8-2010

Evaluating Hydroperiod Response in the Rainwater Basin Wetlands of South-Central Nebraska

Richard D. Wilson
University of Nebraska-Lincoln, richard.wilson7@huskers.unl.edu

EVALUATING HYDROPERIOD RESPONSE IN THE RAINWATER BASIN WETLANDS OF SOUTH-CENTRAL NEBRASKA

by

Richard D. Wilson

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Natural Resource Sciences

Under the Supervision of Professor F. Edwin Harvey

Lincoln, Nebraska

August, 2010

EVALUATING HYDROPERIOD RESPONSE IN THE RAINWATER BASIN WETLANDS OF SOUTH-CENTRAL NEBRASKA

Richard Duane Wilson, M.S.

University of Nebraska, 2010

Adviser: F. Edwin Harvey

A collection of wetlands in south-central Nebraska make up a region called the Rainwater Basin. This basin contains closed-basin wetlands formed in loess. The wetlands receive water from precipitation and irrigation runoff. Since the early 1900s, wetland area in the basin has decreased dramatically due to intensive agriculture which either altered or removed the wetlands. The Rainwater Basin wetlands provide many ecological services and thus, should be preserved, but are most noted for the resting, breeding, and feeding habitat they provide for millions of migratory birds that is not provided elsewhere in this region along the continental flyway.

Given the limited research on some of the physical, chemical, and biological processes that occur within these wetlands, research needed to be conducted on how these wetlands affect groundwater quality of the High Plains Aquifer, on how the restoration practice of sediment removal impacted groundwater quality, and on the effect of sedimentation and hydroperiod on plant and wetland bird communities. In an effort to understand these research goals, this study attempted to define the hydrology of individual, representative wetlands within the basin. The specific goal of this study was to determine and understand seasonal wetland hydroperiods and to determine the magnitude of evapotranspiration (ET) and infiltration and their impact on water loss from

the selected sites. Three sites, Lindau WPA, Moger (North) WPA, and Griess WPA, were investigated to better understand these processes.

Hydroperiods were determined by stilling well and topographical survey data. Shallow drive-point wells provided information on water movement within the wetland sediments. ET was calculated using the Bowen Ratio Energy Budget (BREB) method. Precipitation was determined by tipping bucket rain gages and with data provided by the High Plains Regional Climate Center (HPRCC). Infiltration was modeled using a water balance approach during periods when precipitation was not occurring and data from surface water storage volumes and ET could be used.

Study results show that surface water volumes are highly dependent on the magnitude of precipitation events and the soil water content. In addition, dry, desiccated soils can reduce surface storage during precipitation events because of rapid infiltration into fractures. Fractures can subsequently close after being wetted reducing infiltration rates. ET magnitude was dependent on available energy to a site, but it was also dependent on the exposed surface area of the wetland. Wetlands with contained water volumes and small exposed surface areas such as Moger (North) WPA lost less water to ET than the large exposed water surface area of Lindau WPA. However, with the contained volume and higher surface water head pressures, Moger (North) WPA had larger infiltration rates than Lindau WPA. Overall, based on the modeling, infiltration removed more water by volume from the wetland surface storage than did ET.

ACKNOWLEDGEMENTS

I would like to acknowledge the individuals of my graduate committee. I would like to thank Dr. Timothy Arkebauer for helping me better understand atmospheric processes and how to quantify evapotranspiration. I want to also thank him for providing his time to review my thesis and for making it a better document. Next, I would like to thank Dr. Dean Eisenhauer for advising me through both my undergraduate and graduate career. I am grateful for the time he has provided over the past seven years. I also thank him for reviewing my thesis and aiding me in better understanding unsaturated soil flow processes. Finally, I would like to thank Dr. Ed Harvey for giving me the opportunity to obtain my Masters degree in Hydrologic Sciences. I am grateful to have performed research under his guidance. I thank him for giving me a wide range of independence in this research. I have learned a lot while preparing this thesis, and am grateful for the knowledge he has passed on to me.

I would like to thank my colleagues who have aided me on this project. Thanks to Sarah Foster for sharing long hours working in the Rainwater Basin and providing helpful comments in the development of my thesis. I will remember our random conversations and outbursts in the office and in the field to break the boredom and exhibit our frustration. I congratulate her on her research and wish her good luck on her future endeavors. Thanks to James Gilbert for being a mentor on my project. His advice and assistance in the field and the lab is greatly appreciated. I could not have completed this project without his help. I congratulate him on his new career and wish him good luck on all of his future endeavors. Thanks to Orin Regier for his assistance. He was a great co-worker. The success of this project depended on the long hours he put in the field with me. Thanks for breaking the boredom of long road trips by constantly having things to talk about and the occasional fat joke. I wish him good luck on all of his future endeavors. Thanks to Dustin Greene for helping in the field as well as preparing equipment for the field. I was glad to have his assistance. I wish him good luck on all of his future endeavors.

I would like to thank Matt Marxsen and the CSD drilling crew for inserting the aquifer observation wells on Rainwater Basin wetlands and for providing access to their equipment and supplies. His assistance in researching these wetlands was greatly appreciated.

I would like to thank my parents, Nason and Marjorie, for supporting me and allowing me to have the freedom to obtain my degree. They are the greatest parents a person can have, and I could never thank them or love them both enough. I would like to thank my siblings, Ruthann, Russell, and Robin, and their families for encouraging me through this process. I have learned a lot from all of them, and I feel my life would not be this great without all of their help. I would like to thank my girlfriend, Adrienne. She has been wonderful in encouraging me through my research. I know I was unbearable at times, but I am glad she remained by me. I love her and am so glad to have her in my life.

Finally, I would like to thank the agencies and their personnel that have helped bring this project to fruition. I would like to thank the Nebraska Game & Parks Commission (NGPC) for obtaining the grant funding from the U.S. Environmental Protection Agency. With the NGPC, I would like to thank Ted LaGrange and Randy Stutheit for being my guides and providing support for Rainwater Basin activities as well as the managers, Brad Seitz and Richard Knox, for providing me access to their wetlands. I also want to thank Gene Mack, Ronnie Sanchez, and Jeff Drahota with the U.S. Fish & Wildlife Service for providing me with assistance and access to their wetlands. I would like to thank the many individuals involved with the Rainwater Basin Joint Venture (RWBJV) who provided input and background with a special thanks to Ryan Reker for providing me access to the many GIS files developed for the basin.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Appendices

INTRODUCTION

1.1 Rainwater Basin Background

A collection of wetlands in south-central Nebraska make up a region called the Rainwater Basin. The Rainwater Basin is made up of nearly level uplands with wetlands that were formed in irregular shaped, closed-basin depressions (Starks, 1984; Kuzila, 1994; Smith, 2003; LaGrange, 2005). These depressions can be relatively small with some being less than an acre in size while others can be quite large with some that can reach areas greater than 1,000 acres (Kuzila, 1994; NEBRASKAland, 1996). These wetlands pockmark the surface of the region known as the Central Loess Plain (Kuzila & Lewis, 1993; Kuzila, 1994) and are found in approximately 17 counties (NEBRASKAland, 1996). A map of the Rainwater Basin is provided in Figure 1.

Based on soil surveys, there were approximately 100,000 wetland acres present in the early 1900s (NEBRASKAland, 1996; LaGrange, 2005). According to the Nebraska Game and Parks Commission (NGPC), it has been estimated that about 34,000 wetland acres remain, but they are continuing to diminish (Smith, 2003; LaGrange, 2005). Thus, the basin is considered to be endangered because of past acreage loss and the potential for future losses due to agriculture in the region (Murkin, 1998; Haukos & Smith 2003; Smith, 2003; LaGrange, 2005).

The decrease in wetland area was tied heavily to agriculture in the region. The region's fertile soil and an adequate irrigation water supply, due to Platte River diversions and the High Plains Aquifer that underlies the basin, made the region an important source for agriculture commodities (Lugn & Wenzel, 1938; Keech & Dreeszen, 1959; Keech &

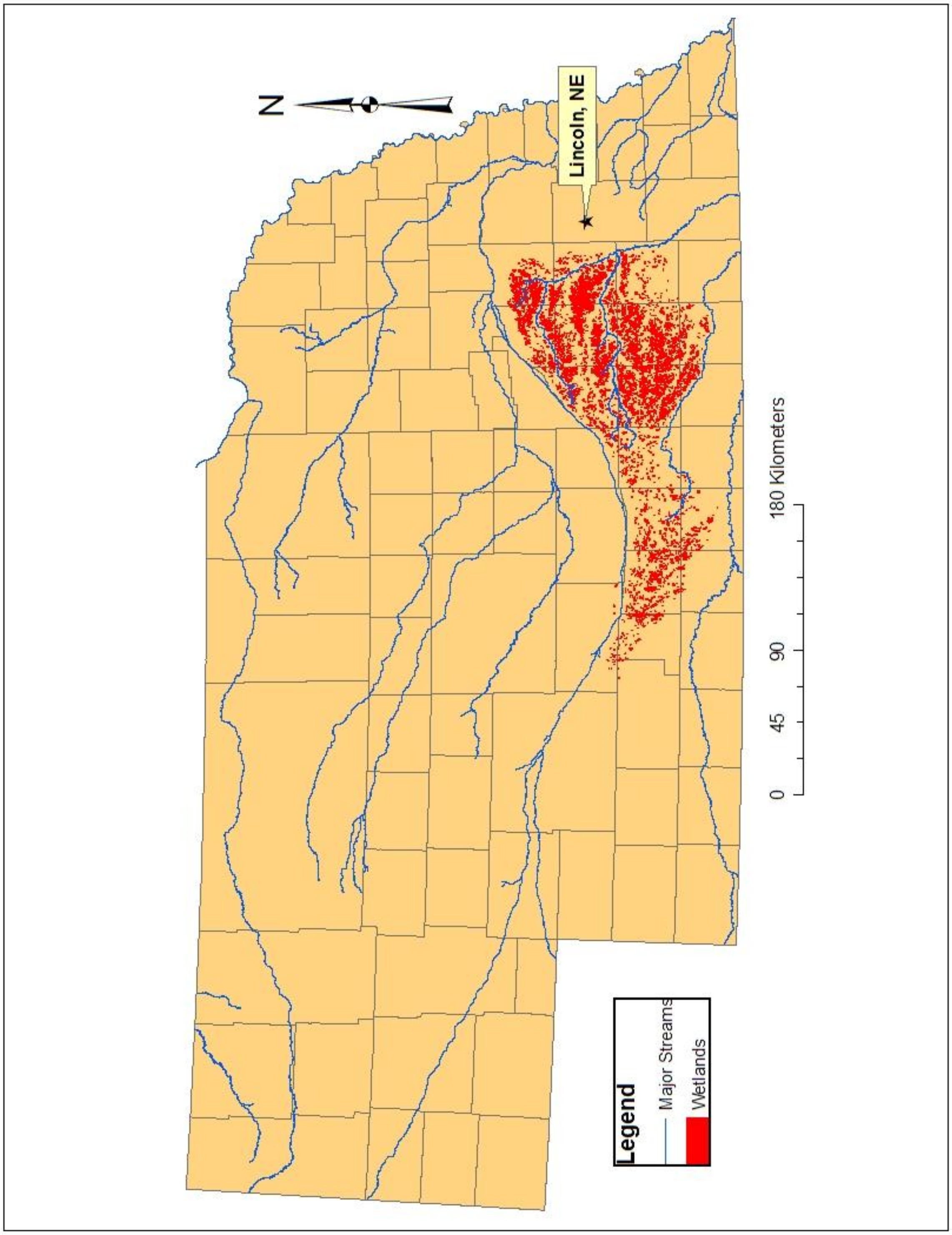


Figure 1: Map of the Rainwater Basin in south-central Nebraska as delineated by the location of individual wetlands' hydric soil footprint. (Delineation does not indicate extent of wetland water body, but presence of hydric soils. Data provided by Ryan Reker of the RWBJV)

Dreeszen, 1968; Ekstein & Hygnstrom, 1996; Smith, 2003; Gurdak & Roe, 2009). As a result, land owners saw the wetlands as "wastelands" or unproductive ground (NEBRASKAland, 1996). Many sites were drained or filled with sediment to bring the sites into production (LaGrange, 2005). Reuse pits were also dug in the center of some wetlands in order to concentrate the volume of water in a smaller surface area (Haukos & Smith, 2003; Smith, 2003; LaGrange 2005). However, not only the wetlands were being altered, but also the uplands were being altered due to crop production. These alterations could cause water to be diverted from the wetland such as terraces withholding water (Smith, 2003), or upland erosion could increase which increases the amount of upland sediment getting into the wetland and altering the wetland hydrology (Haukos & Smith, 2003; LaGrange, 2005).

The need to maintain these sites is similar to the need in other wetlands in that they are necessary to maintain habitat, water quality, provide flood storage, nutrient retention, and sediment trapping (Murkin, 1998; Smith, 2003; LaGrange, 2005; Gurdak & Roe, 2009). However, the most important reason identified as why the Rainwater Basin wetlands need to be protected is their use by migratory birds. The wetlands are important internationally because of their location in a major bird migratory route that bottlenecks in this region and the Platte River Valley (NEBRASKAland, 1996; Smith, 2003; LaGrange 2005). Millions of migratory birds will travel through the basin between wintering grounds in Mexico and the southern United States and the nesting grounds of Canada and the northern United States. It is believed that no other region can provide the necessary habitat for resting, feeding, and breeding (NEBRASKAland, 1996; Smith, 2003; Gurdak & Roe, 2009).

1.2 Study Purpose

Since the High Plains Aquifer is a major source of water for consumptive use within the region, its quality and quantity is of great importance. The wetlands of the Rainwater Basin may have influence on the quality and quantity of groundwater if water recharges from these sites. In research from the Southern High Plains of Texas and New Mexico, playa wetlands have been shown to provide significant recharge when compared to interplaya regions because the wetlands collect runoff and focus the water flow (Zartman, Evans, & Ramsey, 1994; Wood & Sanford, 1995; Scanlon & Goldsmith, 1997; McMahon et al., 2006; Gurdak & Roe, 2009). It was also shown that macropores may provide significant groundwater recharge in or near playas as well as provide a potential pathway for contaminants (Wood, Rainwater, & Thompson, 1997). Because hydrologic data on the connectedness of surface water and groundwater is not currently available, it has not been determined to date if the wetlands of the Rainwater Basin act in a similar manner (NGPC Proposal, 2007). Also, different climate, geology, and wetland formation processes occur within the basin as compared to the Southern High Plains playas. If it is determined that these sites provide focused recharge, it is of great importance to determine if contaminants are also entering the groundwater through these sites or if they are being remediated or retained.

The overall goal of the project which was funded by an United States Environmental Protection Agency (USEPA) grant that is allocated by the NGPC is meant to determine the impact of the Rainwater Basin wetlands on groundwater quality, the influence of sediment removal on groundwater quality, and the effect of sedimentation and hydroperiod on plant and wetland bird communities (NGPC Proposal, 2007). The goal of this study was to determine and understand wetland hydroperiods and determine the magnitude of evapotranspiration (ET) and infiltration on water loss from these sites. The hydroperiod as defined by Mitsch and Gosselink (2007) is “the seasonal pattern of the water level of a wetland and is the wetland’s hydrologic signature.” To gain a better understanding of the Rainwater Basin wetlands’ hydroperiods, the surface water volume changes were monitored continuously over time at several sites with the observed changes being correlated with precipitation, ET, and infiltration.

2.0 STUDY SITES

2.1 Soils & Geology

The Rainwater Basin is located in what is known as the Central Loess Plains (Kuzila & Lewis, 1993; Smith, 2003). Loess has been deposited several times throughout the basin. Research that took place in Clay County, NE indicates that there is approximately a 2.5 to 8.0 m layer of loess at the surface overlaying a paleolandscape consisting of a mixture of loess, alluvium, and eolian sand deposits (Kuzila & Lewis, 1993). The surface deposits can be divided into Peoria loess and the younger Bignell loess (Keech & Dreeszen, 1959; Keech & Dreeszen, 1968; Kuzila & Lewis, 1993). The paleolandscape material belongs to the Gilman Canyon Formation (Kuzila & Lewis, 1993). It was estimated that the surface loess units started being deposited approximately 25,000 years before present (Kuzila & Lewis, 1993; NEBRASKAland, 1996).

The formation of the wetlands is believed to be tied to the Gilman Canyon Formation. The depressions that were originally formed in this formation are now being exhibited at the surface (Kuzila, 1994). However, they have been smoothed out due to the loess deposition that has occurred over time (Kuzila & Lewis, 1993). It also appears that wind deflation was also at work at developing and maintaining these wetlands. Half-moon shaped hills called lunettes are sometimes visible on the southeast and south sides of the wetland depression (Smith, 2003). It was hypothesized that during an arid or semi-arid period 20,000 to 25,000 years ago prevailing winds from the north or northwest eroded sediments from the wetland floor and deposited them on the leeward side of the wetland (Starks, 1984; NEBRASKAland, 1996; Smith, 2003).

Over time precipitation fell and collected in the depressions, and fine material would be eroded within the basin as well as being blown in by wind (Smith, 2003). This collected finer material on the basin floor (Keech & Dreeszen, 1959; Keech & Dreeszen, 1968; NEBRASKAland, 1996). As a result, low permeability sediments formed. With continued wetting and drying of the basin floor sediments, vertic soils developed (Starks, 1984; Kuzila & Lewis, 1993; NEBRASKAland, 1996). Vertic soils exhibit shrink/swell capabilities, and have a large proportion of fine clay (USDA-NRCS, 1999; Sparks, 2003). When wet, the soils are considered to be "sealed up" and hydraulic conductivity is low. However, when dry, the soil volume shrinks and desiccation cracks develop. Because of this shrink/swell process, hydraulic conductivity can change several orders of magnitude and may change within a couple of hours (Bagarello, Iovino, & Reynolds, 1999). Thus, these cracks can be important points for rapid recharge (Zartman, Evans, & Ramsey, 1994; Bronswijk, Hamminga, & Oostindie, 1995; Gurdak & Roe, 2009). Figure 2 shows a few examples of these cracks within wetlands.

The soil series associated with Rainwater Basin wetland sediments are the Massie, Fillmore, Scott, and Butler (Starks, 1984; Smith, 2003). The Massie, Fillmore, and Scott series are described as fine, smectitic, mesic vertic argialbolls (USDA-NRCS, 2010b). The Butler series is described as fine, smectitic, mesic vertic argiaquolls (USDA-NRCS, 2010b). These soils are differentiated by their ability to pond water and relative position within the wetland basin (USDA-NRCS, 2010b). Starks (1984) generalized the relative location of these soils in the wetlands with Massie typically being on the basin floor and Scott, Fillmore, and Butler occurring at higher elevations within the basin. These soil series descriptions can be viewed in Appendix C. Massie, Fillmore, Scott, and Butler soils are also defined as being hydric soils (Smith, 2003). As defined by the USDA-NRCS (2010a), a hydric soil is a soil "formed under saturation, flooding or ponding long enough during the growing season to develop anaerobic conditions in the upper part." The presence of these hydric soils is an important criterion for the classification of a site as a wetland in Nebraska (LaGrange, 2005).

The regional aquifer underlying the Rainwater Basin is the High Plains Aquifer. Throughout most of the High Plains Aquifer region, the water table can be tens to hundreds of feet below the surface (McGuire et al., 2003; Gurdak & Roe, 2009). This is the case for the Rainwater Basin region with water table depths ranging from 15 to 30 meters (50 to 100 feet) below the wetland surface (Foster, 2010). In the western portion of the basin, the aquifer consists of Quaternary loess and alluvial deposits and the Ogallala Formation of the Tertiary system. This aquifer system overlies Upper Cretaceous Pierre shale (Lugn & Wenzel, 1938; McGuire et al., 2003; CSD, 2010). In the eastern portion of the basin, the aquifer consists of the Quaternary deposits only as the Ogallala Formation has "pinched out" or is non-existent. Here, the aquifer system overlies Upper Cretaceous Carlile shale or Niobrara chalk (Keech & Dreeszen, 1959; Keech & Dreeszen, 1968; McGuire et al., 2003; CSD, 2010).

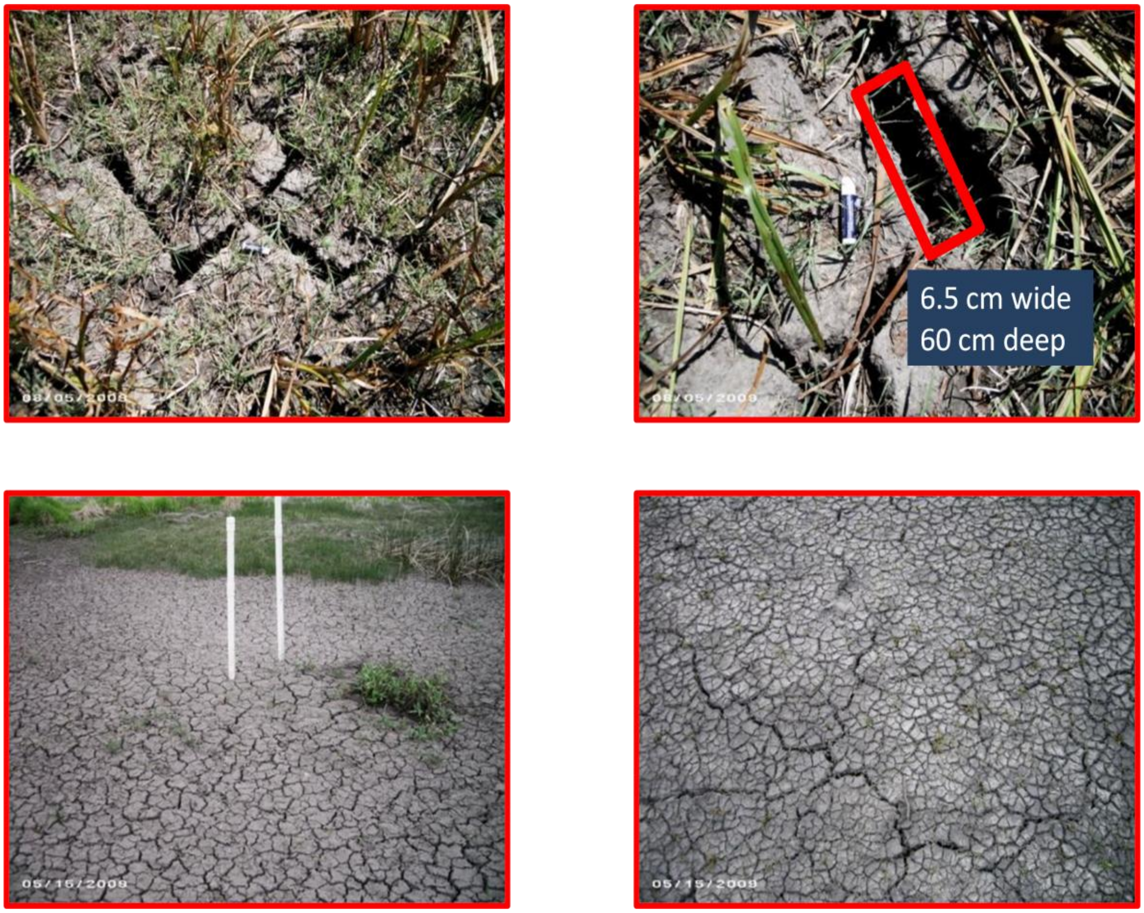


Figure 2: Examples of desiccation cracks forming in wetland sediments.

2.2 Regional Climate

The Rainwater Basin has extreme seasonal climate variations. During summer months, the basin can be very warm while the winter can be long and cold. Based on the 1971-2000 climate normals, the average annual temperature is approximately 10 ℃ with temperatures averaging in the negative single digits for January and the upper twenties for July (HPRCC, 2010). The region has a continental climate (McMahon et al., 2006). Wide variations of daily temperature can occur with cool nights to warm days due to the lack of a large water body nearby to mitigate temperature changes.

Precipitation is variable through the basin. Precipitation input is higher on the eastern side of the basin with volumes becoming progressively less when moving to the west. Based on the 1971-2000 normals, the average annual precipitation in the eastern part of the basin can be almost 750 mm while the western part of the basin receives amounts in the low 500 mm range (HPRCC, 2010). Most precipitation falls during local, spring thunderstorms (Keech & Dreeszen, 1959). Precipitation can become infrequent in late summer (Keech & Dreeszen, 1959; HPRCC 2010). The eastern basin is characterized as a sub-humid climate (Keech & Dreeszen, 1968) while the western portion approaches a semi-arid climate.

2.3 Wetland Selection

Due to the large expanse of the basin, it was impractical to evaluate and monitor all wetlands. Thus, several representative wetlands were selected for this study which were thought to represent the observed changes in climate and geology across the region. Eight wetlands were selected. These were Linder WPA, Lindau WPA, Harms WPA, Moger (North) WPA, Greenhead WMA, Griess WPA, Bluebill (South) WMA, and

Hidden Marsh WMA. The locations of these sites relative to each other are mapped in Figure 3. WPA and WMA stand for Waterfowl Production Area and Wildlife Management Area, respectively. WPA's are managed by the United States Fish & Wildlife Service (USFWS). WMA's are managed by the NGPC.

Since this was an exploratory study, selecting criteria for a site was limited. Criteria for picking wetlands included that the site be (a) publicly owned, (b) that a spread of wetlands from east to west across the basin were used, and (c) that the basins were not breached by human activity. Publicly owned sites were used because it was easier to reach agreements with federal and state agencies to conduct research on their property. Owners of private wetlands were reluctant to have instrumentation placed on their sites which would have limited the full potential of the study. The spread of sites from east to west was used to determine how climate and geology variations across the basin might impact wetland hydrology. Finally, basins not breached by human activity included sites where canals, culverts, and road ditches did not facilitate exchange of water between basins. This criterion was selected to exclude basins where a simplified water balance approach could not be used. Because Nebraska's roads are aligned in a grid system, it was typical that a road would cut across a wetland. Ditches alongside of the road were seen as anthropogenic pathways for water to get into a wetland. Some sites with roads crossing through the wetland had upland topography with significant slopes where water exchange between basins via the ditches did not appear to occur. These sites were still considered for the study. Sites with canals and culverts that allowed for inter-basin water exchange were excluded with one exception. This exception was Linder WPA which has a canal draining onto the site. Several agricultural fields surround both this canal and the wetland. This site was used to see if agricultural contaminants were at higher levels in the water due to these focused flows onto the wetland.

Due to the significant amount of data that was generated from these eight wetlands, only three sites are discussed in this thesis. Lindau WPA, Moger (North) WPA, and Griess WPA are the sites discussed. The data from these three sites show trends that are similar to trends at the other Rainwater Basin wetlands studied. Individual descriptions of these three sites are discussed in the following sections.

There may be some similarities; however, each of the eight wetlands had their own unique characteristics. Every site has differences in wetland shape, climate, geology, upland land use, and timing of when ponding occurs. This thesis will provide insight on what hydrology depressional wetlands in south-central Nebraska exhibit. However, due to the unique nature of each site, this thesis cannot describe the intricacies involved at every wetland within the basin, and its conclusions may not be representative of each individual site's hydrology.

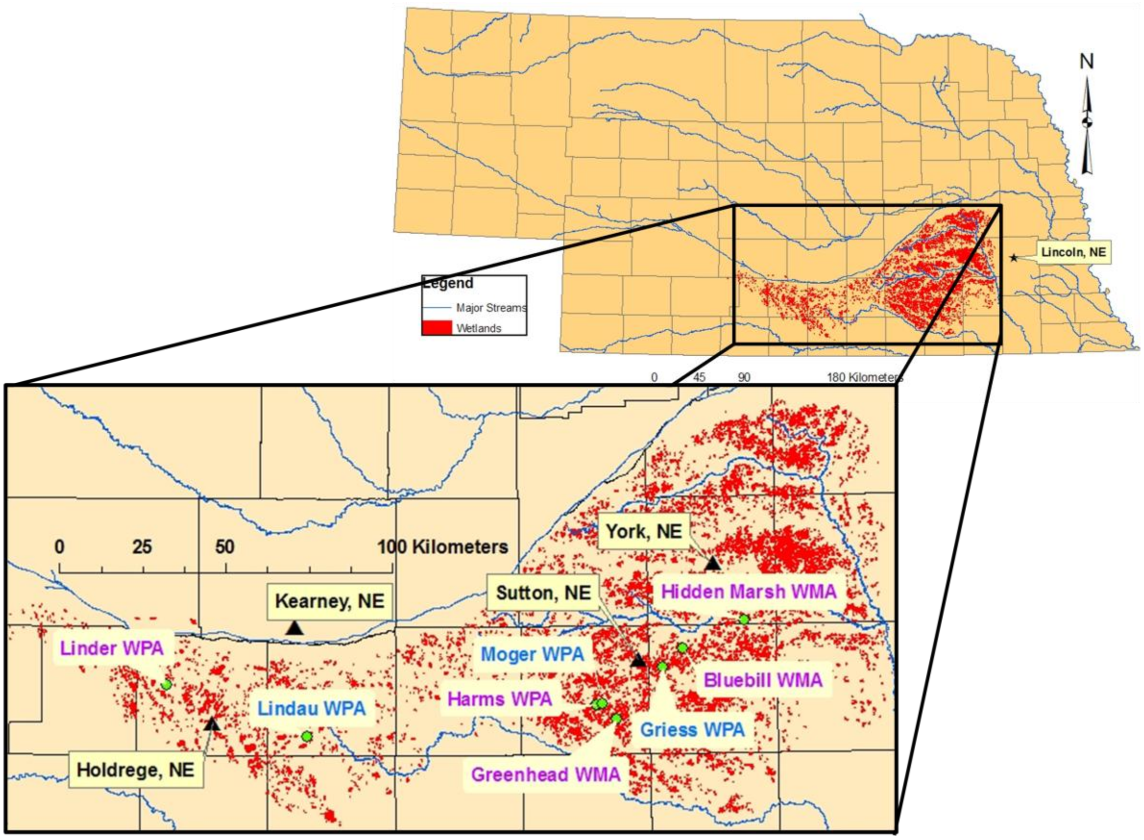


Figure 3: Location of all selected wetlands. (Studied wetlands indicated by green dots. Wetland names with blue text indicate sites discussed in this thesis. Data provided by Ryan Reker of the RWBJV.)

2.3.1 Lindau WPA

Lindau WPA is located roughly 8 miles southwest of Minden, NE in Kearney County. The location of Lindau WPA within the Rainwater Basin is provided in Figure 4. The wetland area is approximately 141 acres based on the hydric soils designation. The wetland floor is dominated by the Massie soil series with the Fillmore soil series on the periphery. The wetland is surrounded by cropped fields. Center-pivot, irrigated fields are located on the northwest and southeast sides, while dryland fields are located on the southwest and northeast corners. Lindau is managed by the USFWS. They allow cattle grazing to occur on the site in order to maintain vegetation. They have also placed a pumping well on site with an outlet towards the wetland. Groundwater is pumped onto the site in dry years during the peak bird migration periods in early spring.

2.3.2 Moger (North) WPA

Moger (North) WPA is located roughly 4 miles east-southeast of Clay Center, NE in Clay County. The location of Moger (North) WPA within the Rainwater Basin is provided in Figure 5. The site is part of a two wetland complex. In order to differentiate which wetland was used, the site is labeled Moger (North) WPA because the north wetland was used. The wetland area is about 60 acres based on the hydric soils designation. The wetland floor is dominated by the Massie soil series with the Fillmore series on the periphery. The site is surrounded by grassland with a small cropped section in the upland area on the northeast side of the wetland. The wetland is managed by the USFWS. A pumping well is on site with the outlet directed towards the wetland. This is meant to flood the site during dry years with groundwater for migrating bird populations. The site was burned in the spring of 2009, and was grazed by cattle during the summer.

2.3.3 Griess WPA

Griess WPA is located approximately 5 miles east-southeast of Sutton, NE in Fillmore County. The location of Griess WPA within the Rainwater Basin is provided in Figure 6. The wetland floor is approximately 77 acres based on the hydric soils designation. The wetland floor is dominated by the Massie soils series with the Scott series on the periphery. Most of the wetland area is privately owned with only about 17 acres managed by the USFWS. The wetland has a road that separates it into northern and southern sections. The USFWS property is on the north side of the road with the road being its southern boundary. The federally owned section is a rectangular section carved out of the wetland area. Cropped fields surround the wetland with some of the wetland area being cropped on the privately owned property. Center-pivot irrigation is occurring in the fields to the east and west of the site. Also, on the private property to the west, it appears that a former runoff pit has been filled with sediment. On the east side of the federal property, there is a sharp increase in elevation when going east onto the private property.

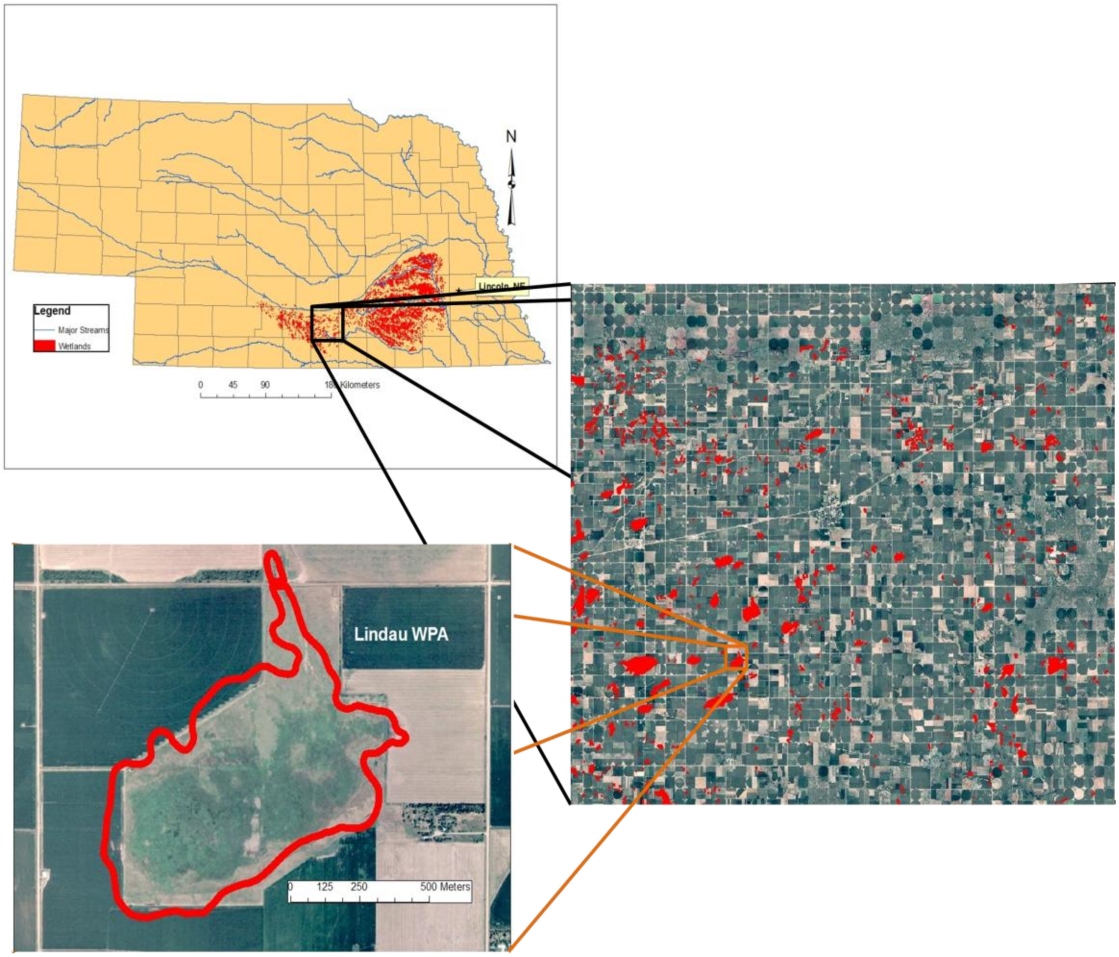


Figure 4: Location of Lindau WPA in the Rainwater Basin.
(Red covered areas and outlines indicate wetland
locations and boundary of wetland sediments.
Data provided by Ryan Reker of the RWBJV.)

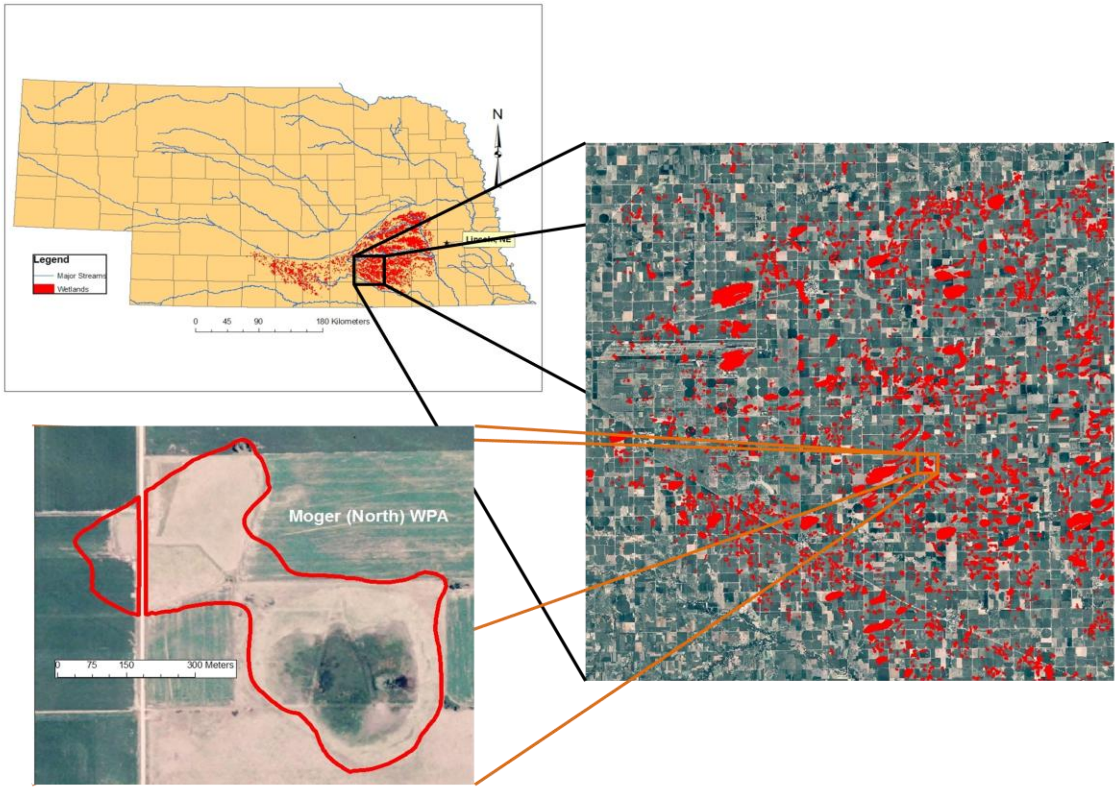


Figure 5: Location of Moger (North) WPA in the Rainwater Basin.
(Red covered areas and outlines indicate wetland
locations and boundary of wetland sediments.
Data provided by Ryan Reker of the RWBJV.)

