical surface inlet sizes: 6”, 8” and 10” inlets with 1” round openings – see APPENDIX B for detailed specifications from Hickenbottom, Inc. Manufacturer specifications assume that surface inlets are running at 50% efficiency.

The capacity of a surface inlet to discharge water is dependent on the water depth in the pothole. The water depth in the pothole was calculated using the previously discussed water balance components. This depth was converted to a capacity based on the equations derived from manufacturer specifications (Figure 4.6). The capacity used in the model is the maximum volume of water the surface inlet can discharge per day per drained wetland area.

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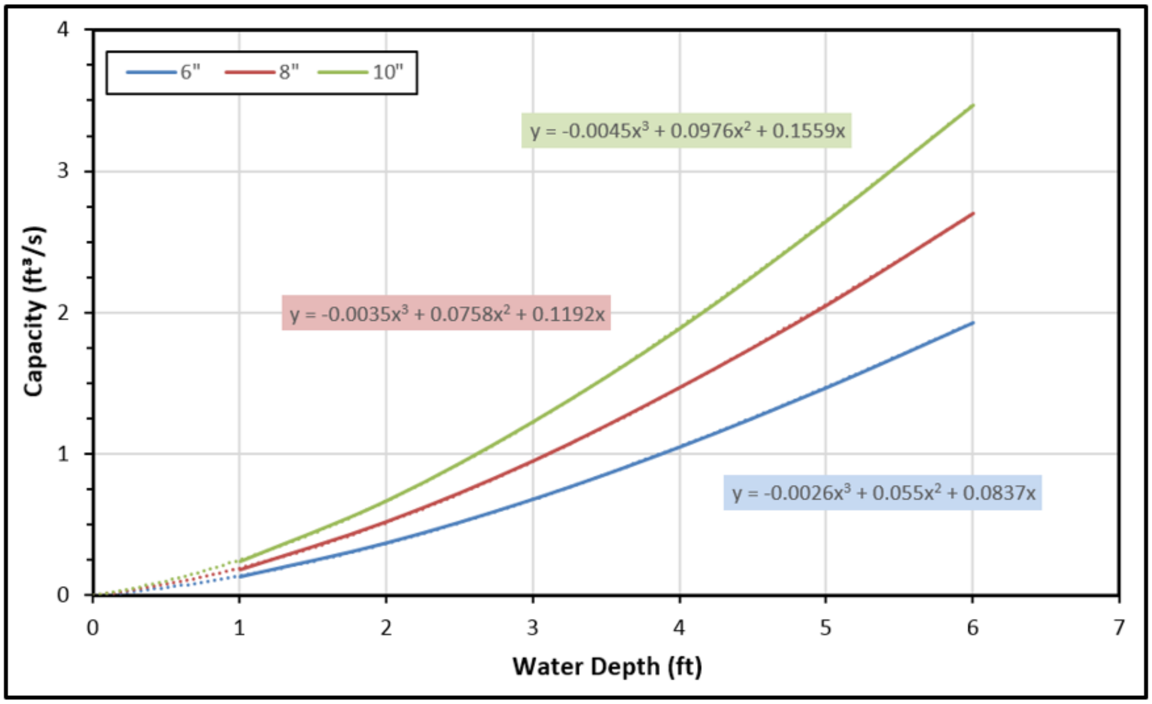

Figure 4.6. Relationship between surface inlet capacity and water depth in pothole derived from manufacturer specifications.

4.4 Limitations

The model provides valuable information for assessing factors that influence the duration of ponding in drained wetlands; however, as with all models, limitations and assumptions used could cause results to differ from observations. Two of the most significant limitations would be the neglect of groundwater influence on ponding and assuming the Ellsworth drained wetland is isolated from other prairie pothole wetlands nearby. The PPWB model neglected groundwater influence because groundwater rarely contributed to surface ponding in the Ellsworth drained wetland (see section 4.2). However, this is not always the case, other studies found that groundwater had a higher impact on ponding in the drained wetlands they evaluated (Politano et al., 2016; Schilling et al., 2016; Roth and Capel, 2012). If the PPWB model were to be used to evaluate the hydrology of another drained wetland, the user must remember that results may differ from the natural environment because groundwater contribution is ignored. The assumption that the Ellsworth drained wetland is a closed and isolated pothole wetland holds true nearly all of the time. The Ellsworth drained wetland only contributes direct runoff to nearby drained wetlands and streams on exceedingly rare occasions. However,

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on these exceedingly rare occasions, the model would have more accurate results if the "fill-spill" concept were included.

Expanding field equipment to include infiltrometer readings, rain gauge, pan evaporation, and more monitoring wells would improve inputs and calibration of the PPWB model. In particular, infiltrometer measurements would improve on the assumption that infiltration is constant from uniform percolation of surface water. Including a rain gauge and measuring pan evaporation at the site would replace the need for using weather information from off-site stations. Additional monitoring wells would improve the understanding of groundwater connection to surface ponding.

4.5 Chapter Summary

Chapter 4 details the development and calibration for the PPWB spreadsheet model. The PPWB model predicts daily ponding depth in the Ellsworth drained wetland. Components of the water balance include precipitation, evapotranspiration (ET), runoff, infiltration, and surface inlet capacity. ET was calculated using the Penman-Monteith method with a crop coefficient for 1.05. The NRCS Curve Number method was used to estimate runoff depth with a CN of 78. Infiltration rate was estimated as 6.87 mm d^{-1} using the Hantush equation for groundwater monitoring. A relationship for surface inlet capacity and depth of water in the pothole was derived from Hickenbottom, Inc. manufacturer specifications for 6", 8", and 10" inlets with 1" round openings.

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CHAPTER 5: SENSITIVITY ANALYIS OF WATER BALANCE PARAMETERS

5.1 Introduction

This chapter describes the effect water balance parameters have on surface ponding in drained wetlands. This analysis was done to improve understanding of what drives and influences ponding. Sensitivity analysis of infiltration, topography, surface inlet presence and capacity, and other factors are outlined in the sections below.

5.2 Depth and Duration of Surface Ponding

Using the calibration and data discussed in Chapter 4, simulated ponding depth in the pothole is shown in Figure 5.1. The PPWB model estimated 136, 51, and 173 days of ponding for 2011, 2012, and 2013, respectively. The amount of ponding is directly related to precipitation. In 2011, 2012, and 2013, the annual precipitation totaled 808 mm, 676 mm, and 884 mm, respectively. The average annual precipitation for these three years is 789 mm, nearly 100 mm less than the long-term (1981-2014) average annual precipitation.

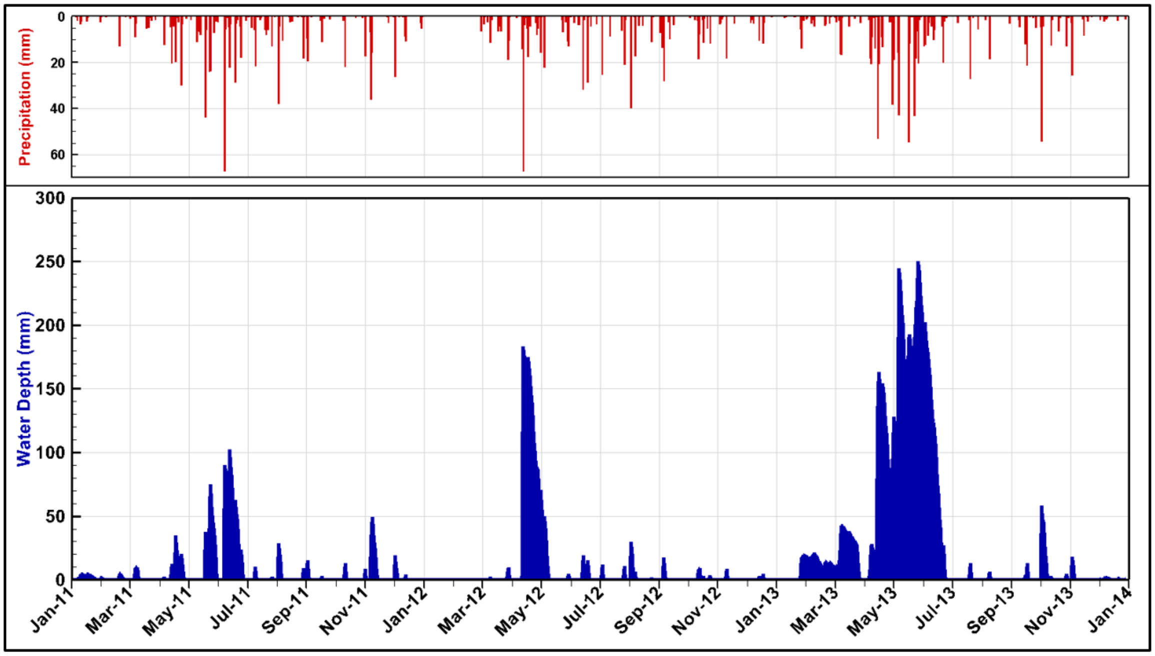

Figure 5.1. Precipitation and simulated ponding for 2011-2013.

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5.3 Effect of Infiltration on Temporary Ponding in Drained Wetlands

Sensitivity of ponding to infiltration rate was illustrated by varying the potential infiltration rate of the Ellsworth drained wetland across a range of rates estimated for similar soils in the Ellsworth, IA area. As expected, infiltration rate has a significant impact on ponding, second only to the amount of precipitation. Using the infiltration estimate of 8.64 mm d^{-1} from Roth and Capel (2012) (see Chapter 2: Literature Review), 160 ponding days were predicted in 2013 (Figure 5.2). In contrast, only 82 days of ponding were simulated using the NRCS infiltration rate estimate of 60.5 mm d^{-1}. This factor of two difference in ponding days was also simulated for 2011. In the drought year of 2012, simulated ponding was even more sensitive to the estimated infiltration rate.

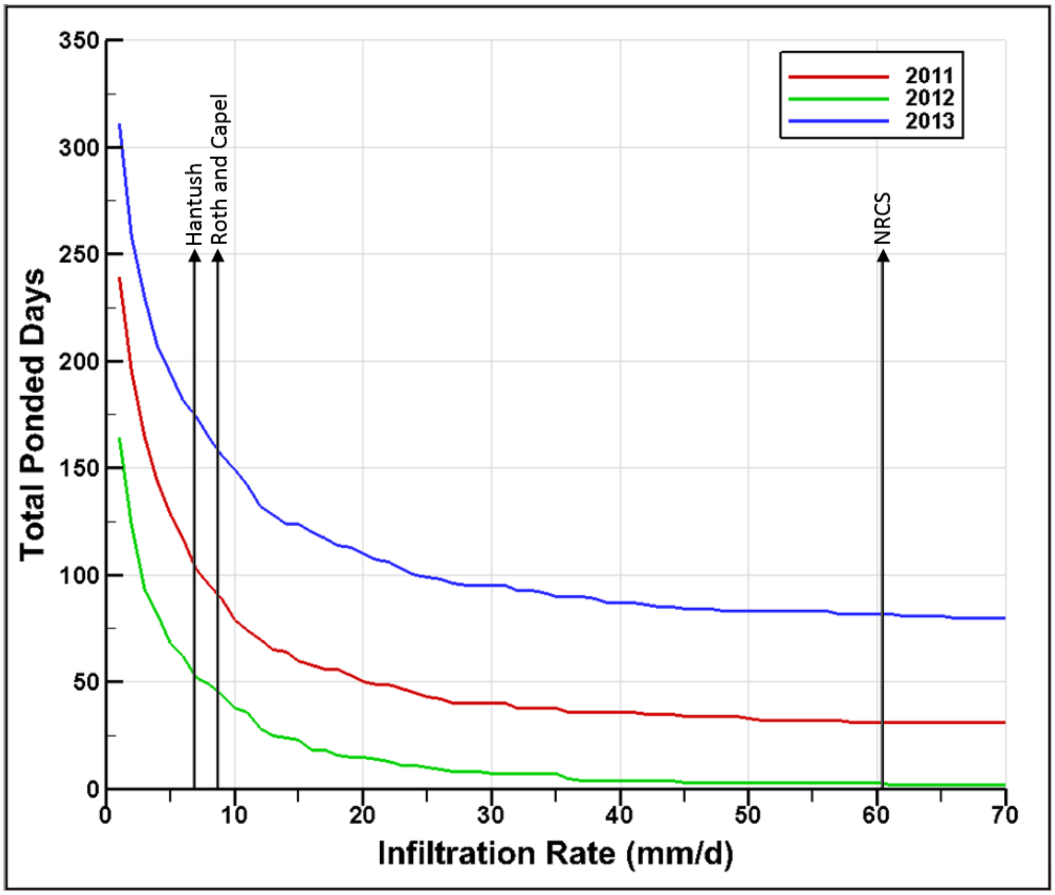

Figure 5.2. Number of days of wetland ponding as effected by infiltration and annual rainfall conditions.

The infiltration rate largely controls the duration of ponding in the Ellsworth drained wetland. For example, at an infiltration rate of 6.87 mm d^{-1}, ponding ranged from 56 to 176 days during the 2011-2013 climate period. If the infiltration rate was an order-

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of-magnitude greater (68.7 mm d^{-1}) the same climate pattern would produce substantially less ponding, ranging from 2 to 80 days. Water balance modeling suggests that ponding duration is most sensitive to infiltration at rates less than 10 mm day^{-1} (Figure 5.2). Because of the significant influence of infiltration rate, it is imperative that studies focused on temporary ponding in potholes have accurate estimates.

The infiltration rate for the Ellsworth soil type included in the NRCS soil survey (60.5 mm day^{-1}) was much higher than estimates provided by Roth and Capel (2012) (8.6 mm day^{-1}) and this study (6.87 mm day^{-1}). The comparability of the Hantush estimated infiltration rate to the Roth and Capel (2012) estimate suggests that these lower bound estimates may be more likely than the NRCS value. In both studies infiltration rate estimates relied on field measurements but vastly different methods were used. Roth and Capel (2012) relied on a detailed water balance study conducted over a field season to estimate the infiltration rate, whereas this study used groundwater monitoring data coupled with the Hantush equation to develop an estimated rate.

There was not an NRCS soil sample taken at the Ellsworth drained wetland, so it is likely that the infiltration was predicated based on soil samples from nearby areas. It is unclear what specific methodology was used to predict infiltration rate at the Ellsworth site. Infiltration rates from Roth and Capel (2012) and the Hantush equation were less than 10 mm day^{-1} and suggest that ponding in these drained potholes may be longer in duration than what would be predicted based on NRCS soil characteristics, which are frequently used for model inputs.

5.3.1 Importance of Infiltration Documented in Other Studies

Others have also noted that infiltration rates serve a primary role for ponding in PPR wetlands. Huang et. al. (2013) stated that infiltration accounts for a majority of the water loss in relatively small wetland. Similar statements about the importance of infiltration were made by Hayashi et. al. (1998) and van der Kamp and Hayashi (2009).

Gray et al. (2001) developed a model to estimate snowmelt infiltration in frozen PPR soils. Study results indicated that frozen prairie pothole soils have limited infiltration capacity which encourages surface ponding during spring snowmelt. The function of groundwater recharge in small wetlands was studied by van der Kamp (1998); in this,

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infiltration was shown to be an important role for maintaining water levels in wells close to prairie pothole wetlands.

5.4 Effect of Topography on Temporary Ponding in Drained Wetlands

The effects of runoff on ponding duration in the drained wetland were evaluated two ways. First, sensitivity of ponding to the area of the catchment draining into the pothole was evaluated for effects of topography. A larger catchment-to-pothole area ratio would deliver more runoff to the pothole and extend ponding duration. The second approach, which is discussed in Section 5.6.2, was to vary the CN across a range of values to evaluate how runoff from different land covers would affect ponding duration. The topography (catchment-to-pothole ratio) had a much greater impact on ponding than changes in the CN.