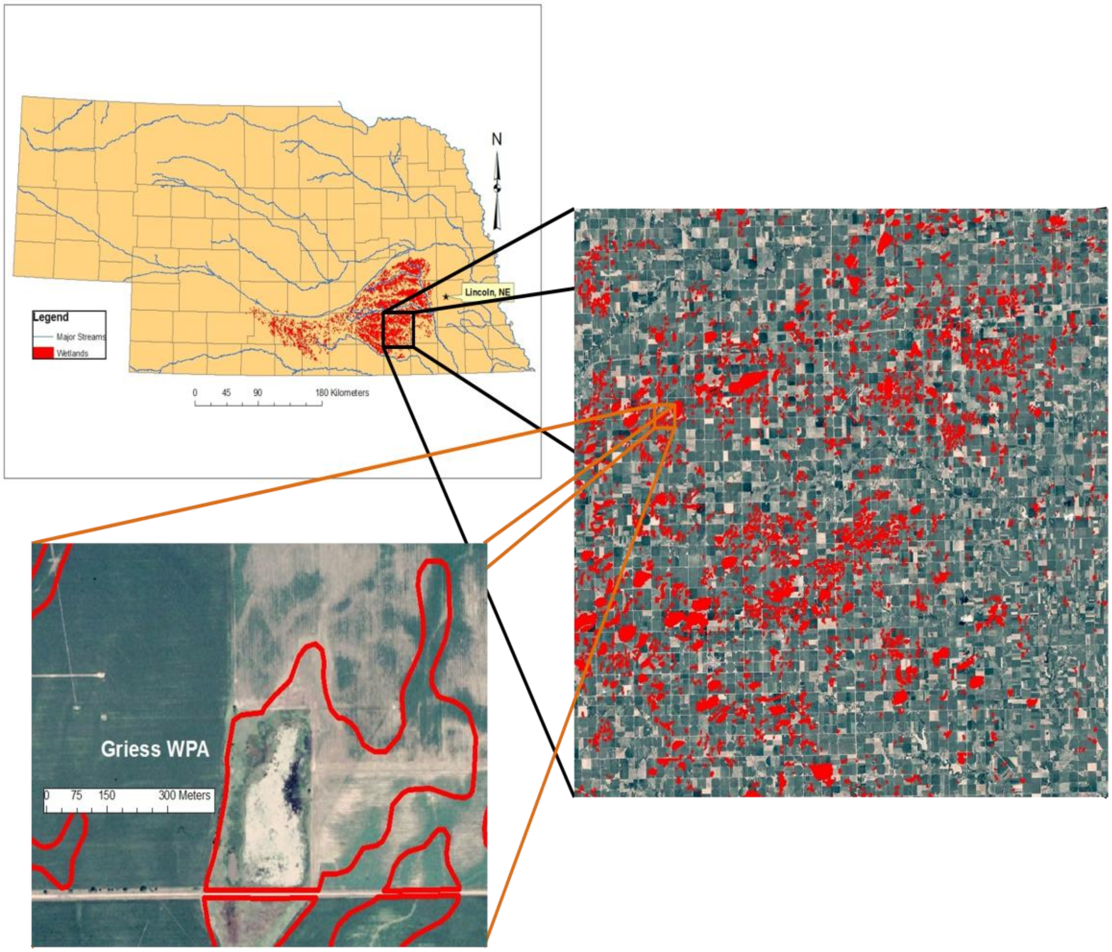


Figure 6: Location of Griess WPA in the Rainwater Basin. (Red covered areas and outlines indicate wetland locations and boundary of wetland sediments. Data provided by Ryan Reker of the RWBJV.)

3.0 METHODS

3.1 Climate Data

3.1.1 Precipitation

Precipitation data were supplied by the High Plains Regional Climate Center (HPRCC). The HPRCC was established to collect climate data in the High Plains region (HPRCC, 2010). The center has several automated weather data collection sites (AWDN) throughout the Rainwater Basin as well as provides access to the National Weather Service's (NWS) data. The weather stations within 30 km of each wetland that had available data were used to estimate local daily precipitation totals by using inverse-distance weighting. The locations of these weather stations are illustrated in Figure 7. The inverse-distance weighting formula used to estimate precipitation at a wetland site from nearby weather stations was:

$$I = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{D_i}\right)}{\sum_{i=1}^{n}\left(\frac{1}{D_i}\right)} \qquad (1)$$

where I is the estimated precipitation at the wetland (mm), z_i is the measured precipitation at weather station i (mm), and D_i is the straight-line distance between the wetland and weather station i (km).

1971-2000 precipitation normals were also obtained from the HPRCC. This provided a historical record of precipitation averages within the area to compare and contrast against. The nearest weather stations to the wetland with available data were used to provide this information. The stations used for each wetland are Minden (NWS) for Lindau WPA, Clay Center 6 ESE (NWS) for Moger (North) WPA, and Geneva (NWS) for Griess WPA.

Precipitation was also collected by weather stations installed by this study on individual wetland sites. The sites that contain a weather station were Lindau WPA and Moger (North) WPA. A Texas Electronics tipping bucket rain gage was used. See Appendix A for gage type, mounting height, and resolution as well as location of the rain gage in the wetland.

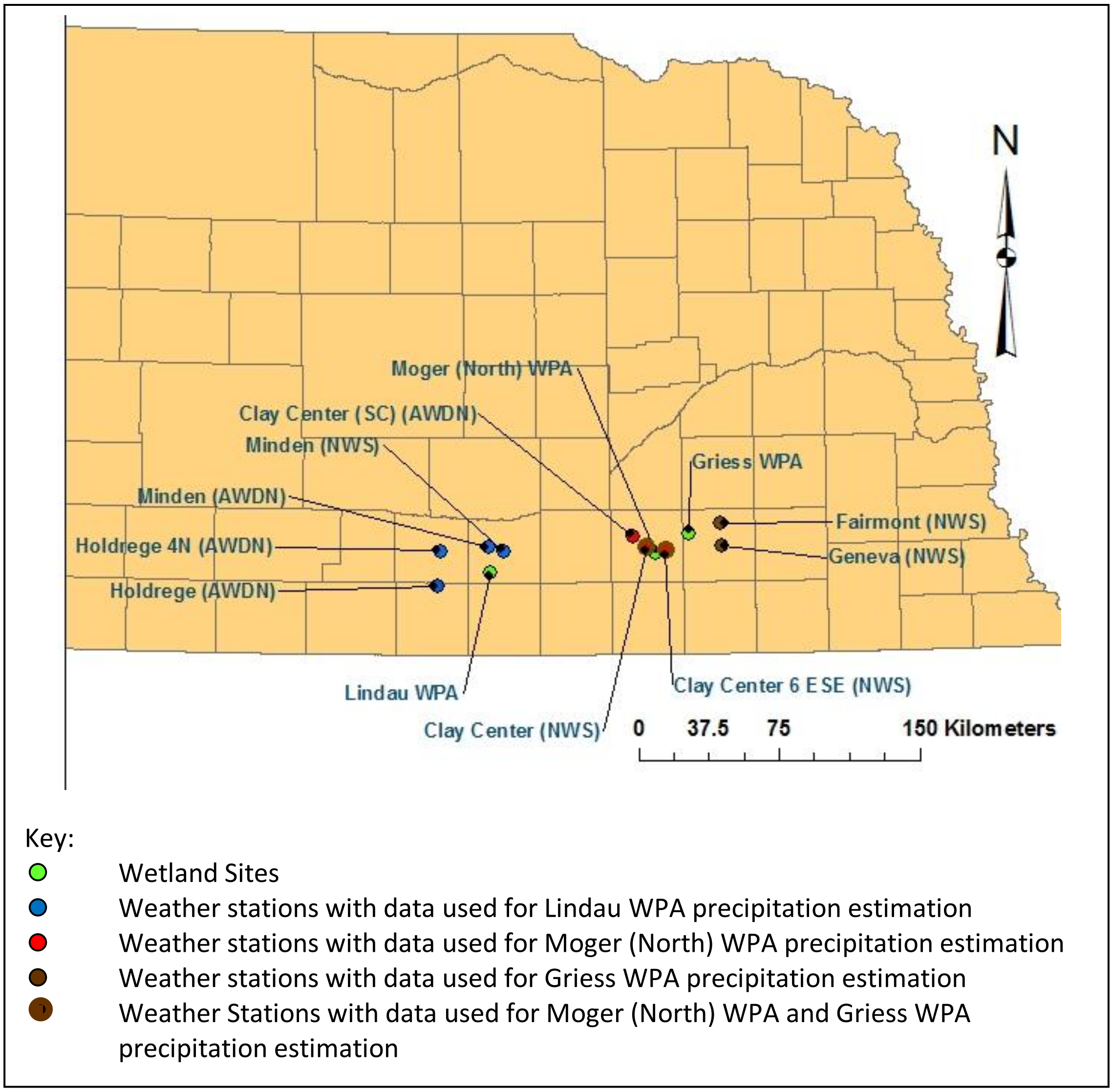


Figure 7: Location of HPRCC AWDN and NWS data collection sites.

3.1.2 Wind

Wind velocity and wind direction data were used to determine if fetch criteria were met for validating ET data. These parameters were measured by a Met One Windset 034B anemometer and vane. Mounting was variable from site to site due to vegetation height restrictions. Mounting elevations and instrument data can be viewed in Appendix A.

Wind velocity outputs were measured in units of meters per second ($m\ s^{-1}$). Wind direction was measured in degrees. After calibration of the sensor, wind flowing from the north would register a 0^{o} output while registering a 90^{o}, 180^{o}, and 270^{o} for wind flowing from the east, south, and west, respectively. Eight cardinal directions were used to indicate direction of wind flow. Each direction had a 45^{o} field of view in which all degrees that fell within the boundaries would be labeled with a single directional notation. Partitioning of degrees to their respective direction can be viewed in Appendix A.

3.1.3 Evapotranspiration

At Lindau WPA and Moger (North) WPA, the Bowen Ratio Energy Budget (BREB) method was used to obtain an estimate of ET. Instrumentation was placed on site to get measurements from the water body or wetland floor. At both sites, tripods were set up approximately in the center of the wetland to obtain proper energy budget readings as well as to ensure that proper fetch was obtained for sensors requiring atmospheric equilibration to the wetland surface. Using the rule 100:1 where for every one unit increase in height of the sensor on the mast would require 100 units in surface distance for equilibration (Stannard et al., 2004), the acceptable fetch was determined by the placement of the highest sensor, prevailing wind direction, and wetland leading edge. The height of the sensors was variable from site to site due to changes in ponded water elevation as well as influences due to the height of vegetation.

The equation used with the BREB method, when water was present, is stated by Stannard et al. (2004) as:

$$ET_{\mathrm{m}} = \frac{Q_{\mathrm{n}}+Q_{\mathrm{v}}+Q_{\mathrm{x}}+Q_{\mathrm{b}}}{\rho[L*(1+\beta)+c*T_{\mathrm{o}}]} \tag{2}$$

where ET_m is the calculated evapotranspiration rate (m s^{-1}), Q_n is the net radiation to the wetland (W m^{-2}), Q_v is the net heat advected to the wetland from precipitation and ground water (W m^{-2}), Q_x is the change in heat stored in the wetland water body (W m^{-2}), Q_b is the heat transferred to the water from the wetland sediments (W m^{-2}), ρ is the density of water (1000 kg m^{-3}), L is the latent heat of vaporization ($2.45*10^6$ J kg^{-1}), β is the calculated Bowen Ratio (unitless), c is the specific heat capacity of water (4,187 J kg^{-1} $^{\circ}C^{-1}$), and T_o is the wetland water-surface temperature (°C) obtained by an Apogee IRR-P® infrared radiometer. The following sections discuss how components of equation 1 were obtained and what assumptions were made.

3.1.3.1 Net Radiation (Q_n)

Net radiation to a site can be summarized by the following equation (Parkhurst et al. 1998):

$$Q_{\mathrm{n}} = Q_{\mathrm{s}} - Q_{\mathrm{r}} + Q_{\mathrm{a}} - Q_{\mathrm{ar}} - Q_{\mathrm{bs}} \tag{3}$$

where Q_s is the incoming solar short-wave radiation (W m^{-2}), Q_r is the reflected solar short-wave radiation (W m^{-2}), Q_a is the incoming atmospheric long-wave radiation (W m-

^{2}), Q_{ar} is the reflected atmospheric long-wave radiation (W m^{-2}), and Q_{bs} is the emitted surface long-wave radiation (W m^{-2}).

The instruments used to collect radiation data were (a) a Kipp & Zonen CMP3® pyranometer to measure incoming solar short-wave radiation, (b) a Kipp & Zonen CNR2® net radiometer to obtain all radiation parameters and provide an output of total short-wave, total long-wave, and net radiation, and (c) an Apogee IRR-P® infrared radiometer to obtain surface temperatures to calculate emitted long-wave radiation. The data from the net radiometer was used to obtain Q_n, but data from the other sensors could be used to determine individual components of the net radiation equation for further investigation.

3.1.3.2 Net Advected Energy (Q_v)

Net energy advected into the wetland by precipitation and groundwater is determined by how much heat is gained or lost by adding or removing water. This parameter requires determining the volume and temperature of the water coming in or leaving a wetland site. This parameter was considered negligible for the wetlands in the Rainwater Basin. There was no groundwater seeping into the sites, and it was assumed, prior to investigation, that the rate of seepage out of these sites when wet was extremely low. The groundwater energy advection is assumed to be zero W m^{-2}. Precipitation can influence the temperature of the water at a site and affect the daily energy budget. However, according to Parkhurst et al. (1998), the temperature of the water may be altered for a short period by precipitation, but solar radiation influences will warm the water back up. They showed that the influence of precipitation would have little influence on the period averages. For the Rainwater Basin wetlands, net energy advected was assumed to be zero W m^{-2}.

3.1.3.3 Heat Storage of Wetland Water Body (Q_x)

The heat energy stored in the wetland water body influences the temperature as well as the latent energy stored there. When calculating stored heat energy, thermal surveys of the wetland occur at specific time intervals. The time between sampling intervals is an energy budget period. The difference in stored heat energy between two sampling periods is called the change in stored heat energy during a budget period. The change in stored heat energy over the budget period represents the amount of energy leaving or entering a system. According to Parkhurst et al. (1998), the stored energy can be calculated by averaging the temperature in horizontal slices of the water volume, calculate the heat stored in each slice, and sum the heat from each slice to obtain a total for the wetland. Due to the size of the research area and limited time for completing research, thermal surveys were not carried out. However, it is assumed that the water body is relatively homogenous due to the shallow nature of these wetlands and the high potential for mixing influenced by the wind. With this assumption, the temperature data supplied by the pressure transducer in the stilling well and the infrared radiometer measuring surface water temperature was used. It was assumed that half of the wetland surface water volume would have the temperature measured by the stilling well and the other half would have a temperature measured by the infrared radiometer. This allowed for an estimate of stored heat energy to be calculated every three hours. The stored heat energy was calculated by the following derived equation (Saur & Anderson 1955; Burba et al. 1999; Sánchez-Carrillo et al. 2004):

$$Q_{\mathrm{I}} = \left(\frac{1}{2}\right) \rho c \frac{V_{\mathrm{I}}(T_{\text{stilling well I}} + T_{\text{radiometer I}})}{A_{\mathrm{I}}} \quad (4)$$

where Q_I is the stored heat energy of water body at time I (J m^{-2}), V_I is the volume of stored surface water at time I (m^3), A_I is the surface area of the water at time I (m^2), $T_{\text{Stilling well I}}$ is the temperature measured in the stilling well at time I (°C), and $T_{\text{radiometer I}}$ is the temperature of the water surface measured by the infrared radiometer at time I (°C).

The change in stored energy over the budget period was calculated as (Saur & Anderson 1955; Parkhurst et al. 1998):

$$Q_{\mathrm{x}} = (Q_2 - Q_1) * 9.26 * 10^{-5} \quad (5)$$

where the subscripts 1 and 2 represent the calculated heat energy at the beginning and end of the energy budget period, respectively, and $9.26*10^{-5}$ is used to convert from J m^{-2} to W m^{-2} when the measurement period is 3 hours.

3.1.3.4 Heat Transfer between Sediments & Wetland Water Body (Q_b)

The heat transferred between the water body and sediments was assumed to be negligible in the computation of ET. According to Parkhurst et al. (1998), including these data would increase ET on average about 2.5 percent. Others excluded using this term in their calculations because most energy was being stored in the wetland water body (Burba et al., 1999; Sánchez-Carrillo et al., 2004). It was initially assumed that the Rainwater Basin wetlands would be similar to those authors' researched wetlands and that sensors would not be required to determine the soil heat flux impact on ET. Thus, based on reviewed literature, it was not deemed necessary to measure this quantity.

3.1.3.5 Bowen Ratio (β)

The Bowen ratio is the term that relates sensible heat flux to latent heat flux in the following equation (Perez et al., 1999):

$$\beta = \gamma \left(\frac{\Delta T}{\Delta e_a}\right) \tag{6}$$

where β is the Bowen ratio (dimensionless), γ is the psychrometric constant (kPa $^{\circ}C^{-1}$), ΔT is the temperature difference between two vertical measurement points ($^{\circ}$C), and Δe_a is the actual vapor pressure difference between two vertical measurement points (kPa).

The psychrometric constant was obtained through the equation (Perez et al., 1999):

$$\gamma = \frac{c_a P}{0.622L} \tag{7}$$

where c_a is the specific heat of air (1.01 kJ $kg^{-1}\,^{\circ}C^{-1}$), P is the atmospheric pressure (kPa), and L is the latent heat of vaporization (2,450 kJ kg^{-1}).

The temperature and vapor pressure differences were obtain by two Vaisala HMP45C® temperature/RH probes at two different heights above the wetland. The vapor pressure was calculated from the relative humidity (RH) outputs by the following equation (Dingman, 2002):

$$e_a = RH\frac{e_s}{100\%} \tag{8}$$

where e_a is the actual vapor pressure (kPa), e_s is the saturated vapor pressure (kPa), and RH is the relative humidity (%).

Saturated vapor pressure, which is a function of temperature, was calculated by the following equation (Dingman, 2002):

$$e_s = 0.611 \exp\left(\frac{17.3 * T}{237.3 + T}\right) \quad (9)$$

where e_s is the saturated vapor pressure at atmospheric temperature (kPa) and T is the atmospheric temperature (°C).

3.1.4 Weather Station Data Collection & Analysis

Climate data measurements were made every five minutes and averaged over a half-hour period. A Campbell Scientific CR1000® datalogger was used to record and store the data. Sensor type, mounting height, and precision information for all equipment are provided in Appendix A.

ET was calculated every half-hour. All data observations were averaged every half-hour except the measurements necessary for the heat storage of the water body. The heat storage calculation was made utilizing the temperature reading of the stilling well pressure transducer which is recording every three hours (one hour for a period at Lindau WPA). Thus, the change in heat storage was calculated every three hours (one hour). The total gain or loss of energy was divided equally among each half-hour period. It was assumed the gain or loss of energy was constant over the three (one) hour period.

Once ET was calculated every half-hour, exclusion criteria were applied to the outputs. The need for these criteria was to ensure that incorrect values attributed to mathematical breakdown of the Bowen ratio equation, insufficient fetch, the wetland site having no stored surface water, or data that is measured less than the resolution limit of the sensor were not used for estimating ET. Cases where the BREB method fails are established by Perez et al. (1999). Their criteria were applied to the ET data sets to exclude data where the Bowen ratio was incorrect and where measurements fell within the resolution limits of the sensors. Fetch was considered insufficient if wind was approaching the ET tower from a direction that did not have proper distance of wetland surface based on the 100:1 rule needed for equilibrated atmospheric conditions. GIS was utilized to determine which wind directions provided sufficient wetland surface for boundary layer equilibration based on the field of view of the highest elevated temperature/RH sensor. Water volumes were monitored on both Lindau WPA and Moger (North) WPA to ensure that the site was not dry during the ET measurement period.

3.2.0 Piezometers

3.2.1 Drive-point Wells

Drive-point wells were used on the sites to monitor soil water pressure head for periods when water was ponded on the surface. They were also used to record water movement inflow and outflow to the wells due to changes to surface water levels and varying soil water contents. Five wells were installed at each wetland site. The wells were constructed using 3.81 cm I.D. Schedule 40 PVC pipe. Typical well casing length was 1.52 m, but casing extensions were used when wetland water levels could overtop the well if wetland water levels were at their maximum. The screen length was 13.34 cm. The screen consisted of 55 drilled holes with each hole having a diameter of 0.635 cm. A schedule 40 PVC drive-point tip, purchased from Nebraska Pump Company, was glued to the end of the well. The wells were driven into the soil with a post driver. The mid-point of the screen was placed at approximately 0.76 meters below the surface. Some wells had screen depths that were shallower due to restrictive soil features which could not be overcome by human-powered installation. The well cap had two vents drilled on the side to allow for the free flow of air into and out of the casing and to ensure that a vacuum would not be created within the riser pipe. The wells were labeled as DW1, DW2, DW3, DW4, and DW5. Figure 8 and Figure 9 show examples of the drive-point wells. Geographic locations of these wells on each site and screen depths in soils are provided in Appendix A. Figure 11, Figure 12, and Figure 13 show the locations of drive-point wells on Lindau WPA, Moger (North) WPA, and Griess WPA, respectively.

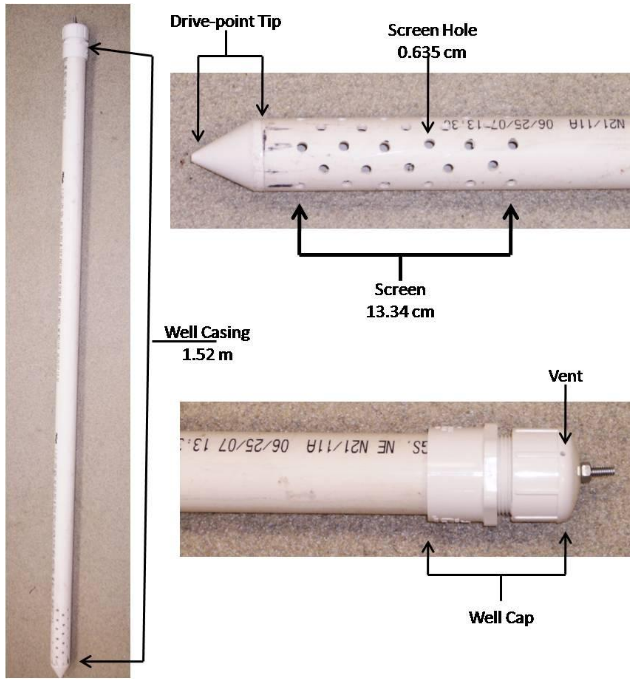


Figure 8: Diagram of drive-point well.

Figure 9: Example of an installed drive-point well (left) and stilling well (right).

3.2.2 Pressure Transducers

Solinst® Levelogger pressure transducers were placed into the drive-point wells to monitor continuous water temperature and level changes. These instruments are fully enclosed, non-vented pressure transducers. They were hung in the wells using a stainless steel wire cable attached to an eye bolt screwed into the well cap. The transducers were hung so that the ports on the sensor were even with the bottom of the well screen. To compensate for atmospheric pressure influences on the Levelogger, a Solinst® Barologger was used to measure the atmospheric pressure. For each reading, the atmospheric pressure value was subtracted from the pressure reading provided by the Levelogger to obtain a water level in the well. The Barologger was hung directly beneath the cap of the stilling well on the site. Temperature and water level readings were sampled every 3 hours. However, on Lindau WPA, there was a period from 8/18/09 to 10/26/09 when readings were sampled every hour. See Appendix A for type and accuracy/precision information of the pressure transducers.

3.3.0 Surface Water Area & Volumes

3.3.1 Topography

All sites were surveyed to map basin topography. An Epoch™ 25 L1/L2 RTK GPS System was used to make the survey. Elevations were determined relative to the system base which was sited over a fixed point. The fixed point on each site was a shallow, aquifer observation well except at the Griess WPA site. At Griess WPA, the drive-point well, DW1, was the fixed point where the system base was situated. Figure 10 shows an example of how the base station was situated when surveying of a site began. See Appendix A for system properties and location and elevation of the base station on each wetland site. Grid spacing of elevation points changed from site to site due to size of wetland or time constraints to completing the survey. Additional points were obtained in order to have site equipment elevations such as drive-point wells, stilling wells, weather stations, and etc. as well as to better delineate areas with significant gradients or highly variable topography. Locations of where elevations were recorded for all three sites are provided on maps in Appendix B.

3.3.2 Stilling Wells

A stilling well equipped with a Solinst® Levelogger pressure transducer was installed on each wetland site to monitor surface water levels. The stilling well was constructed out of 3.81 cm I.D. Schedule 40 PVC pipe. Typical well casing length was 1.52 m, but casing extensions were used when wetland water levels could overtop the well if water levels were at their maximum. The well contained a 13.34 cm long screen with the bottom of the screen flush with the soil surface. The pressure transducer was suspended in the well by a stainless steel wire cable. The ports on the transducer were level with the bottom of the screen. As mentioned earlier, a Solinst® Barologger was hung directly beneath the cap of the stilling well. Readings of temperature and water level were obtained every 3 hours except for the period mentioned earlier for Lindau WPA. The well was labeled as SW. Figure 9 shows an example of a stilling well. Location information of the stilling well on each wetland site and screen depth relative to the soil surface is provided in Appendix A. Figure 11, Figure 12, and Figure 13 show the location of the stilling well on Lindau WPA, Moger (North) WPA, and Griess WPA, respectively.

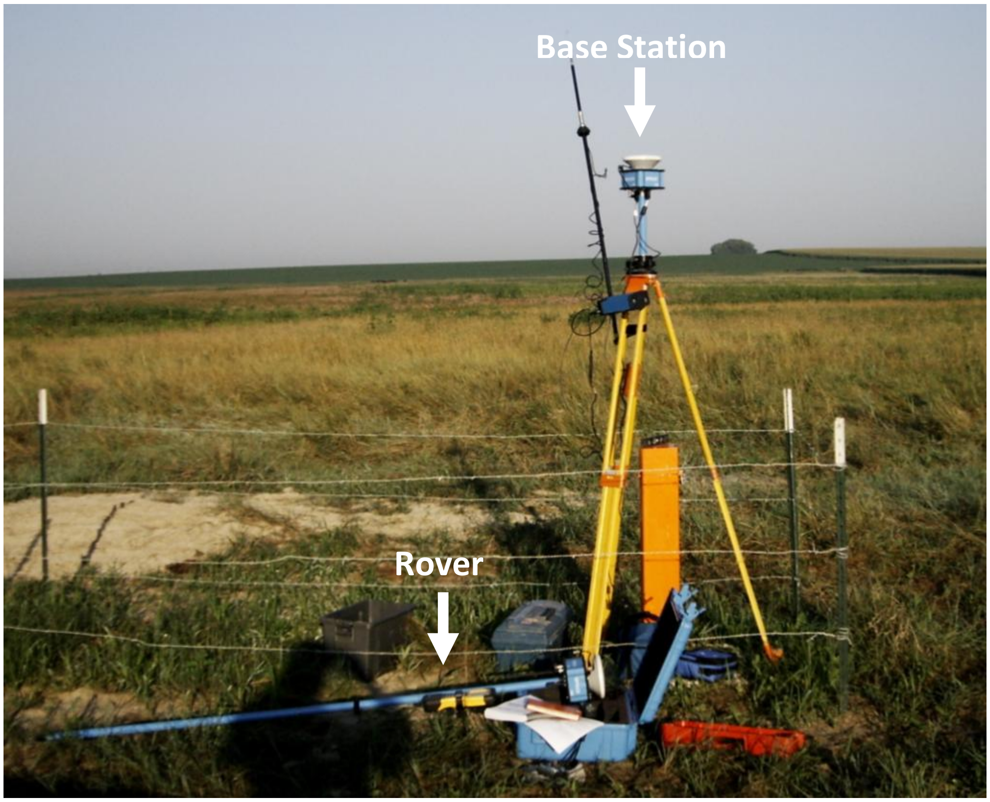


Figure 10: GPS surveying equipment featuring base station centered over shallow aquifer observation well and rover.

Figure 11: Location of equipment on Lindau WPA.

Figure 12: Location of equipment on Moger (North) WPA.

Figure 13: Location of equipment on Griess WPA.

3.3.3 Wetland Stage-Storage Curves

Stage-Storage curves were developed in order to equate either water surface area or volume to a specific water level within the wetland. First, data points from the topographic survey were imported into ESRI™ ArcGIS® 9.0 software. Surface elevations were extrapolated from the data points by using the Natural Neighbors statistical program. From this surface elevation map, contours were developed. Area was determined in the enclosed polygons created by the contours. It was assumed that areas associated with low elevations would be covered first with water and successive areas of higher elevations would be covered as water level rose. This allowed for a curve to be developed that tied total surface area of the water to the water level in the wetland.

The Average End Area Method was used to calculate total volume of water held between contours. The equation used to calculate volume between contours was (Autodesk, Inc., 2011; Schwab, Fangmeier, & Elliot, 1996):

$$V_{\mathrm{I}} = \left(\frac{A_{\mathrm{L}}+A_{\mathrm{U}}}{2}\right) * d \tag{10}$$

where V_I is the volume of water held between contours (m^3), A_L is the total surface area enclosed within the lower contour (m^2), A_U is the total surface area enclosed within the upper contour (m^2), and d is the distance between the lower and upper contours (m). This method provides an estimate of volume between the two contours. As elevation increases, the volume is accumulated which gives a total volume in the wetland associated with a specific water level.

With these curves developed, known fitting equations were matched to the curve to calculate a value for surface area or volume from a measured surface water level. In order to have better agreement between the curve and equations, the curve was divided into sections. These sections had equations developed using Microsoft's Excel® regression analysis. The curves were sectioned so that all developed equations would have an r^2 value equal to or greater than 0.95. Equations were tested by inserting surface water level data from the site and analyzing the output. Equations were accepted as long as high water levels did not produce lower area and volume outputs when compared to a lower water level. Also, equations were not used if values became negative.

3.3.4 Surface Water Volume Changes

One of the goals of the research was to estimate how stored surface water volume changes with time and what influences (ET, Precipitation, and Recharge) may alter the rate of change. Daily averaged volumes were graphed during the monitoring periods to give a time series of how volume changes. The rate of change was determined by taking the difference between the daily averaged volumes over a single day period. If a negative rate occurred, this meant that water was being removed from surface storage while a positive rate means an increase in surface storage.

3.4 Infiltration Estimation

With an estimate of surface water volume change and ET at Lindau WPA and Moger (North) WPA, modeling was performed to estimate infiltration into the wetland sediments from the surface water storage. A water balance approach was used to estimate infiltration by the following equation:

$$I = P + R - ET - \Delta S \tag{11}$$

where I is infiltration (m^3), P is precipitation (m^3), R is runoff (m^3), and ΔS is the change in surface water volume (m^3). Since runoff was not quantified, times when precipitation occurred were excluded from being used in the infiltration estimation. The equation used for time periods when precipitation is not occurring is:

$$I = -ET - \Delta S. \tag{12}$$

The boundaries of this model are the air-water interface and the water-sediment interface. All inputs and outputs of water to or from the surface storage volume are occurring across these two boundaries.

To insert data into the equation, input values had to be temporally modified. ΔS data were calculated from differences between volume measurements that were obtained every three hours by the stilling well pressure transducer readings and stage-storage curve equations. Half-hour ET data was summed in three hour blocks to coincide with the change in surface water volume periods. If a single ET data point was missing (due to excluding criteria mentioned in the Evapotranspiration section), then a 3 hour summation was not calculated and infiltration was not calculated for this period. An exception to this rule was if one data point was missing in the early morning or late evening where the ET was assumed to be small and would not significantly affect the 3 hour total. This was applied if the adjacent data point value of ET was less than 10^{-5} m. Once an ET value for the three hour period was obtained, it was multiplied with the surface area value (determined by the stilling well water levels and stage-storage curve equations) at the beginning of the modeled period. It was assumed that the surface water removed by ET during the modeled period would occur across the initial surface area of the water. The surface area at the end of the model period would be the result of ET and infiltration removing water from the site. Periods that were modeled to estimate infiltration volume were dependent on if ET estimates were available. Also, to account for possible runoff occurring over more than one period, periods with precipitation that occurred during or in the previous period would have values excluded and infiltration would not be estimated. ET volumes and surface water volumes were plugged into equation 12 to obtain an infiltration volume. This infiltration volume was converted to a depth of surface water loss by dividing the infiltration volume over the surface area that the water body extended over at the beginning of the model period. Obtaining this depth of surface water loss requires the assumption that infiltration is evenly distributed over the ponded surface area. Infiltration rates from the available infiltration data points were also calculated.

4.0 RESULTS

4.1.0 Climate Data

The following section provides climate information for the Rainwater Basin wetlands during specific periods of the years 2008 and 2009. The compilation of this information will aid in the interpretation of how wetland hydroperiods are influenced by atmospheric inputs and outputs of water in the south-central Nebraska climate.

4.1.1 Precipitation

During the investigative period, a dichotomy of climates occurred with one year having more precipitation than normal and the other having less precipitation than normal. 2008 was considered a wet year relative to the 1971-2000 precipitation normals. During the period from 3/1/08 to 11/30/08, total precipitation was in the low 800 mm for all three wetland sites. However, during the same period in 2009, the precipitation total was about half of the 2008 total. Totals for each wetland are displayed in Figure 14. 2008 precipitation totals resemble average values that are typical for the humid eastern portion of the basin. 2009 precipitation totals represent values that are lower than the average values expected in the semi-arid western portion of the basin. The values used for the precipitation totals were provided by the High Plains Regional Climate Center and using inverse-distance weighting for all three sites. However, actual precipitation measurements were substituted for the HPRCC data on Lindau WPA and Moger (North) WPA when precipitation gages were installed and activated on 5/14/09 and 5/13/09, respectively.

The precipitation totals were obtained during the growing season in south-central Nebraska. However, snow can have significant input of water to these wetlands. This was evident from personal observations during the months of December through

February. At this time though, there has been no quantification of total snow water input to these sites.

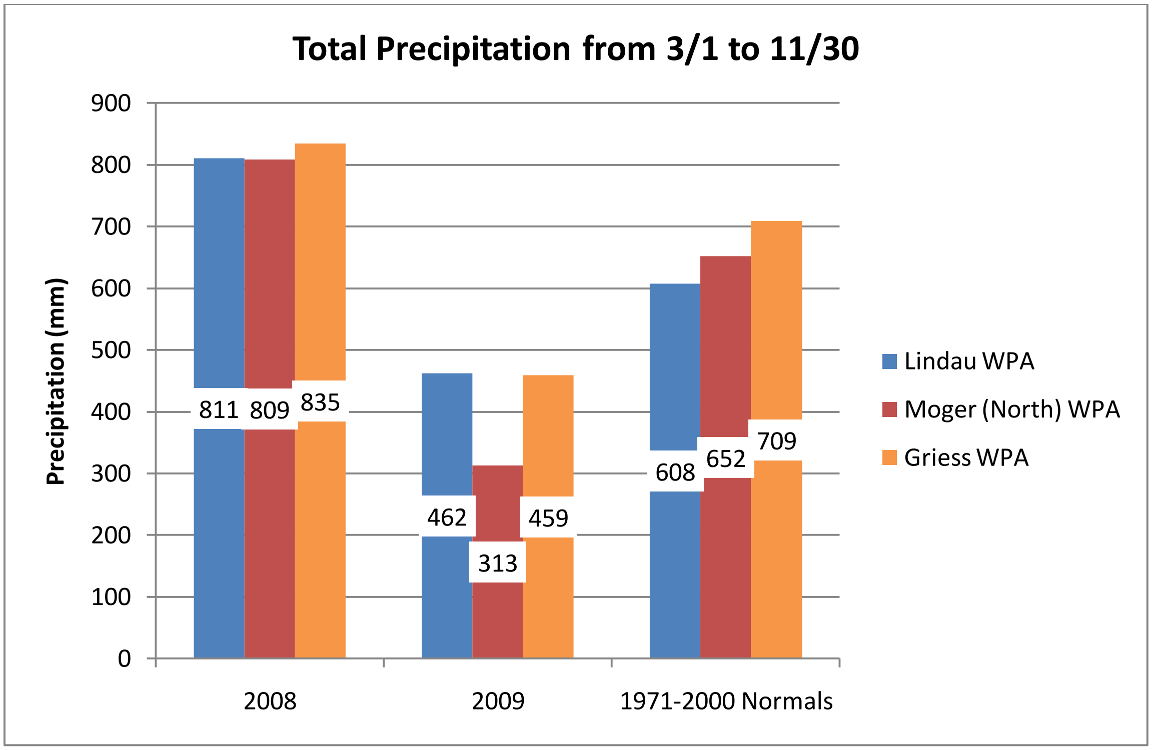


Figure 14: Estimated total precipitation falling on wetland from March 1st to November 30th during each year and 1971-2000 normals.

4.1.1.1 Lindau WPA

For 2008 and 2009, precipitation events at Lindau WPA during the measurement period resembled typical distributions for wet and dry periods during a year except for October when compared to the 1971-2000 normals. Precipitation events at the site occurred frequently in the spring and fall months. The events during the spring and fall months added significant depths of water to the wetlands during these periods. In the summer months, events were sporadic and typically had reduced input relative to the spring and fall periods. The events and magnitudes for Lindau WPA can be seen on the hyetographs in Figure 15 and Figure 16 for 2008 and 2009, respectively. Monthly total precipitation can be viewed in Figure 17. When comparing between years, there were more days with precipitation events in 2008 than in 2009. 2008 also saw more events with significant precipitation. This information is provided in Table 1.

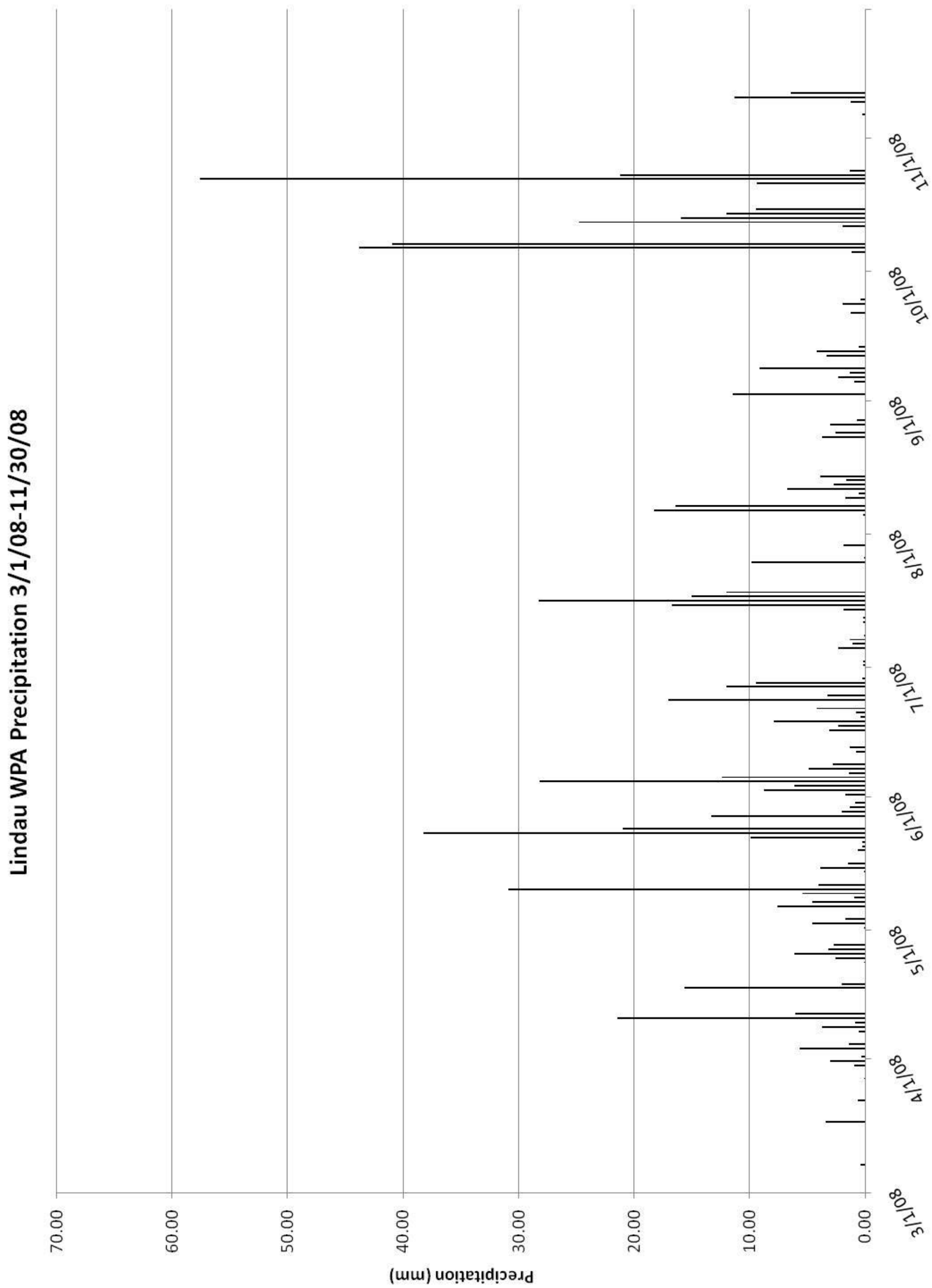


Figure 15: Lindau WPA hyetograph for period of March 1st to November 30th of 2008.

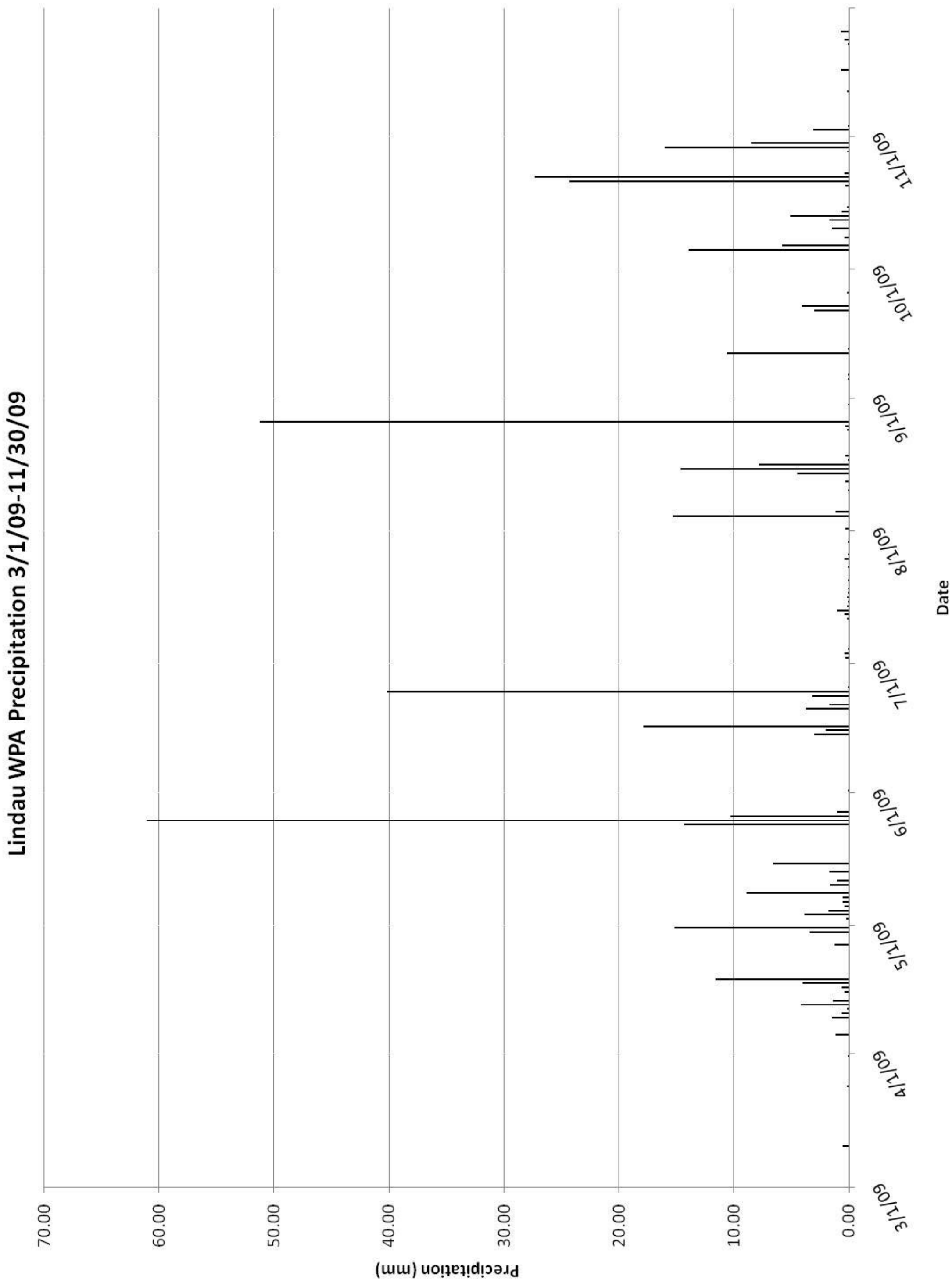


Figure 16: Lindau WPA hyetograph for period of March 1st to November 30th of 2009.

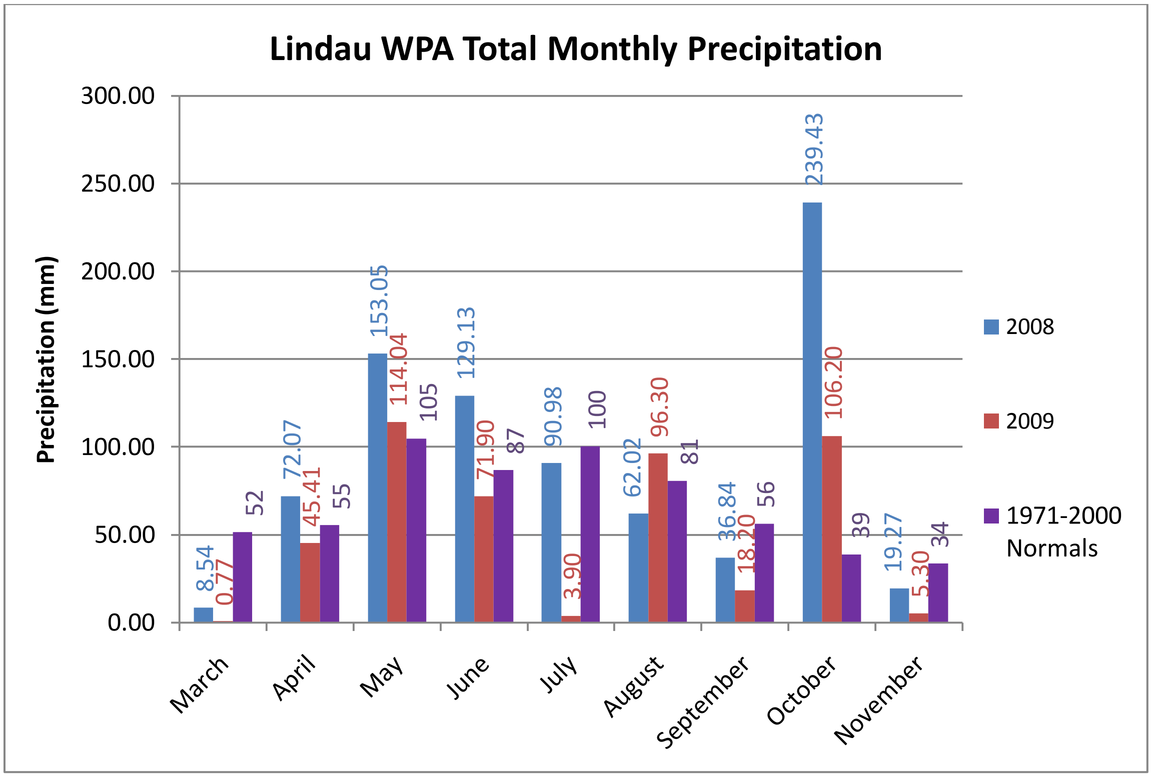


Figure 17: 2008 and 2009 Lindau WPA total monthly precipitation from March to November.
(1971-2000 Normals obtained from Minden (NWS) weather station.)

	Lindau WPA	
	2008	**2009**
Total Days in Period	275	275
Total Days with Precipitation	120	99
Total Days with Precipitation >10 mm	25	15
Total Days with Precipitation (%)	44	36
Total Days with Precipitation >10 mm (%)	9	5

Table 1: Lindau WPA total days with precipitation and significant precipitation (>10mm) from March to November of 2008 and 2009.

4.1.1.2 Moger (North) WPA

Moger (North) WPA exhibited similar patterns of precipitation events and water inputs when compared to Lindau WPA. Significant amounts of precipitation occurred in the spring and fall months with sporadic events in the summer. The hyetographs for the Moger (North) WPA wetland site can be viewed in Figure 18 and Figure 19 for 2008 and 2009, respectively. Monthly total precipitation can be viewed in Figure 20. Similar to the Lindau WPA site was that 2008 had more days with precipitation and more days with significant precipitation than in 2009. This information can be viewed in Table 2.

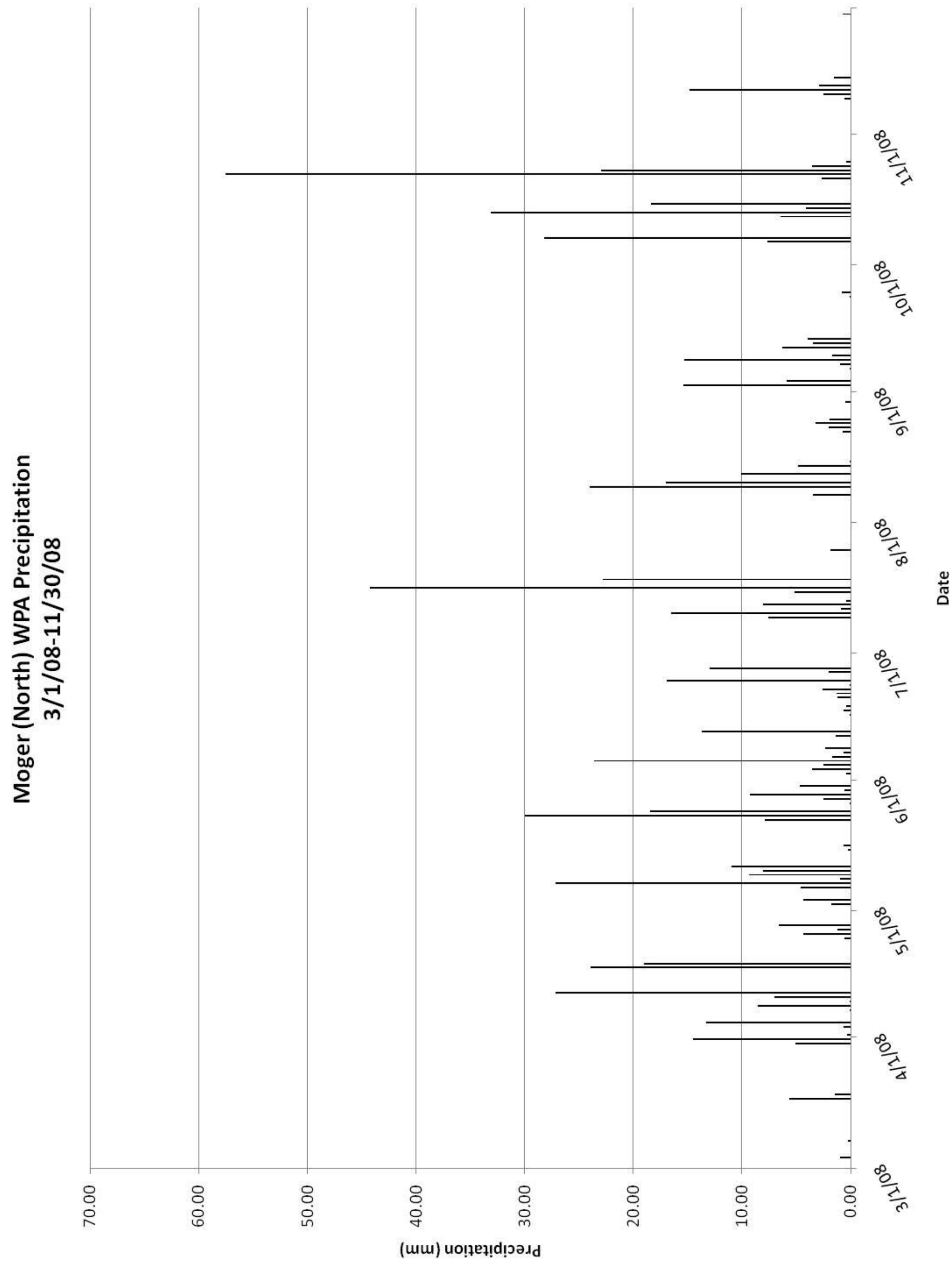


Figure 18: Moger (North) WPA hyetograph for period of March 1st to November 30th of 2008.

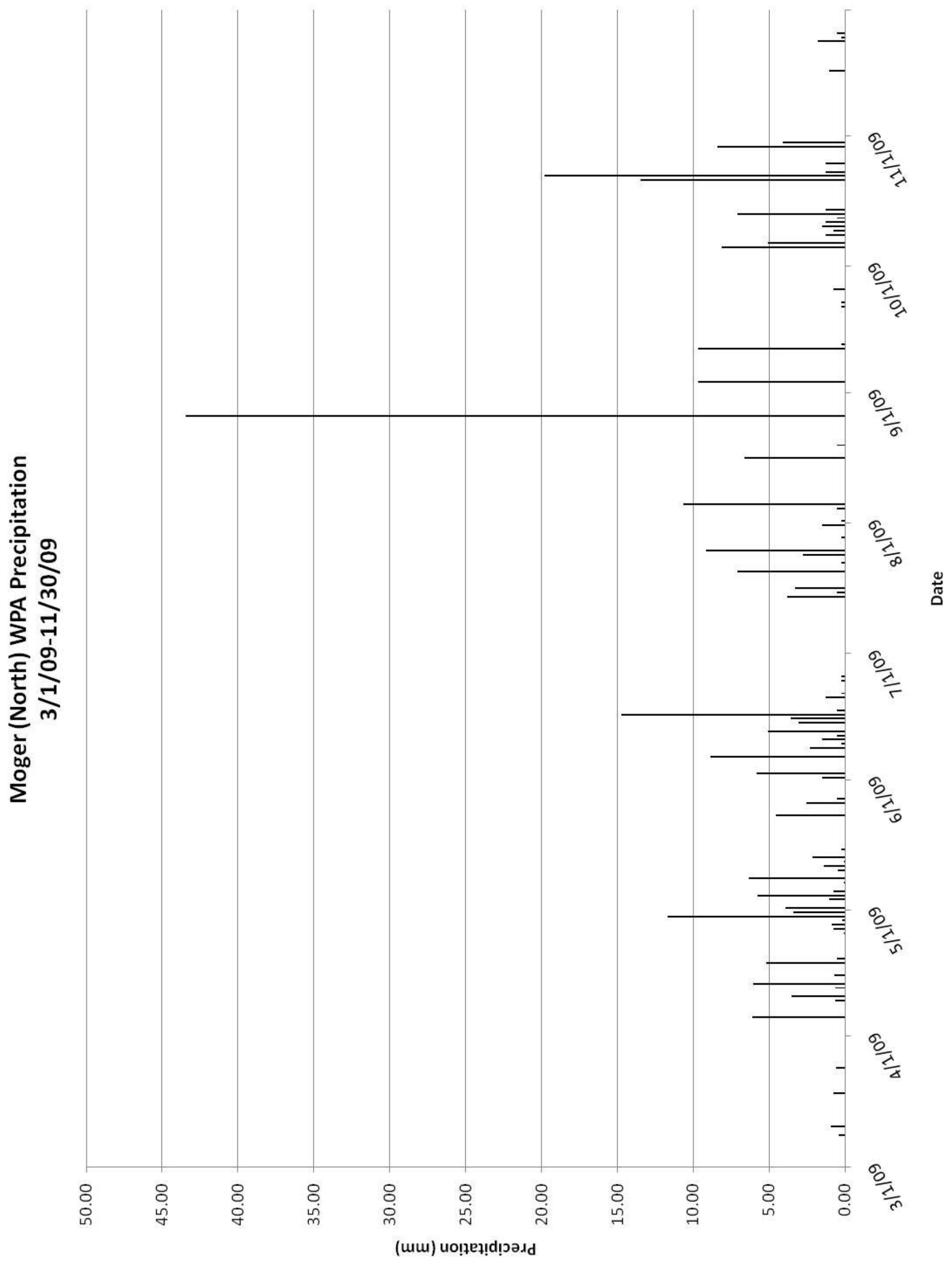


Figure 19: Moger (North) WPA hyetograph for period of March 1st to November 30th of 2009.

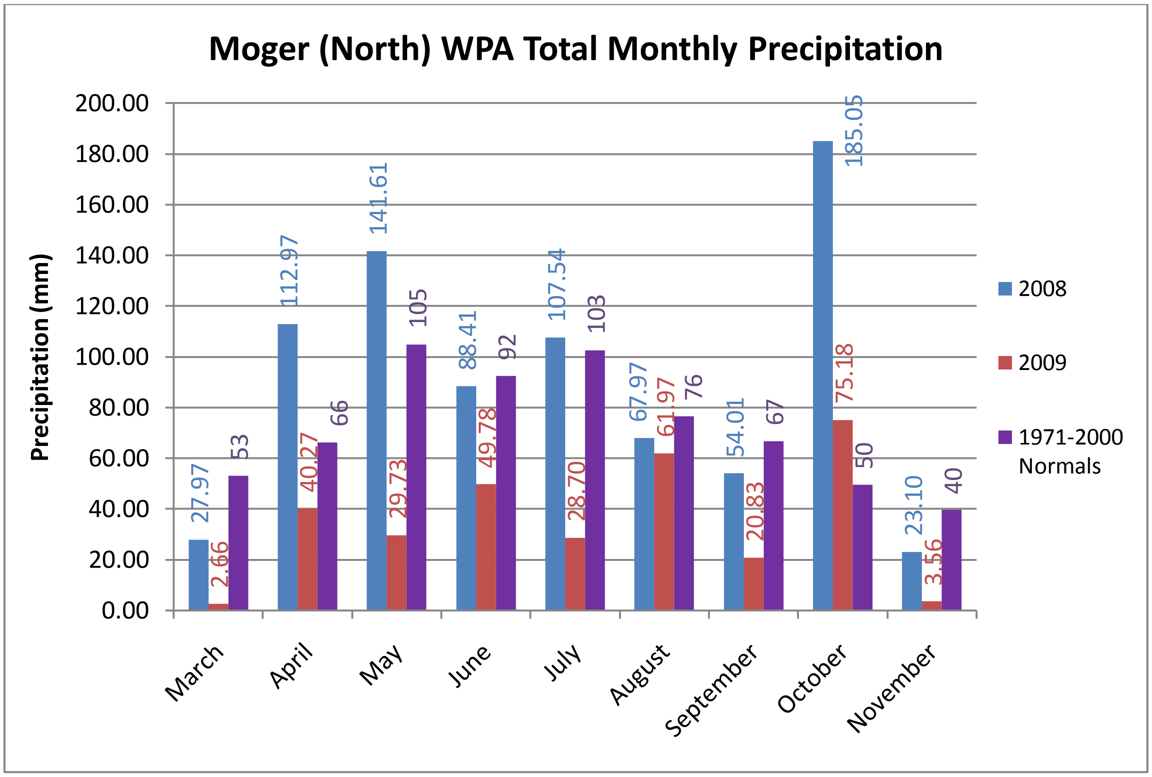


Figure 20: 2008 and 2009 Moger (North) WPA total monthly precipitation from March to November.
(1971-2000 Normals obtained from Clay Center 6 ESE (NWS) weather station.)

	Moger (North) WPA	
	2008	**2009**
Total Days in Period	275	275
Total Days with Precipitation	105	88
Total Days with Precipitation >10mm	27	6
Total Days with Precipitation (%)	38	32
Total Days with Precipitation >10mm (%)	10	2

Table 2: Moger (North) WPA total days with precipitation and significant precipitation (>10mm) from March to November of 2008 and 2009.

4.1.1.3 Griess WPA

Griess WPA exhibited similar patterns of precipitation events and water inputs when compared to Lindau WPA and Moger (North) WPA. Significant amounts of precipitation occurred in the spring and fall months with sporadic events in the summer. The hyetographs for the Griess WPA wetland site can be viewed in Figure 21 and Figure 22 for 2008 and 2009, respectively. Monthly total precipitation can be viewed in Figure 23. However, there was a change in the total days of precipitation and total days with significant precipitation. 2009 had more days with precipitation events than 2008. However, the days with significant amounts of precipitation were greater in 2008. This information can be viewed in Table 3.

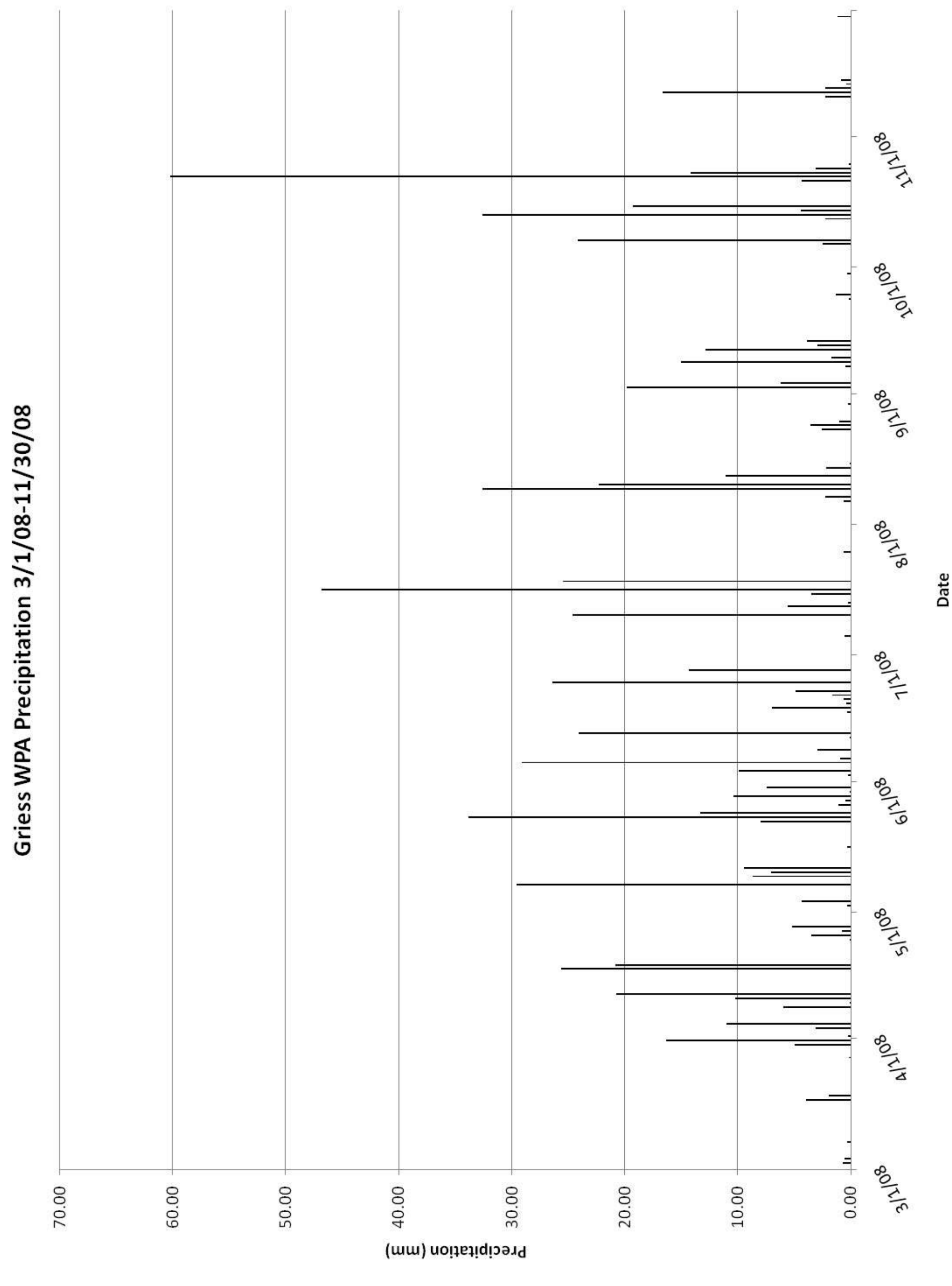


Figure 21: Griess WPA hyetograph for period of March 1st to November 30th of 2008.

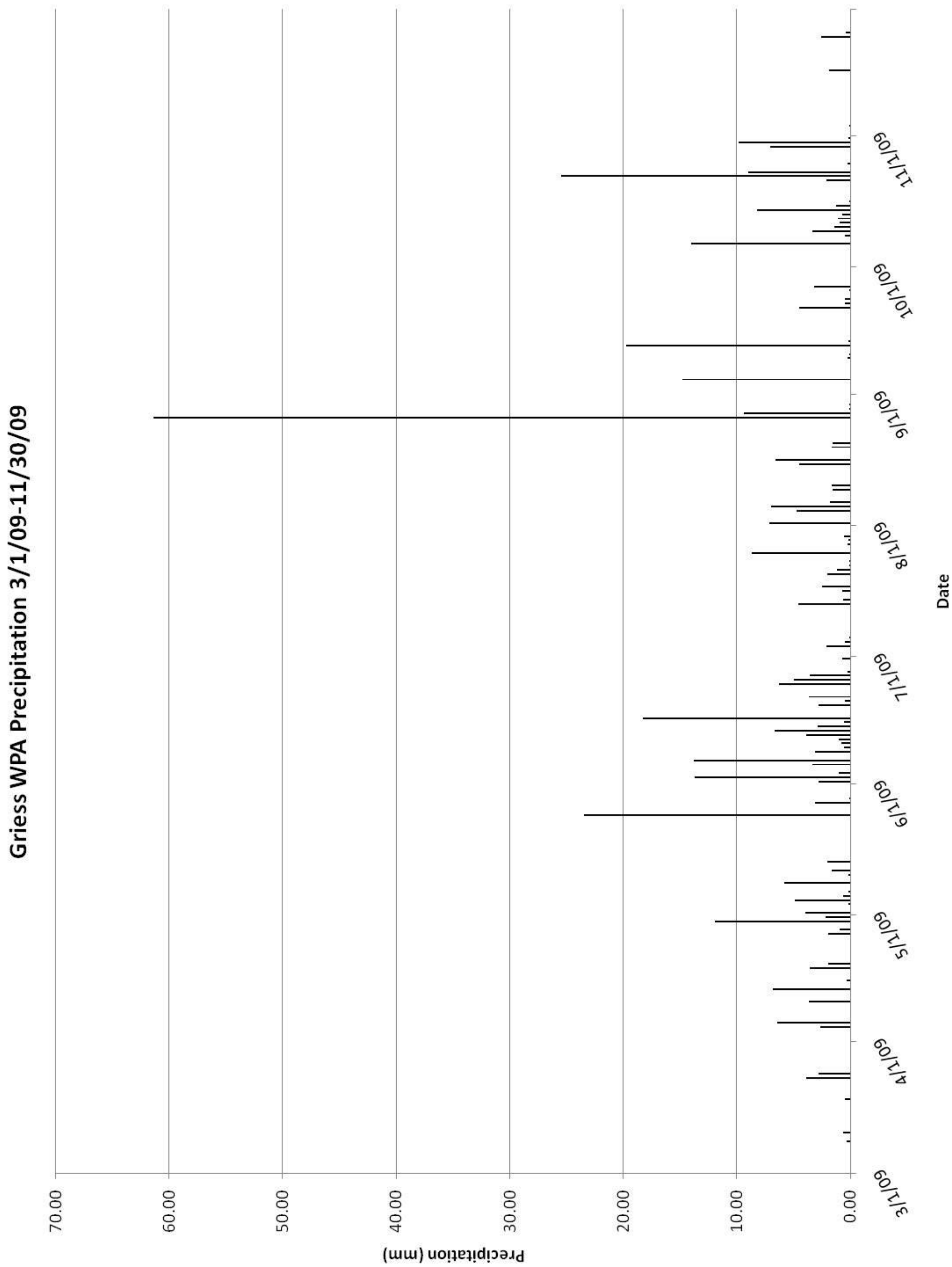


Figure 22: Griess WPA hyetograph for period of March 1st to November 30th of 2009.

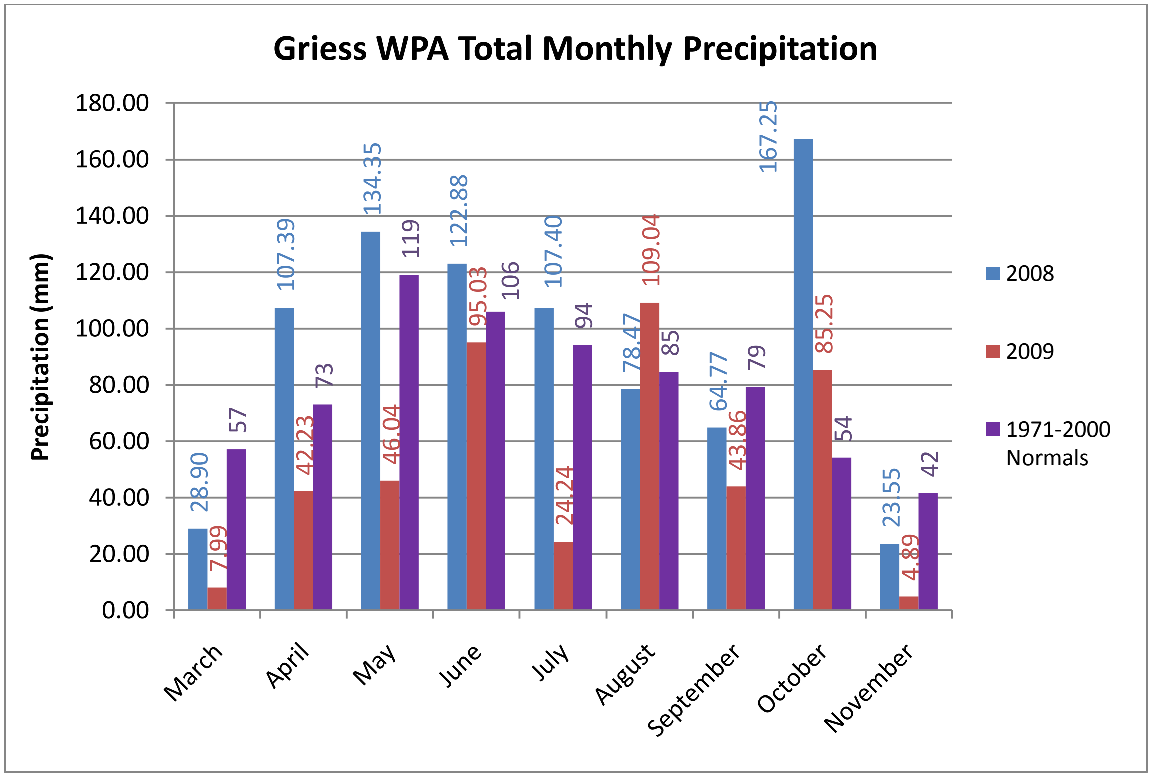


Figure 23: 2008 and 2009 Griess WPA total monthly precipitation from March to November.
(1971-2000 Normals obtained from Geneva (NWS) weather station.)

	Griess WPA	
	2008	**2009**
Total Days in Period	275	275
Total Days with Precipitation	98	110
Total Days with Precipitation >10mm	29	10
Total Days with Precipitation (%)	36	40
Total Days with Precipitation >10mm (%)	11	4

Table 3: Griess WPA total days with precipitation and significant precipitation (>10mm) during the study periods of 2008 and 2009.

4.1.2 Wind Data

4.1.2.1 Lindau WPA

Wind data was collected on Lindau WPA beginning on 5/14/09 when the weather station was erected. During 2009, daily averages of wind velocity were obtained during the period from 5/15 to 10/25. This time period was used in order to coincide with data obtained by stilling well observations. Daily mean wind velocity is presented in Figure 24. In May and early June, wind velocities were high, but showed a decreasing trend. These high velocities are a result of intense, spring thunderstorms. The high wind velocity mean on 5/20/09 can be attributed to a storm event that produced tornadic activity near the wetland. From mid-June till the beginning of October, wind velocities were relatively low. These low wind velocities are typical in south-central Nebraska (Global Energy Concepts, Inc., 1999). In October, an upward trend in wind velocities appears to occur.

Wind direction data was used to determine if there was proper fetch for estimating evapotranspiration. Partitioning of dominant wind direction during the period from 5/15 to 10/25 can be viewed in Table 4. Sufficient fetch at Lindau WPA was obtained if winds were flowing from the north, northeast, northwest, southwest, and west. This occurred 64.9% of the time during the monitoring period.