In addition to infiltration rate, the catchment-to-pothole ratio is an important factor that contributes to pothole ponding duration. Duration of ponding increases with increasing catchment area draining to the pothole (Figure 5.3). Using the climate conditions from 2011 to 2013, ponding would have occurred for approximately 370 days assuming a catchment-to-pothole ratio of 10:1 and 473 days for a ratio of 20:1. Beyond a ratio of 90:1, ponding would have been nearly continuous for the duration of the study period. The total ponded days for the three-year simulation increases approximately linearly with catchment area, the increase is not perfectly linear because the relationship between runoff and curve number (using the NRCS CN method) is not linear for CNs less than 100 (SCS, 1986). The average increase in total ponded days is 7.9 days for each one acre increase in catchment area (Figure 5.3).

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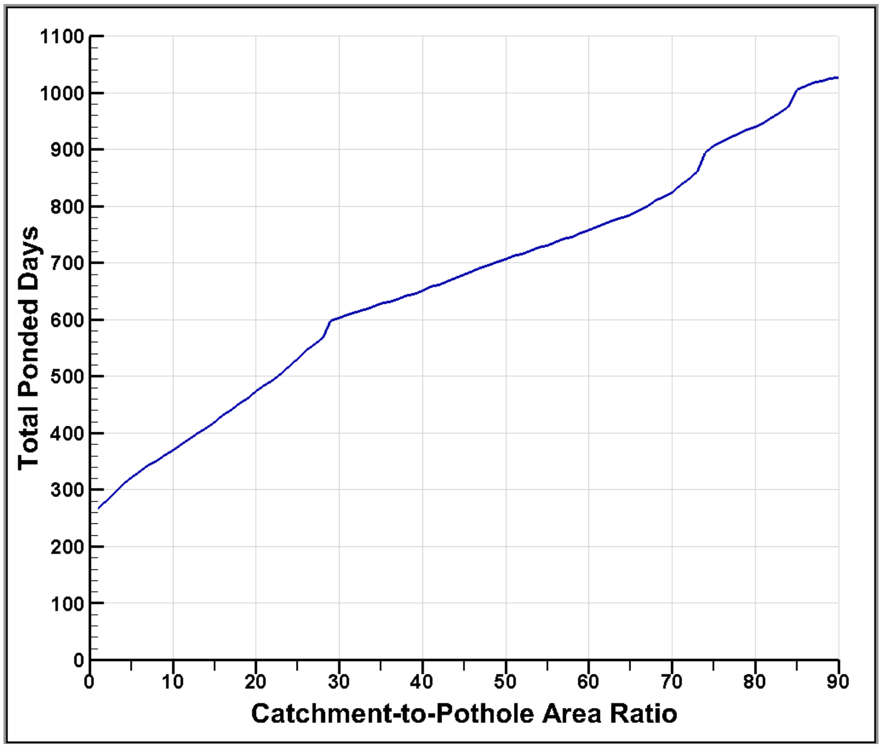

Figure 5.3. Total days with simulated ponded conditions for a range of catchment-to-pothole ratios for 2011-2013.

5.4.1 Importance of Topography Documented in Other Studies

Drained wetlands with a larger catchment-to-pothole ratio have more annual ponded days. This is consistent with results of a study of restored wetlands in the lower PPR (Iowa, Minnesota, and South Dakota) (Galatowitsch, 1996). An evaluation of 58 recently restored wetlands over three years showed that wetlands generally failed to reflood (surface ponding) when the catchment-to-pothole ratio was 2.5:1 or less. Wetlands with a 4:1 or greater ratio were flooded for the entire three-year study duration (Galatowitsch, 1996).

In addition to increased ponding days, catchment-to-pothole ratio has also been utilized as an important criteria for citing nutrient treatment wetlands (Crumpton et al., 2006). As part of the Iowa Conservation Reserve Enhancement Program (CREP), wetland restorations for nitrate reduction with a 200:1 to 50:1 watershed/wetland ratio are approved for the program. Even though CREP wetlands are much different than prairie pothole wetlands, the topography (catchment-to-pothole area ratio) has been cited as an important factor for successful restoration in both types of wetlands. Wetlands with a larger catchment-to-pothole ratio have shown a significant increase in nitrate removal

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efficiency (Crumpton et. al., 2006). Monitoring data shows that the CREP wetlands with this ratio remove 40% to 90% of the nitrate flowing into them (Iovanna et al., 2008).

5.5 Effect of Surface Inlets on Temporary Ponding in Drained Wetlands

While not present in the Ellsworth drained wetland, surface inlets are very common to the area. A surface inlet is a direct connection to subsurface tiling through which any ponded water simply bypasses slow infiltration and instead, discharges into the subsurface tile drainage system. Both the presence and capacity of a surface inlet affects ponding dynamics, although the presence of an inlet has a more profound impact than varying the inlet capacity. A 6-inch, surface inlet with an efficiency of 50% reduces predicted ponding days by approximately 50%, from 338 days to 171 days (Table 5.1). Increasing the size of the surface inlet to 10-inch diameter reduces ponding by an additional 48 days. During a wet year such as 2013, the existence of a 10-inch surface inlet in the drained wetland would have reduced the total ponded days by nearly 65% (Figure 5.4).

Table 5.1. Comparison of surface inlet size to total days with ponding for 2011-2013.

Scenario	Days ponded (2011-2013)	Time ponded
No surface inlet	338	30.8%
6” inlet	171	15.6%
8” inlet	142	13.0%
10” inlet	123	11.2%

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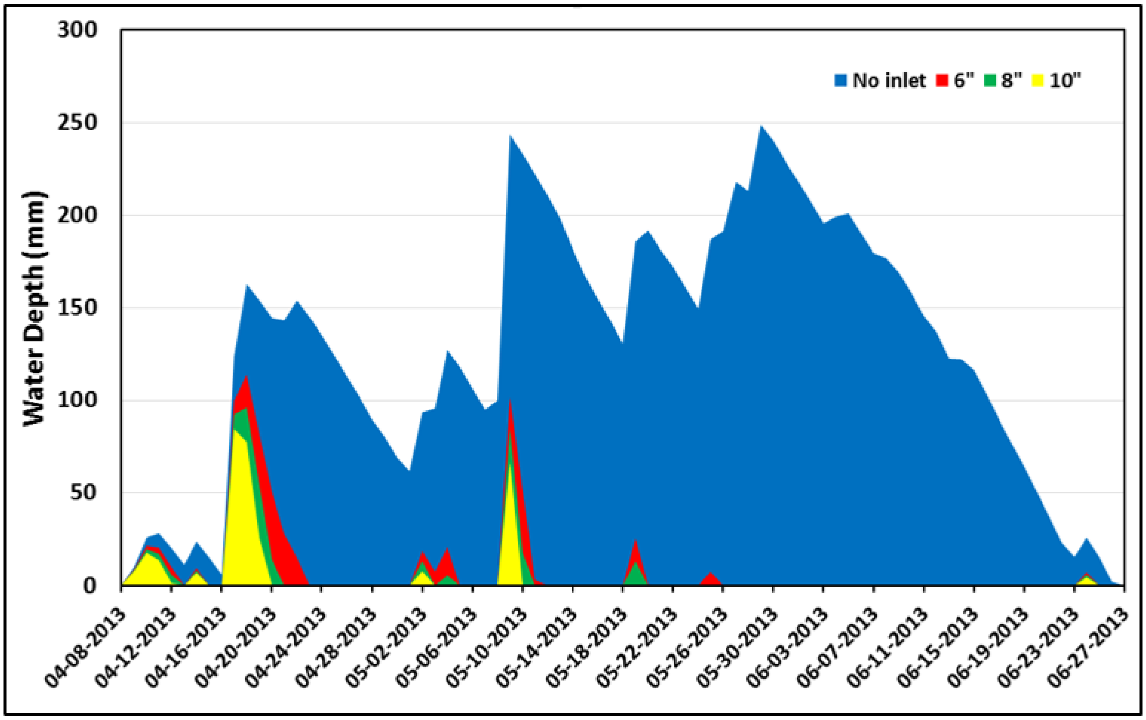

Figure 5.4. Water depth in the Ellsworth drained wetland for varying surface inlet sizes during 2013 (a wet spring).

The mere presence of a surface inlet in a drained wetland significantly alters the pothole hydrology and overwhelms other ponding factors. The capacity of a surface inlet was less important than presence/absence of a surface inlet in a drained wetland. A larger surface inlet resulted in less than a 50 day difference in the total ponded days for the 2011-2013 simulation period, when compared to a smaller size inlet. With the cost per surface inlet being more than double the cost for a smaller size inlet ($54 for a 10” inlet and $24 for a 6” inlet; Hickenbottom Manufacturing, Inc.), there would likely be little economic benefit to having a larger surface inlet, provided inlets are maintained and kept free of debris.

5.5.1 Importance of Surface Inlet Presence Documented in Other Studies

In a study of tile flow from a drained watershed with surface inlets, Schilling and Helmers (2008) found that surface inlets mimic sinkholes by contributing to rapid conveyance of water and nutrients from agricultural fields. In the Roth and Capel (2012) field study, the presence of a surface inlet contributed to 95% of the release of ponded water, with evapotranspiration and infiltration rate accounting for very little of the water outflow.

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5.6 Effect of Other Factors on Temporary Ponding in Drained Wetlands

While infiltration rate, catchment-to-pothole ratio, and presence of surface inlets are major factors that affect ponding depth and duration, other potential elements were also evaluated. Factors included in this section include the effects of different crop coefficient on ET and influence on runoff from different land covers as varied by the CN value.

Changing the ET crop coefficient (assuming corn or soybean vegetation instead of shallow, open water) showed little change in ponding duration and there was no change in ponding duration when comparing corn and soybean vegetation. The crop coefficients used for corn, soybean, and shallow open water are outlined in Table 5.2. In 2011 ponding duration increased by less than 0.5% when assuming a crop coefficient of corn/soybean; increased duration of ponding was higher in 2012 and 2013 at 1.3% and 2.4%; respectively. There is no clear reason why ponding duration had a larger increase from the crop coefficient for 2012 and 2013 than 2011.

Table 5.2. Crop coefficients.

Growing Stage	Shallow, open water	Corn	Soybean
Beginning	1.05	1.2	1.15
Intermediate	1.05	1.2	1.15
Final	1.05	0.35	0.5

Different land covers, represented by changes in the CN did not particularly influence the ponding duration. According to the USDA TR-55 (Urban Hydrology for Small Watersheds) the CN typically ranges from 50-85 for land covers (row crops and pasture) common to the DML landscape. Sensitivity analysis showed that having a CN between 50 and 70 caused almost no changes in the total ponded days during the simulation period. For CNs ranging from 70-85, there was an increase in ponding days; however, the increase in ponding days was not significant when compared to the other water balance parameters, thus rendering the CN to have a smaller impact on ponding.

5.7 Chapter Summary

Chapter 5 describes results from sensitivity analyses of infiltration, topography, surface inlet presence and capacity, ET crop coefficient, and land cover. Sensitivity analysis was completed to improve understanding of what factors significantly influence

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ponding. In the absence of surface inlets, infiltration rate was found to have a substantial impact on ponding, second only to the amount of precipitation. When a surface inlet is present in a drained wetland, however, the hydrology is significantly altered and ponding impact from other factors becomes negligible. Topography also affects ponding for drained wetlands with a larger catchment-to-pothole ratio. Other factors had less significant influence on ponding duration.

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CHAPTER 6: MODEL VALIDATION

6.1 Introduction

The intent of model validation is to compare simulated results to actual data to see how well the model is able to replicate observed ponding. This proved difficult because very little documentation of surface ponding in the Ellsworth drained wetland exists. The groundwater monitoring data was useful when the water table rose above the surface in 2013. Other efforts to validate the PPWB model include visual evidence of surface ponding and crop impact in annual aerial photographs.

6.2 Groundwater Monitoring

During the groundwater monitoring period, the water table was rarely above the ground surface. During the wet spring of 2013, however, the water table rose above the surface 32 times between March and June. For each day where the groundwater was above the surface, the PPWB model had also simulated surface ponding on that day (Figure 6.1). Comparing the depths on the individual days was not prudent to validation efforts because of the inconsistency in the data collection location. The groundwater level was collected in the Ellsworth drained wetland, whereas, the surface water ponding was estimated using data collected at a weather station 20 miles away.

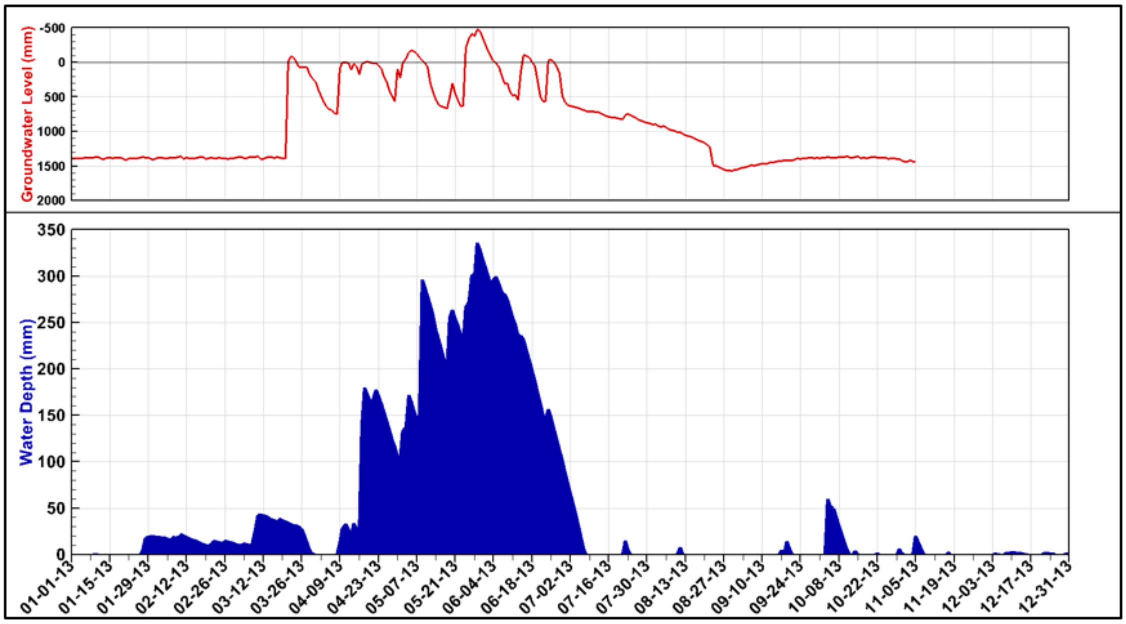

Figure 6.1. Comparison of the groundwater table and simulated ponding.

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6.3 Aerial Photographs

The model simulation period was extended to 12 years (2004-2015) so visual validation of ponding impact on crops using aerial photos could be completed. This method does not provide validation for the simulated depth of the drained wetland, but it does increase confidence in simulated ponding duration. Observations of corn yield impact from inundation (Ritter and Beer, 1969 and Nielsen, 2011) indicate a 40% reduction in crop yield typically occurs when there are 3.5 days of consecutive ponding during the early stages of growing. Also, an additional 1-2 days (4-5 consecutive days of ponding) resulted in no crop yields during that season. This information was used to determine if the simulated ponding would cause negative impact on crop yields. Table 6.1 has the year and month the aerial photograph was taken and shows the negative impact comparison for aerial photographs and the PPWB model. See APPENDIX C for aerial photographs and simulated daily water ponding depth for the annual growing season.

Table 6.1. Comparison of negative crop impact based on evidence of ponding from aerial photographs and the model estimate.