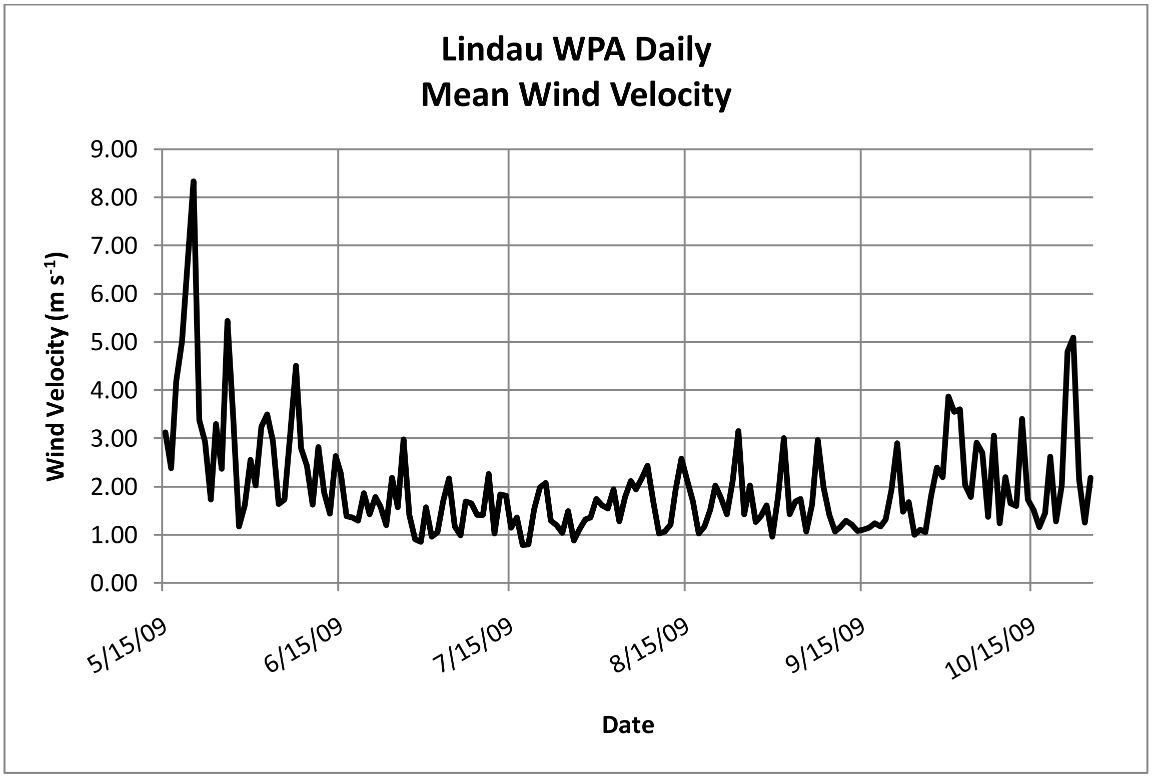


Figure 24: Lindau WPA daily mean wind velocity from 5/15/09 to 10/25/09.

Wind Direction	%		%
N	18.5	Sufficient Fetch	64.9
NE	16.0	Insufficient Fetch	35.1
E	10.9		
SE	13.1		
S	11.2		
SW	13.5		
W	6.5		
NW	10.3		

Table 4: Percentage of monitoring period, 5/14/09 to 10/26/09, of dominant wind direction and fetch consideration for Lindau WPA.

4.1.2.2 Moger (North) WPA

Wind data was collected on Moger (North) WPA beginning on 5/13/09 when the weather station was erected. During 2009, daily averages of wind velocity were obtained during the period from 5/14 to 10/24. This time period was used in order to coincide with data obtained by stilling well observations. Daily mean wind velocity is presented in Figure 25. In May and early June, wind velocities were high, but showing a decreasing trend. Similar to Lindau WPA, these high velocities are a result of intense, spring thunderstorms. From mid-June till the beginning of October, wind velocities were relatively low with a small rise in late August. In October, it appears that an upward trend was beginning.

Partitioning of dominant wind direction during the period from 5/14 to 10/24 can be viewed in Table 5. Sufficient fetch at Moger (North) WPA was obtained if wind were flowing from the north, northwest, south, southwest, and west. This occurred 62.7% of the time during the monitoring period.

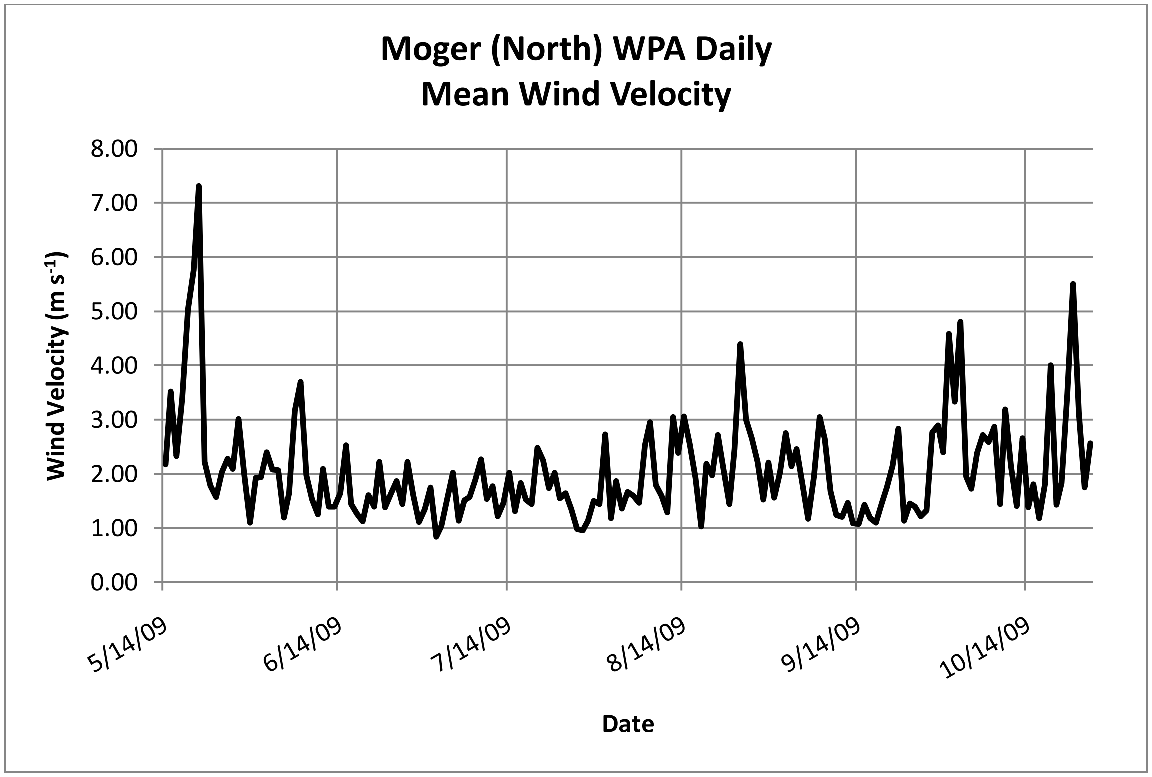


Figure 25: Moger (North) WPA daily mean wind velocity from 5/14/09 to 10/25/09.

Wind Direction	%		%
N	25.0	Sufficient Fetch	62.7
NE	17.2	Insufficient Fetch	37.3
E	13.6		
SE	6.6		
S	2.7		
SW	5.9		
W	14.0		
NW	15.1		

Table 5: Percentage of monitoring period, 5/13/09 to 10/25/09, of dominant wind direction and fetch consideration for Moger (North) WPA.

4.1.3 Evapotranspiration Data

4.1.3.1 Lindau WPA

ET estimates were calculated every half-hour from 5/14/09 15:00 to 10/25/09 23:30 for Lindau WPA. ET values are graphed in Figure 26. Gaps in the data are related to the exclusion criteria. Most excluded values occurred at night. 35.1% of the data could be excluded due to insufficient fetch. Based on the values that were not excluded, ET is relatively high in May and June. As the year progresses into October, ET shows a decreasing trend. The decrease is the result of a decrease of net radiation as the year progresses. Net radiation values for the study period can be viewed in Figure 27. The correlation between net radiation and ET has an r^2 of 0.81. This correlation is graphed in Figure 28. Solar radiation is a large component of the net radiation value. June will see the highest input of solar radiation due to small solar zenith angles. As the year progresses to October, the zenith angle increases due to the sun moving closer to the southern horizon. A larger zenith angle means a decrease in solar radiation flux which attributes to the decrease in net radiation at the wetland site.

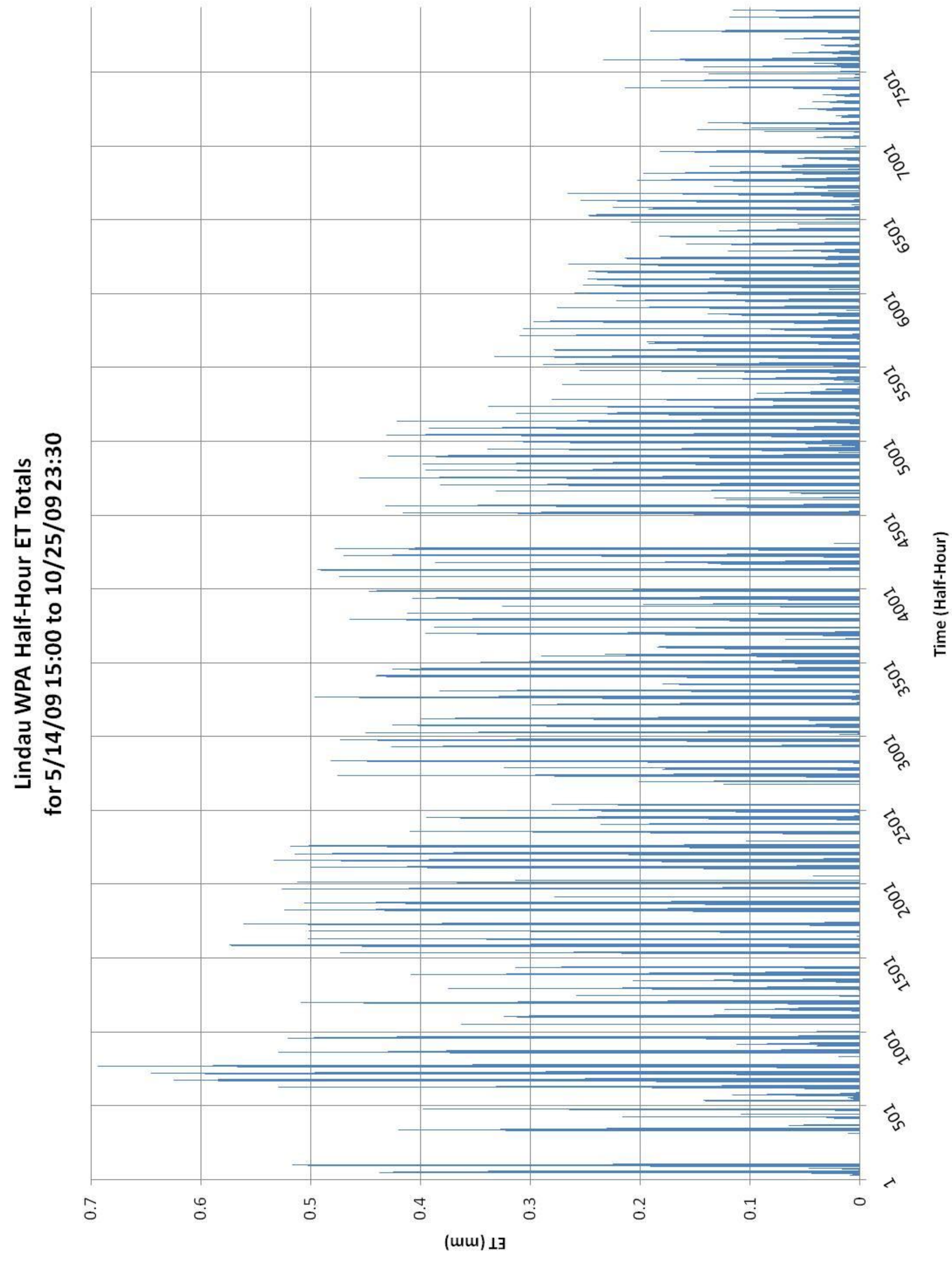


Figure 26: Lindau WPA half-hour ET totals from 5/14/09 15:00 to 10/25/09 23:30.

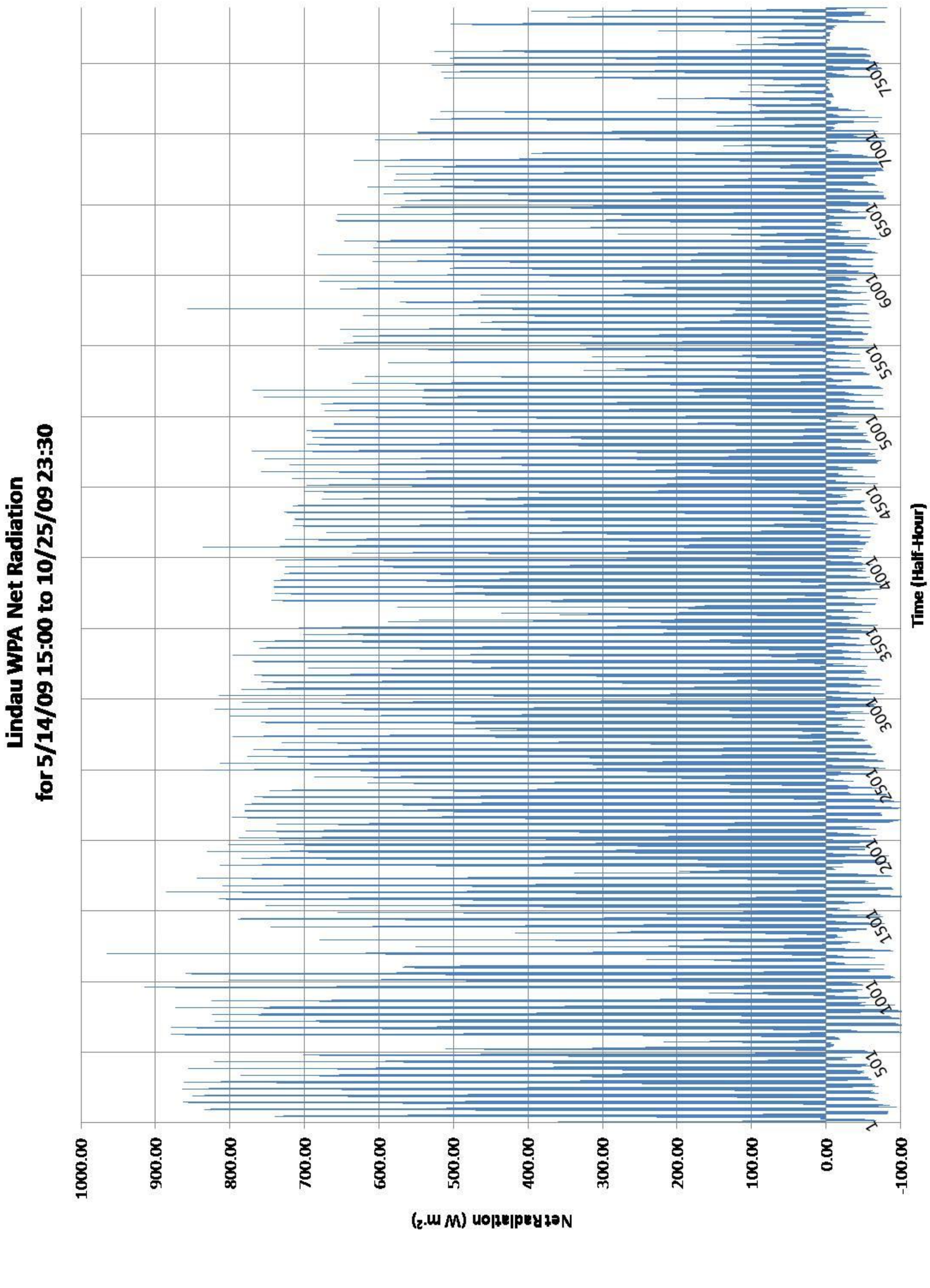


Figure 27: Lindau WPA net radiation from 5/14/09 15:00 to 10/25/09 23:30.

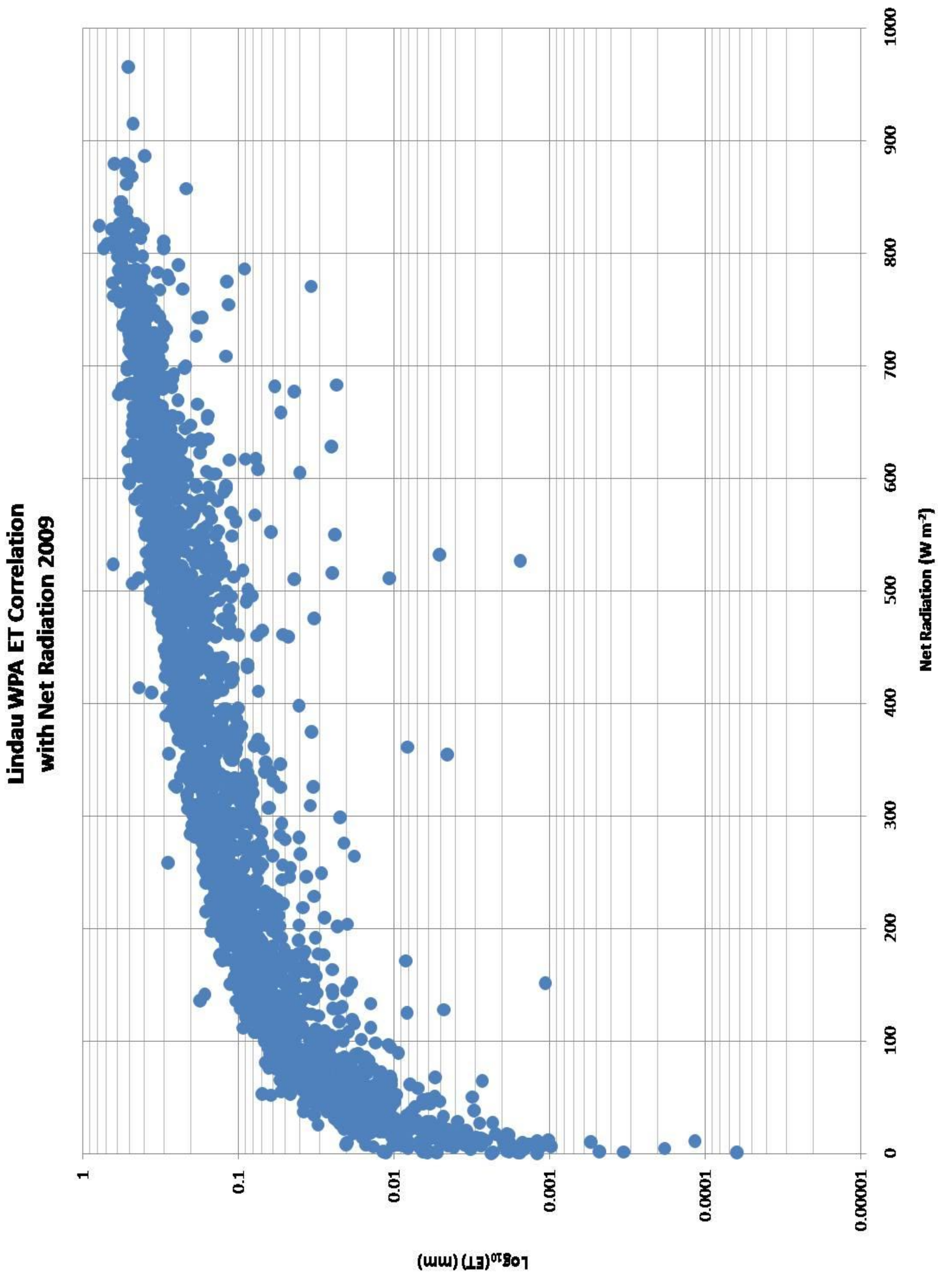


Figure 28: Lindau WPA ET correlation with net radiation.

4.1.3.2 Moger (North) WPA

ET estimates were calculated every half-hour from 5/13/09 19:30 to 10/24/09 23:30 for Moger (North) WPA. ET values are graphed in Figure 29. Gaps in the data are related the exclusion criteria. Similar to Lindau WPA, most excluded values occurred at night. 37.3% of the data could be excluded due to insufficient fetch. Based on the values that were not excluded, ET is relatively high in early portions of the monitoring period. As the year progresses into October, ET decreases. The decrease is the result of a decrease of net radiation as the year progresses. Net radiation values for the study period can be viewed in Figure 30. The correlation between net radiation and ET had an r^2 of 0.71. The correlation is graphed in Figure 31. The lower correlation between ET and net radiation when compared to Lindau WPA values may be due to either sensible heat advection or temperature inversions occurring more frequently over Moger (North) WPA. Moger (North) WPA appeared to have more times when sensible heat fluxes were directed towards the wetland surface than what occurred at Lindau WPA. This added heat energy caused an increase of ET on specific dates above the available net radiation. It was not determined in this study if this was the result of sensible heat advection or if temperature inversions were increasing ET. However, there were concerns that some of the sensible heat fluxes directed towards the wetland were extremely large. Though ET could possibly be twice as much than what can be provided by net radiation alone (Brakke, Verma, & Rosenberg, 1978), it was decided to exclude these data points with large sensible heat values. An arbitrary value of sensible heat directed towards to the wetland surface was set at 200 W m^{-2} until further investigation could occur to determine the cause of the large values. Thus, any ET value with a sensible heat flux value with greater magnitude than 200 W m^{-2} was excluded. This exclusion criterion has already been incorporated into the data that is presented in Figure 29.

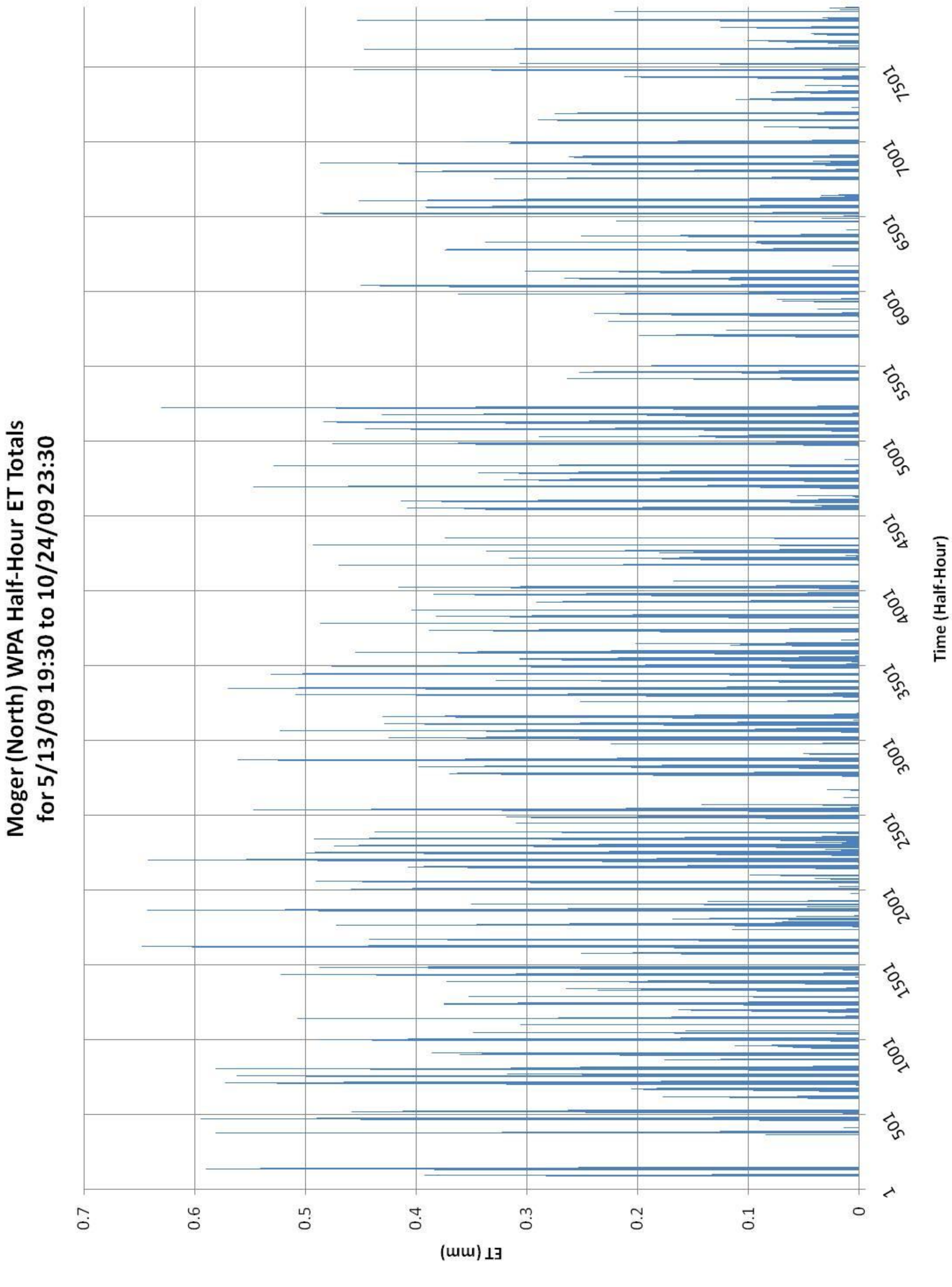


Figure 29: Moger (North) WPA half-hour ET totals from 5/13/09 19:30 to 10/24/09 23:30.

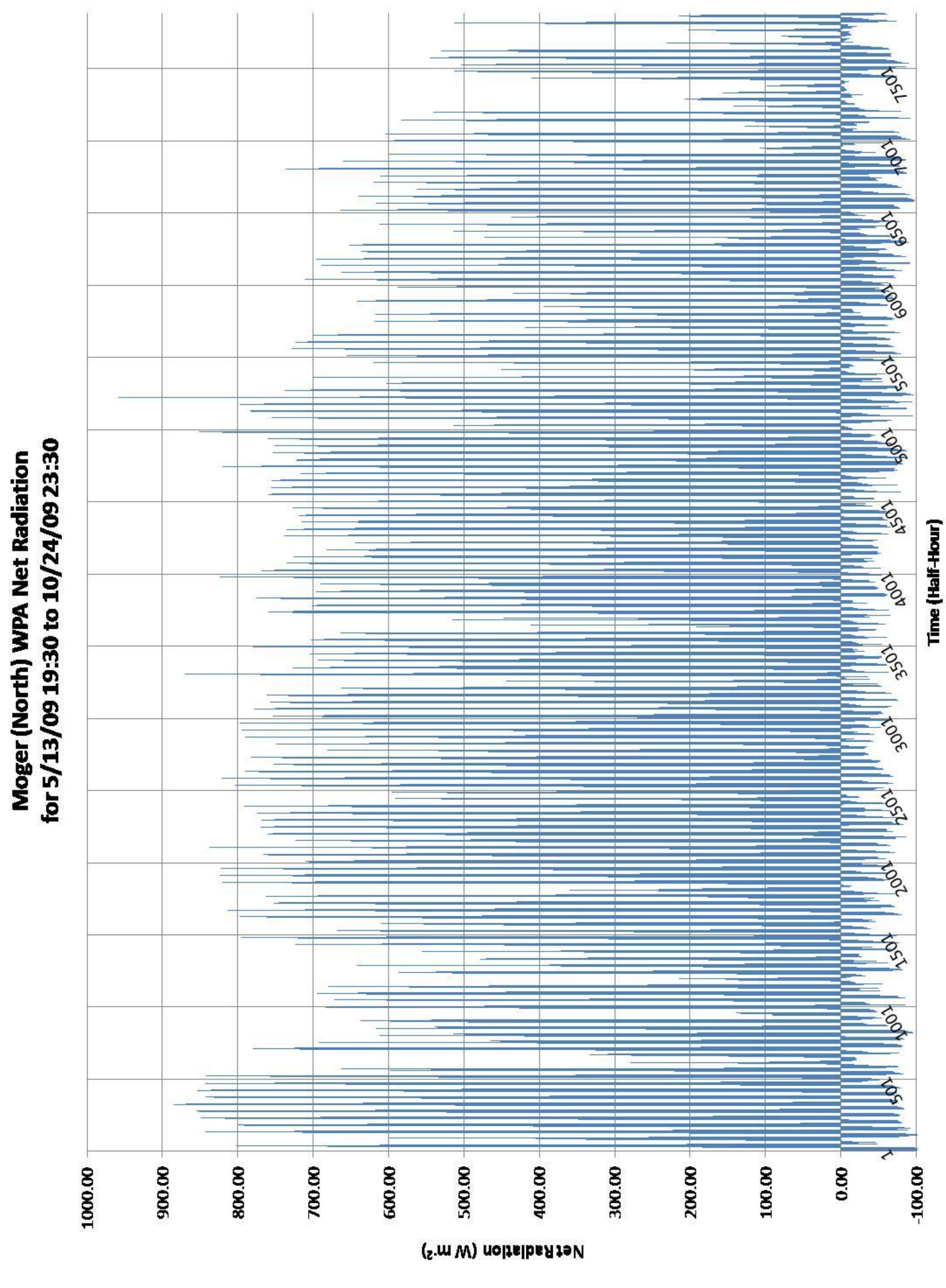


Figure 30: Moger (North) WPA net radiation from 5/13/09 19:30 to 10/24/09 23:30.

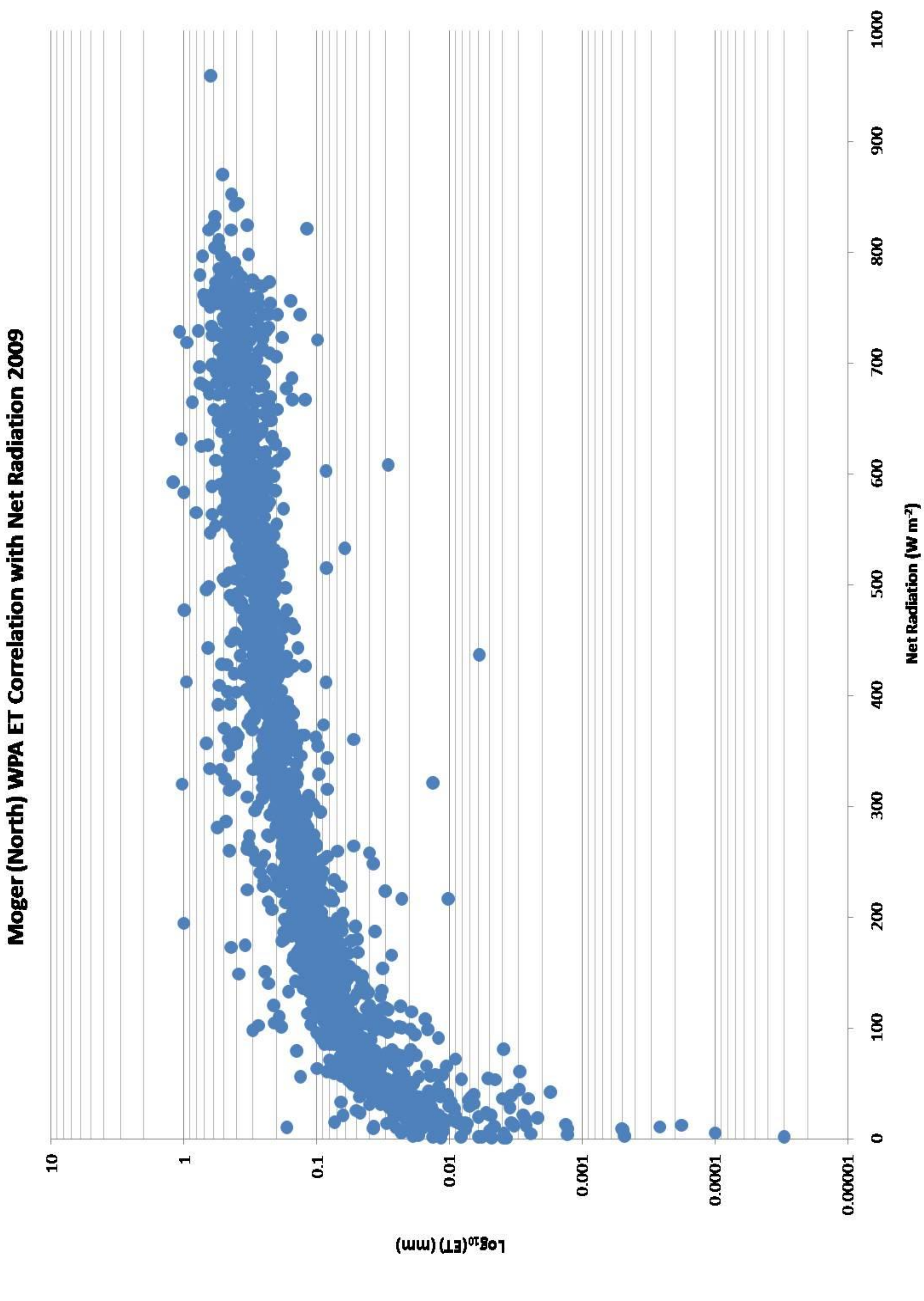


Figure 31: Moger (North) WPA ET correlation with net radiation.

4.2.0 Drive-point & Stilling Well Water Level Data

The following section provides drive-point and stilling well information for the Rainwater Basin wetlands during specific periods of the years 2008 and 2009. The compilation of this information will aid in the interpretation of how wetland hydroperiods and sediments are influencing subsurface water movement.

4.2.1 Lindau WPA

Drive-point wells and the stilling well were installed on the Lindau WPA in late August of 2008. Pressure transducers were installed in these wells on 9/1/08. These wells and pressure transducers were used to monitor surface water levels of the wetland and the subsurface water movement in the wetland sediments. The pressure transducers obtained measurements every 3 hours during the 2008 measurement period. Pressure transducers were removed from the wells on 10/21/08 due to concerns about ice developing on the transducer during the winter months which can cause damage to the pressure transducer membranes. A time-series of daily averaged water levels and total precipitation are provided in Figure 32. During the measurement period, the stilling well monitored a steady decline of surface water from 9/1/08 till 10/5/08. DW1, DW3, DW4, and DW5 remained dry during this same period. DW2 water level remained constant over this period. Some precipitation events occurred during this period with minimal influence on the water levels of both the drive-point and stilling wells. Based on visual observation on 9/30/08, very little surface water remained. There were saturated sediments surrounding SW and DW2. However, most of the wetland floor was dry. Desiccation cracks were present on the periphery. The site had recently been grazed by cattle. Vegetation was short on the periphery and non-existent near the remaining surface water. From 10/5/08 to 10/7/08, significant amounts of precipitation fell on the wetland.

This event caused an increase in surface water level. It also caused a rapid increase in the water levels of DW1, DW3, DW4, and DW5. This sudden increase from dry to maximum water level occurred in less than a 3 hour period. DW2 saw a minor increase in water level. From 10/7/08 to 10/21/08, DW1, DW3, DW4, and DW5 saw a decline in water levels or became dry again. Another series of precipitation events occurred from 10/11/08 to 10/15/08. These events also increased surface water level. However, this event had little to no influence on the drive-point wells' water levels. The difference in water flow to the wells during the two major precipitation events could be the result of the dynamic nature of the vertic soils. During the initial precipitation event, soils around DW1, DW3, DW4, and DW5 were dry and had extensive desiccation cracks. The cracks acted like preferential pathways that moved water from the surface to the screen of the well in the sediments. Once the sediments were saturated, the cracks were "sealed" and flow through the soil was limited by the hydraulic conductivity of the clay sediments and pressure head potential of the wetland water body. This can be seen in the steady decrease of water levels in the drive-point wells as well as no increase of water levels due to the second set of precipitation. Also, there was minimal influence of either series of precipitation events on DW2 water levels which was located in saturated, non-desiccated sediments.

Pressure transducers were placed back in the wells on 3/18/09. The sensors monitored water levels until 10/26/09 when they were again removed. The sensors took measurements every 3 hours until 8/18/09. On this date, the sensors were changed to obtain measurements every hour. It was believed that a finer time resolution of water level changes was needed to see the influence of temporally short precipitation events.

During the previous winter, DW2 lost its cap and the stilling well was bent. It was believed that the frozen water in the wetland may have caused these damages. The SW was replaced and a new cap was placed on DW2. While the cap was missing from DW2, precipitation filled the stem of the well. This essentially caused a “slug test” in the sediments. The water was not removed, but was monitored over the 2009 monitoring period. Daily averages of water levels and precipitation totals are graphed in Figure 33. Surface water levels were variable throughout 2009, but stayed relatively high when compared to 2008. Surface water levels didn’t approach zero even though less precipitation occurred in 2009 when compared to 2008. It appears that the water levels were maintained at the high levels due to the timing and magnitude of specific precipitation events. Two major precipitation events which occurred on 5/26/09 and 8/26/09 added significant amounts of water to the wetland which created high water levels. DW3 and DW4 remained dry during most of the period. DW4 showed some responses to precipitation events in August, but became dry relatively quickly. DW5 showed a decrease in water level from the beginning of the measurement period until 6/17/09. From this point until the end of the period, DW5 remained dry. DW1 data was excluded from the analysis of the wetland for 2009. Rapid oscillations in water level were occurring at every precipitation event. It appeared that organisms burrowed next to the well casing which caused a preferential flow path for water movement during precipitation events. Data was excluded from 4/22/09 to 5/14/09 for DW2 due to a malfunction of the pressure transducer. DW2 showed a steady decrease in water level throughout the monitoring period. In 2009, grazing occurred on the site. However, due to the presence of research equipment, the site was segregated and fenced to keep cattle from causing damage to the equipment. As a result, vegetation became extensive in the lower elevations of the wetland site where cattle were excluded. The water surface was not visible due to vegetative cover in some parts of the wetland.

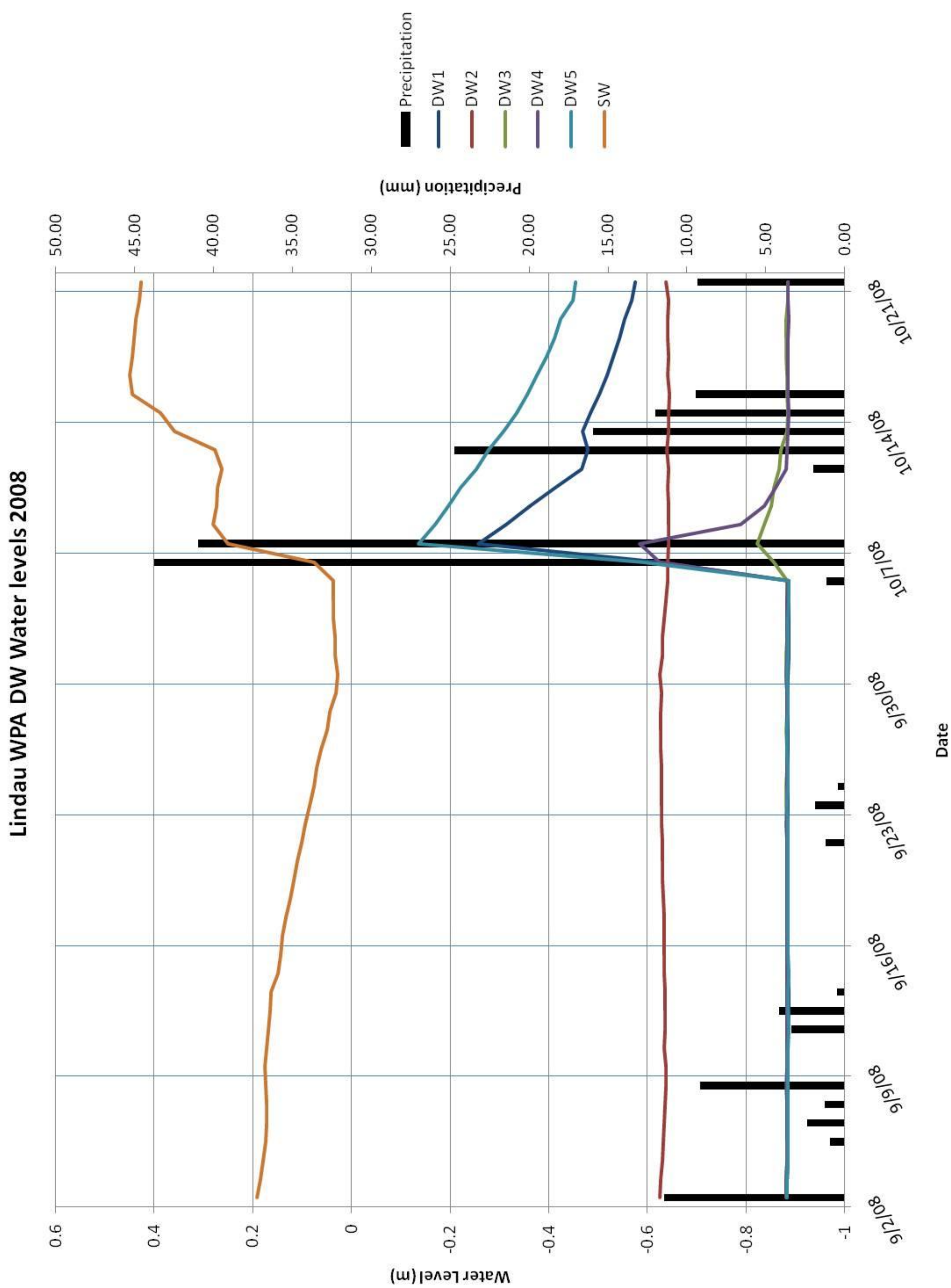


Figure 32: Lindau WPA 2008 drive-point and stilling well water levels.

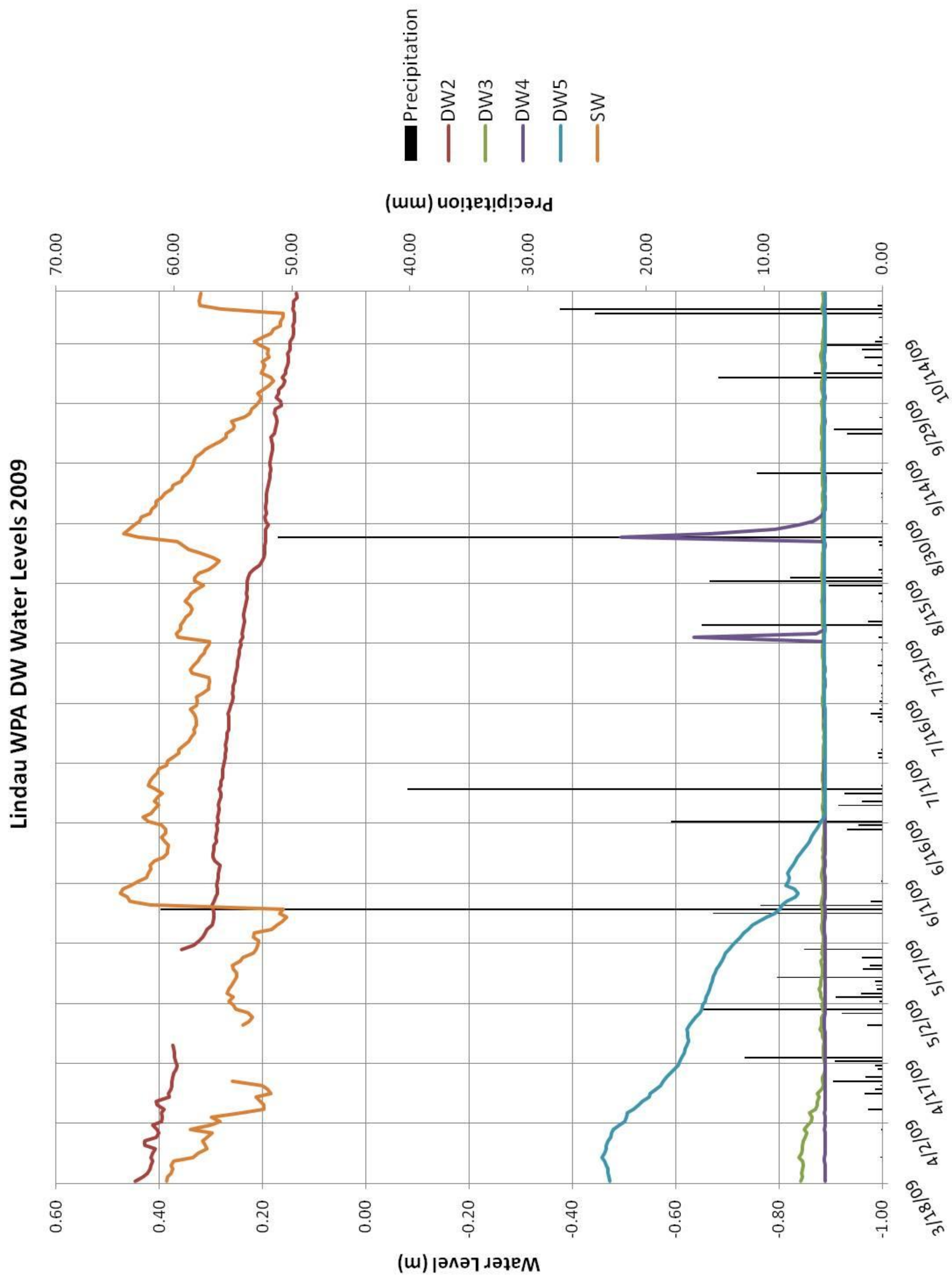


Figure 33: Lindau WPA 2009 drive-point and stilling well water levels.

4.2.2 Moger (North) WPA

Drive-point wells and the stilling well were installed in late August 2008 at Moger (North) WPA. Pressure transducers were installed on 9/11/08 and removed 10/20/08. Measurements occurred every 3 hours. Daily averages of water levels of all wells and total precipitation can be seen on Figure 34. Throughout most of September and early October, surface water level decreased steadily. Precipitation events on 10/6/08, 10/7/08, and from 10/12/08 to 10/15/08 caused increases in the surface water levels. All drive-point wells showed very minor changes over the monitoring period. However, there appeared to be a steady increase in water levels after those major precipitation events. When wells were installed, sediments were saturated or had water ponded. Thus, extensive desiccation cracks were not present, and sediments appeared "sealed" throughout most of the monitoring period around the drive-point wells.

Pressure transducers were placed back in the wells on 4/24/09. To avoid possible fire damage to the pressure transducers due to controlled burning of vegetation in the wetland by the U.S. Fish & Wildlife Service, the sensors were not put in at the site until late April. The sensors monitored water levels until 10/25/09 when they were removed for winter. DW2 and SW were moved to a new location on 4/24/09. These wells were moved to a deeper portion of the wetland. The new location is listed in Appendix A. Daily averages of water levels in all wells and total precipitation are graphed on Figure 35. Data was initially excluded from all wells during the period from 6/13/09 to 7/2/09 due to a malfunctioning Barologger. Leveloggers could not be corrected to account for atmospheric pressure influences by the Barologger on site. However, since Harms WPA is within about 1.6 kilometers (one mile) of Moger (North) WPA, its Barologger data was used to correct this excluded data. This was assuming that atmospheric pressure differences are minor over that distance. This corrected data is graphed in Figure 35. All data from DW2 was excluded due to well failure. Sedimentation of the well encapsulated the pressure transducer. The variable water level appeared to be influenced by sediment affecting the membrane of the transducer. Data was also excluded for DW5 during the periods of 8/7/09 to 8/19/09 and 10/8/09 to 10/25/09 because cattle on the site rubbed the well casing off at the couplings or broke the casing. This pulled the transducer out of the casing.

From 4/24/09 to 6/14/09, water levels decreased in the wetland. Around 6/15/09 several days of precipitation caused a spike in surface water levels. The water level rose till 6/25/09. From 6/25/09 to 8/10/09 water levels decreased. On 8/5/09, it was visually observed that a small pool of water remained on the site. The sediments around the wetted area were extremely dry and had wide and deep desiccation cracks. Measurements of desiccation cracks on 8/5/09 revealed some reached up to 6.5 cm wide and a few cracks reaching up to 90 cm deep. Surface water levels started increasing on 8/10/09 with stair step increases with minimal periods of decline. These increases can be attributed to precipitation events. Drive-point water levels were highly variable throughout the monitoring period. DW1 and DW3 had decreasing water levels early on and were dry during most of the monitoring period. However, due to the precipitation events in mid-June, a small rise in water level occurred in these wells. DW5 showed some increases that were related to precipitation events, but were minor increases. DW4 water levels decreased until 6/16/09. Water levels increased until 6/20/09. After this date, water levels decreased with rapid decline occurring from 6/23/09 to 6/28/09. The water levels in DW4 decreased until 8/10/09. On this date, a significant water level increase occurred. This was followed by successive decreases and increases of water levels until 9/12/09. On this date, ponded water was at the DW4. Effective sealing of the sediments could have occurred at this time. There was a steady decline of water out of the well until late October precipitation caused a rapid increase. This may be indicative of preferential flow pathways caused by desiccation cracks near the well. Also, the erratic nature of DW4 when compared to other wells may be due to its shallow screen depth.

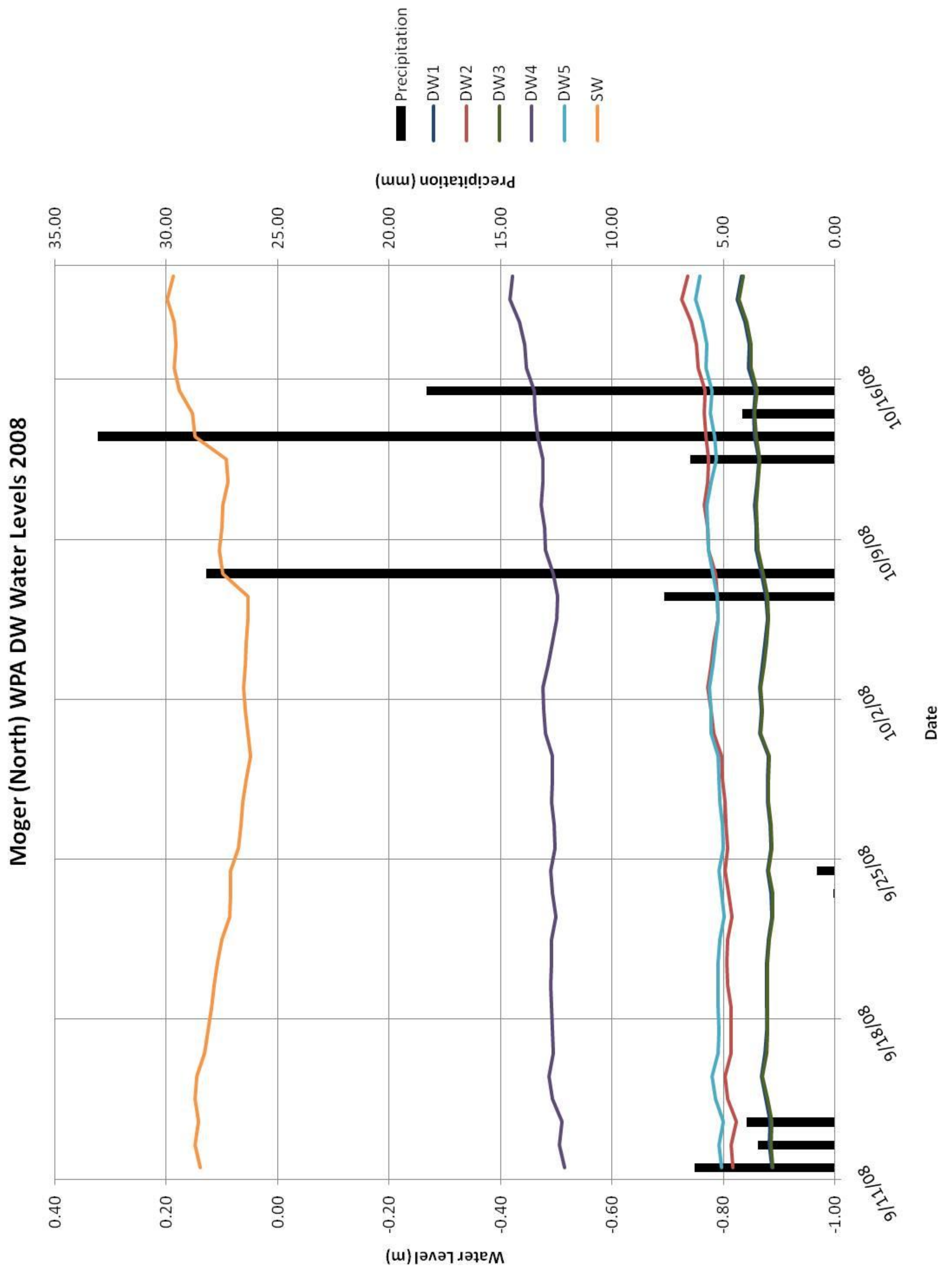


Figure 34: Moger (North) WPA 2008 drive-point and stilling well water levels.

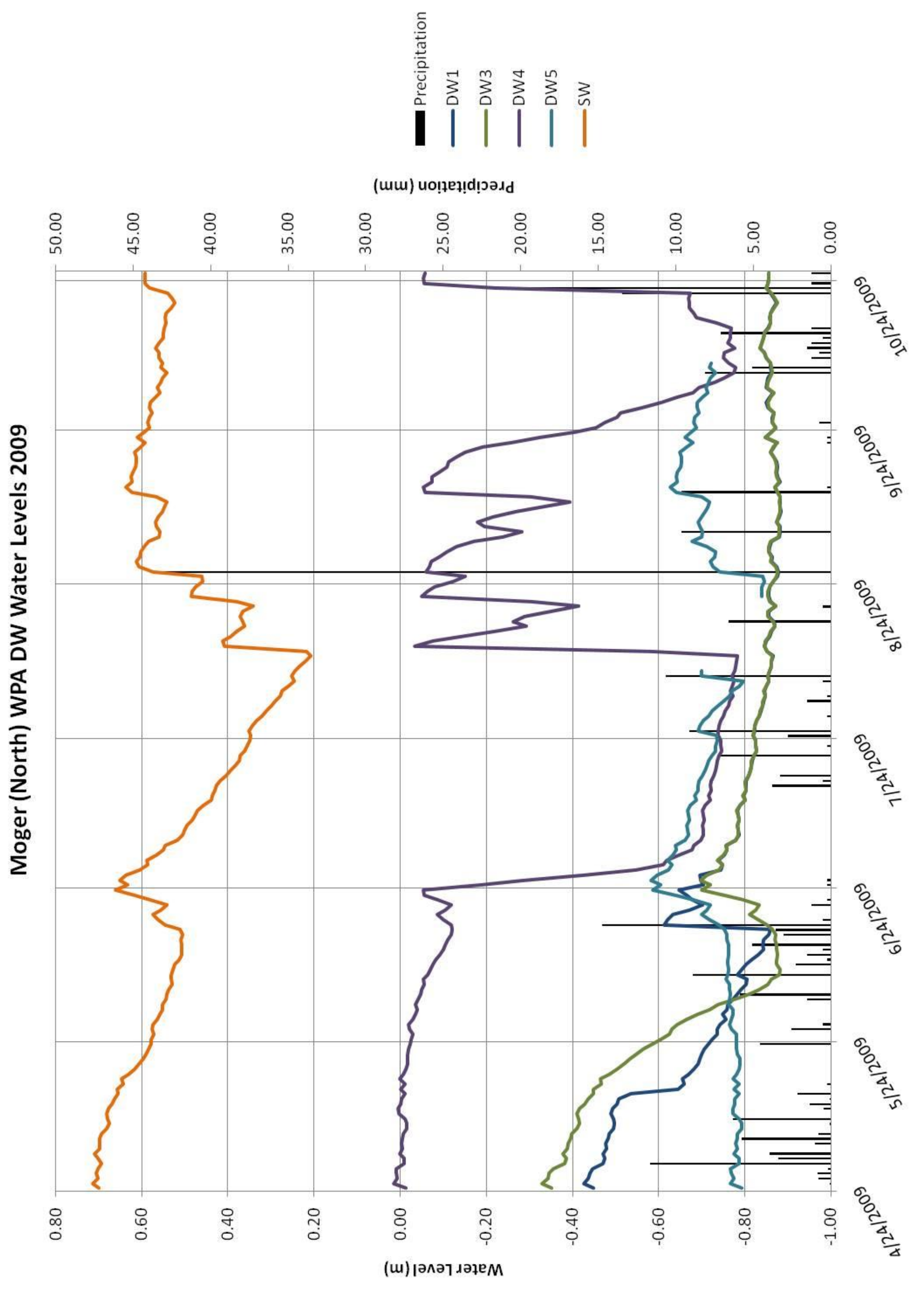


Figure 35: Moger (North) WPA 2009 drive-point and stilling well water levels.

4.2.3 Griess WPA

Drive-point wells and stilling wells were installed in late August 2008 at Griess WPA. Pressure transducers were installed on 9/11/08 and removed 10/20/08. Measurements occurred every 3 hours. Daily averages of water levels of all wells and total precipitation can be seen in Figure 36. Surface water levels decreased steadily from 9/11/08 to 10/6/08. Precipitation events on 10/6/08 and 10/7/08 and from 10/12/08 to 10/15/08 caused water levels to increase. Water levels of the drive-points showed very little change over the monitoring period. During the monitoring period, the entire wetland on the federal owned property had ponded water. All drive-point wells were in sediments that had ponded water during the entire monitoring period of 2008.

Pressure transducers were placed back in the wells on 4/24/09. The sensors monitored water levels until 10/25/09 when they were removed for winter. Daily averages of water levels and total precipitation is graphed in Figure 37. Surface water levels were low when sensors were placed back into the wells. As was apparent on visual observation, DW2 and SW were not in the deepest portion of the wetland. The deepest point in the wetland occurs near DW3. Thus, the surface water level could not be monitored at times during the 2009 monitoring period. Through visual observation, there was a steady decline in surface water over the monitoring period. Figure 38 shows the decline in surface water volume over time. By visual observation on 8/17/09, no surface water was present and only sediments near DW3 were saturated. Dry sediments had extensive desiccation cracks develop. Early in the monitoring period, the drive-point wells showed very little change. From a period that starts 7/3/09 and runs to about 8/3/09, the drive-point wells show a rapid decrease in water level. The rapid decrease occurs first in DW1 and is followed by DW4, DW5, and DW2, successively. The order at which these wells dry out can be loosely correlated to how far the well is from the deepest point of the wetland. DW1 is the farthest from the low point in the wetland followed by DW5, DW2 and DW4. The reason DW4 may have lost water earlier than DW5 and DW2 is due to its location adjacent to dense vegetation. Vegetation possibly removed water quicker than what could be redistributed due to drainage or purely soil water evaporation. DW3 remained in saturated sediments through the entire monitoring period of 2009. Water level decreases were not as drastic. On 8/26/09, a significant precipitation event occurred at the wetland. As a result, there were significant increases in not only the surface water levels but also in DW1, DW2, DW4, and DW5. It is believed that the desiccated nature of the soils allowed preferential pathways for water movement deep into the soil profile. Once the soils were saturated and sealed, decreases in water levels in these drive-point wells occurred at a somewhat steady rate. DW3 did not have a spike of water level due to the 8/26/09 precipitation event. This was probably due to the soil being saturated with no preferential pathways deep in the soil. However, after the 8/26/09 event, water levels in DW3 began to rise. The increased pressure head at the surface due to ponded water was probably causing this rise in the well at a fairly steady rate.

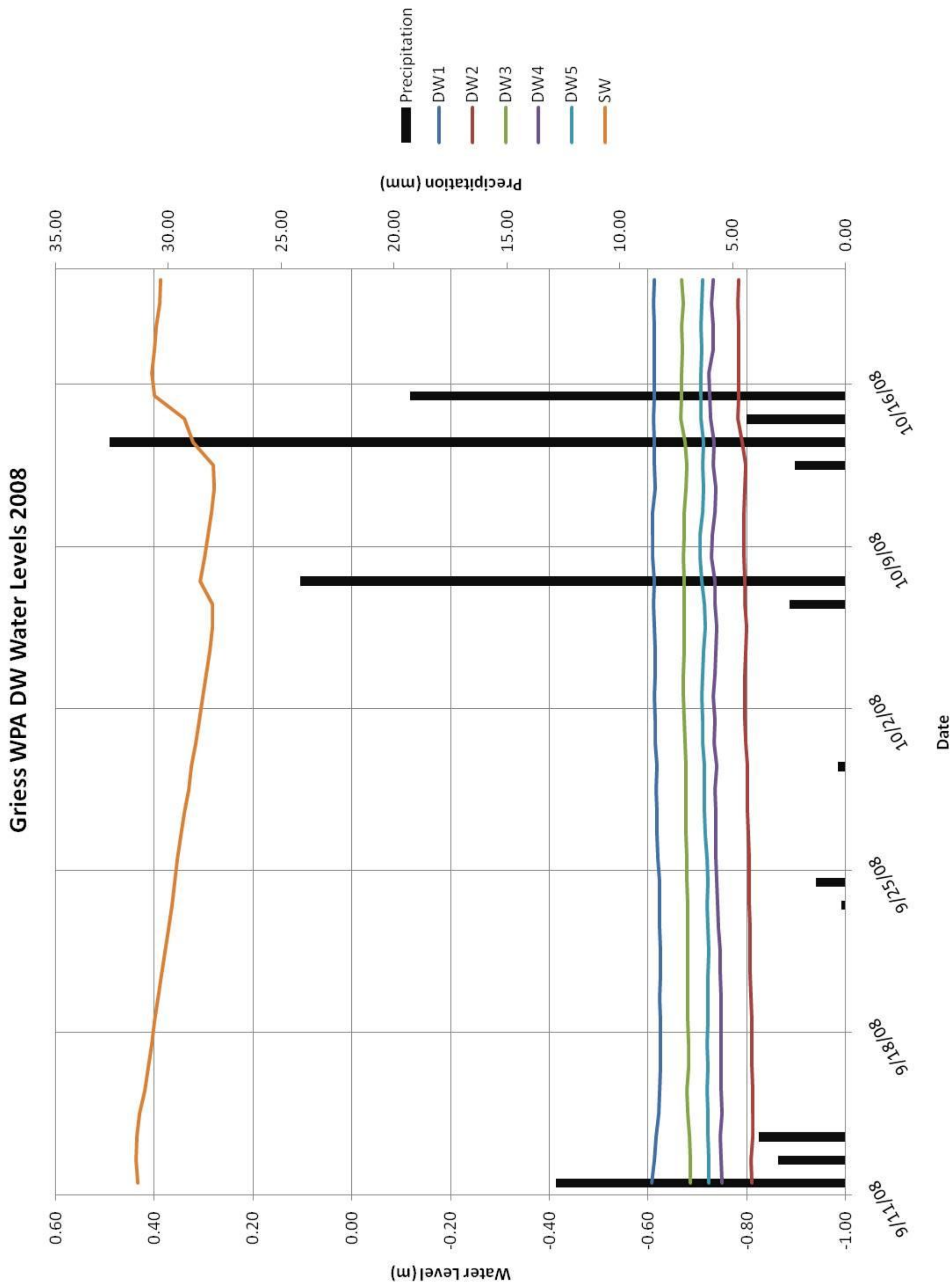


Figure 36: Griess WPA 2008 drive-point and stilling well water levels.

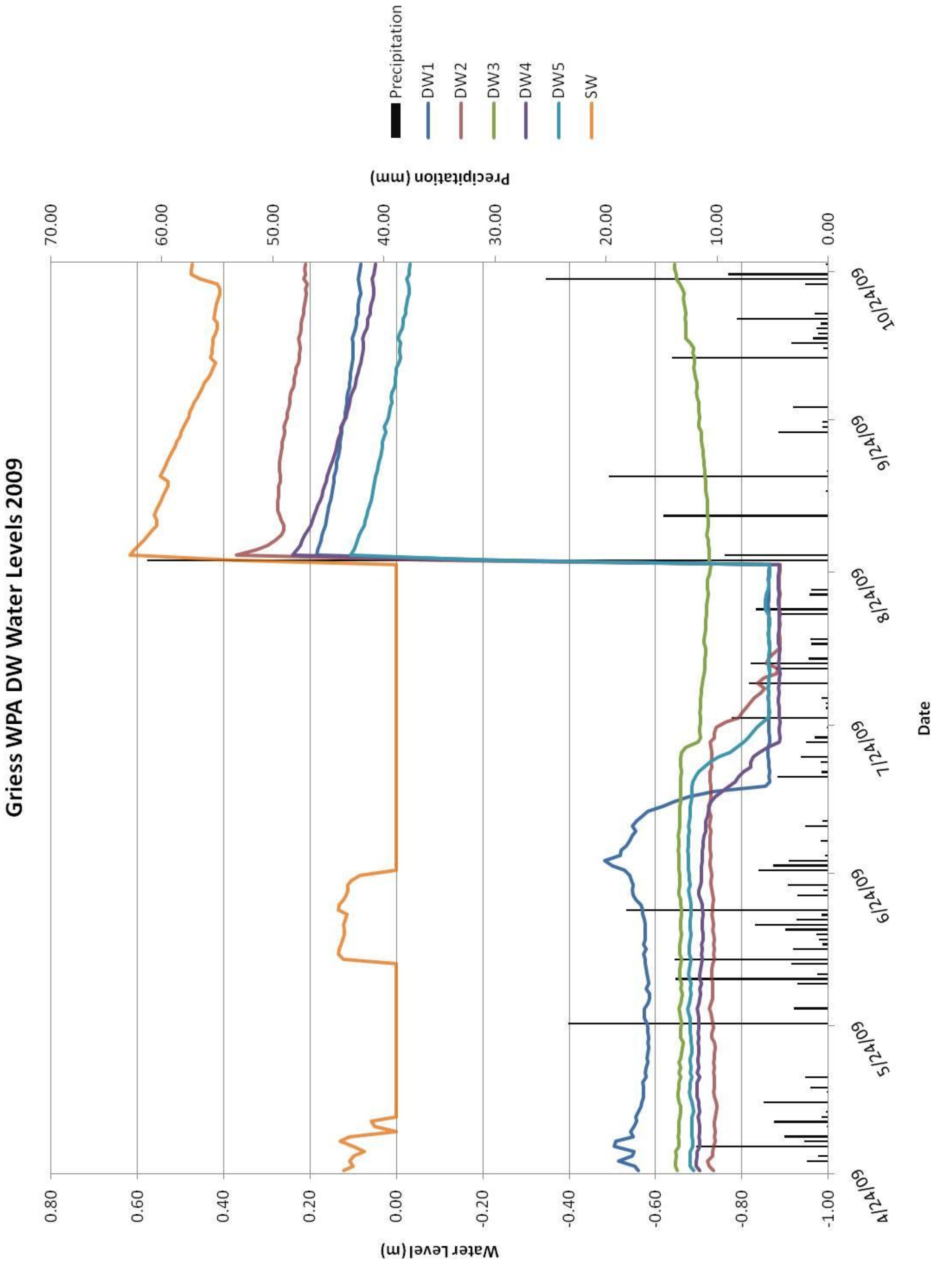


Figure 37: Griess WPA 2009 drive-point and stilling well water levels.

Figure 38: Griess WPA surface water decline during 2009.
(Orange arrow indicates same tree in each photo.)

4.3.0 Wetland Surface Area & Volume Data

The following section provides surface water storage information for the Rainwater Basin wetlands during specific periods of the years 2008 and 2009. The compilation of this information will aid in the interpretation of how wetland surface area and volumes change over a monitoring period and what influences precipitation may have on that volume.

Rainwater Basin wetlands were surveyed at the beginning of August 2009. Most sites were dry or had low levels of water ponded on the surface. The data from these surveys were used to develop the wetland stage-storage curves to determine water surface area and volume as a function of water elevation. The stage-storage curves for Lindau WPA, Moger (North) WPA, and Griess WPA are provided in Appendix B. The equations that were developed from these curves to calculate volume as well as the water level ranges where the equations can be applied are also provided in Appendix B.

4.3.1 Lindau WPA

The survey of Lindau WPA indicated that the deepest portion of the site is an oval region in the center of the wetland that is about 170 meters lengthwise from north to south. When the wetland fills with water, this depression would fill first. Once the depression was filled, ponded water would extend to the west before covering area to the east of the depression. The topography of Lindau WPA can be viewed in Figure 39. There is relatively large relief in the depression and at the edge of the wetland when compared to the region between these two points. Thus, when the wetland initially fills up, water volume will increase with very little surface area increase. Once water level increases past the depth of the depression, an increase in water volume resulted in a large increase in surface area. Finally, when the surface water reaches the edge of the wetland, water volume would increase again with smaller increases in surface area. This characteristic of the wetland was made apparent by plotting surface area against volume. This can be seen in Figure 40.

During 2008, water levels during the period from 9/1 to 10/21 were input into the surface water volume stage-storage curve equations. The daily average of those volume outputs are graphed in Figure 41. The water volume followed the same trend as the stilling well water levels. The explanation of these increases was discussed in the previous drive-point and stilling well section. However, since there is not a linear relationship between water level and volume, the magnitude of water added to a site was not apparent. The increase in water volume as a result of the precipitation events from 10/5 to 10/7 (85.88 mm) was about 5,000 m^3. The increase in water volume as a result of the precipitation events from 10/11 to 10/15 (64.16 mm) was about 25,000 m^3. It is theorized that a significant portion of the initial precipitation event infiltrated deep into the soil profile due to desiccation cracks as well as being used to increase soil moisture. Thus, runoff from this event was low and infiltration was high. When the second precipitation event occurred, the surface layers were either saturated from the previous event or became saturated relatively quickly. This resulted in more precipitation being stored as surface water on the wetland floor even though the amount of precipitation was lower than the earlier event.

The 2009 surface stored water volumes for the measurement period 3/18 to 10/24 are graphed in Figure 42. The increases and decreases of the volumes follow the same trend as the stilling well measurements mentioned in the previous sections for Lindau WPA.

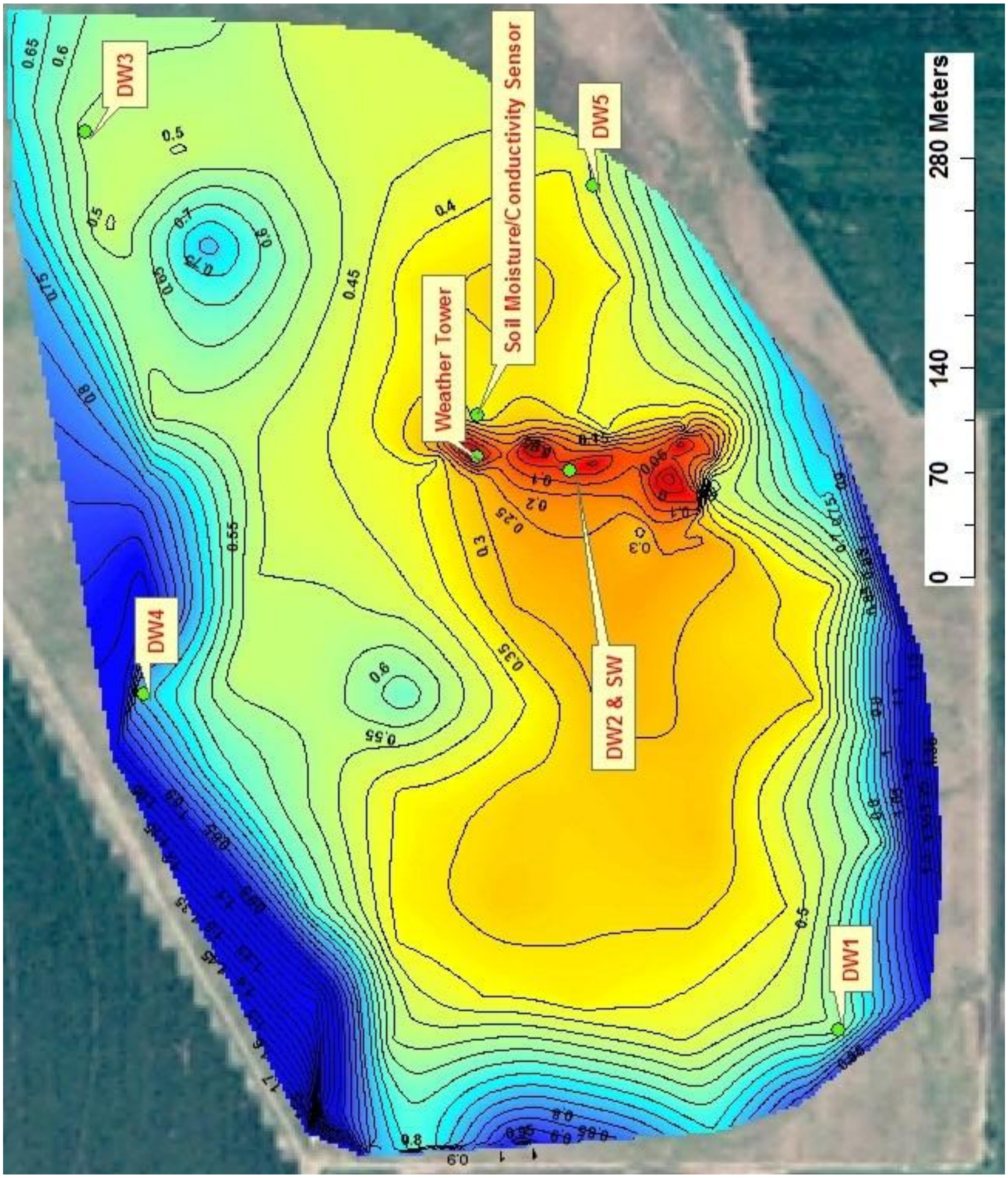


Figure 39: Lindau WPA detailed topographic map.

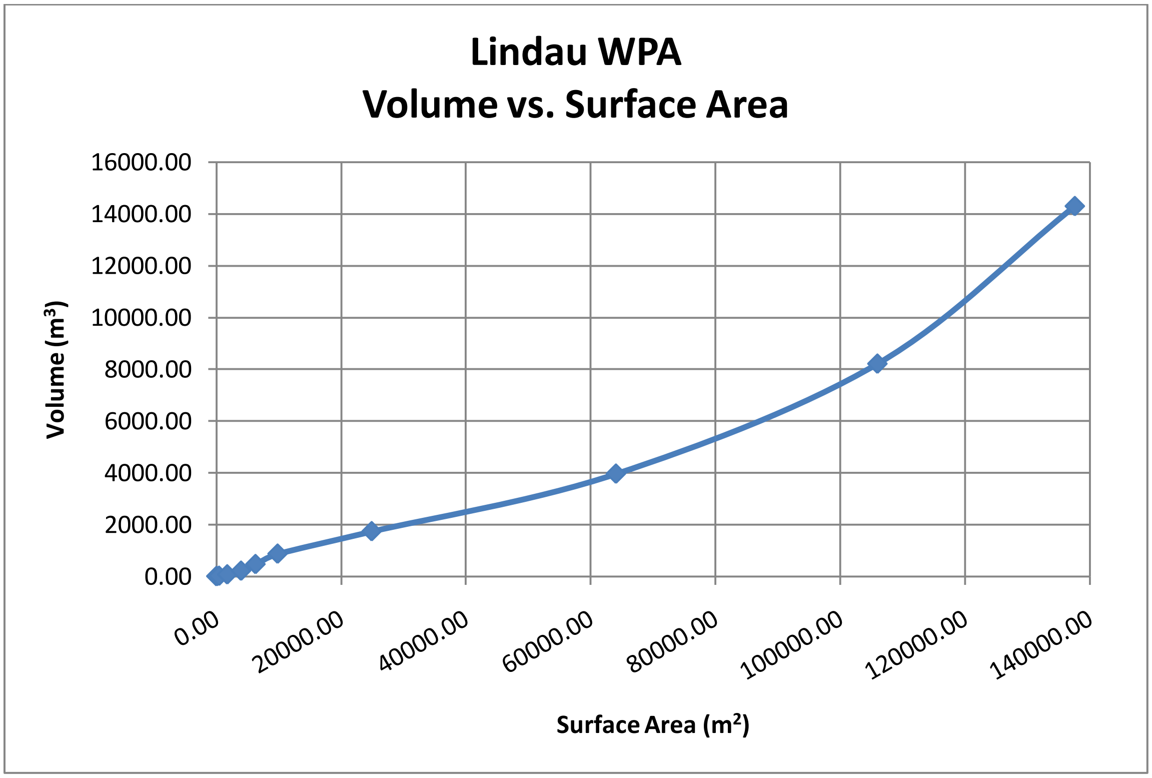


Figure 40: Lindau WPA wetland volume and surface area correlation.