Year	**Month**	**Negative Impact from Aerial Photo**	**Negative Impact from PPWB Model**
2004	October	No	Yes
2005	August	No	Yes
2006	October	No	No
2007	September	Yes	Yes
2008	October	Yes	Yes
2009	September	Yes	Yes
2010	September	Yes	Yes
2011	September	Yes	Yes
2012	June	No	No
2013	September	Yes	Yes
2014	September	Yes	Yes
2015	October	Yes	Yes

Aerial photography indicated negative yield impacts from ponding in eight of the twelve years. The model predicted significant ponding in each of these impacted years. In 2004 and 2005, the aerial photographs showed no impact on crops while the model simulated ponding to the extent that crop impact would be expected. It is unclear why the model did not correctly simulate ponding duration for 2004 and 2005.

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Impact occurred in eight of the last nine years. Some years (2008, 2010) it was clear that no crop production occurred in the drained pothole whereas other years (2009, 2011) had less impact. On one occasion, 2006, there looked to be a positive impact on crop production when compared to the crop yield in the upland areas. Two thousand six was a drought year, and during extreme drought years, drained wetland have been found to produce a higher crop yield than upland areas because of their ability to hold water (Jones, 2015).

In addition to evaluating the crop impact in aerial photographs, some years showed surface ponding on the day the aerial photo was taken. Knowing the month the aerial was taken provides a general time period of the observed ponding event which can be compared to model simulated ponding for that observation. For example, the 2010 aerial photo (APPENDIX C) was taken in September with a noticeable amount of surface ponding. The simulated ponding results estimate more than 305 mm of ponding during the entire month of September in 2010.

6.4 Chapter Summary

Little observed data in the Ellsworth drained wetland made model validation difficult; fortunately, groundwater monitoring during 2013 showed 32 instances where the water table was measured above the surface. For those 32 days, the model also showed simulated ponding. A comparison of expected crop impacts (based on simulated ponding) and observed impacts (based on aerial photographs) provided validation in 10 out of the 12 years. Based on the model results, 2004 and 2005 should have shown an impacted crop; however, there was no evidence of impact in aerial photographs. One potential explanation for why there was no visual crop impact in 2004 and 2005 is the possibility that the farmer was able to re-plant the crop after the extended ponding event in the early growing season. Eight out of the last twelve years had reduced crops yields and in some years (2008, 2010) it was clear that no crop production occurred at all. The 2010 aerial photograph was taken on a day in September with a noticeable amount of surface ponding. While the exact day the photo was taken is unknown, the PPWB model simulated more than 305 mm of ponding during the entire month of September. Even with the lack of site-specific hydrologic and meteorologic data for Ellsworth drained wetland, the model appears to predict actual ponding conditions reasonably well.

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CHAPTER 7: LONG-TERM SIMULATION OF TEMPORARY PONDING IN DRAINED WETLANDS

7.1 Introduction

This chapter discusses the future outlook of the Ellsworth drained wetland through an evaluation of historic trends and future climate projections. Two hundred years (1900-2099) of data were used to evaluate climate and ponding trends. The NWS COOP data was used for 1900-1997, NOAA GSOD data was used for 1997-2015, and future climate prediction data for 2016-2099 came from Chris Anderson, a climatologist at Iowa State University.

7.2 Model Adjustments

The only available datasets for a 200 year simulation period are maximum and minimum air temperature and precipitation. The databases of observed conditions used in the 200 year simulation period are the NWS Cooperative Observer Program (COOP) for 1900-1997 and NOAA GSOD for 1997-2015. The future climate projection dataset for 2016-2099 came from Chris Anderson, a climatologist at Iowa State University. The NWS COOP and NOAA GSOD datasets are from weather stations located in Ames, IA. The future climate dataset was predicted for Webster City, IA. Webster City is approximately 14 miles northwest of the Ellsworth drained wetland (Figure 7.1).

Evapotranspiration could not be calculated using the Penman-Monteith method because it requires data that is not available. Looking back at the comparison of seven ET methods (Section 4.3.1 Evapotranspiration), the Hargreaves and Priestley-Taylor methods had similar results as Penman-Monteith for 2011-2013. The Hargreaves method was chosen because in requires less inputs (only maximum and minimum air temperature) than the Penman-Monteith and Priestley-Taylor methods. See Section 4.3.1 to review details about the Hargreaves equation.

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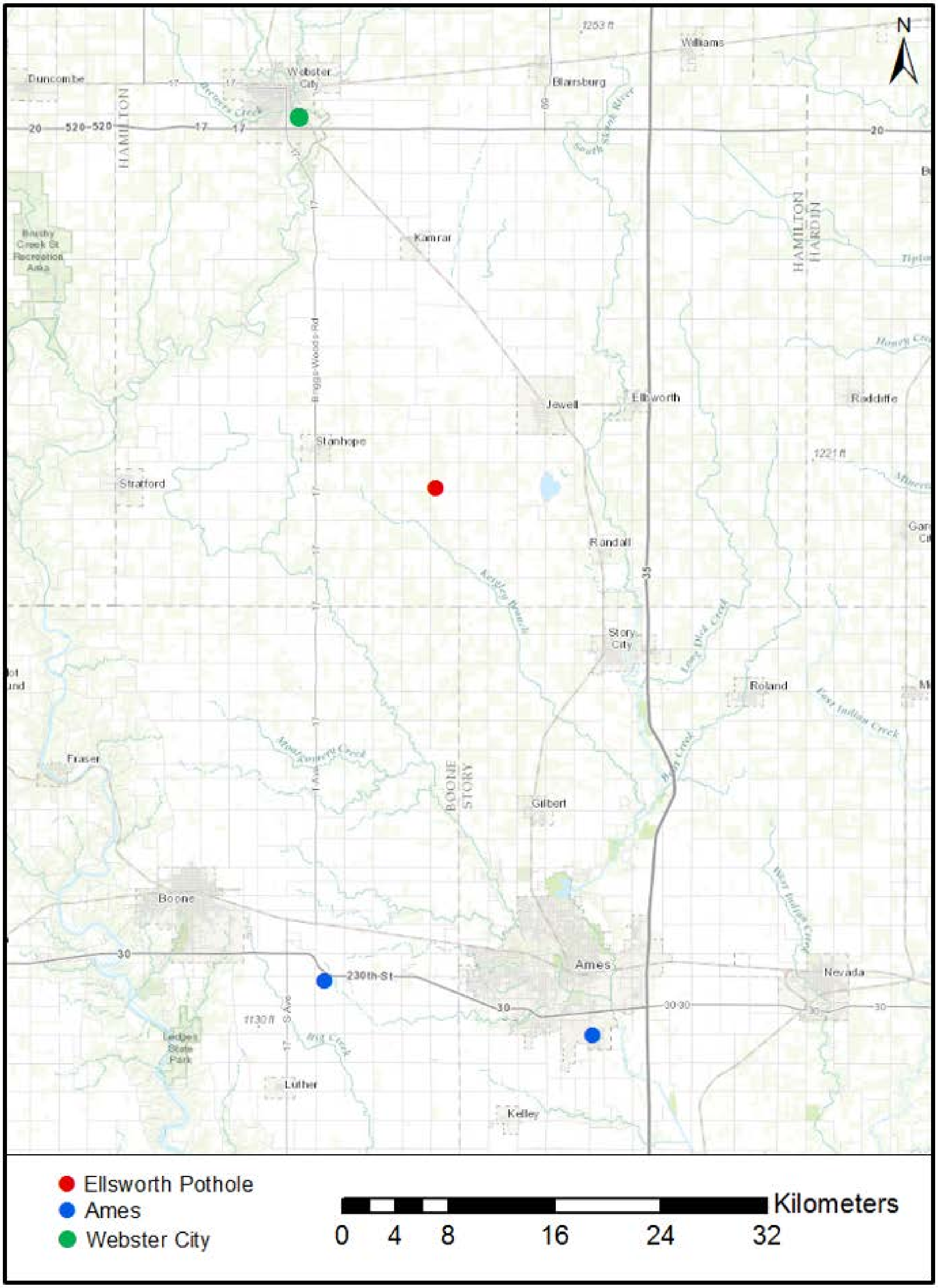

Figure 7.1. Weather station locations for databases used in the long-term simulation.

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Soil temperature is needed to account for reduced infiltration in frozen soil in the Ellsworth drained wetland. If soil temperature is above 32°F it is assumed that water is infiltrating at a rate of 6.87 mm d^{-1}, when soil temperature is below freezing, there is no infiltration. Soil temperature monitoring began in 1986 in the Ellsworth area. For data prior to monitoring and the future climate prediction, soil temperature was estimated using the equation:

$$Estimated\ Soil\ Temperature\ (°\text{F}) = 10DayAvgT + STC \tag{7}$$

where,

10DayAvgT is the 10-day running average of the mean air temperature (°F) and STC is the Soil Temperature Coefficient (°F)

The method for determining the STC is discussed in the next section and all STC values are summarized in APPENDIX D: SOIL TEMPERATURE COEFFICIENTS.

7.2.1 Soil Temperature Coefficient

A unique soil temperature coefficient was developed for each Julian day of the year. The coefficient was constructed using 28 years of daily average 4 inch soil temperature and maximum and minimum air temperature data from the ISU AgClimate database. The steps taken to reach the calculated soil temperature coefficient are outlined below.

(1) After calculating the daily average air temperature (°F), a 10-day running average of air temperature (10dayAvgT, °F) was computed to reduce any influence of air temperature extremes (Zheng, 1993). Running averages for the first nine data entries were calculated using 1-day to 9-day running averages.

(2) The difference in measured soil temperature (MeasST, °F) and 10dayAvgT was calculated for every day in the dataset.

$$\Delta = MeasST - 10dayAvgT \tag{8}$$

(3) The soil temperature coefficient (STC, °F) is the average of calculated Δ for each Julian day (i) ranging from 1 to 366.

$$STC\ (i) = \left(\sum_{j=1986}^{2013} \Delta_i(j)\right) \div 28 \tag{9}$$

For example, the STC for Julian day 1 (January 1st) is

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$$STC(1) = \sum_{j=1986}^{2013} \Delta_1(j) = \Delta(1/1/1986) + \Delta(1/1/1987) + \cdots + \Delta(1/1/2013) = 6.16$$

7.3 Historic Hydrologic Trends

Over the last 116 years, annual precipitation has increased at an average rate of 0.054 inches per year. In 1900, the average annual precipitation was approximately 29 inches, while the 2015 average annual precipitation was approximately 35 inches (Figure 7.2). While annual precipitation data is important and useful, the impact of precipitation on ponding can be better represented with seasonal precipitation.

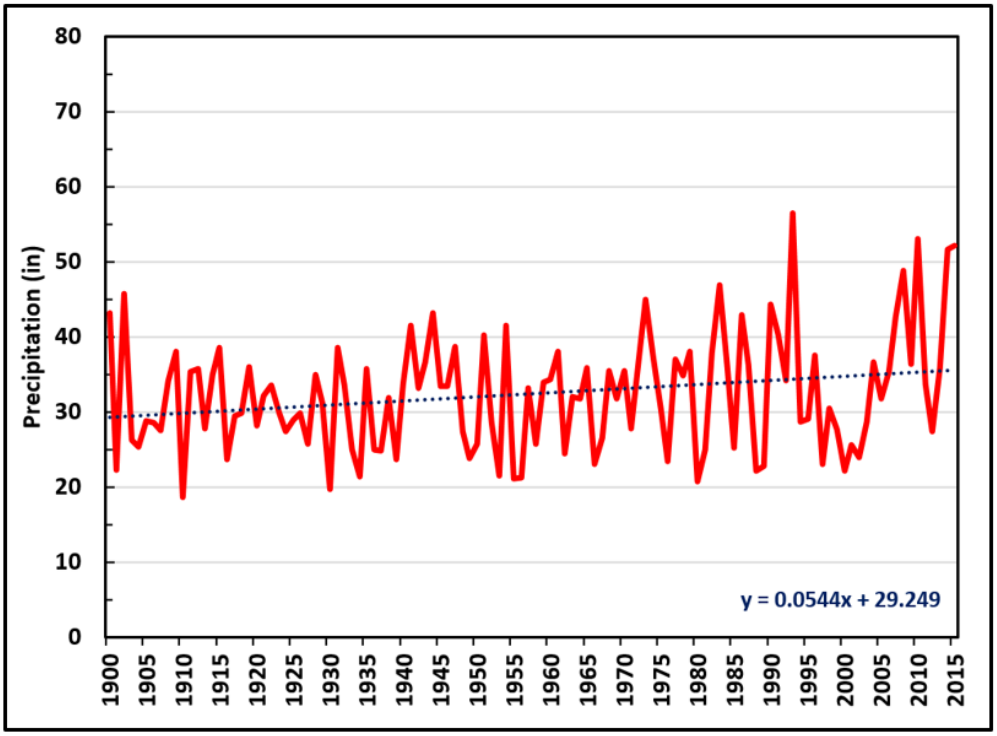

Figure 7.2 Annual precipitation from 1900-2015.

Evaluation of seasonal precipitation shows a shift in seasonality during spring and summer. In spring (Figure 7.3.A) the seasonal precipitation has increased by an average of 0.026 inches/year since 1900. The average increase in spring precipitation is more than double (0.054 inches/year) when evaluating just the last 20 years (since 1995). Seasonal precipitation for summer (Figure 7.3.B) has increased more than that of spring, with an average increase of 0.035 inches/year since 1900 and 0.18 inches/year since 1995. There has been almost no change in average seasonal precipitation for fall (Figure 7.3.C) or winter (Figure 7.3.D) since 1900.

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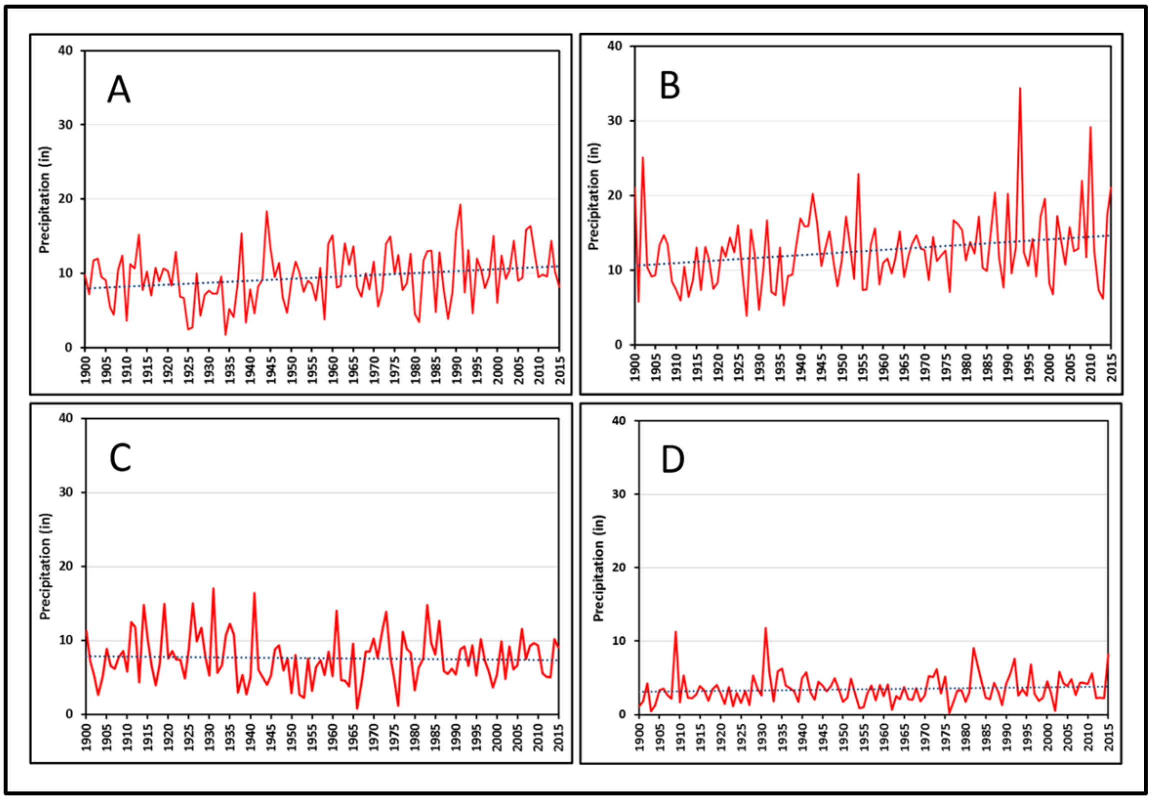

Figure 7.3. Changes in the average amount of precipitation falling in A: spring, B: summer, C: fall, and D: winter.

As expected, the model suggests that the average annual total ponded days has been steadily increasing over the last 116 years (Figure 7.4). Simulated total ponded days has been increasing by approximately 0.32 days/year. This rate of increase for total ponded days since 1900 assumes that subsurface tile drainage was installed prior to 1900 and that no new artificial drainage will be installed in the next 84 years. It is unknown when the tile drainage was actually installed, if the tile drainage was installed after 1900, rate of increase would be different as more ponding would have occurred in years prior to the tile installation.

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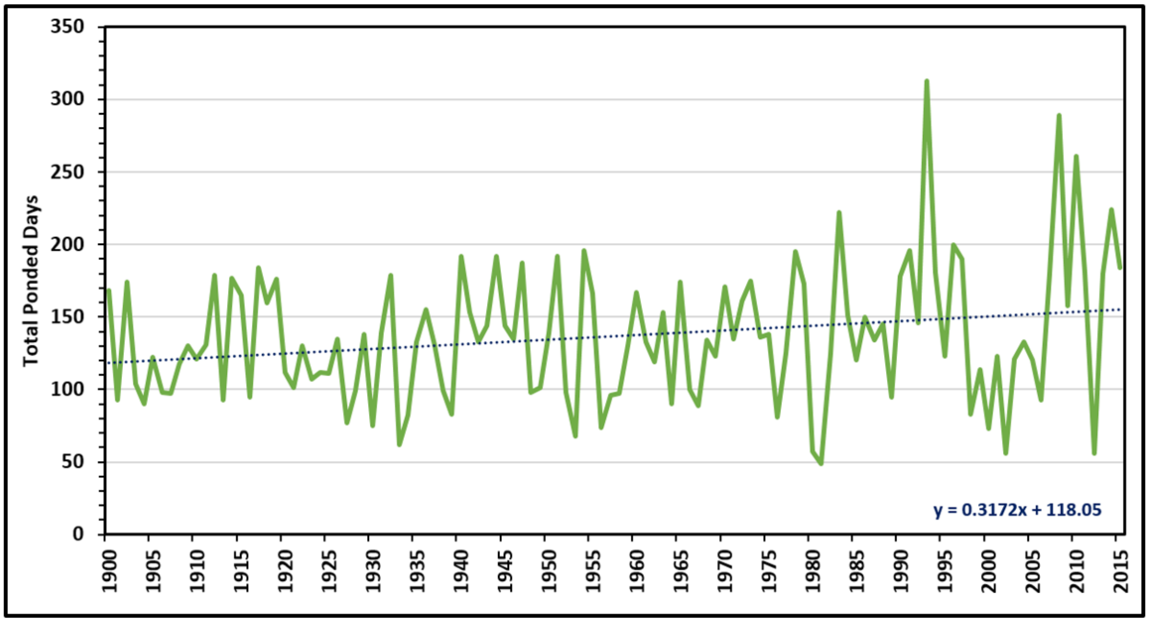

Figure 7.4. Total ponded days simulated from the model for 1900-2015.

7.4 Climate Projections and Hydrologic Trends

Hydrologic trends for the next 84 years (2016-2099) were evaluated in a similar fashion as the historic analysis. The average annual precipitation is expected to continue increasing. The rate of increase is estimated to be about 0.13 inches/year. The 2099 estimated annual precipitation is 48.5 inches (Figure 7.5). The shift in seasonality is expected to continue increasing for spring and summer, also. The total ponded days is projected to increase at a rate of 0.45 days/year for the next 84 years (Figure 7.6).

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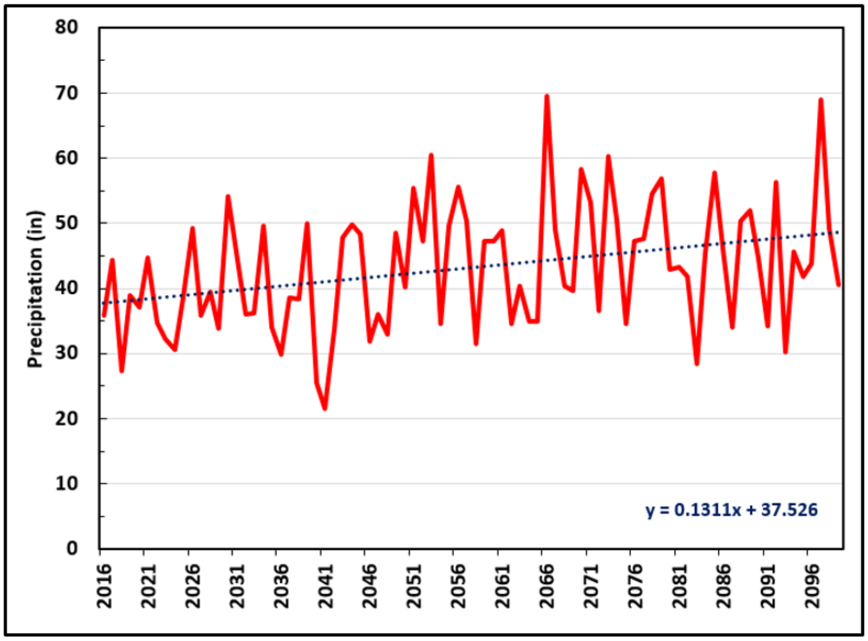

Figure 7.5. Predicted average annual precipitation for 2016-2099.

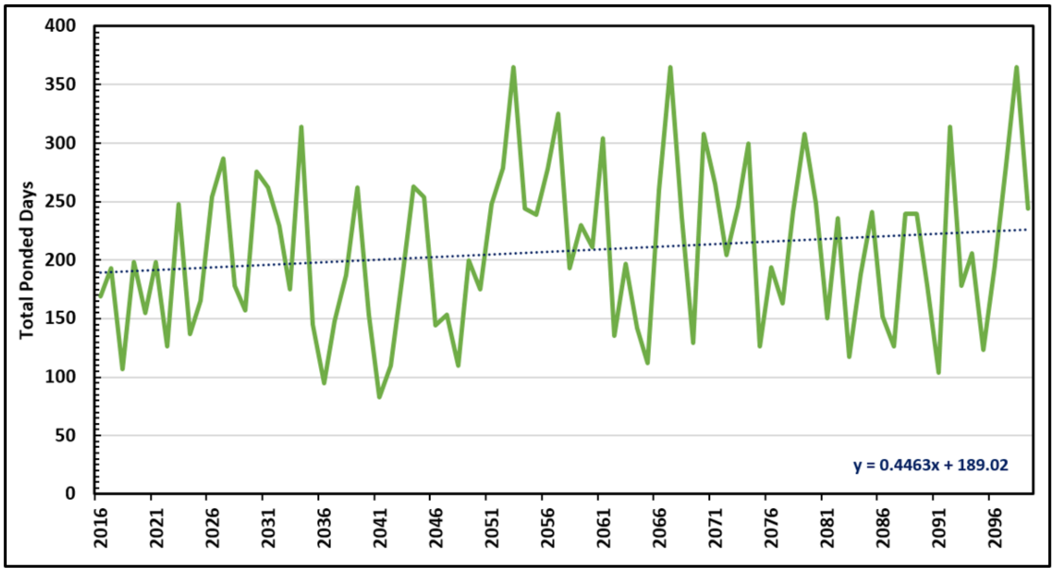

Figure 7.6. Total ponded days simulated from the model for 2016-2099.

7.5 Chapter Summary

Chapter 7 is an overview of the future outlook of the Ellsworth drained wetland based on 116 years of historic data and 84 years of future climate projections. The 200 years of data came from three different databases: NWS COOP data was used for 1900-1997; NOAA GSOD data was used for 1997-2015; and future climate prediction data for 2016-2099 came from Chris Anderson, a climatologist at Iowa State University. The

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model had to be modified by using Hargreaves method in place of the Penman-Monteith for potential ET calculation because only data for maximum and minimum air temperature and precipitation are available for the 200 years. Average annual precipitation has been increasing at a rate of 0.054 inches/year for the last 100 years. Evaluation of seasonal precipitation showed a shift in seasonality for spring and summer. The average annual precipitation is expected to reach 48.5 inched by 2099. As a result, total ponded days are also expected to increase.

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CHAPTER 8: IMPLICATIONS

8.1 Introduction

This chapter discusses the possible implications of continued farming of drained wetlands. Agricultural implications include mitigation strategies to balance ecosystem needs with production agriculture and impacts of future predicted trends with regards to climate. Environmental implications include insight for wetland restoration.

8.2 Agriculture Implications

A better understanding of geomorphic and land use controls on temporary ponding of drained wetlands in the PPR can be used to develop mitigation strategies that balance ecosystem needs with agriculture. For example, in some areas where conditions are appropriate (low infiltration rates, high catchment to pothole ratio), ponding will inevitably occur and these sites may be optimal candidate locations for full wetland restoration. If these sites have a surface inlet, full wetland restoration may not be necessary. Rather, a surface inlet management program that could be implemented to manage the ponding duration and depth in the pothole may be more appropriate. A temporary plugging of the surface inlet in the spring would allow the pothole to fill and provide ecosystem benefits for migratory waterfowl. If sited in potholes with low infiltration rates, ponding would be present for an extended period of time when it was needed the most. At the conclusion of the avian migratory period, the plug could be removed. The model indicates that the ponded water would drain quickly for planting of crops. After fall harvest, farmers could be incentivized to plug surface inlets to promote temporary ponding. Improved management of drained wetland would produce both agricultural and ecosystem benefits.

It is important to consider long-term trends and future outlook of climate condition when evaluating the continued farming of drained prairie pothole wetlands. Trends show that ponding duration is increasing at a rate of 0.32 days/year and most of the additional days are occurring during spring and summer months. The increase in ponding days during spring and summer is likely to negatively impact crop yield.

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8.3 Environmental Implications

Results of this study have implications for management of farmed and drained potholes. Wetlands improve water quality, offer food and habitat for many reptile, amphibian, and migratory species, provide flood and drought control, and facilitate groundwater recharge (Crumpton et al, 2006; Sather et al, 1984). In the intensive agricultural districts of north-central Iowa, wetlands, whether they are artificially drained or not, negatively impact crop yields when excessive ponding occurs during the growing season. Ponding duration in excess of four to six days affects the yields and viability of corn and soybean crops (Ritter and Beer, 1969). The average yield of soybeans under flooded conditions is 25% lower than a non-flooded location (VanToai et al., 1993). According to a study that evaluated the profitability of farming prairie pothole wetlands, upland areas had an average profit per acre that is nearly double than the average profit per acre of farmed prairie pothole wetlands (Jones, 2015). This supports the notion that transitioning these potholes away from susceptible production agriculture and toward potential candidate sites for wetland restoration. Creating, restoring, or enhancing these “wet spots” (Schilling et al, 2013) on the landscape can provide ecosystem benefits for migratory waterfowl (Murphy and Dinsmore, 2015), macro- and micro-invertebrates (Euliss, 1999), vegetation (Galatowitsch, 1996).

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CHAPTER 9: SUMMARY AND CONCLUSIONS

This Master's thesis set out to accomplish 3 goals:

1. Develop a water balance model for a drained wetland located in Ellsworth, IA.
2. Use the PPWB model to evaluate how site-specific controls affect the frequency, depth, and duration of surface ponding in the drained wetland.
3. Discuss implications for agriculture and wildlife value based on historic and future climate projection trends.

To accomplish these goals, a water balance spreadsheet model was developed and calibrated with datasets from nearby weather stations. The model was used to evaluate how site-specific controls influence the frequency, depth, and duration of surface ponding. The results of the simulations were then used to discuss implications related to agriculture and wildlife.

9.1 Development and Calibration of the PPWB Model

The PPWB spreadsheet model was developed for a drained wetland located in Ellsworth, IA. It is a surface water model that predicts the water depth and duration using the equation: $D_i = D_{i-1} + P_i + RO_i - I_i - ET_i - SI_i$ where, $\mathrm{D_i}$ is the water depth on day i, $\mathrm{D_{i-1}}$ is the water depth on day i-1; $\mathrm{P_i}$ is the precipitation on day i, $\mathrm{RO_i}$ is the surface on day i, $\mathrm{I_i}$ is the infiltration rate on day i, $\mathrm{ET_i}$ is the evapotranspiration rate on day i, and $\mathrm{SI_i}$ is the surface inlet capacity on day i. The modeling period is from 2011-2013, which coincides with the period of groundwater table monitoring. The groundwater contribution was not considered for ponding at the Ellsworth site because continuous monitoring for the study period indicated that groundwater rarely contributed to ponding.

The model requires maximum and minimum air temperature and dew point, precipitation, mean wind speed, pressure, and mean four inch soil temperature. The closest weather station to the Ellsworth drained pothole the Ames Municipal Airport Weather Station, is located 20 miles south of the site in Ames, IA. Weather information data were downloaded from multiple databases via the Iowa Environmental Mesonet.

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Reference Evapotranspiration (ET) was calculated (in mm day^{-1}) using the Penman-Monteith method. A crop coefficient of 1.05, assumed for shallow, open water (Allen et al., 2006), was used to adjust from Reference ET to daily ET rates. Runoff was predicted (in mm day^{-1}) using the NRCS Curve Number (CN) method (SCS, 1986) for small watersheds. An initial CN of 78, which corresponds to row crops (straight rows), good conditions, and Hydrologic Soil Group B, was used (SCS, 1986). The CN was then adjusted on a daily basis for antecedent moisture conditions using a methodology documented by Huffman et al. (2011). The daily infiltration rate was estimated (in mm day^{-1}) using the Hantush equation. The Hantush equation for groundwater mounding (Hantush, 1967), in conjunction with groundwater monitoring data, provided an estimate suitable for the Ellsworth drained wetland. The Hantush equation for groundwater rise describes the response of groundwater mounds from uniform percolation (Hantush, 1967). After calibrating the equation to site specific parameters, the calculated infiltration rate was 6.87 mm d^{-1}.

Three sizes of commonly used surface inlets were evaluated in this study. Manufacturing specifications (Hickenbottom, Inc.) were used to quantify the potential impact of three typical surface inlet sizes: 6”, 8” and 10” inlets with 1” round openings. The capacity of a surface inlet to discharge water is dependent on the water depth in the wetland and is expressed as the maximum volume of water the surface inlet can discharge per day per drained wetland area.

9.2 Sensitivity Analysis of Water Balance Parameters

Sensitivity analyses of infiltration, topography, surface inlet presence and capacity, ET crop coefficient, and land cover performed to improve understanding of what factors significantly influence ponding. In the absence of surface inlets, infiltration rate was found to have a substantial impact on ponding, second only to the amount of precipitation. Because of the significant influence of infiltration, it is imperative that studies focused on temporary ponding in potholes have accurate estimates of infiltration rates. When a surface inlet is present in a drained wetland, the hydrology is significantly altered and ponding impact from other factors becomes negligible. The capacity of a surface inlet was less important than presence/absence of a surface inlet in a drained wetland. A larger surface inlet resulted in less than a 50 day difference in the total ponded

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days for the 2011-2013 simulation period, when compared to a smaller size inlet. Topography also affects ponding when the drained wetland has a larger catchment-to-pothole ratio, duration of ponding increased approximately linearly, with an average increase of 7.9 days for a one acre increase in catchment area. Other factors (ET crop coefficient and CN) had little influence on ponding.