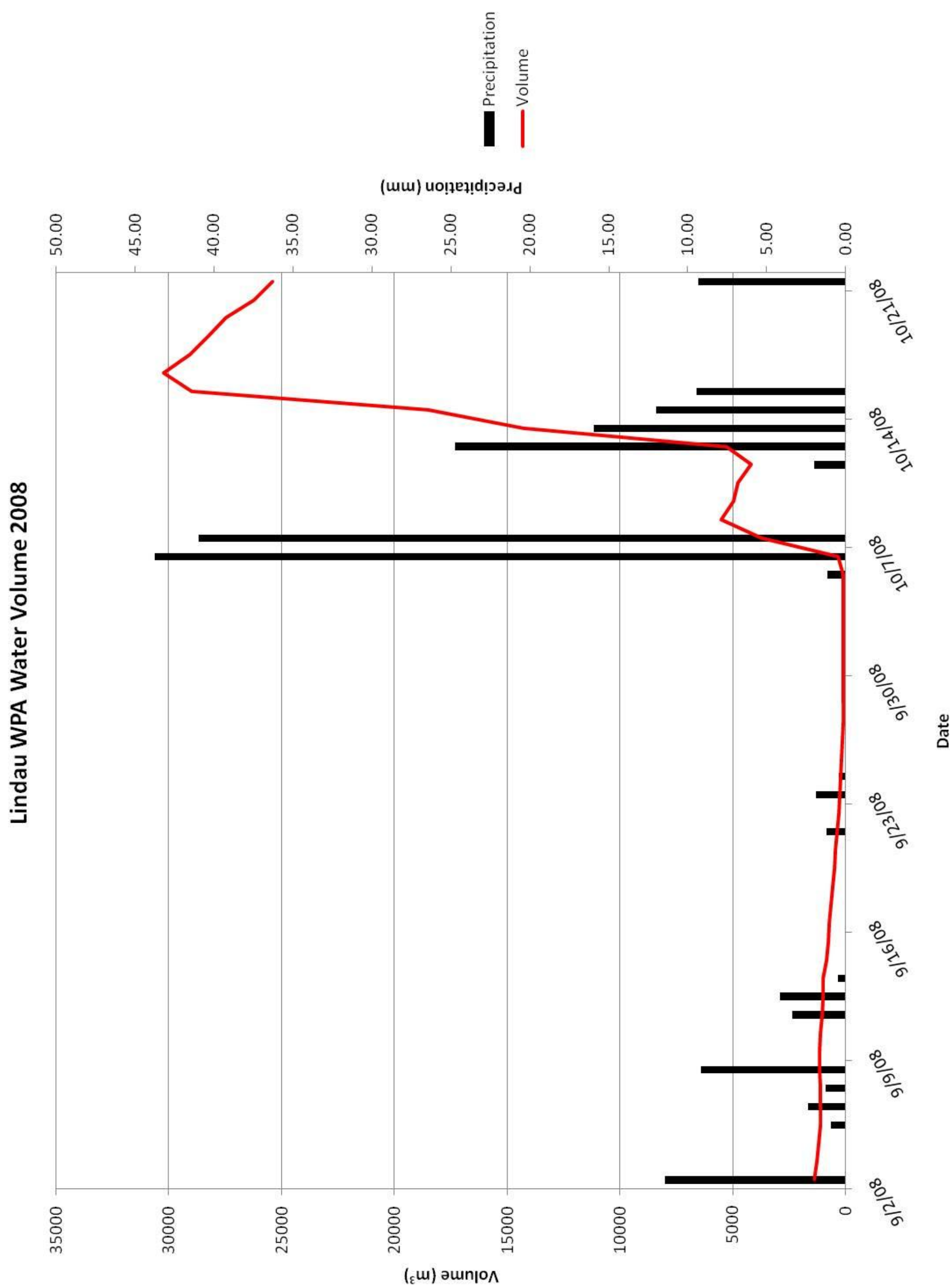


Figure 41: Lindau WPA daily average volume time-series for 2008 monitoring period.

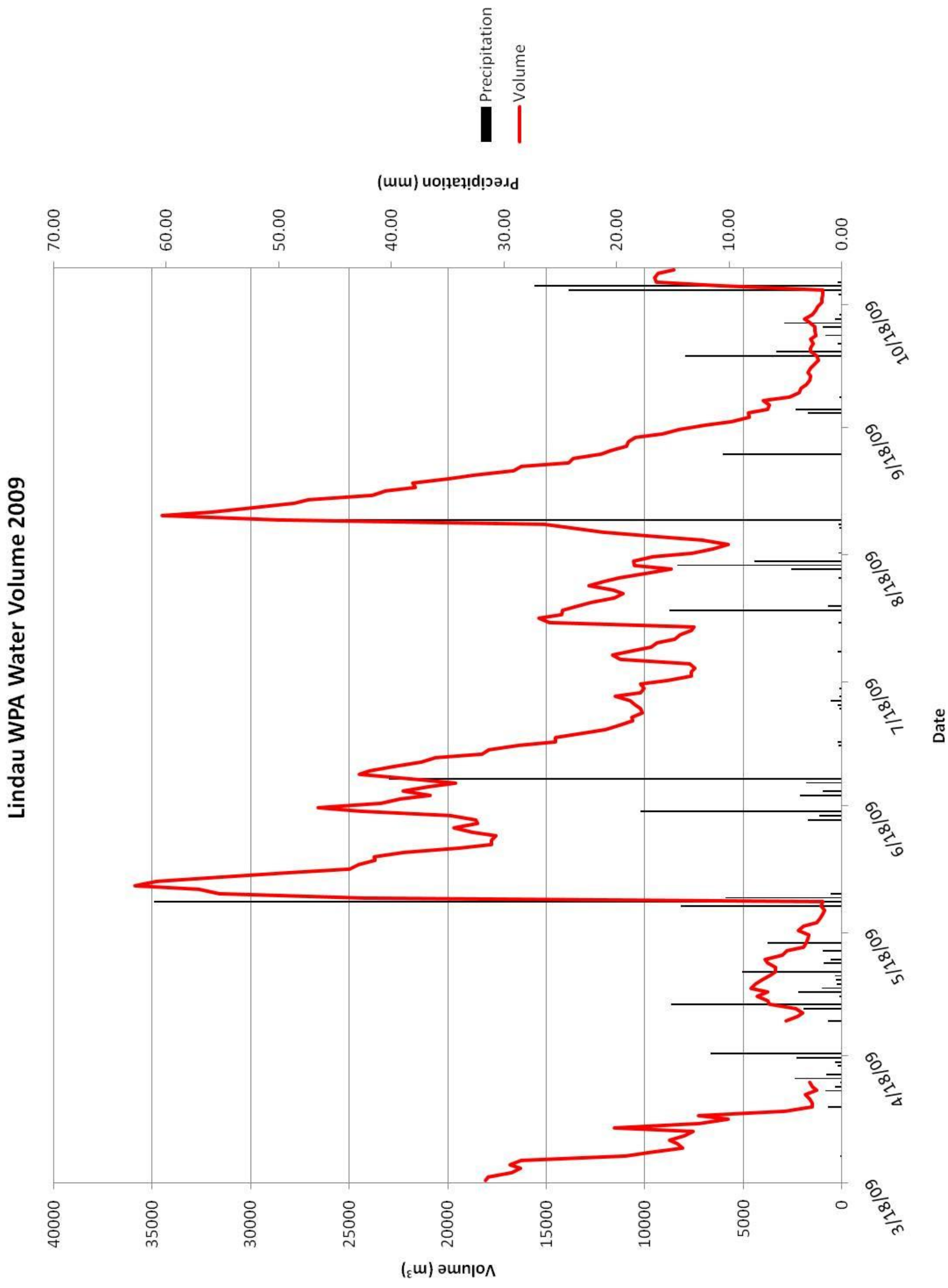


Figure 42: Lindau WPA daily average volume time-series for 2009 monitoring period.

4.3.2 Moger (North) WPA

The survey of Moger (North) WPA indicated that the deepest portion of the site was an oval region in the eastern portion of the wetland floor that was about 95 meters lengthwise from east to west. When the wetland fills with water, this depression would fill first. Once the depression was filled, ponded water would extend to the west, north, and south before covering areas to the east of the depression. The topography of Moger (North) WPA is shown in Figure 43. There are relatively large reliefs in the depression and at the edge of the wetland when compared to the region between these two points. Similar to Lindau WPA, when the wetland fills up initially, water volume will increase with very little surface area increase. Once water level increases past the depth of the depression, an increase in water volume resulted in a larger increase in surface area. Finally, when the surface water reaches the edge of the wetland, water volume would increase again with smaller increases in surface area. This behavior of the wetland can be seen by plotting surface area against volume (Figure 44).

During 2008 and 2009, daily averaged volumes obtained from the stage-storage curve functions showed increasing and decreasing trends similar to the stilling well water levels. These daily averaged volumes as well as daily total precipitation are graphed in Figure 45 and Figure 46 for 2008 and 2009, respectively.

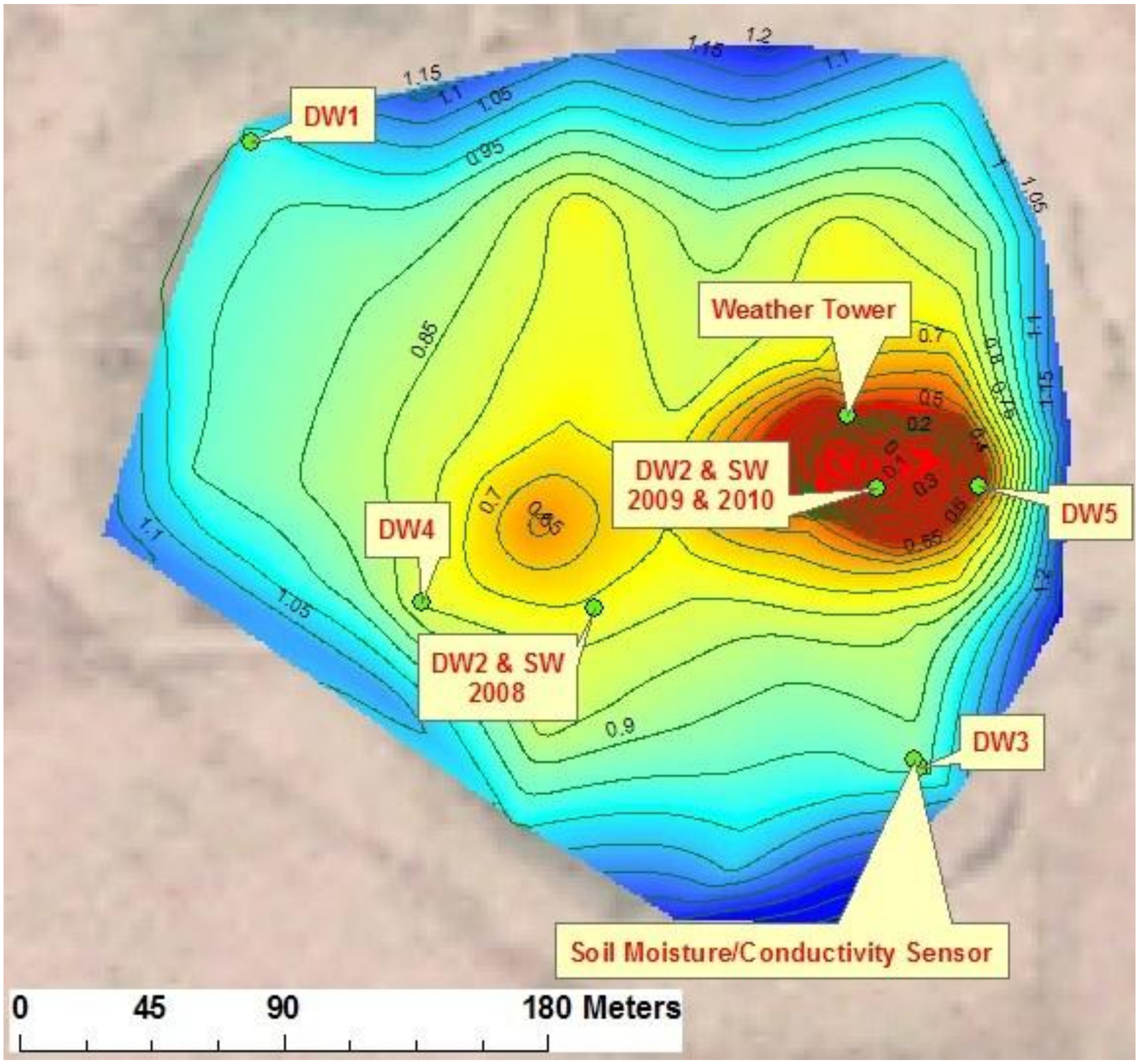


Figure 43: Moger (North) WPA detailed topographic map.

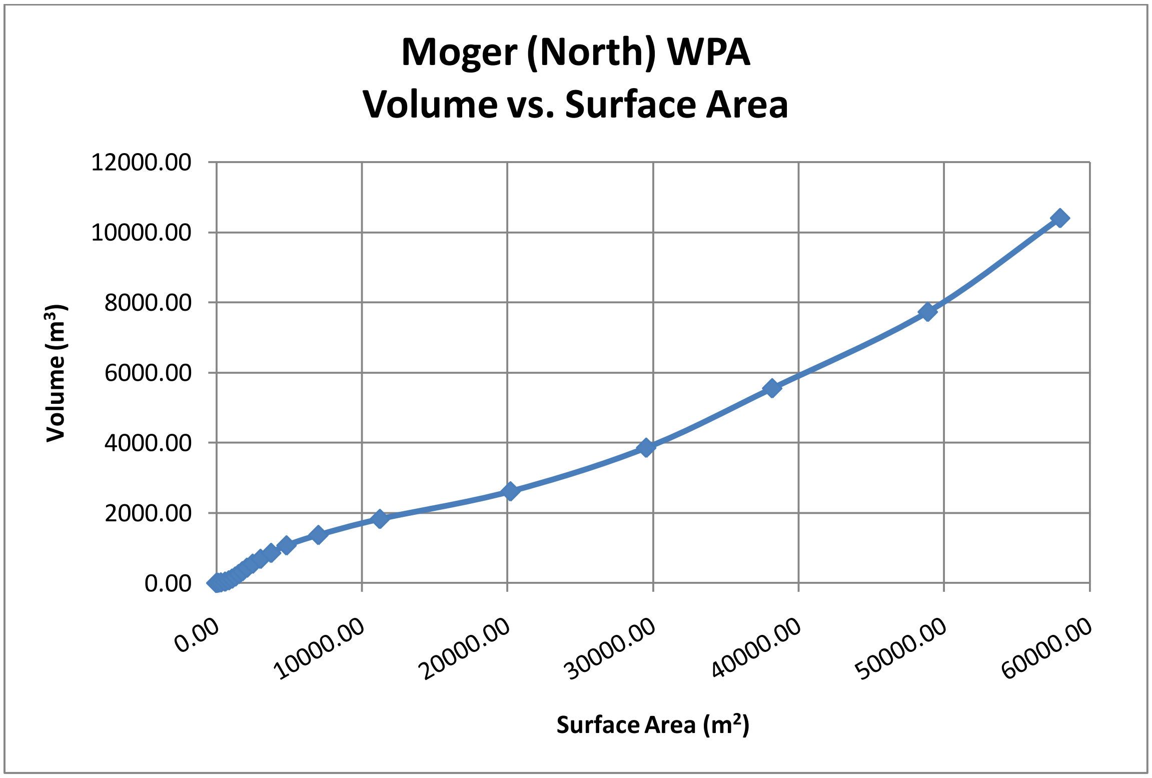


Figure 44: Moger (North) WPA wetland volume and surface area correlation.

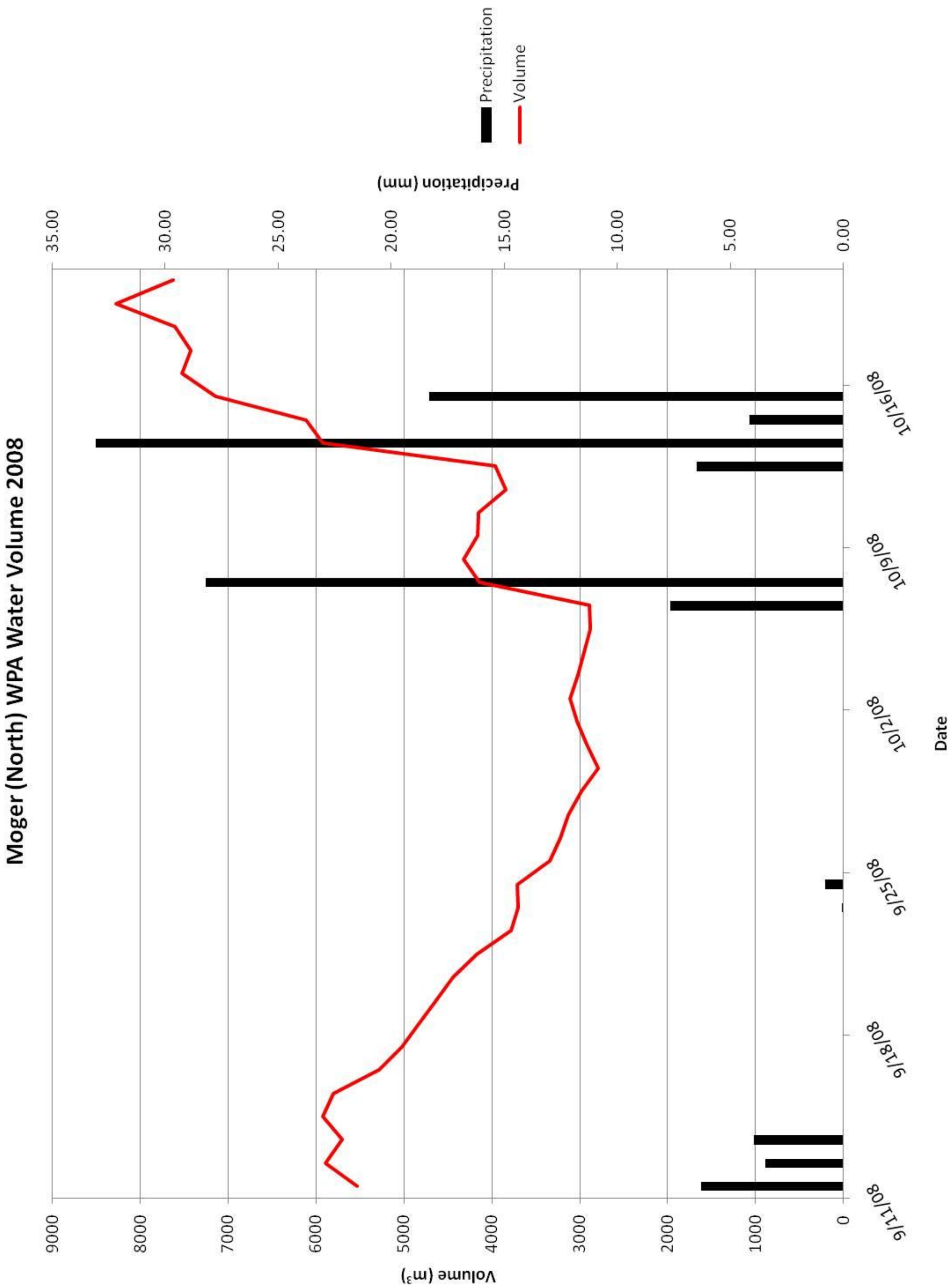


Figure 45: Moger (North) WPA daily average volume time-series for 2008 monitoring period.

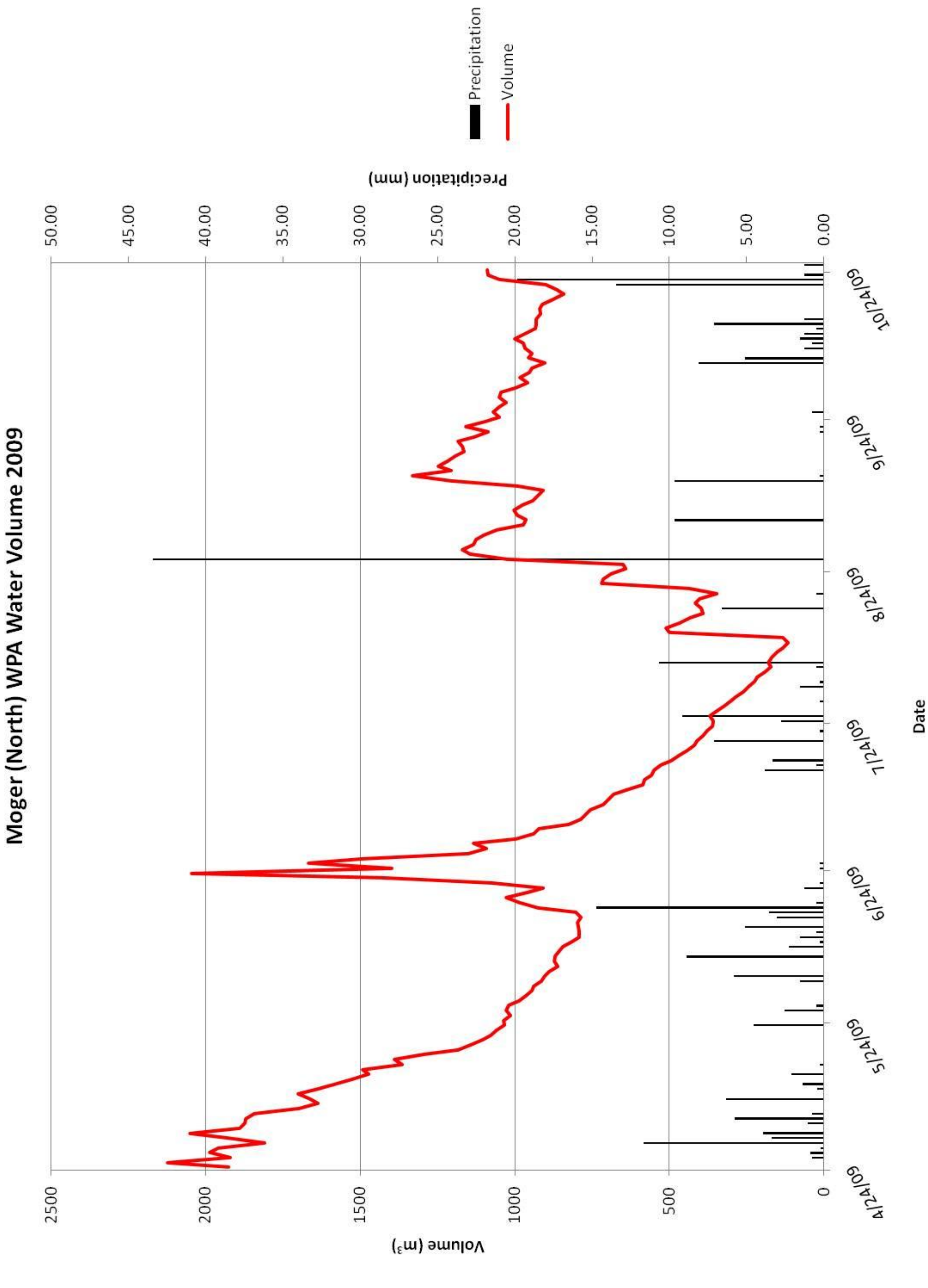


Figure 46: Moger (North) WPA daily average volume time-series for 2009 monitoring period.

4.3.3 Griess WPA

The survey of Griess WPA indicated that the deepest portion of the site is an area near DW3. The wetland bottom has very low relief. There are large gradients at the eastern edge of the wetland due to the sharp increase from the wetland floor to the cropped field. The topography of the wetland can be viewed in Figure 47. When the wetland fills with water, volume of the water is distributed over a large area. Unlike Lindau WPA and Moger (North) WPA which required a depression to be filled before the volume could be extended over a large area of the wetland, Griess WPA has an exponential relationship between surface area and volume. This information can be viewed in Figure 48.

During 2008 and 2009, daily averaged volumes obtained from the stage-storage curve functions showed increasing and decreasing trends similar to the stilling well water levels. These daily averaged values as well as daily total precipitation are graphed in Figure 49 and Figure 50 for 2008 and 2009, respectively.

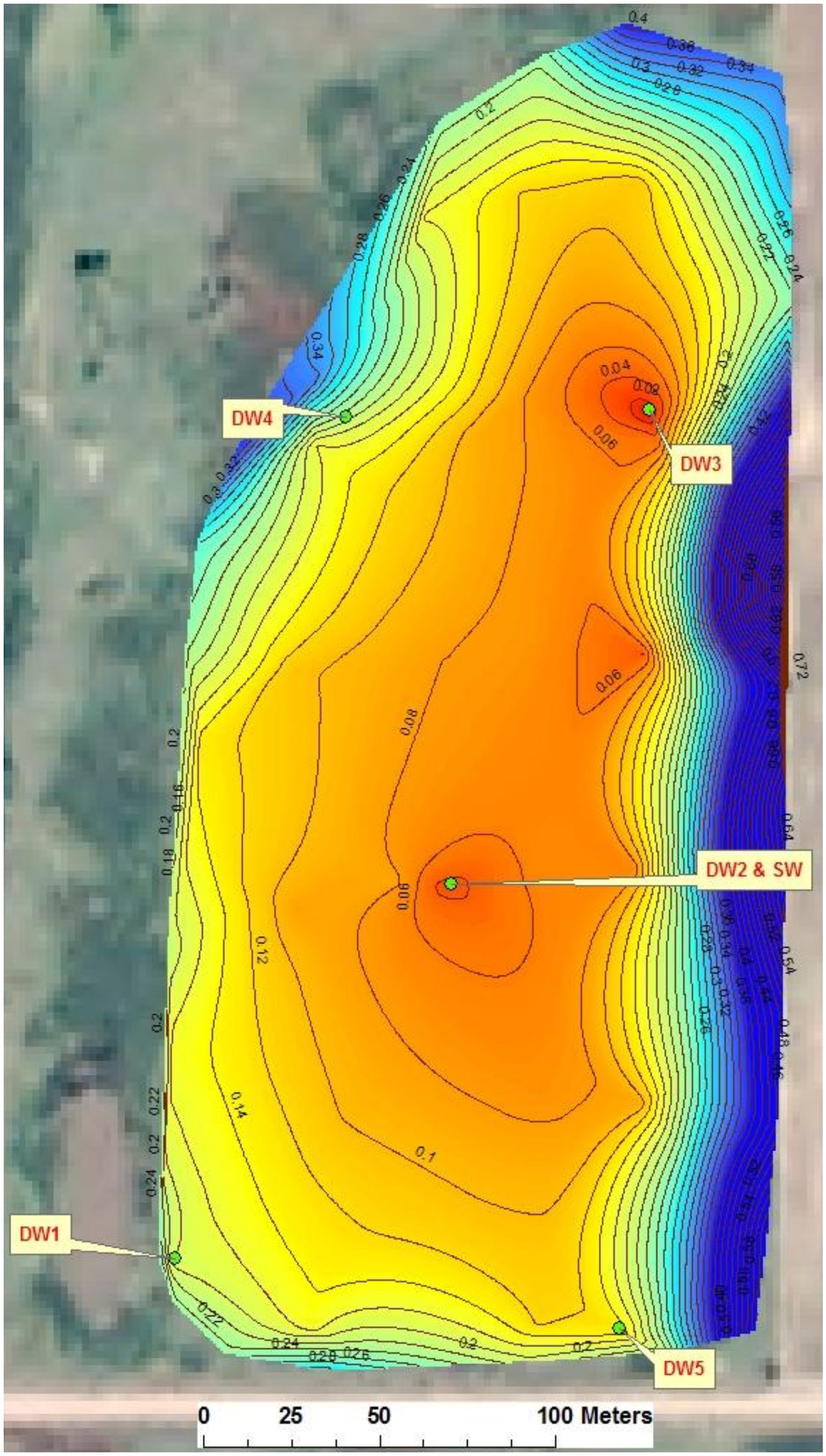


Figure 47: Griess WPA detailed topographic map.

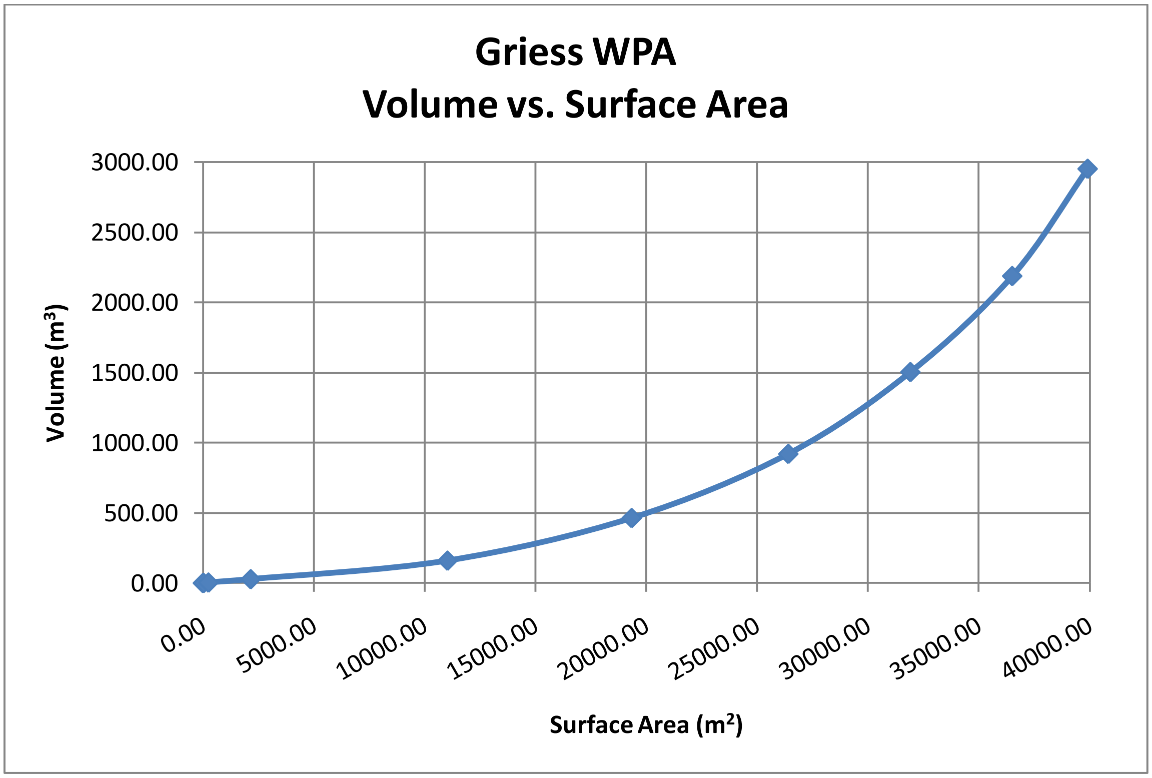


Figure 48: Griess WPA wetland volume and surface area correlation.

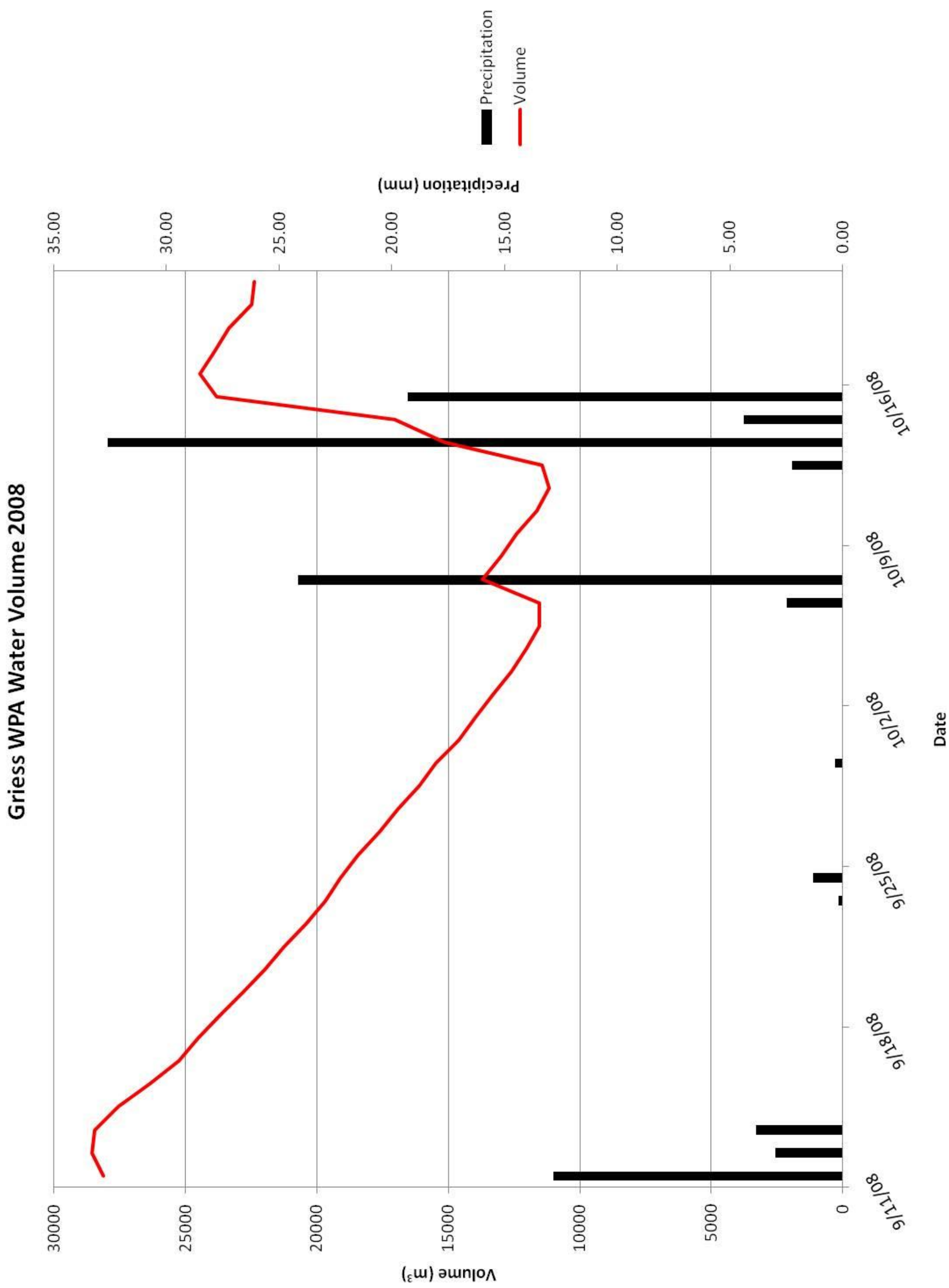


Figure 49: Griess WPA daily average volume time-series for 2008 monitoring period.

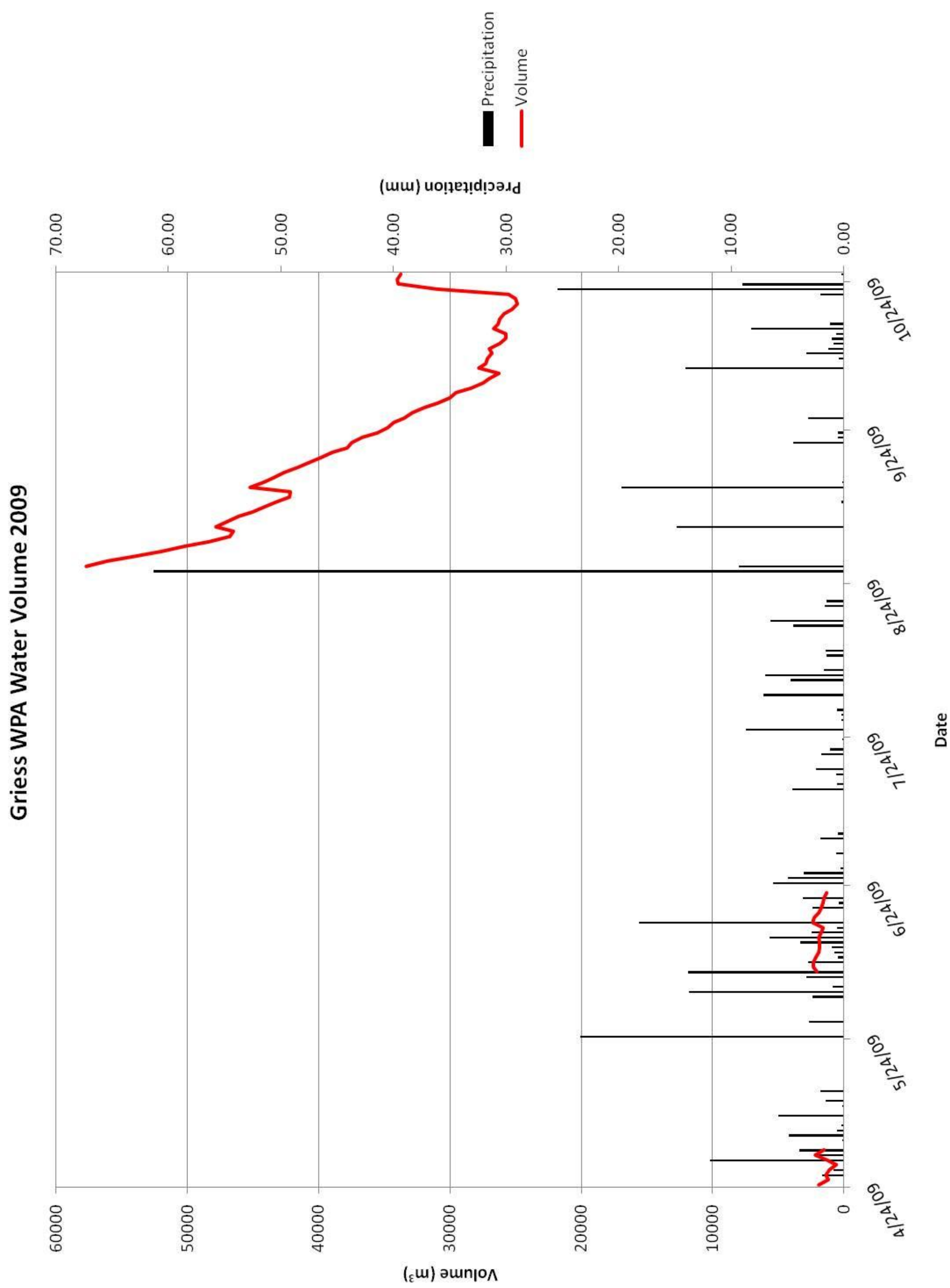


Figure 50: Griess WPA daily average volume time-series for 2009 monitoring period.