9.3 Model Validation

The intent of model validation is to compare simulated results to actual data to see how well the model is able to replicate observed ponding. This proved difficult because very little documentation of surface ponding in the Ellsworth drained wetland exists. Groundwater monitoring data, specifically days when the water table rose above the surface in 2013, was used to compare with simulated ponding days. Other efforts to validate the PPWB model include visual evidence of surface ponding and crop impact in annual aerial photographs.

In 2013, the water table rose above the surface 32 times between March and June. For each day where the groundwater was above the surface, the PPWB model also simulated surface ponding on that day. A comparison of negative impact from aerial photographs and the PPWB model was done for 12 years (2004-2015). Prairie pothole water balance modeling correctly estimated crop impact 10/12 years. In 2004 and 2005 the aerial photographs showed no impact on crops but the model simulated ponding to the extent that crop impact would be expected. It is unclear why the model did not correctly simulate ponding duration for 2004 and 2005; however, it is possible possibility that the farmer was able to re-plant the crop after the extended ponding event in the early growing season. Eight out of the twelve years showed visual impact on crop yields with impact occurring eight of the last nine years. In some years (2008 and 2010) it was clear that no crop production occurred in the drained pothole whereas other years (2009 and 2011) ponding had less impact on yield.

9.4 Long-term Simulation

The long-term simulation of the Ellsworth drained wetland was completed using 116 years of historical data and 84 years of future climate projections. The 200 years of data came from three different databases: NWS COOP data was used for 1900-1997;

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NOAA GSOD data was used for 1997-2015; and future climate prediction data for 2016-2099 came from Chris Anderson, a climatologist at Iowa State University. The model had to be modified to use Hargreaves method for the potential ET calculation because only data for maximum and minimum air temperature and precipitation are available for the 200 years. It is important to consider long-term trends and future outlook of climate condition when evaluating the continued farming of drained prairie pothole wetlands. Trends show that, in the absence in increased subsurface drainage ponding duration is projected to increase at a rate of 0.32 days/year and most of additional days are occurring during spring and summer months. The increase in ponding days during spring and summer is likely to negatively impact crop yield.

9.5 Final Remarks

As part of the Iowa DNR Wetland Program Development (WPD) project, the purpose of this thesis was to expand the basic hydrology component of the project to include surface water hydrology by developing a PPWB spreadsheet model. The PPWB model was used to evaluate how site-specific characteristics affect the frequency, depth, and duration of surface ponding in drained wetlands. It would be both beneficial and wise if the results of the PPWB modeling efforts are used by relevant government agencies and conservation and agricultural groups who are interested in the environmental implications of policy decisions related to agriculture and water quality. The model will be made available upon request. Requests can be made to Stephanie Then or Keith Schilling at the University of Iowa, IIHR Hydroscience & Engineering.

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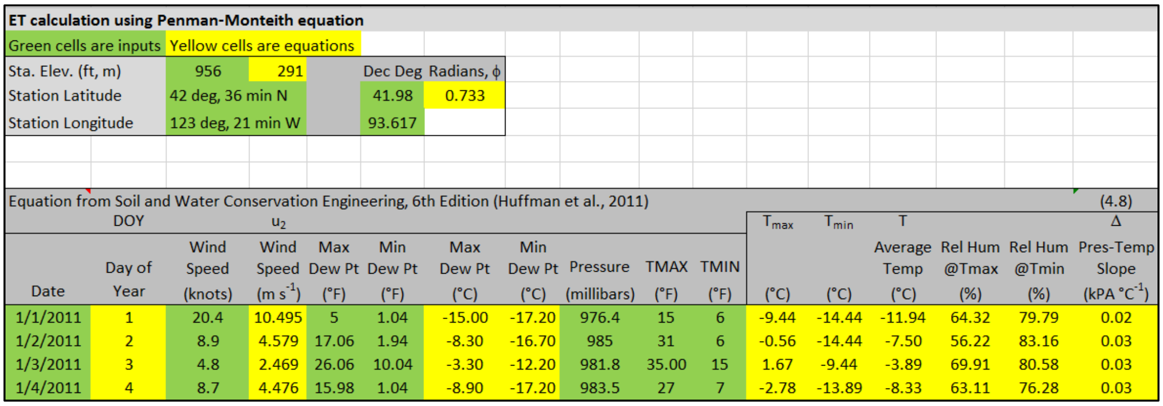
APPENDIX A: SPREADSHEET MODEL SCREENSHOTS



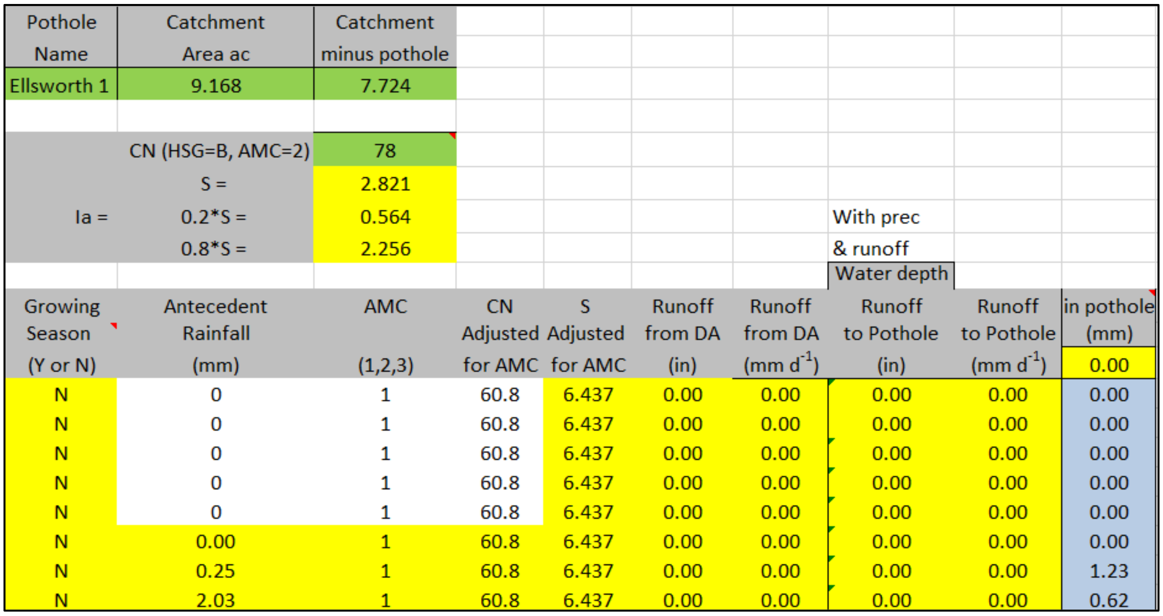
ET calculation using Penman-Monteith equation

Green cells are inputs Yellow cells are equations

Sta. Elev. (ft, m)	956	291	Dec Deg	Radians, ϕ
Station Latitude	42 deg, 36 min N		41.98	0.733
Station Longitude	123 deg, 21 min W		93.617	

Equation from Soil and Water Conservation Engineering, 6th Edition (Huffman et al., 2011) (4.8)

Date	DOY Day of Year	Wind Speed (knots)	u_2 Wind Speed (m s^{-1})	Max Dew Pt (°F)	Min Dew Pt (°F)	Max Dew Pt (°C)	Min Dew Pt (°C)	Pressure (millibars)	TMAX (°F)	TMIN (°F)	T_{max} (°C)	T_{min} (°C)	T Average Temp (°C)	Rel Hum @Tmax (%)	Rel Hum @Tmin (%)	Δ Pres-Temp Slope (kPA °C^{-1})
1/1/2011	1	20.4	10.495	5	1.04	-15.00	-17.20	976.4	15	6	-9.44	-14.44	-11.94	64.32	79.79	0.02
1/2/2011	2	8.9	4.579	17.06	1.94	-8.30	-16.70	985	31	6	-0.56	-14.44	-7.50	56.22	83.16	0.03
1/3/2011	3	4.8	2.469	26.06	10.04	-3.30	-12.20	981.8	35.00	15	1.67	-9.44	-3.89	69.91	80.58	0.03
1/4/2011	4	8.7	4.476	15.98	1.04	-8.90	-17.20	983.5	27	7	-2.78	-13.89	-8.33	63.11	76.28	0.03



Pothole Name	Catchment Area ac	Catchment minus pothole
Ellsworth 1	9.168	7.724

	CN (HSG=B, AMC=2)	78
	S =	2.821
Ia =	0.2*S =	0.564
	0.8*S =	2.256

Growing Season (Y or N)	Antecedent Rainfall (mm)	AMC (1,2,3)	CN Adjusted for AMC	S Adjusted for AMC	Runoff from DA (in)	Runoff from DA (mm d^{-1})	Runoff to Pothole (in)	Runoff to Pothole (mm d^{-1})	With prec & runoff Water depth in pothole (mm)
									0.00
N	0	1	60.8	6.437	0.00	0.00	0.00	0.00	0.00
N	0	1	60.8	6.437	0.00	0.00	0.00	0.00	0.00
N	0	1	60.8	6.437	0.00	0.00	0.00	0.00	0.00
N	0	1	60.8	6.437	0.00	0.00	0.00	0.00	0.00
N	0	1	60.8	6.437	0.00	0.00	0.00	0.00	0.00
N	0.00	1	60.8	6.437	0.00	0.00	0.00	0.00	0.00
N	0.25	1	60.8	6.437	0.00	0.00	0.00	0.00	1.23
N	2.03	1	60.8	6.437	0.00	0.00	0.00	0.00	0.62

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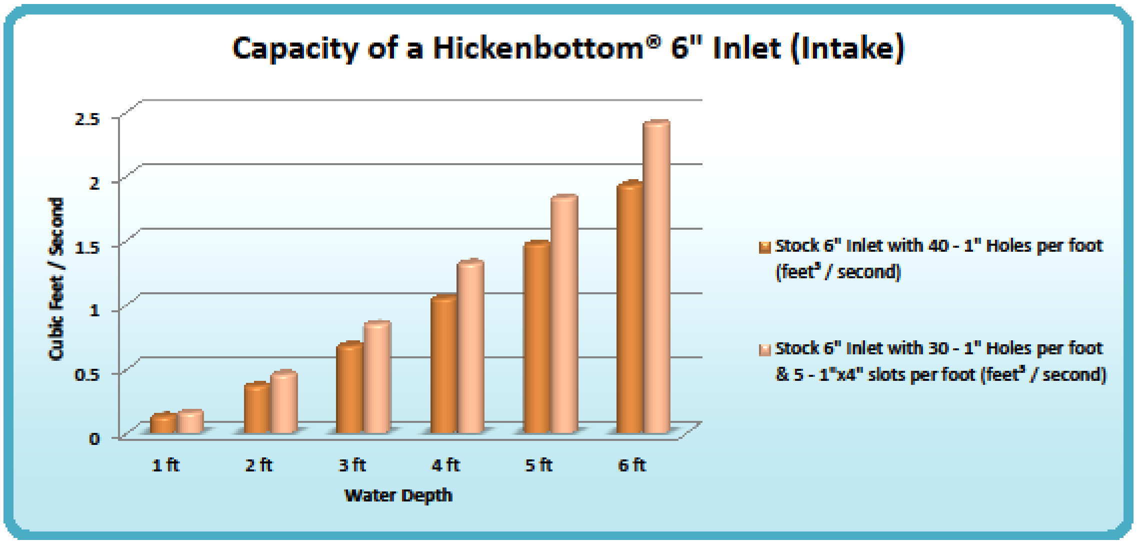
APPENDIX B: SURFACE INLET MANUFACTURER SPECIFICATIONS

Hickenbottom® Inc.

Look for the bright orange inlet - Hickenbottom's Trademark®



Water Depth	Stock 6" Inlet with 40 - 1" Holes per foot (feet³ / second)	Stock 6" Inlet with 30 - 1" Holes per foot & 5 - 1"x4" slots per foot (feet³ / second)
1 ft	0.13	0.16
2 ft	0.37	0.46
3 ft	0.68	0.85
4 ft	1.05	1.32
5 ft	1.47	1.83
6 ft	1.93	2.41
The inlet capacities listed in the chart above are based upon the assumption that one half of the holes and/or slots are plugged.		

Note: Basis for the capacities listed above are taken from chart SCS E.F.M., Amend IA 30, Aug. 1986, Page 1A 8-103 (48)

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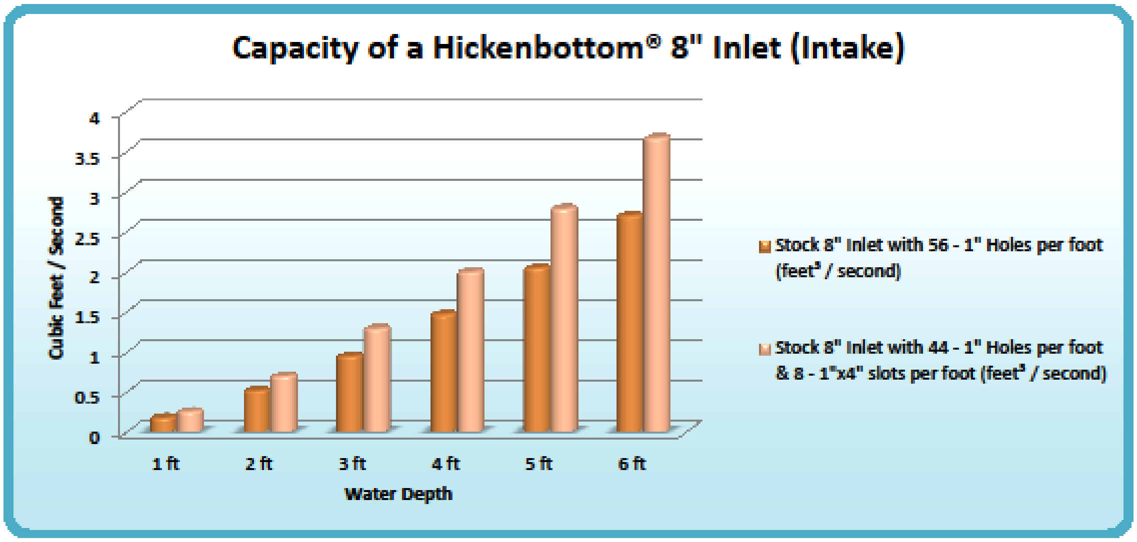

Water Depth	Stock 8" Inlet with 56 - 1" Holes per foot (feet³ / second)	Stock 8" Inlet with 44 - 1" Holes per foot & 8 - 1"x4" slots per foot (feet³ / second)
1 ft	0.18	0.26
2 ft	0.52	0.7
3 ft	0.95	1.29
4 ft	1.47	2
5 ft	2.05	2.79
6 ft	2.7	3.67
The inlet capacities listed in the chart above are based upon the assumption that one half of the holes and/or slots are plugged.		