4.3.4 Wetland Daily Volume Changes

The rate of volume change time series for Lindau WPA, Moger (North) WPA, and Griess WPA are provided in Figure 51 through Figure 56 during monitoring periods of each site for 2008 and 2009. All three sites showed similar trends. Values associated with rapid water volume increase are associated with precipitation events. After these rapid increases in volume, surface stored water volumes begin to decrease. The rate of volume decrease after these precipitation events is large initially, but appears to approach a steady state as more time passes since a precipitation event occurred. It is hypothesized that after a significant increase in surface water volume, areas that were not saturated had water ponded over them. These sediments possibly had more unsaturated pore space for water infiltration when compared to sediments that had water ponded over them for a significant period of time. Thus, a significant portion of the water infiltration will go to filling the unsaturated pore space of the soil matrix. Horizontal and vertical capillary influences as well as gravity allowed for rapid infiltration into these dry sediments which probably aided in the rapid decrease of surface water volume, initially. As time progresses, the surface area of the water body has decreased, but saturated sediments remain on the periphery. Thus, the potential for horizontal movement by capillary action may be diminished, and infiltration is primarily vertical. Minor changes during this steady state rate of change periods could be associated to changes in the ET rate and changes in potential energy associated with the changing elevation of the surface water body.

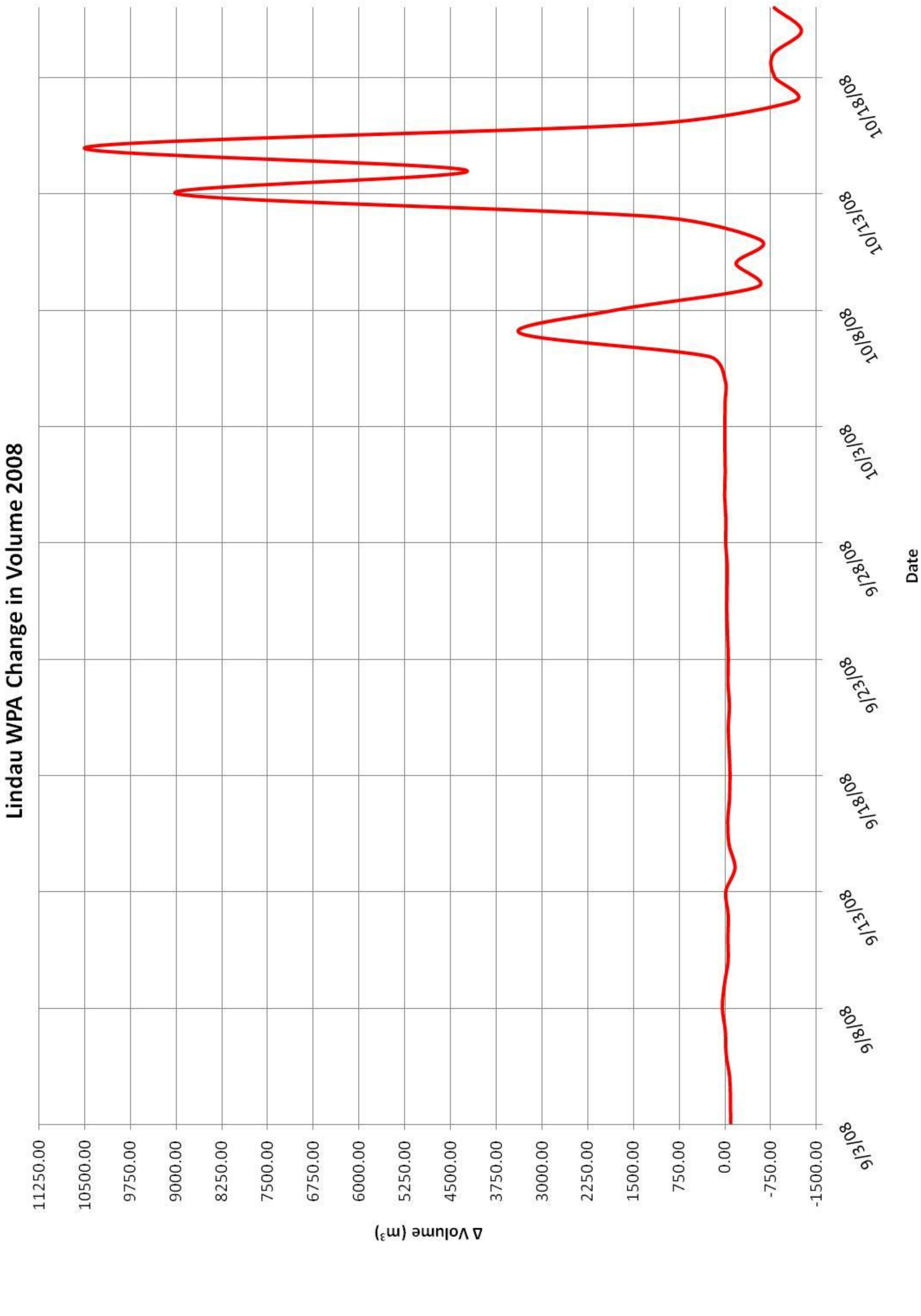


Figure 51: Lindau WPA daily volumetric rate of change for 2008 monitoring period.

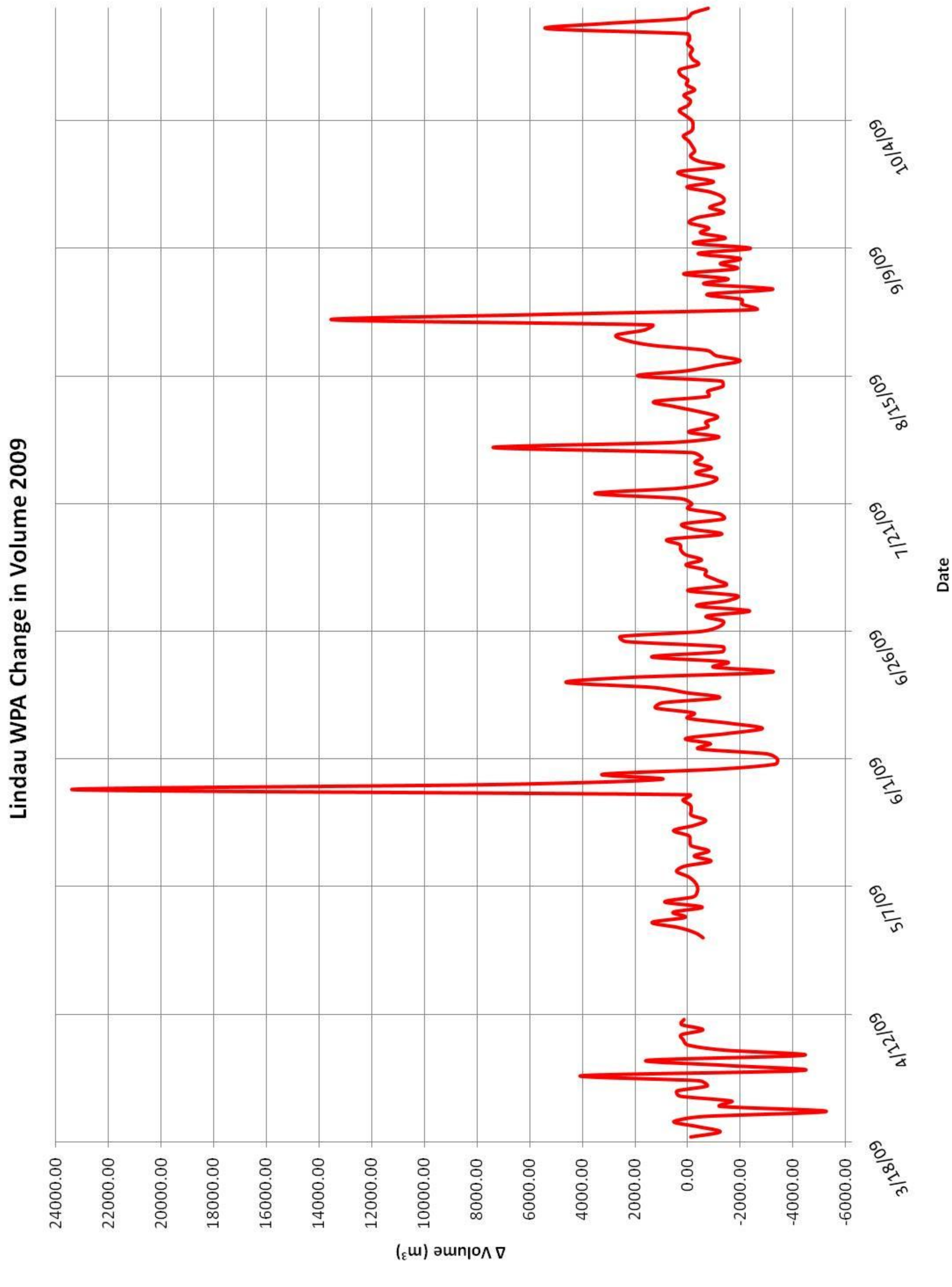


Figure 52: Lindau WPA daily volumetric rate of change for 2009 monitoring period.

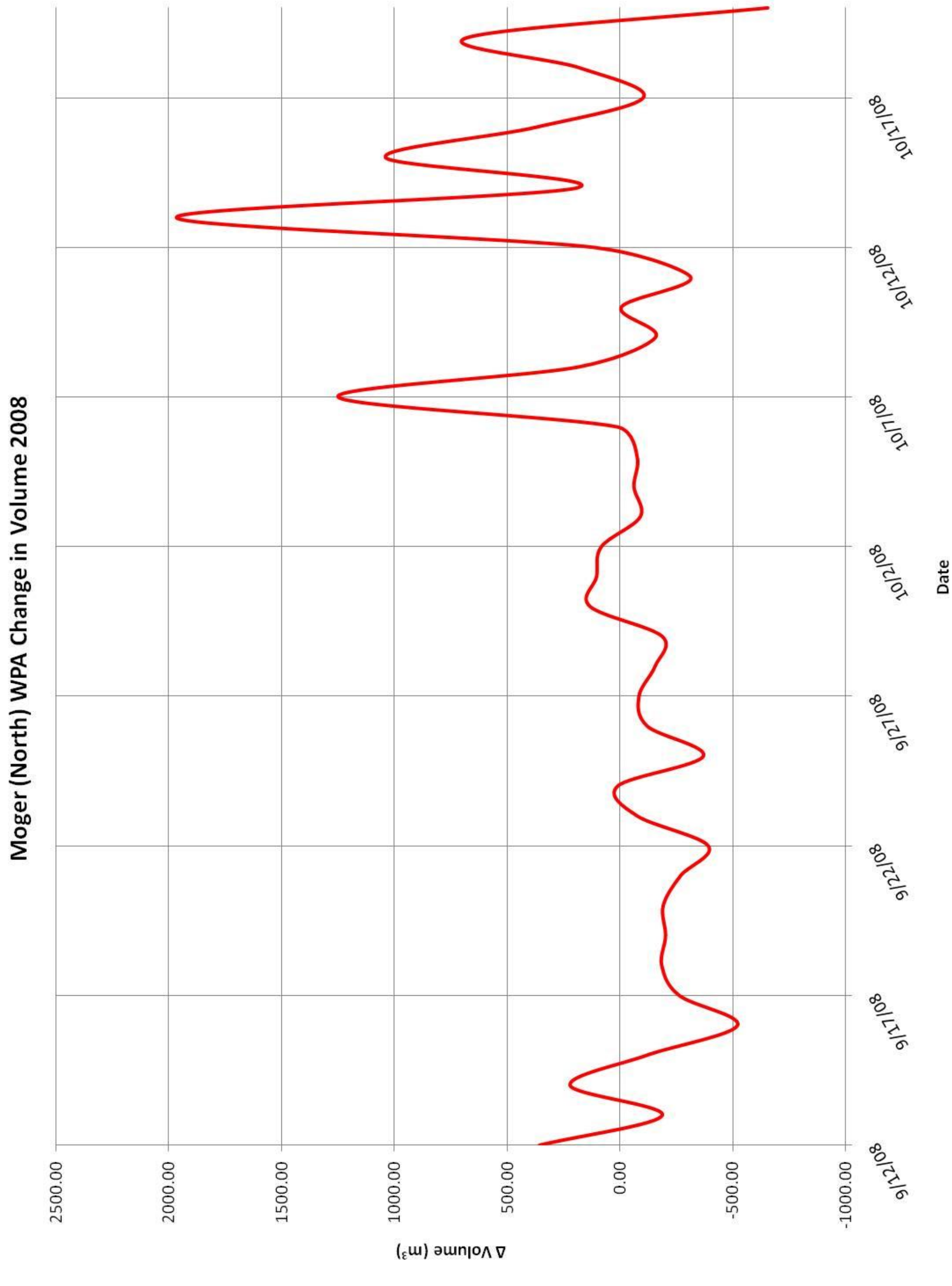


Figure 53: Moger (North) WPA daily volumetric rate of change for 2008 monitoring period.

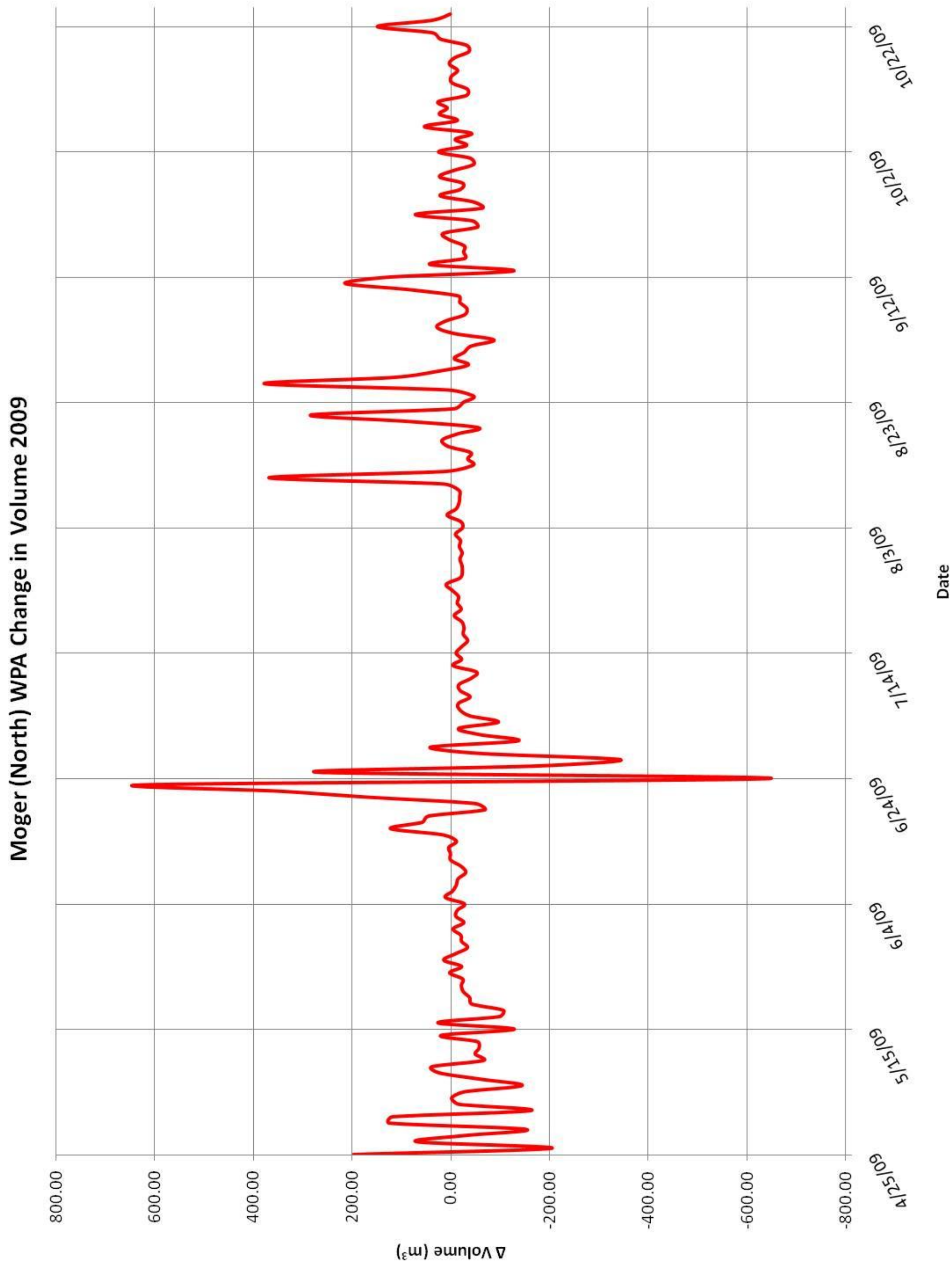


Figure 54: Moger (North) WPA daily volumetric rate of change for 2009 monitoring period.

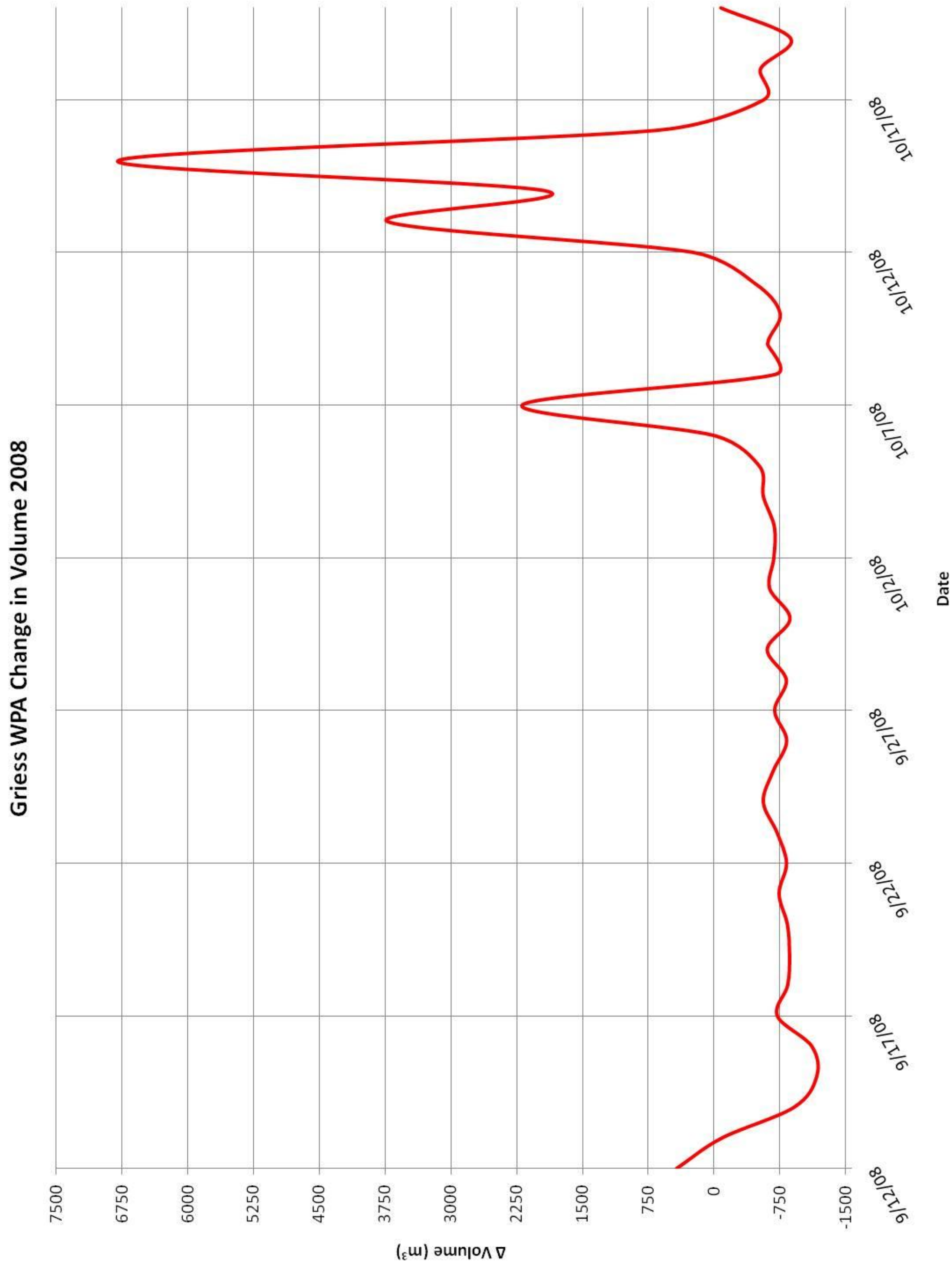


Figure 55: Griess WPA daily volumetric rate of change for 2008 monitoring period.

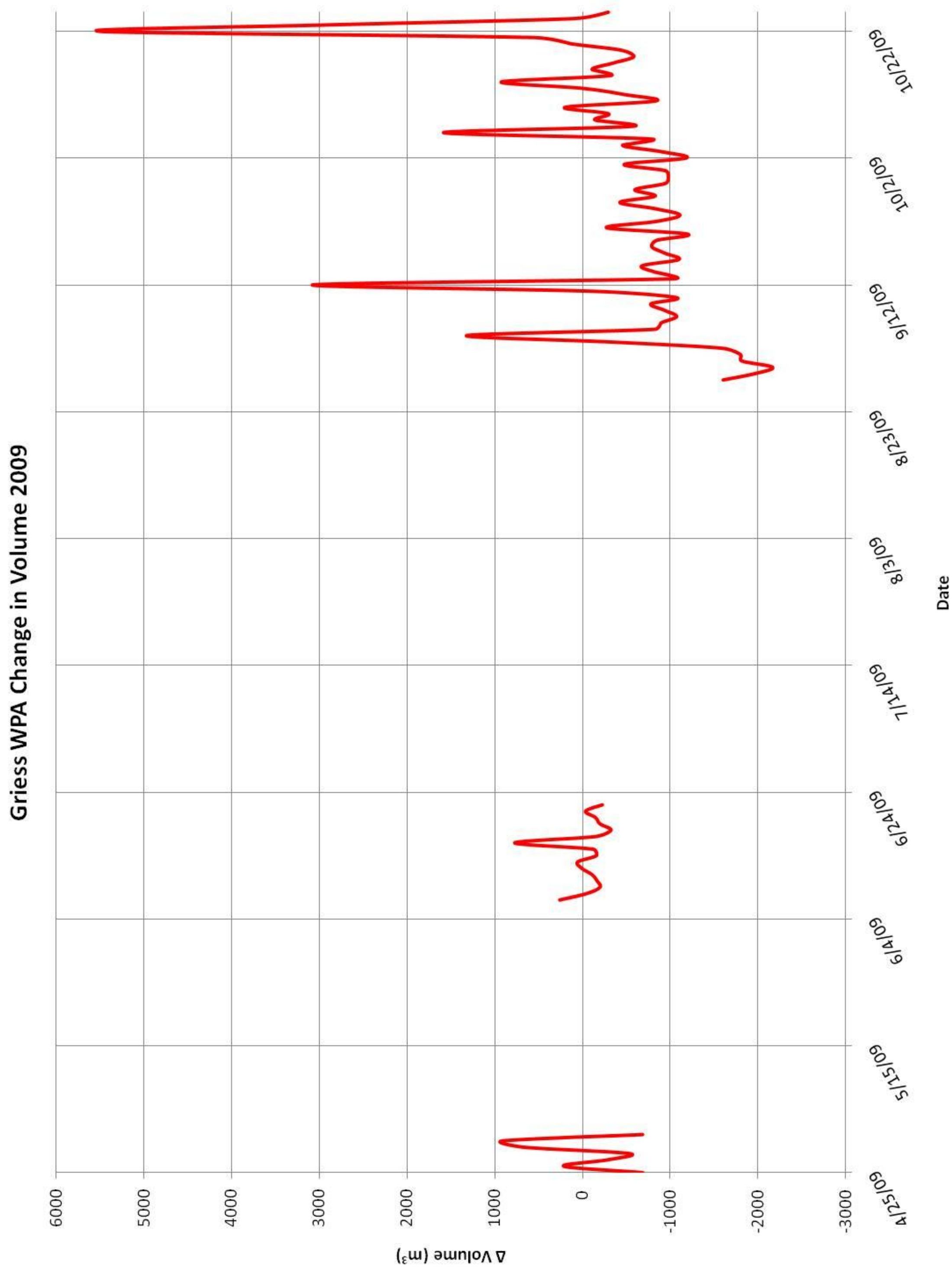


Figure 56: Griess WPA daily volumetric rate of change for 2009 monitoring period.

4.3.5 Volume Estimate Error

As a result of using the stage-storage curve approach to estimate surface water volume, error will be inherent in the calculation due to several factors. Error can arise depending on how precise the survey was of the wetland and on how accurate the fitting equations are that are used to model the wetland. Error can be introduced due to changes in the wetland environment such as shrink/swell of the soil volume or vegetation displacement of water during the growing season. Finally, it can also depend on how much fluctuation may occur of the water level measurement when outside forces (wind) influence the water body.

In Figure 57 through Figure 62, daily standard deviations of wetland water volumes were calculated during the monitoring periods of 2008 and 2009 for all three sites. These values coincide with the daily volume averages mentioned in the previous sections. Most of the standard deviation spikes for all sites tend to coincide with precipitation events. Volume increases as a result of precipitation events typically occur in a period of a couple hours. Thus, taking daily averages on these dates resulted in large deviations. Typically, after these large increases of volume due to precipitation, deviations will initially be high and show a decreasing trend similar to the decreasing trend in surface water volume. At higher volumes, there was more oscillation in standard deviations. At extremely low volumes, standard deviations can become steady and remain low.

These standard deviations are indirectly reflecting the topography. At low volumes, water levels are low. As is the case for Lindau WPA and Moger (North) WPA, at low water levels, water is confined to the depression on these sites. Though there will be some fluctuations in water levels due to outside influences, the change in volume and surface area will be minimal. This results in small standard deviations. However, at high volumes, water extends over more of the wetland surface where minor fluctuations in water level can result in significant changes in surface area and volume. This can result in the high standard deviations that are associated with high volumes.

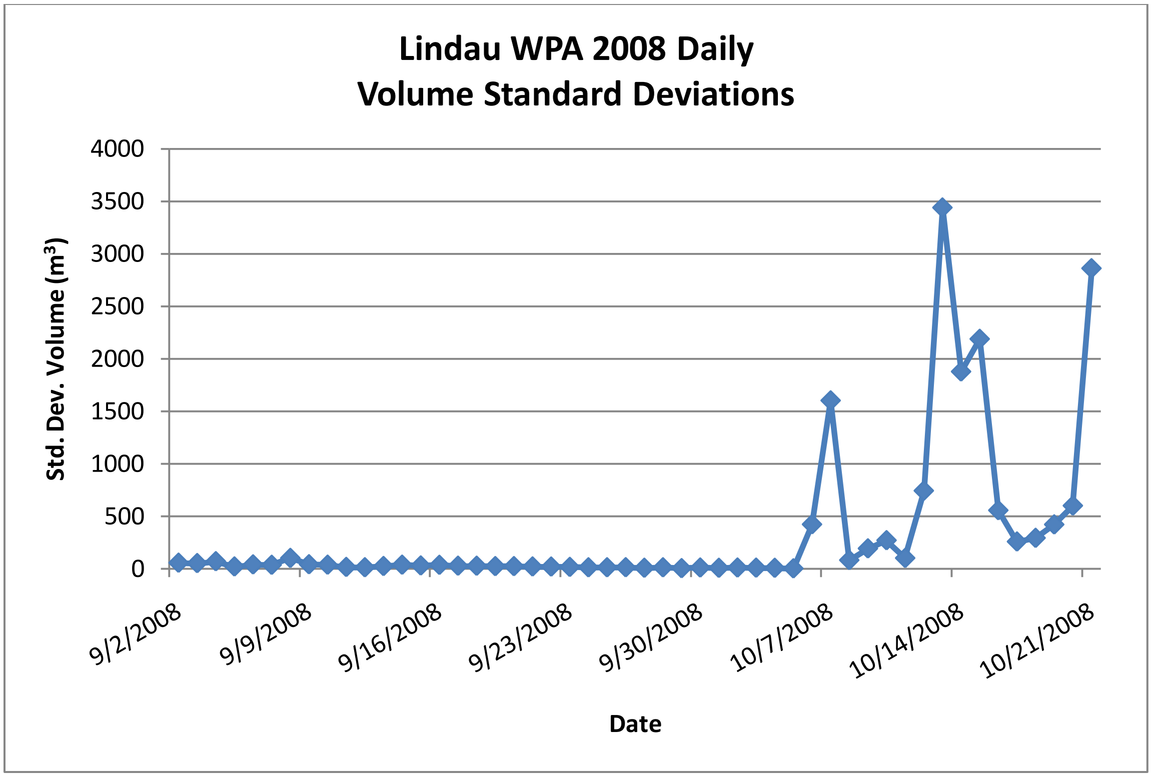


Figure 57: Lindau WPA 2008 daily volume standard deviations.

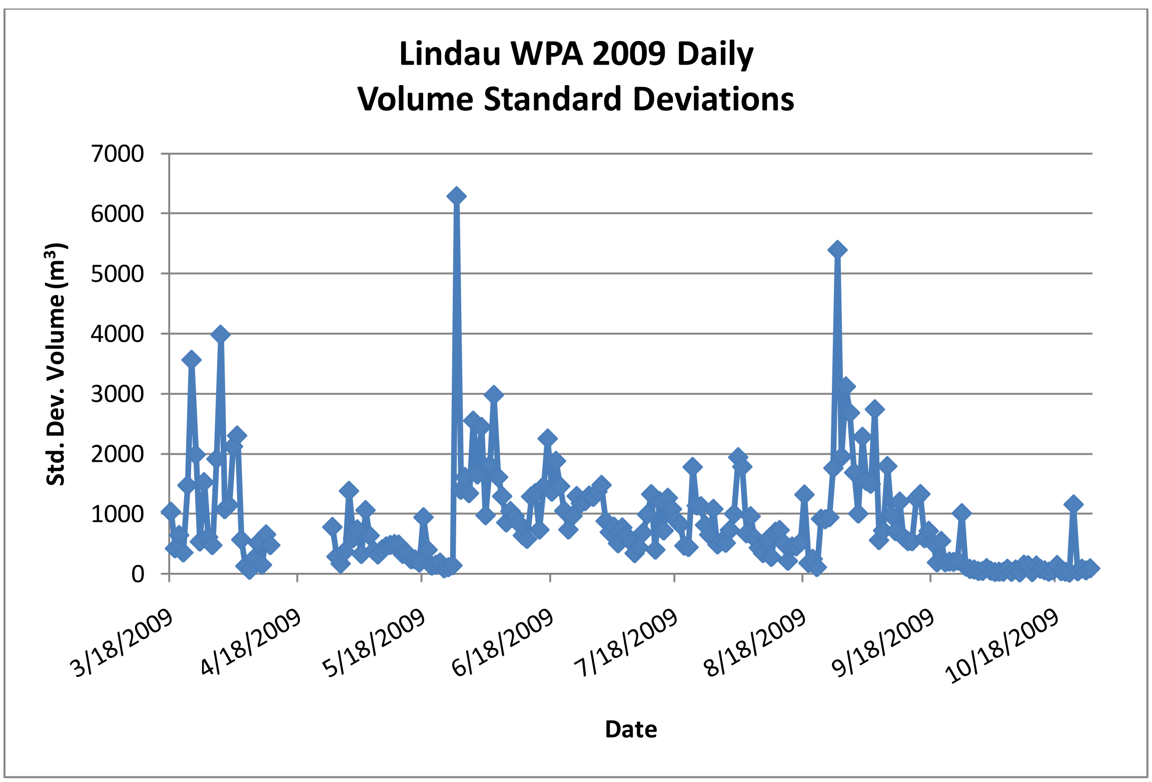


Figure 58: Lindau WPA 2009 daily volume standard deviations.

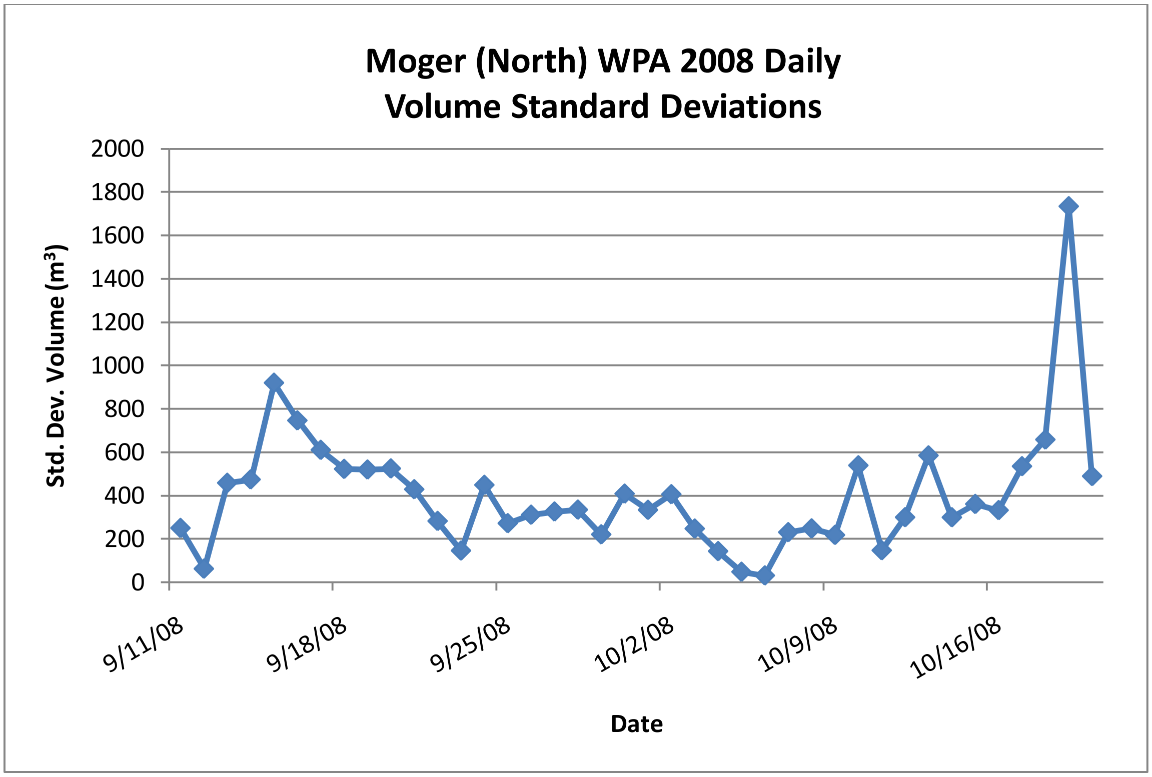


Figure 59: Moger (North) WPA 2008 daily volume standard deviations.