Note: Basis for the capacities listed above are taken from chart SCS E.F.M., Amend IA 30, Aug. 1986, Page 1A 8-103 (48)

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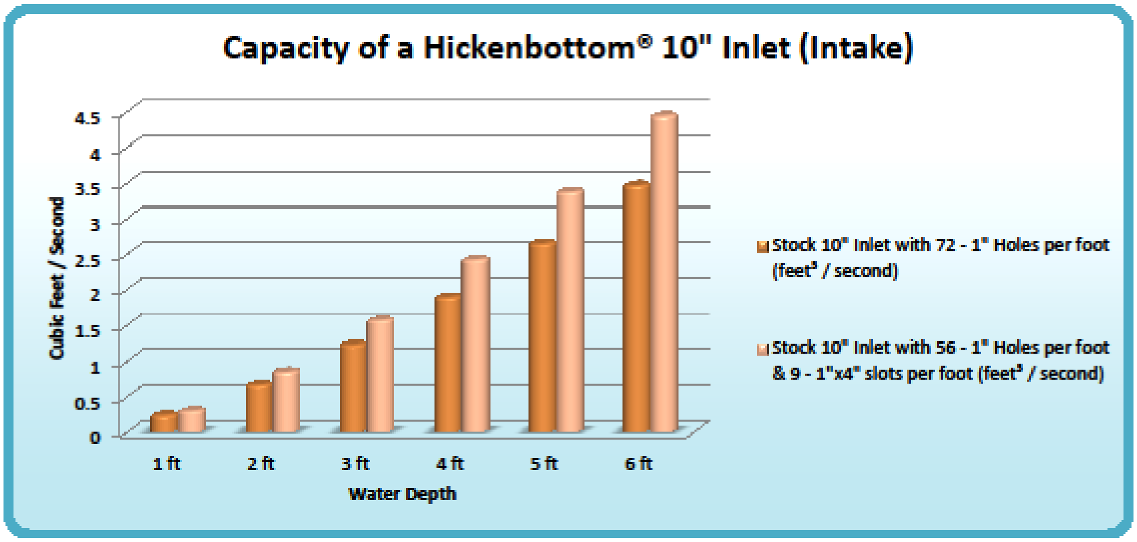

Water Depth	Stock 10" Inlet with 72 - 1" Holes per foot (feet³ / second)	Stock 10" Inlet with 56 - 1" Holes per foot & 9 - 1"x4" slots per foot (feet³ / second)
1 ft	0.24	0.3
2 ft	0.67	0.85
3 ft	1.23	1.57
4 ft	1.89	2.42
5 ft	2.65	3.38
6 ft	3.47	4.44

The inlet capacities listed in the chart above are based upon the assumption that one half of the holes and/or slots are plugged.

Note: Basis for the capacities listed above are taken from chart SCS E.F.M., Amend IA 30, Aug. 1986, Page 1A 8-103 (48)

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APPENDIX C: AERIAL PHOTOGRAPHS

Appendix C includes aerial photographs and graphs of simulated water ponding for 2004-2015. The blue filled area on the graphs represent the simulated water ponding depth and the pink represents the days and depths of more than five consecutive ponding days. See Section 6.3 for more information about the influence of consectutive days of ponding on crop yields.

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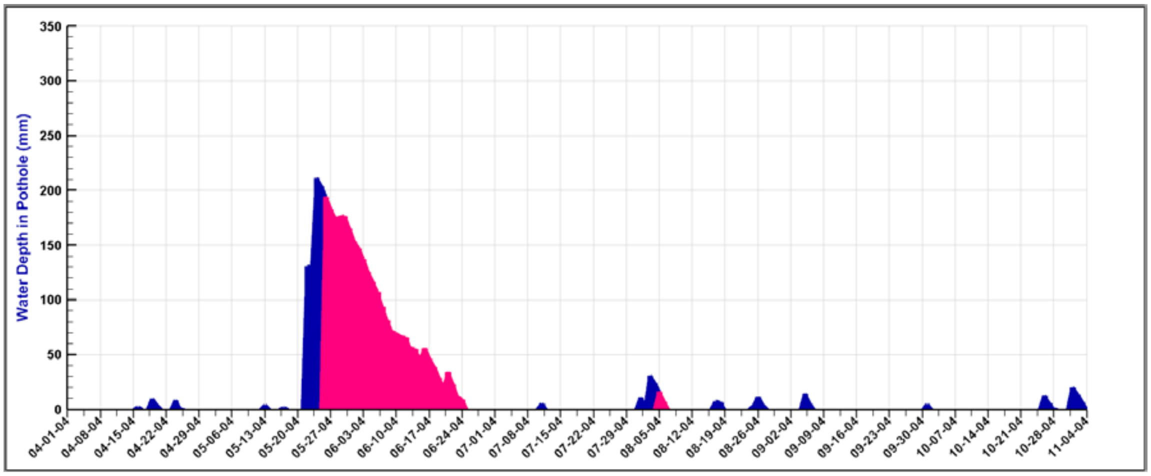
C.1 Aerial Photograph: October 2004



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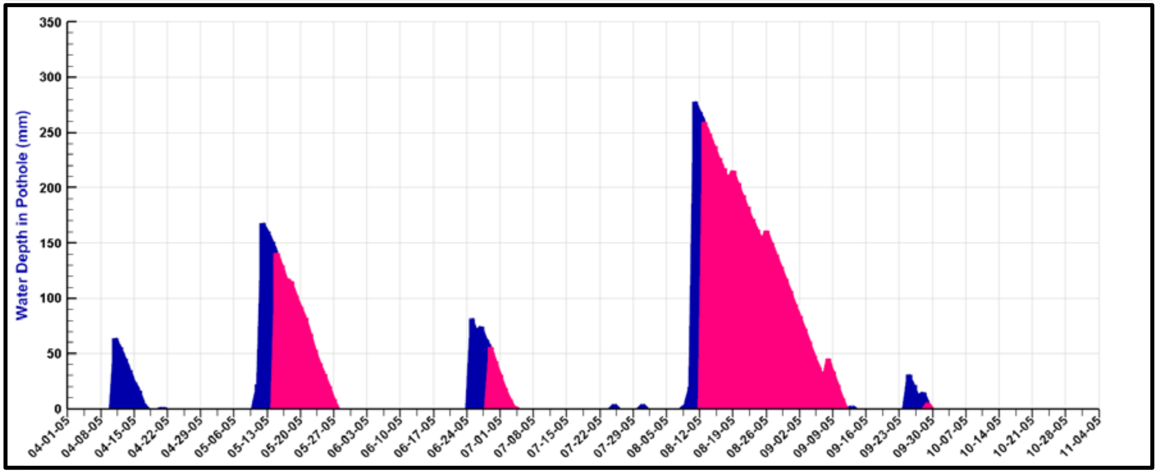
C.2 Aerial Photograph: August 2005



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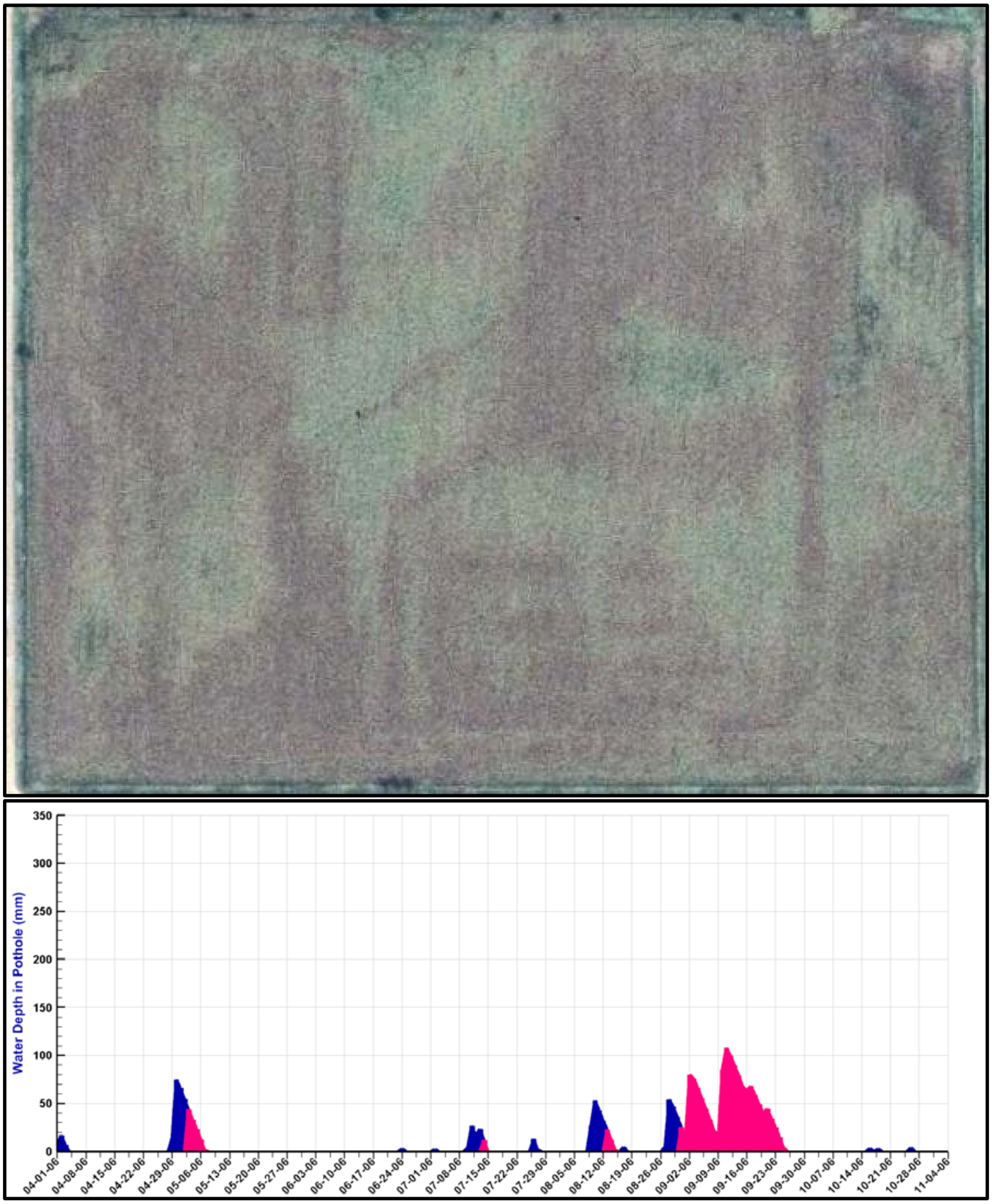
C.3 Aerial Photograph: October 2006



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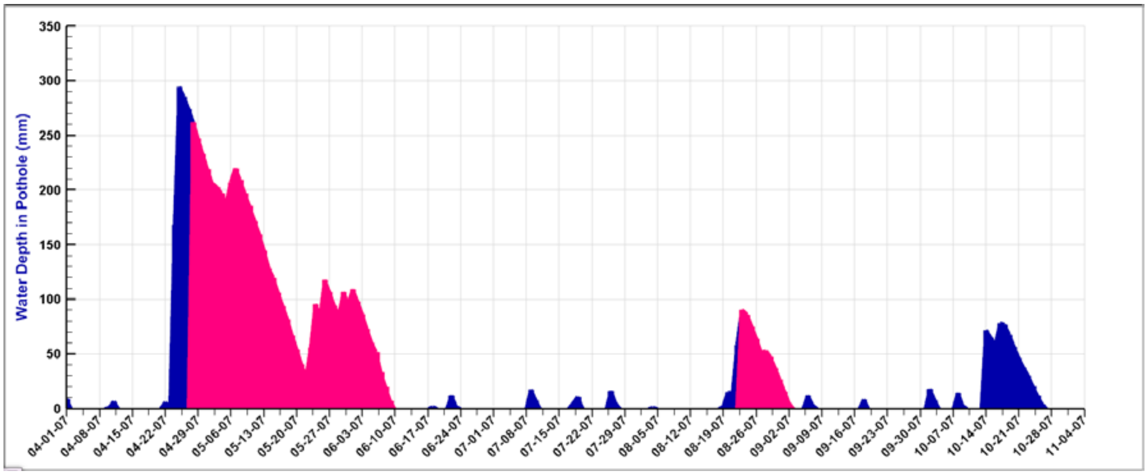
C.4 Aerial Photograph: September 2007

Infrared



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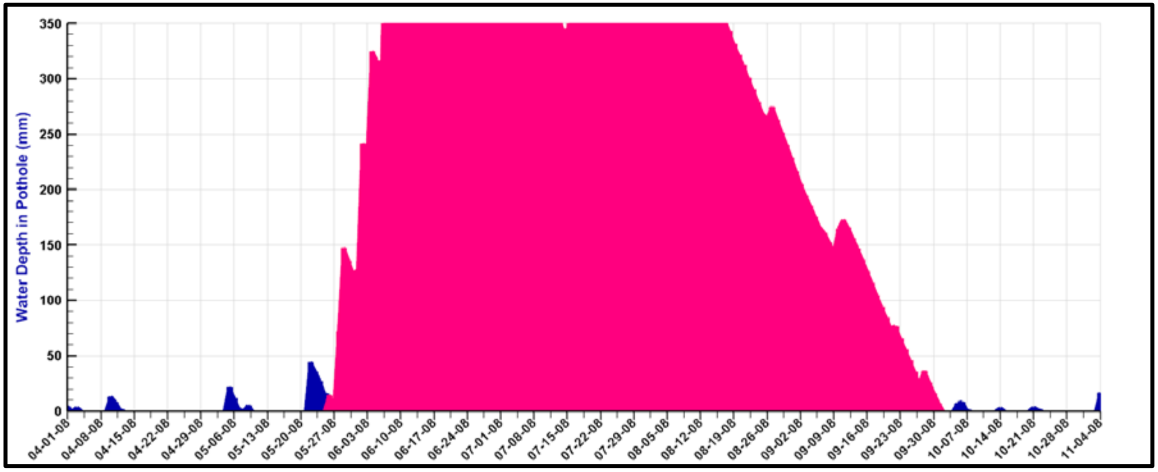
C.5 Aerial Photograph: October 2008



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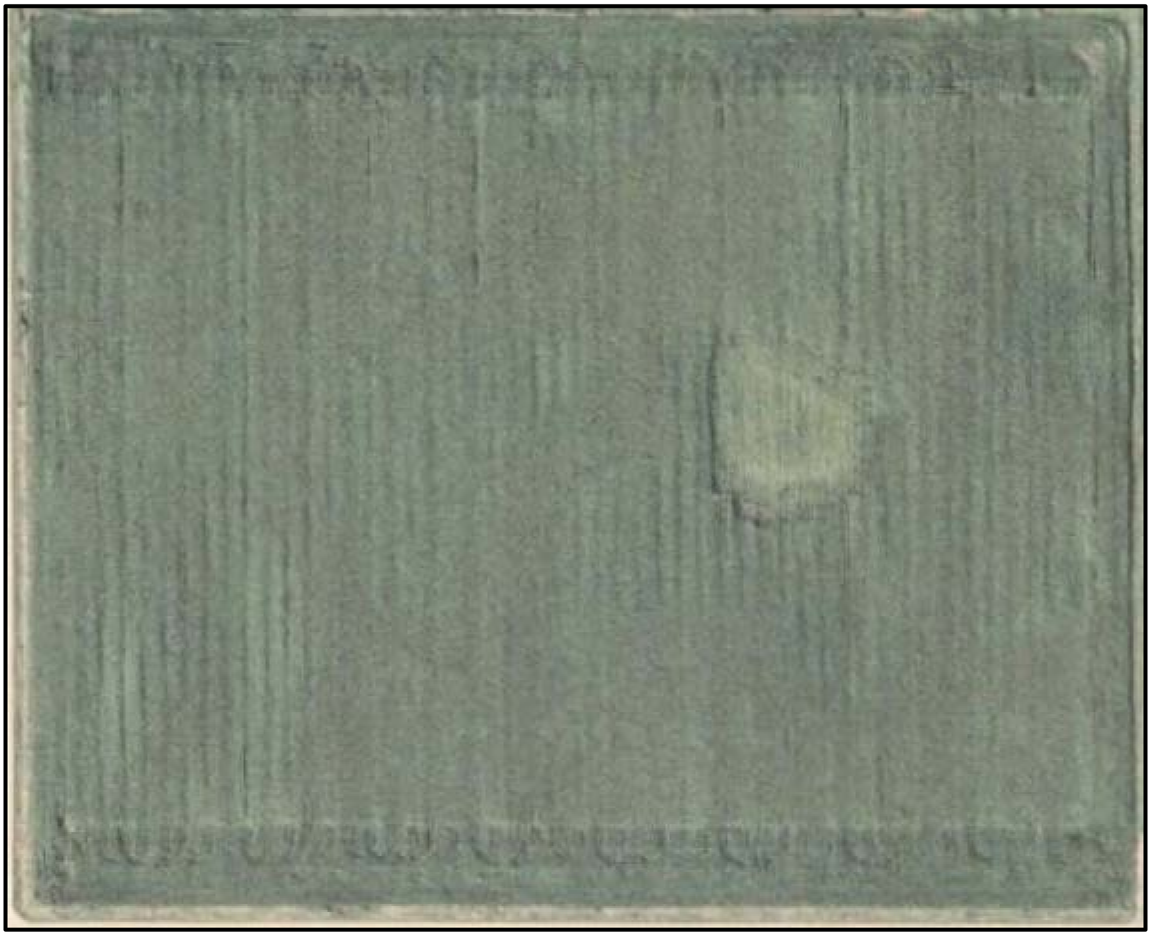
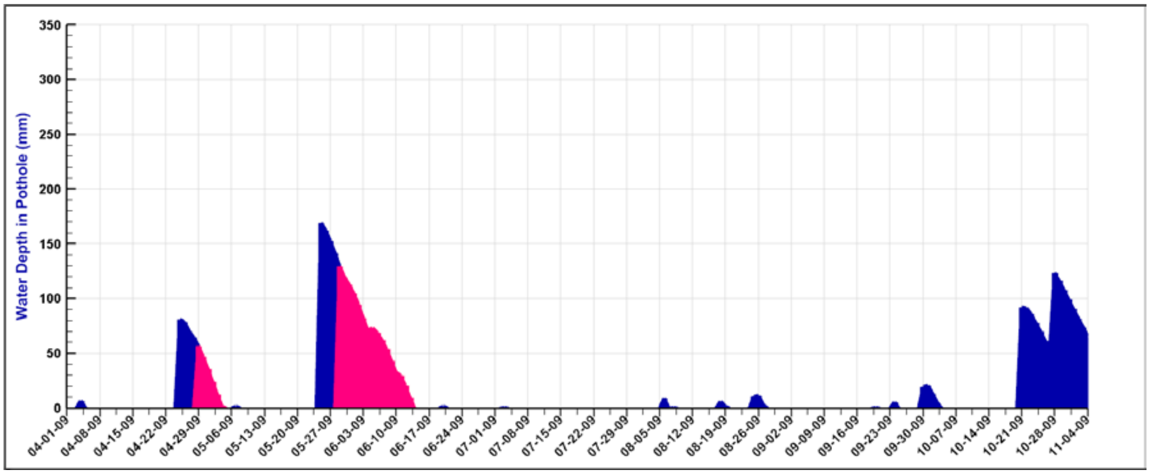
C.6 Aerial Photograph: September 2009





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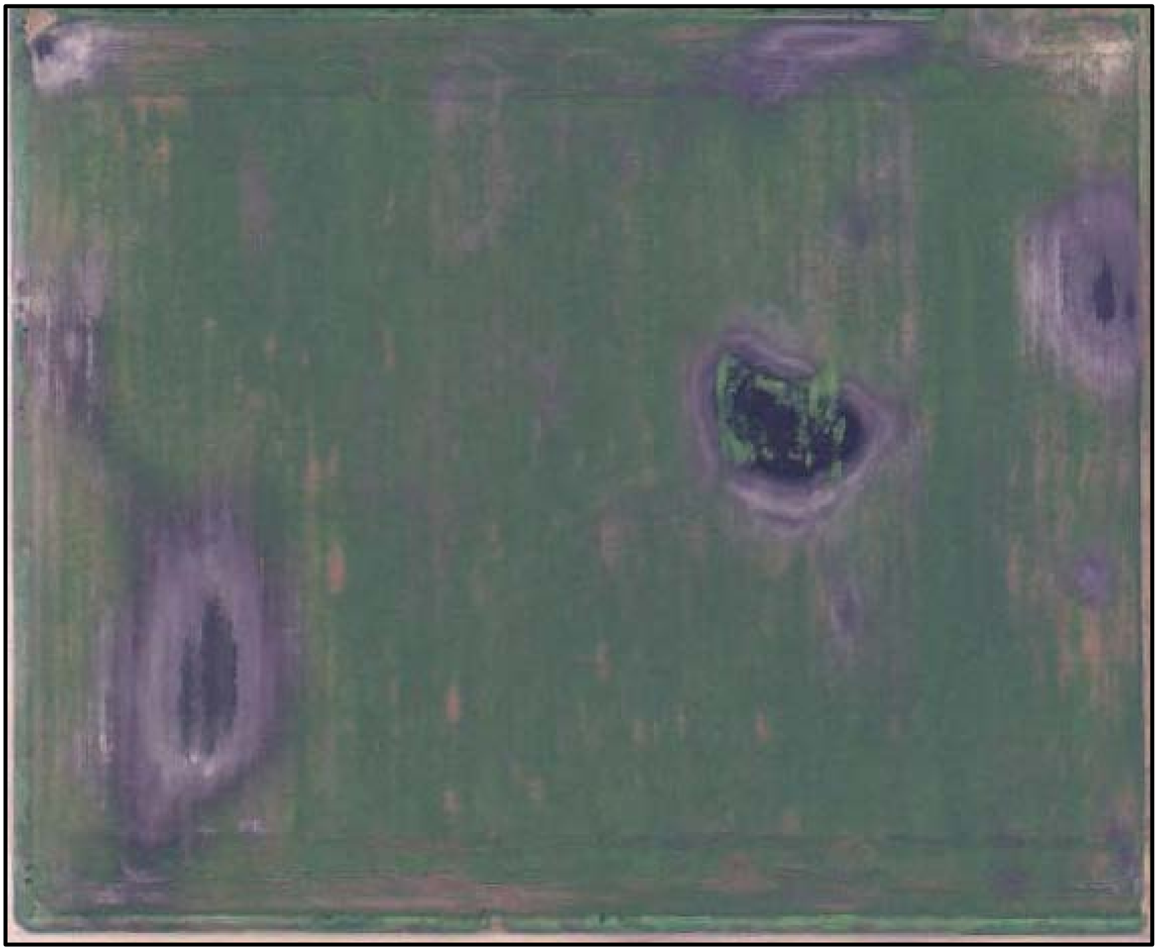
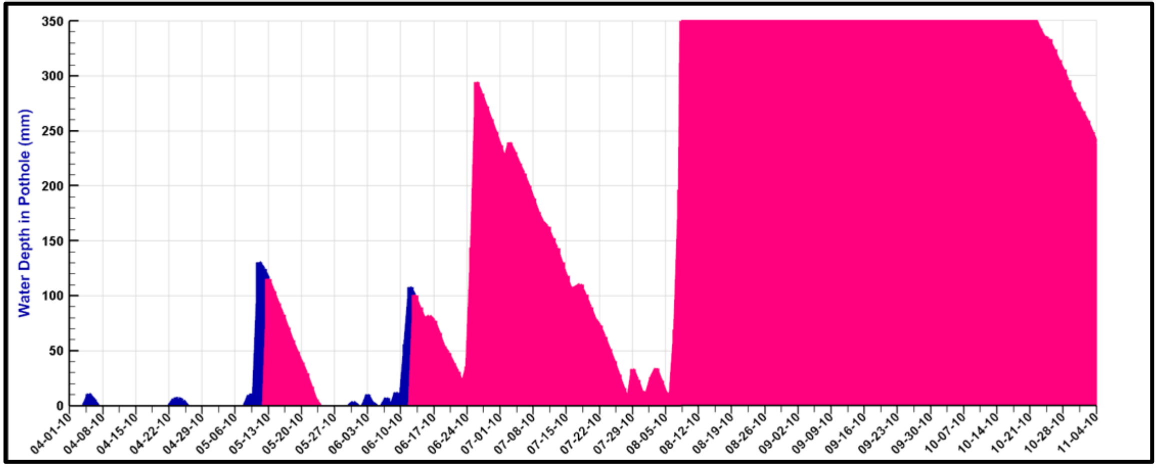
C.7 Aerial Photograph: September 2010





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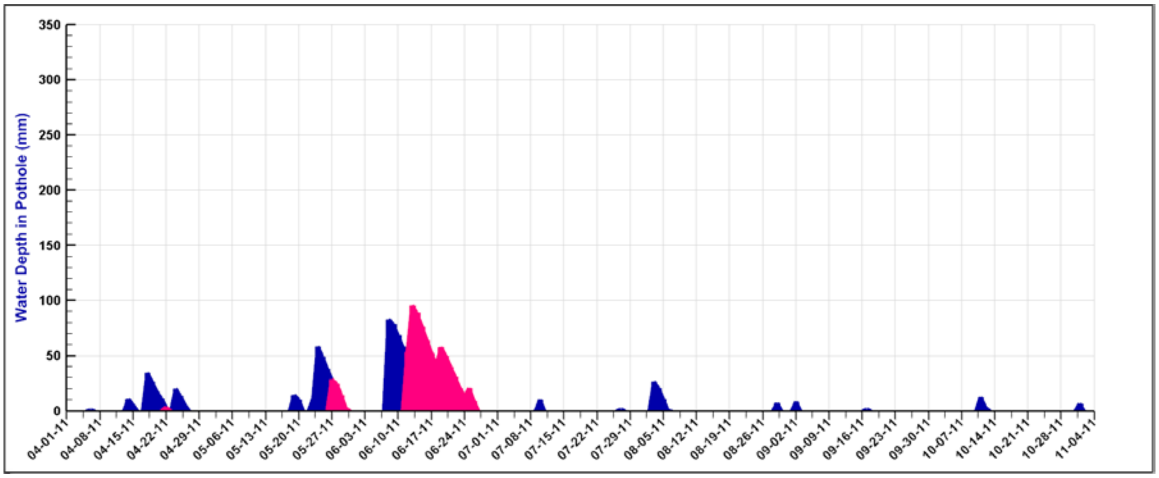
C.8 Aerial Photograph: September 2011



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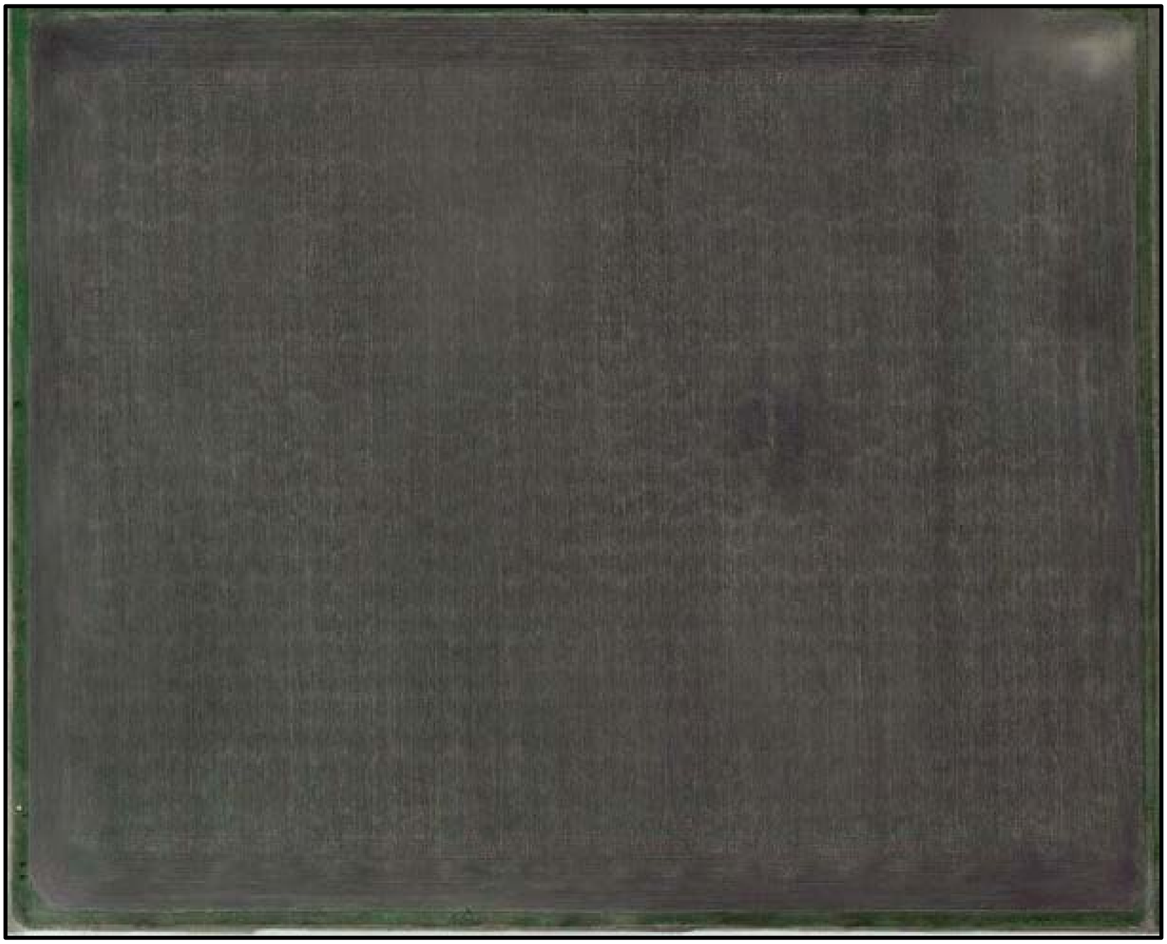
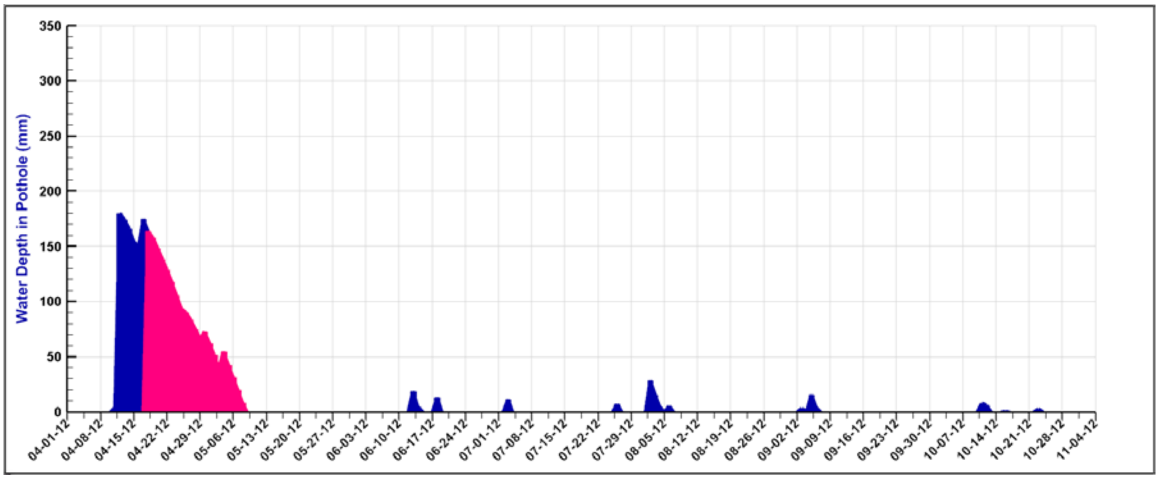
C.9 Aerial Photograph: June 2012





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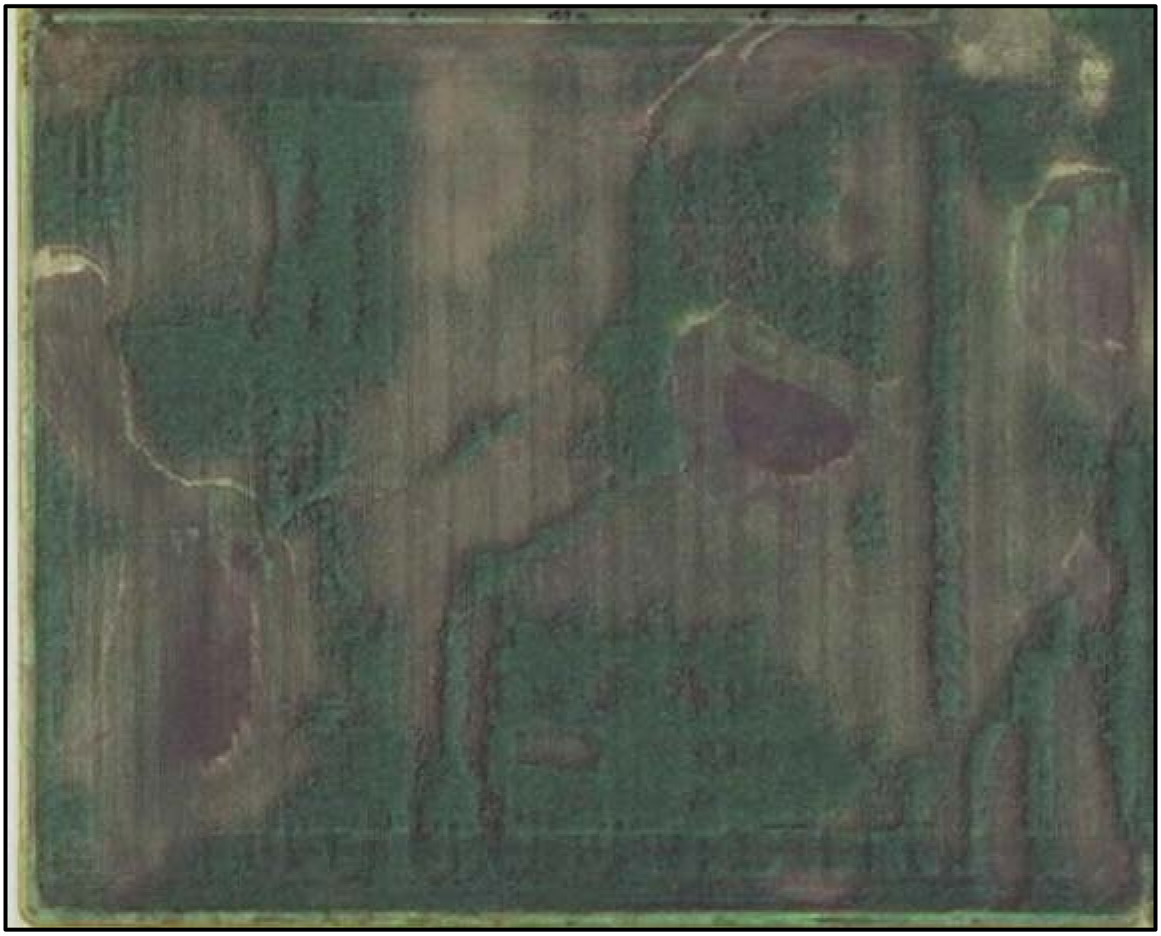
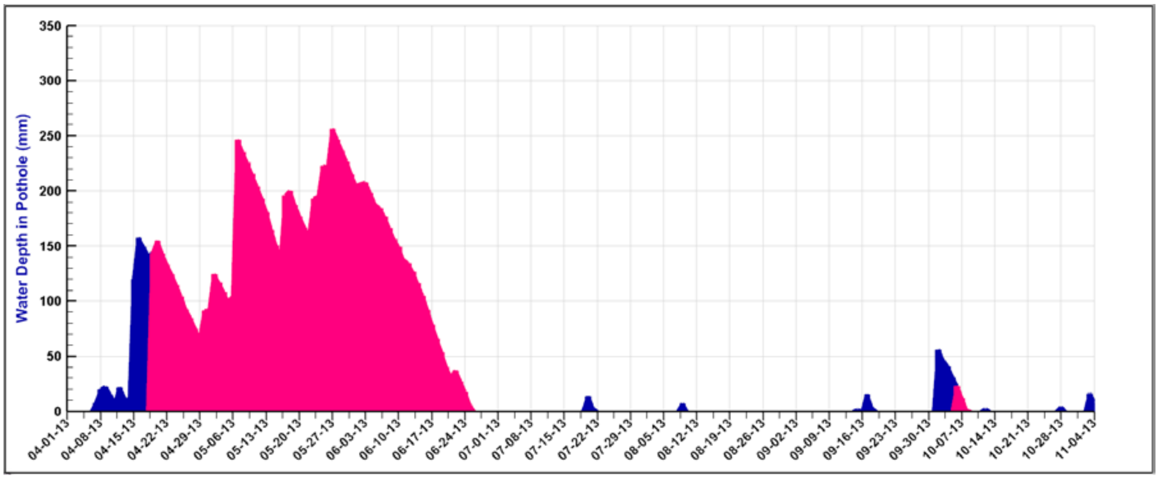
C.10 Aerial Photograph: September 2013





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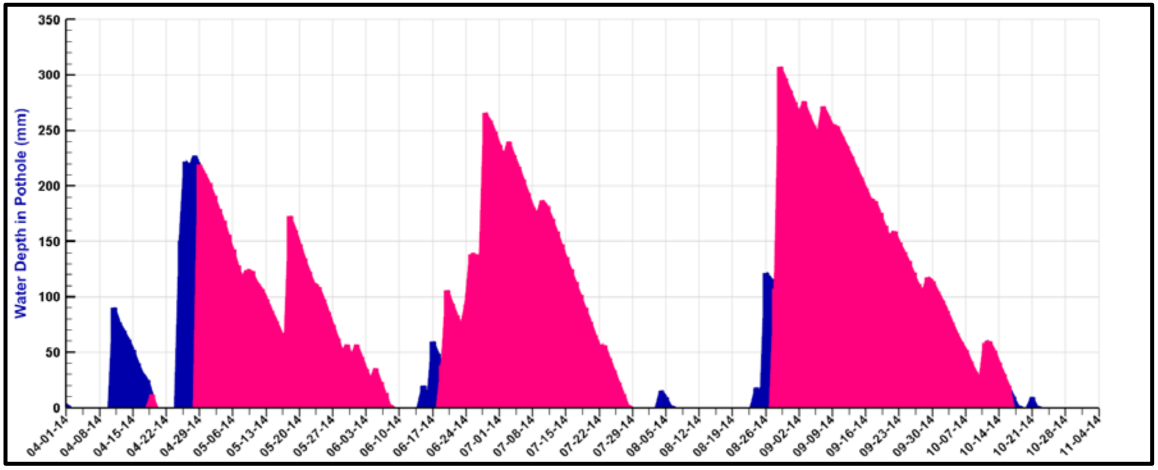
C.11 Aerial Photograph: September 2014



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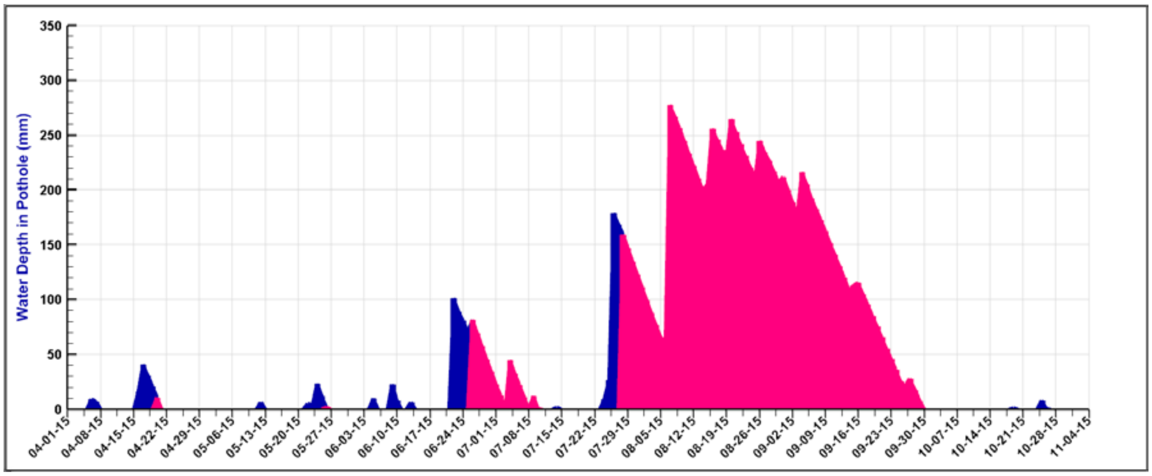
C.12 Aerial Photograph: October 2015



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APPENDIX D: SOIL TEMPERATURE COEFFICIENTS

Table C.1. Soil temperature coefficients (STC) for each Julian day (JD).

JD	STC	JD	STC	JD	STC	JD	STC	JD	STC	JD	STC	JD	STC
1	6.16	**54**	4.14	**107**	0.98	**159**	4.54	**211**	4.29	**263**	-0.42	**315**	-0.35
2	5.64	**55**	4.70	**108**	0.79	**160**	3.41	**212**	4.41	**264**	-0.67	**316**	-0.37
3	5.34	**56**	4.69	**109**	1.72	**161**	3.53	**213**	4.94	**265**	-0.78	**317**	-0.28
4	5.24	**57**	4.04	**110**	0.94	**162**	3.16	**214**	5.23	**266**	-0.28	**318**	0.65
5	5.29	**58**	3.26	**111**	0.51	**163**	3.61	**215**	5.03	**267**	-0.58	**319**	0.97
6	6.30	**59**	2.38	**112**	-0.16	**164**	3.80	**216**	4.77	**268**	0.02	**320**	1.20
7	6.12	**60**	-1.28	**113**	0.27	**165**	2.83	**217**	3.59	**269**	0.82	**321**	0.50
8	6.24	**61**	2.24	**114**	0.41	**166**	1.41	**218**	1.97	**270**	1.42	**322**	0.54
9	7.58	**62**	2.17	**115**	1.79	**167**	1.01	**219**	1.91	**271**	1.41	**323**	1.20
10	7.34	**63**	2.65	**116**	1.60	**168**	2.02	**220**	2.82	**272**	1.48	**324**	0.13
11	7.51	**64**	2.10	**117**	0.50	**169**	2.12	**221**	3.58	**273**	1.55	**325**	-0.44
12	7.23	**65**	2.66	**118**	0.37	**170**	2.46	**222**	4.15	**274**	2.10	**326**	-0.41
13	6.71	**66**	3.20	**119**	-0.50	**171**	2.53	**223**	4.36	**275**	1.97	**327**	-0.07
14	6.89	**67**	3.12	**120**	0.43	**172**	2.60	**224**	4.23	**276**	0.30	**328**	0.41
15	6.60	**68**	2.09	**121**	0.55	**173**	2.71	**225**	3.73	**277**	-0.61	**329**	0.04
16	7.03	**69**	2.00	**122**	0.09	**174**	2.34	**226**	3.09	**278**	-1.54	**330**	0.02
17	7.38	**70**	2.03	**123**	-0.23	**175**	1.80	**227**	3.79	**279**	-1.36	**331**	0.25
18	6.56	**71**	2.30	**124**	0.04	**176**	2.38	**228**	3.83	**280**	-1.70	**332**	0.32
19	6.84	**72**	1.75	**125**	1.17	**177**	2.66	**229**	3.99	**281**	-1.24	**333**	0.39
20	7.29	**73**	1.66	**126**	1.87	**178**	2.65	**230**	4.04	**282**	-0.86	**334**	0.91
21	7.80	**74**	1.75	**127**	2.24	**179**	3.07	**231**	3.52	**283**	-0.53	**335**	0.78
22	7.93	**75**	0.46	**128**	3.02	**180**	2.77	**232**	2.93	**284**	-0.69	**336**	1.31
23	7.71	**76**	0.99	**129**	3.08	**181**	2.36	**233**	3.35	**285**	-0.38	**337**	2.37
24	7.52	**77**	0.70	**130**	2.74	**182**	2.53	**234**	4.30	**286**	-0.03	**338**	2.74
25	8.02	**78**	-0.36	**131**	2.26	**183**	3.19	**235**	4.48	**287**	-0.28	**339**	2.96
26	7.60	**79**	-0.36	**132**	1.60	**184**	3.68	**236**	4.38	**288**	-0.53	**340**	2.93
27	8.31	**80**	-0.29	**133**	0.05	**185**	3.65	**237**	3.74	**289**	-0.35	**341**	2.71
28	8.18	**81**	-0.40	**134**	-0.54	**186**	3.81	**238**	3.37	**290**	-0.62	**342**	2.76
29	7.74	**82**	-0.20	**135**	0.62	**187**	3.74	**239**	3.07	**291**	-0.76	**343**	2.93
30	7.62	**83**	0.03	**136**	1.00	**188**	4.52	**240**	2.78	**292**	-1.79	**344**	3.88
31	7.84	**84**	0.59	**137**	1.82	**189**	4.57	**241**	2.79	**293**	-1.90	**345**	4.00
32	7.10	**85**	0.33	**138**	1.56	**190**	3.76	**242**	2.45	**294**	-1.23	**346**	4.70
33	6.09	**86**	1.31	**139**	1.46	**191**	3.03	**243**	2.31	**295**	-0.76	**347**	5.11
34	5.78	**87**	1.03	**140**	2.67	**192**	2.72	**244**	2.19	**296**	-0.80	**348**	5.12
35	5.72	**88**	0.00	**141**	1.85	**193**	1.97	**245**	2.29	**297**	-0.01	**349**	5.18
36	5.96	**89**	-0.09	**142**	1.66	**194**	1.87	**246**	1.98	**298**	-0.40	**350**	5.01
37	6.36	**90**	-0.14	**143**	1.59	**195**	2.66	**247**	1.68	**299**	-0.91	**351**	5.51
38	6.65	**91**	-0.46	**144**	1.10	**196**	3.72	**248**	1.61	**300**	-0.85	**352**	5.37
39	6.41	**92**	-0.25	**145**	-0.18	**197**	4.73	**249**	1.37	**301**	-1.35	**353**	5.87
40	6.19	**93**	0.66	**146**	-1.09	**198**	5.10	**250**	2.18	**302**	-1.62	**354**	5.96
41	6.63	**94**	0.51	**147**	-0.90	**199**	5.46	**251**	1.63	**303**	-0.86	**355**	6.14
42	6.68	**95**	-0.28	**148**	0.46	**200**	4.73	**252**	0.98	**304**	-0.94	**356**	6.05
43	6.29	**96**	-0.10	**149**	2.05	**201**	6.14	**253**	0.69	**305**	-1.42	**357**	5.75
44	6.21	**97**	1.01	**150**	3.56	**202**	6.00	**254**	0.68	**306**	-1.56	**358**	6.05
45	5.86	**98**	0.70	**151**	4.04	**203**	5.03	**255**	1.53	**307**	-1.91	**359**	6.81
46	5.75	**99**	0.30	**152**	2.57	**204**	4.33	**256**	1.63	**308**	-2.05	**360**	7.53
47	5.21	**100**	0.36	**153**	2.03	**205**	3.98	**257**	1.20	**309**	-1.03	**361**	7.32
48	5.41	**101**	0.63	**154**	1.87	**206**	3.99	**258**	-0.13	**310**	-1.60	**362**	7.71
49	5.19	**102**	0.89	**155**	1.80	**207**	4.38	**259**	-0.03	**311**	-0.93	**363**	7.68
50	4.71	**103**	-0.22	**156**	1.88	**208**	4.43	**260**	0.57	**312**	-1.07	**364**	7.44
51	4.70	**104**	0.98	**157**	3.49	**209**	4.19	**261**	1.16	**313**	-0.44	**365**	6.53
52	4.48	**105**	2.27	**158**	4.32	**210**	4.15	**262**	0.72	**314**	-0.09	**366**	6.53
53	3.87	**106**	1.95										

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