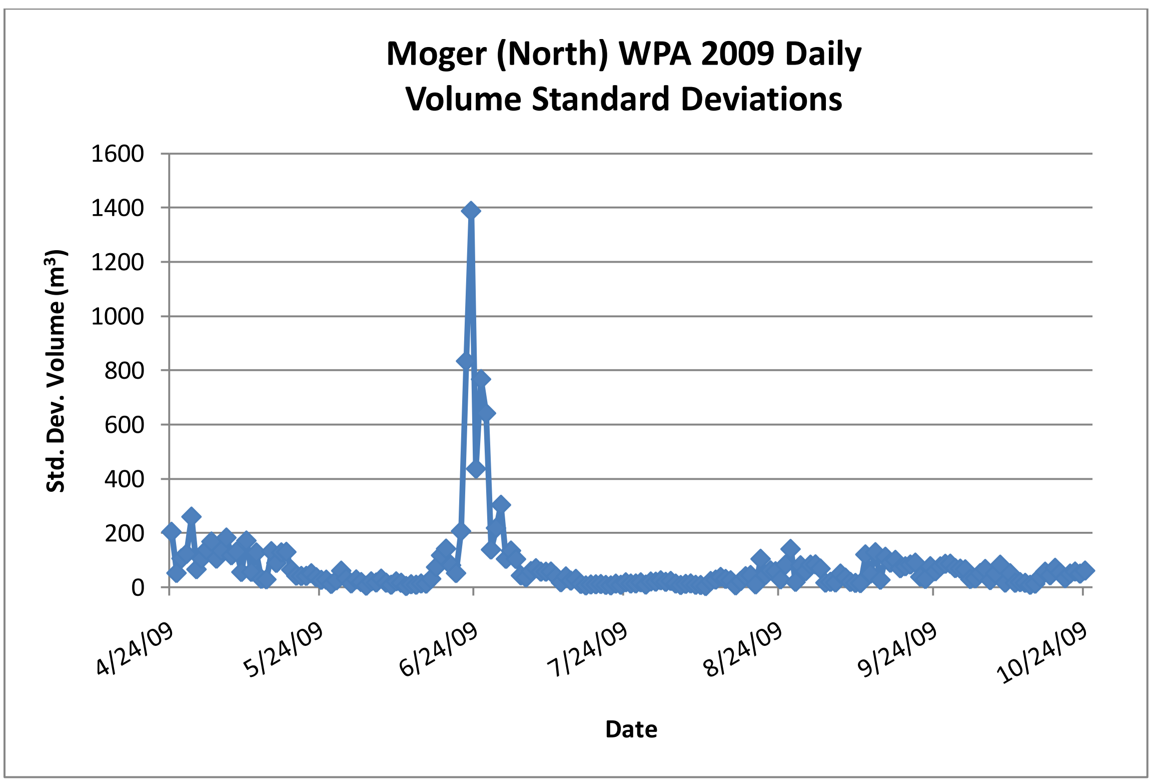


Figure 60: Moger (North) WPA 2009 daily volume standard deviations

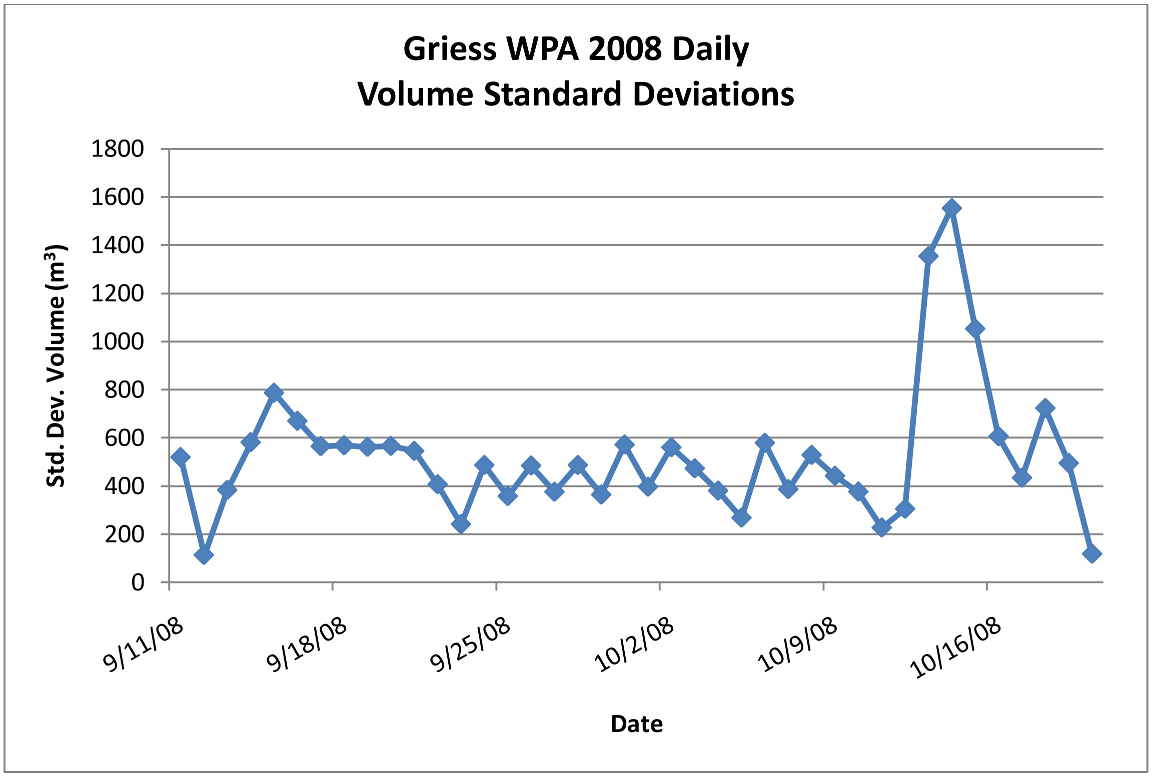


Figure 61: Griess WPA 2008 daily volume standard deviations

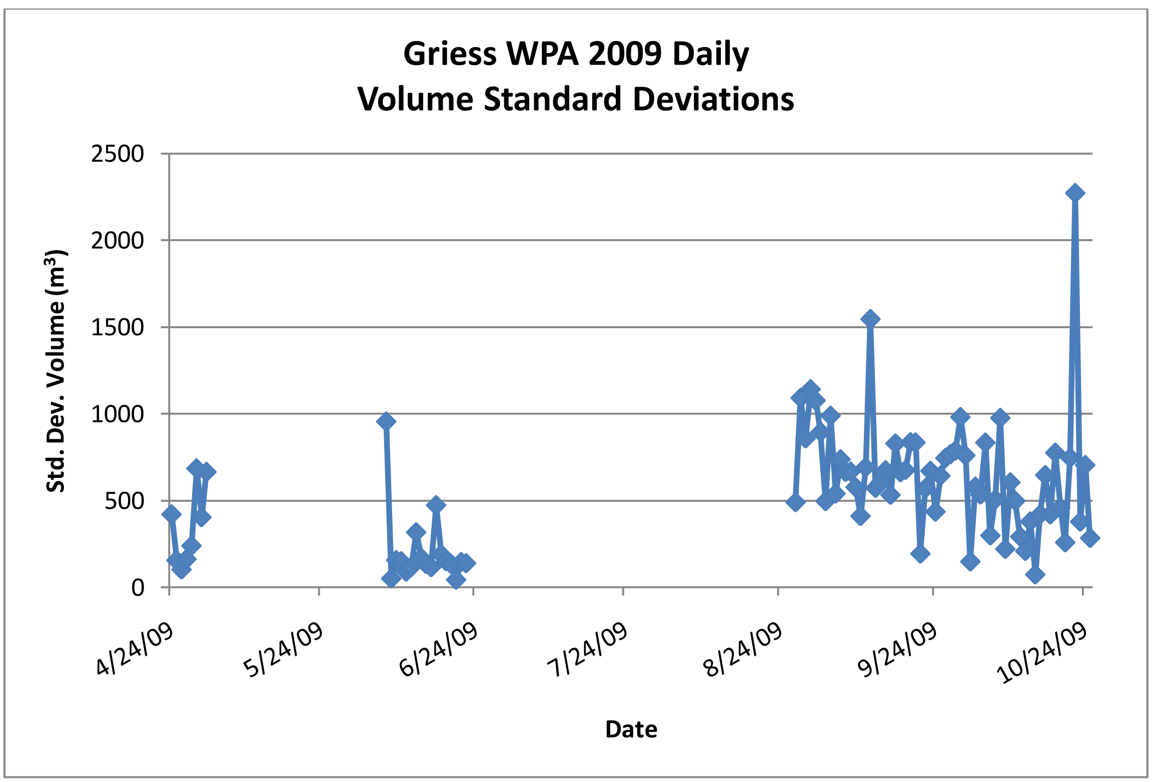


Figure 62: Griess WPA 2009 daily volume standard deviations

4.4 Infiltration Estimation

Modeling was performed on Lindau WPA and Moger (North) WPA data to obtain an estimation of infiltration into the wetland sediments. Figure 63 and Figure 64 show the calculated volume of water being removed via ET for Lindau WPA and Moger (North) WPA, respectively. The decline of ET as a mechanism for removing water due to seasonal changes can be clearly viewed for Lindau WPA where a large increase of surface water volume in late August caused minor increases in ET volume when compared to ET volumes calculated from earlier in the season with similar or lower surface water volumes. The ET volumes calculated here are highly dependent on the exposed surface area of the water body. The values calculated at Lindau WPA were typically an order of magnitude greater than the ET calculated from Moger (North) WPA. During the monitoring period, water surface area at Moger (North) WPA was small compared to Lindau WPA because the volume was concentrated within the depression on the site.

Figure 65 and Figure 66 show the estimated volume of water removed from the wetland surface water as infiltration for Lindau WPA and Moger (North) WPA, respectively. The infiltration volumes are variable. This is due to several factors such as variable surface water volume estimates, changes in infiltration rates, and the accuracy of the ET estimate. However, the trend appears where an increase in surface water volume will result in an increase in infiltration volume while low surface water volumes will have low infiltration volumes.

In Figure 67 and Figure 68, the ratio of infiltrated water volume to total water volume loss is graphed for Lindau WPA and Moger (North) WPA, respectively. If the ratio was greater than 0.5, more of the surface water volume removed from the wetland occurred as infiltration. If the ratio was less than 0.5, more of the surface water volume removed from the wetland occurred as ET. For Moger (North) WPA, there was a seasonal impact on which process removed more water volume than the other. Early in the monitoring period, ET could be dominant in removing water from the wetland due to having more potential energy to remove water from a site. However, as the monitoring period approaches September and October, the range of ratios decrease to where water loss was occurring mostly as infiltration. This was probably the result of the decreasing available energy for ET in late summer and early fall. Also, this could be due to the limited amount of surface area of the water body exposed to the atmosphere which would result in less water being made available for ET. Lindau WPA does not show this distinct seasonal trend similar to Moger (North) WPA. However, differences in exposed surface area and depth of ponded water may have caused a wider range in ratios throughout the monitoring period at Lindau WPA when compared to Moger (North) WPA. Of the available data, water volume loss occurred more times as infiltration than it did as ET. The ratio of infiltrated water volume to surface water volume loss was above 0.5 approximately 60% of the time for Lindau WPA and 83% of the time for Moger (North) WPA.

In Figure 69 and Figure 70, depths of surface water loss to infiltration are graphed. For Lindau WPA, the depths are counter-intuitive. The largest water loss occurs at the lowest volumes of water stored in the wetland near the end of September and into October. This may be the result of an incorrect assumption made to obtain the depths. It was assumed that the volume lost to infiltration would occur evenly across the wetted surface area. However, this assumption does not take into account variability in hydraulic conductivity across the wetland floor nor does it account for variable head pressures from the stored water. Assuming that hydraulic conductivity was similar across the wetland during ponded water periods, head pressures would be higher within the depression than on the low gradient areas outside of the depression. It could be assumed that fluxes of infiltration would be higher within the depression and decrease further away from the depression. It is possible that the larger depths calculated at the low wetland water volumes may be more reflective of the true nature of the wetland in which a limited portion of the wetland floor is allowing quicker infiltration.

For Moger (North) WPA, the surface water loss depths showed a similar trend to the infiltration volumes. Unlike Lindau WPA during 2009, water volume was maintained in the depression with few periods where water extended over large portions of the wetland floor. Since water was maintained within the depression, infiltration may be focused and the error involved with evenly distributing the infiltration across the ponded surface is minimal.

In Figure 71 and Figure 72, infiltration rates are graphed for Lindau WPA and Moger (North) WPA, respectively. For Lindau WPA, the infiltration rates obtained from the modeling procedure ranged from $5.0x10^{-5}$ to $5.0x10^{-2}$ m day^{-1}. The geometric mean of the rates was $6.4x10^{-3}$ m day^{-1}. For Moger (North) WPA, the infiltration rates ranged from $8.0x10^{-5}$ to 0.44 m day^{-1}. The geometric mean of the rates was $2.5x10^{-2}$ m day^{-1}.

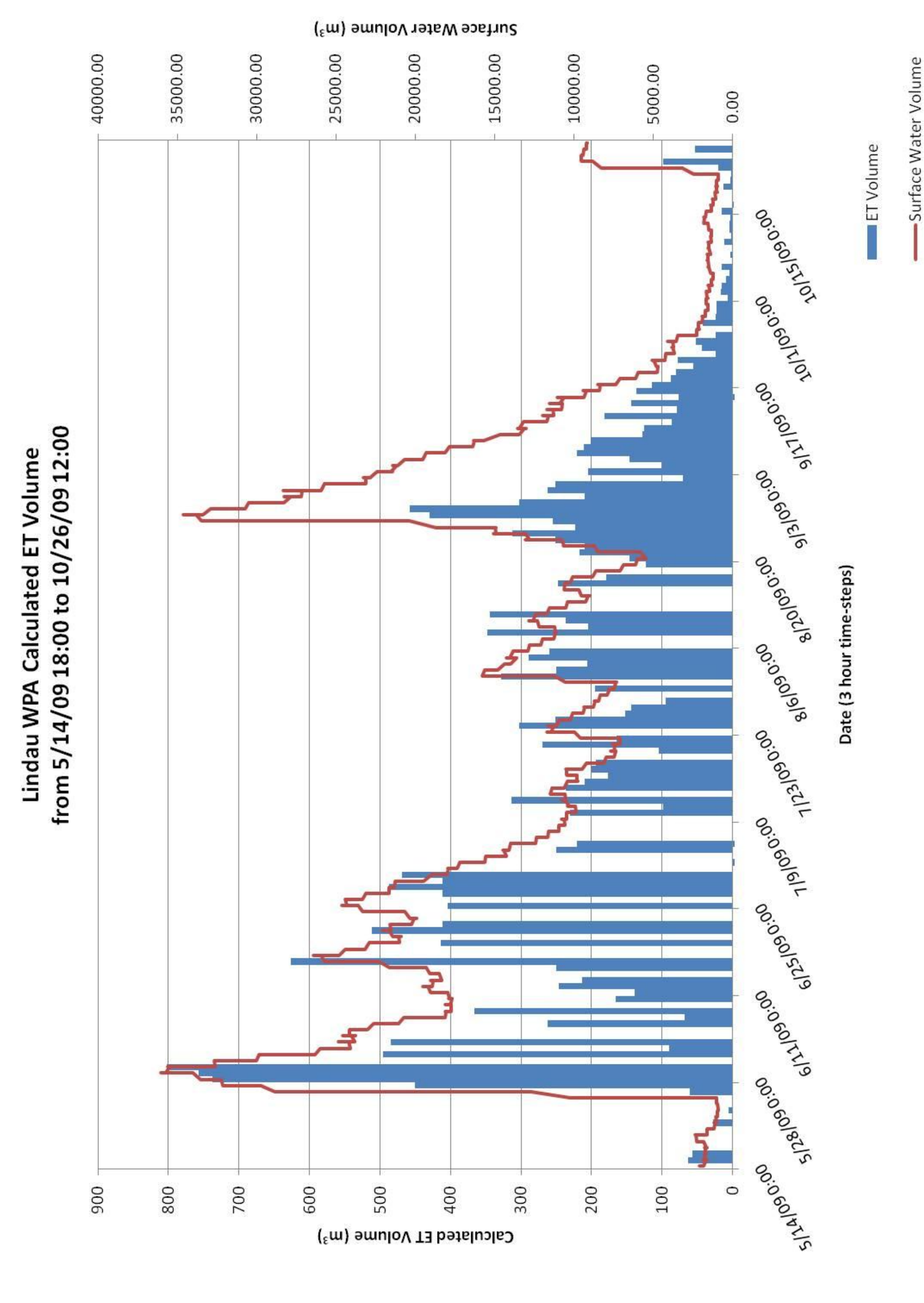


Figure 63: Calculated ET volumes time-series for Lindau WPA.

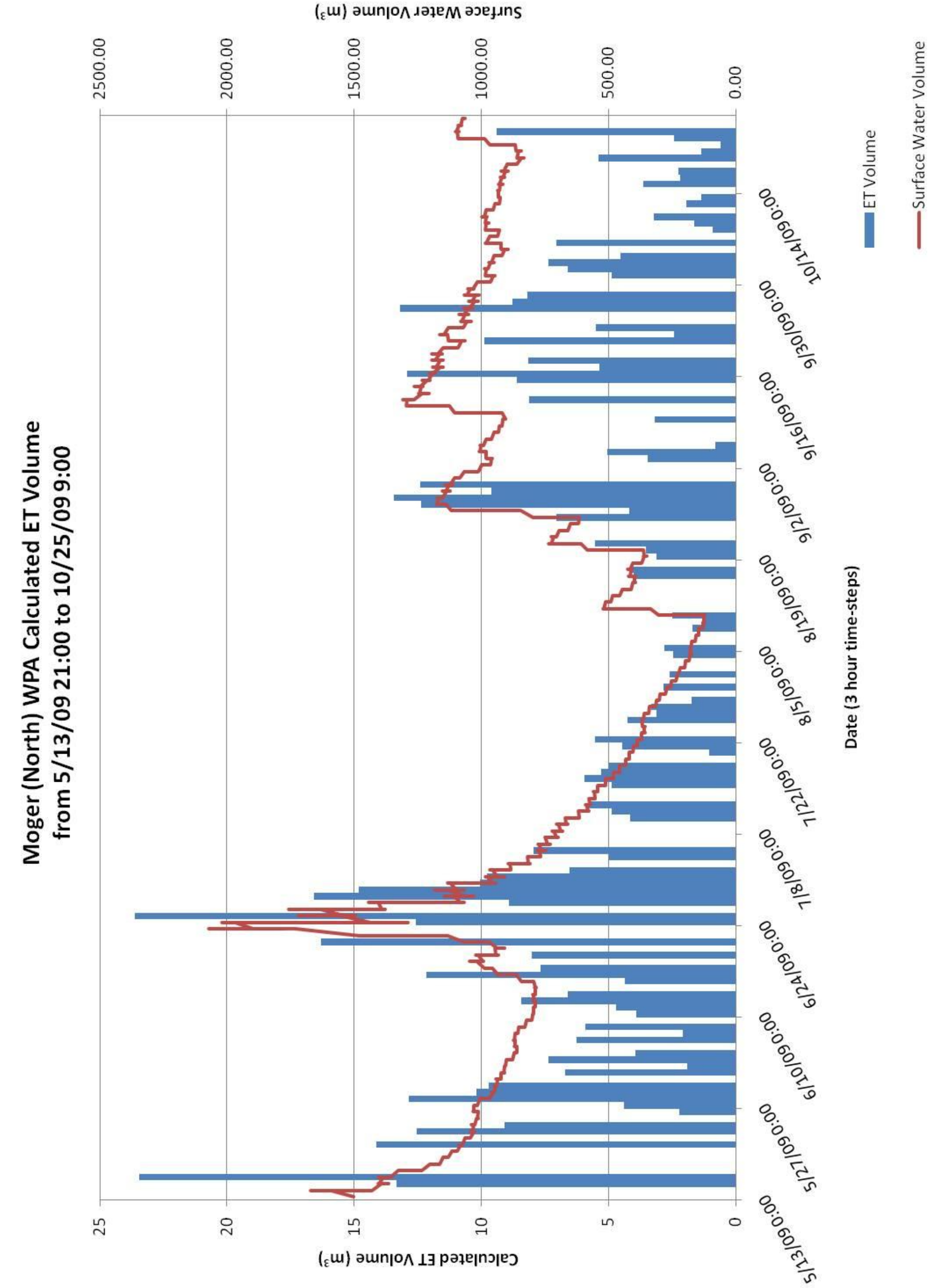


Figure 64: Calculated ET volumes time-series for Moger (North) WPA.

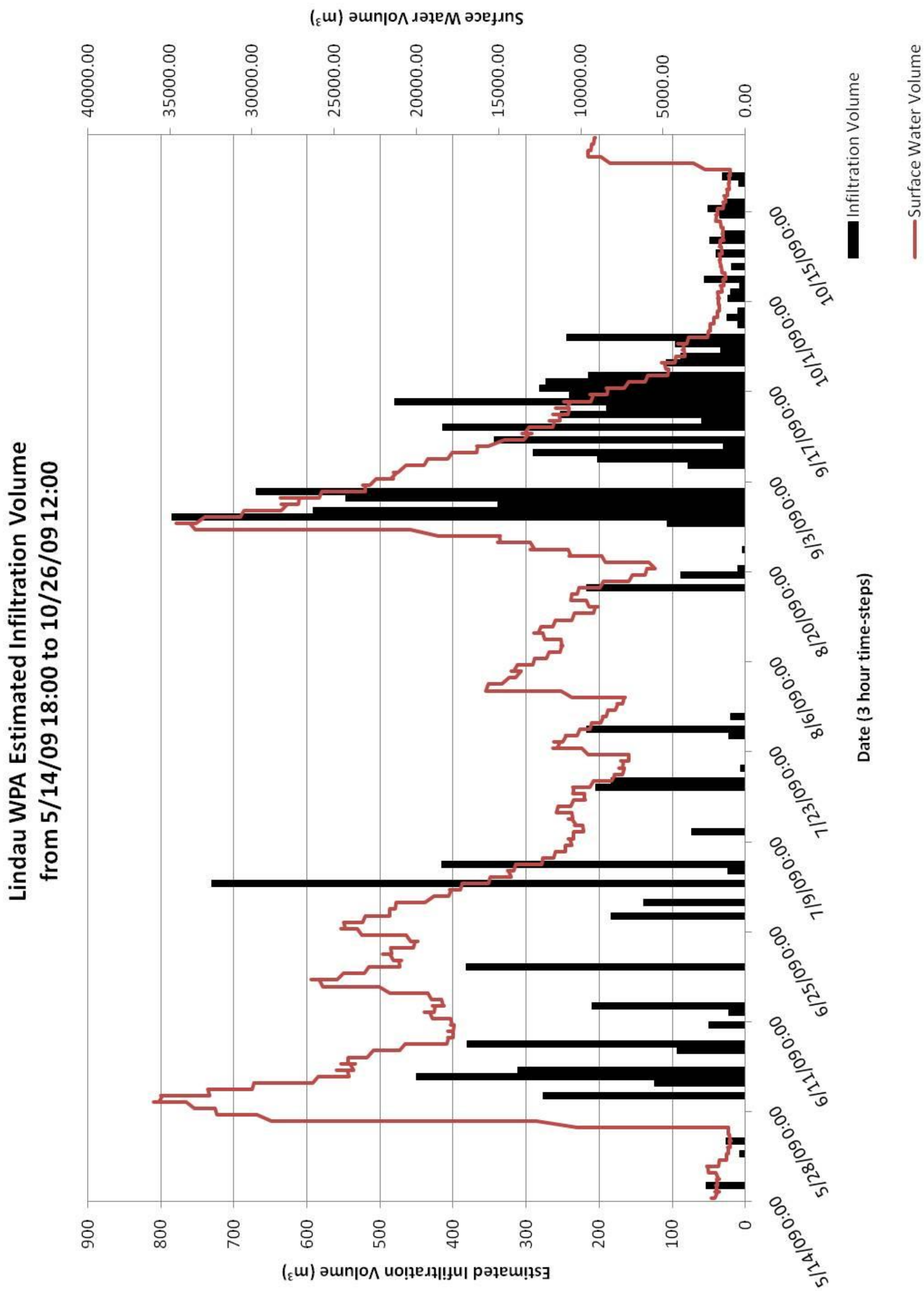


Figure 65: Estimated infiltration volumes time-series for Lindau WPA.

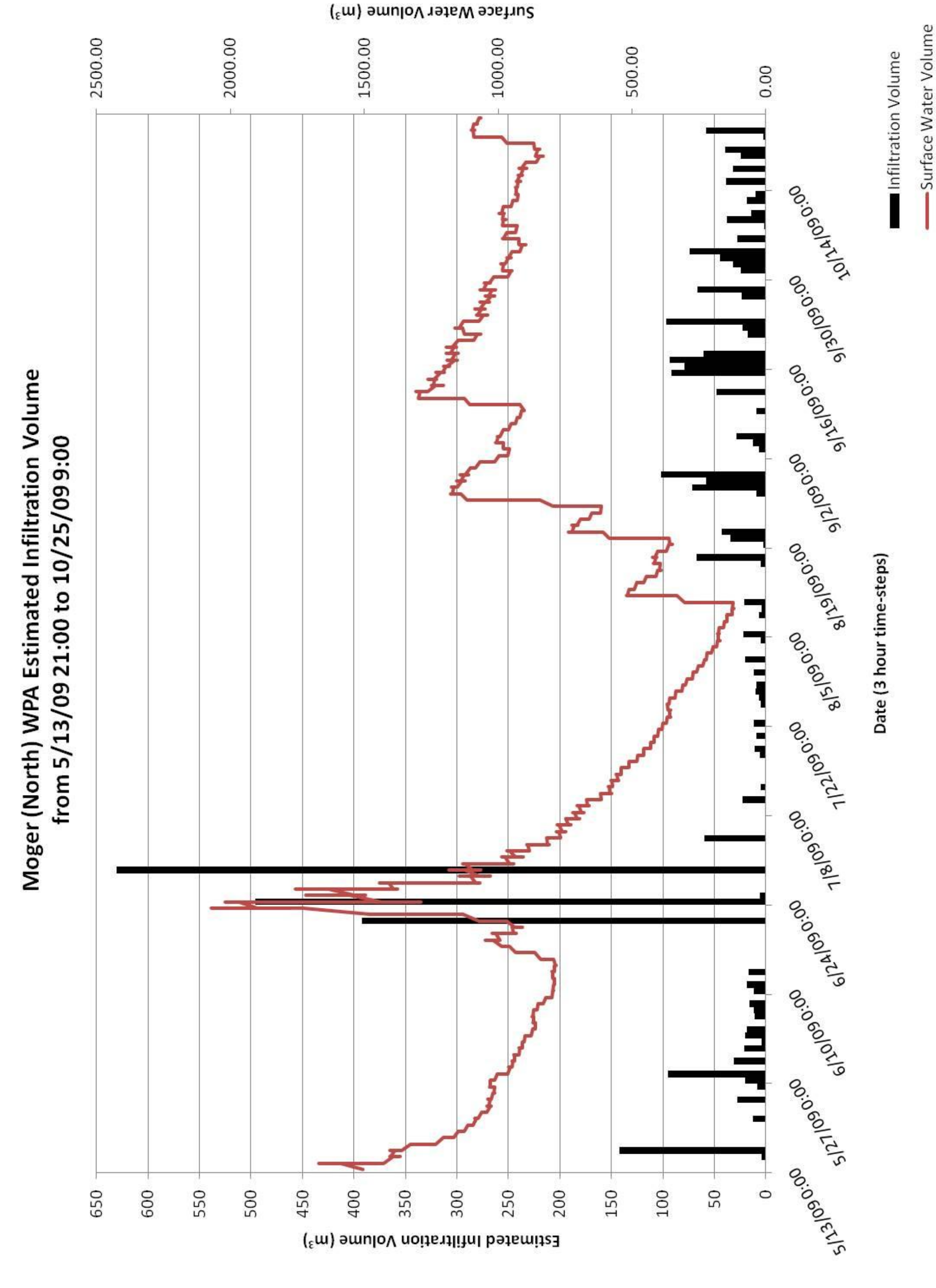


Figure 66: Estimated infiltration volumes time-series for Moger (North) WPA.

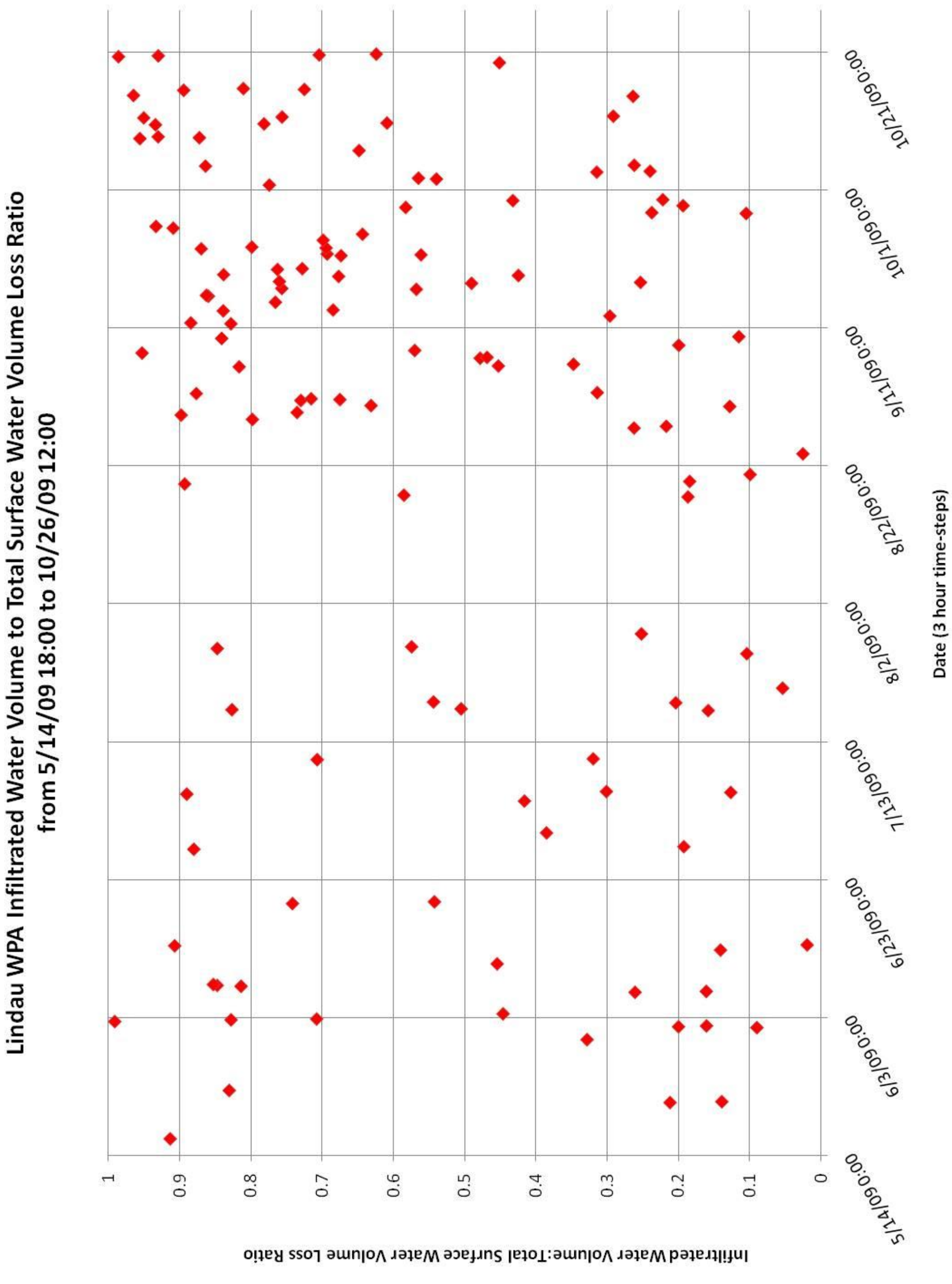


Figure 67: Lindau WPA infiltrated water volume to total surface water volume loss ratios.

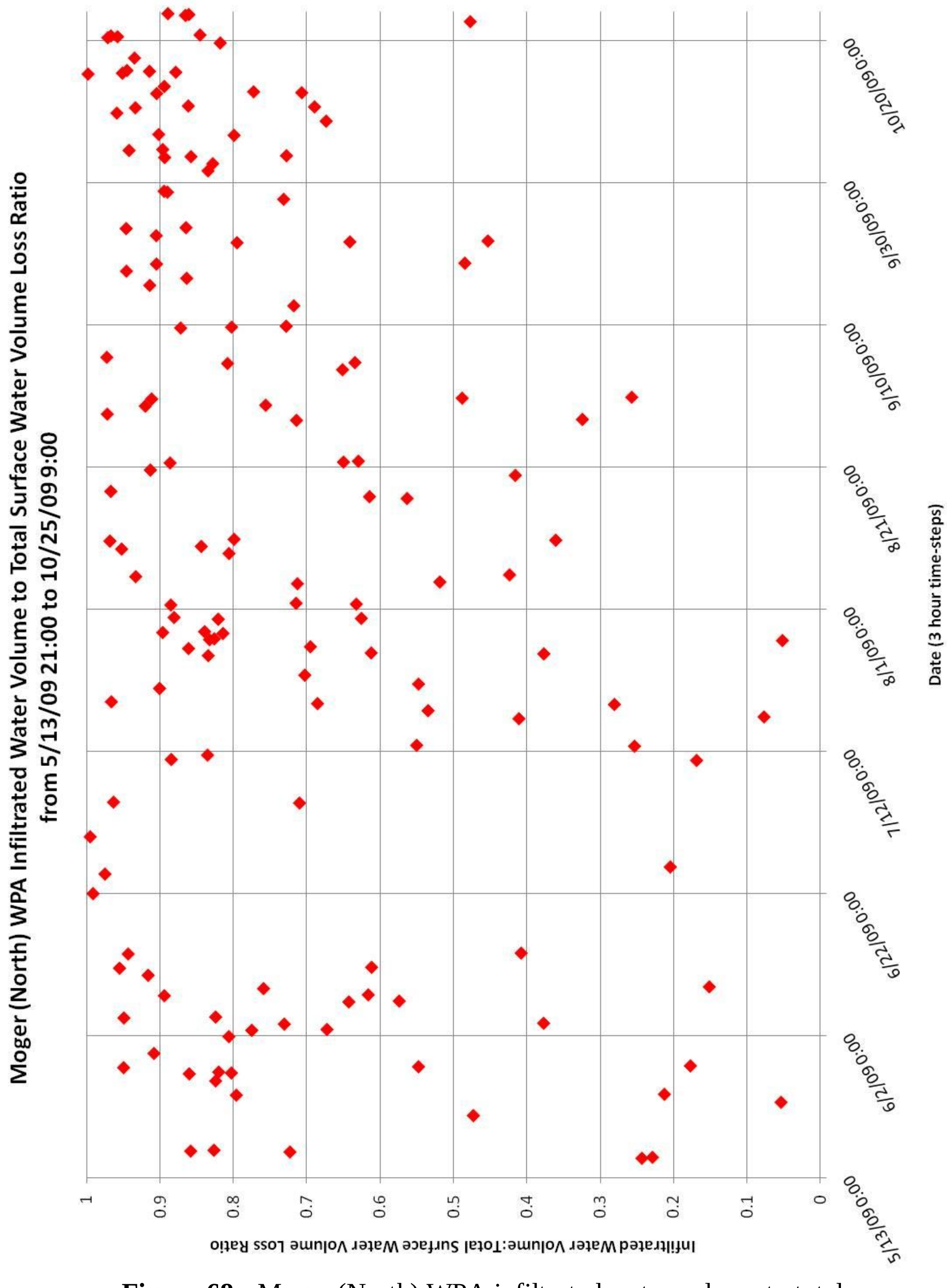


Figure 68: Moger (North) WPA infiltrated water volume to total surface water volume loss ratios.

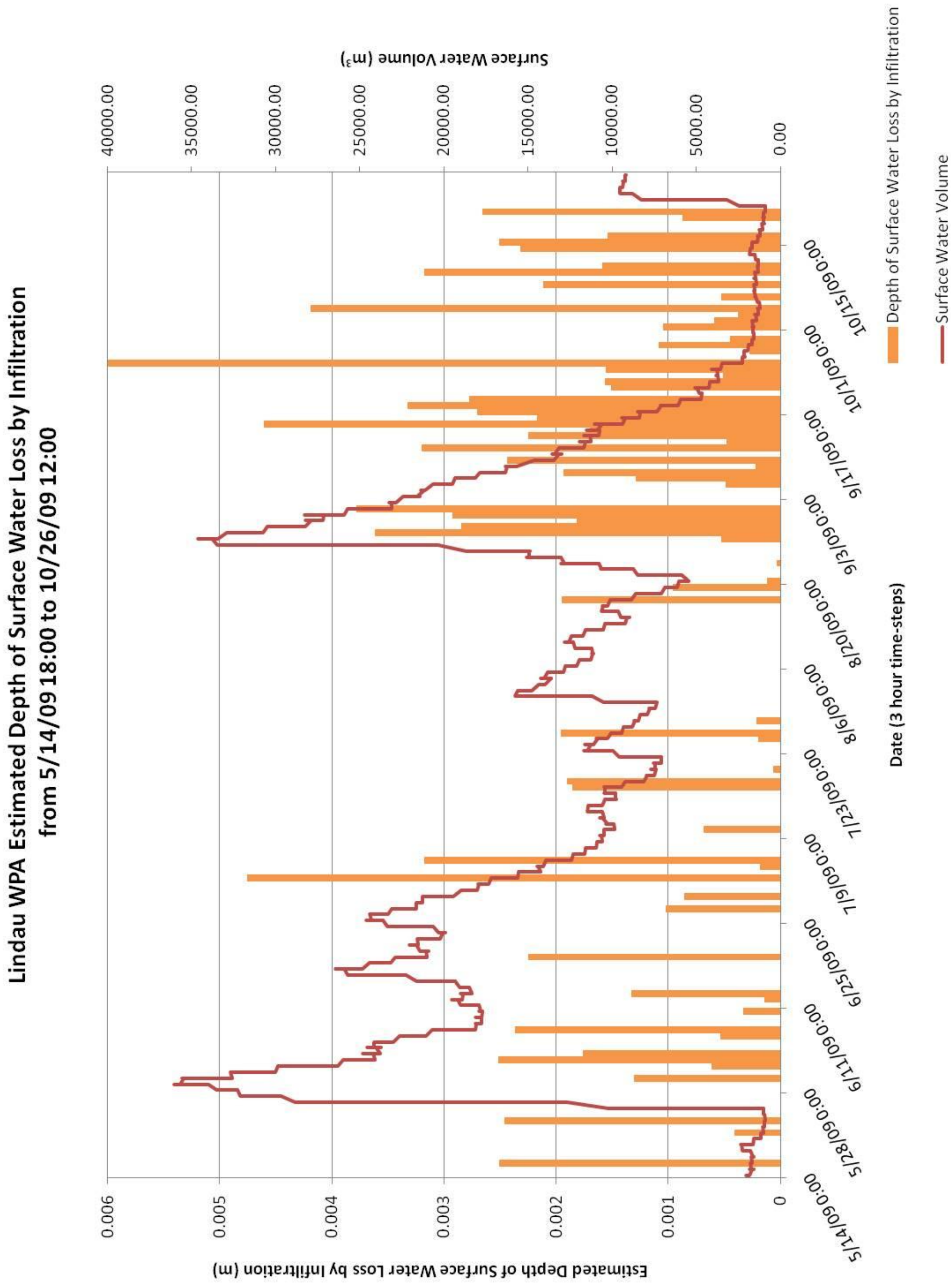


Figure 69: Estimated surface water loss depth to infiltration time-series for Lindau WPA.

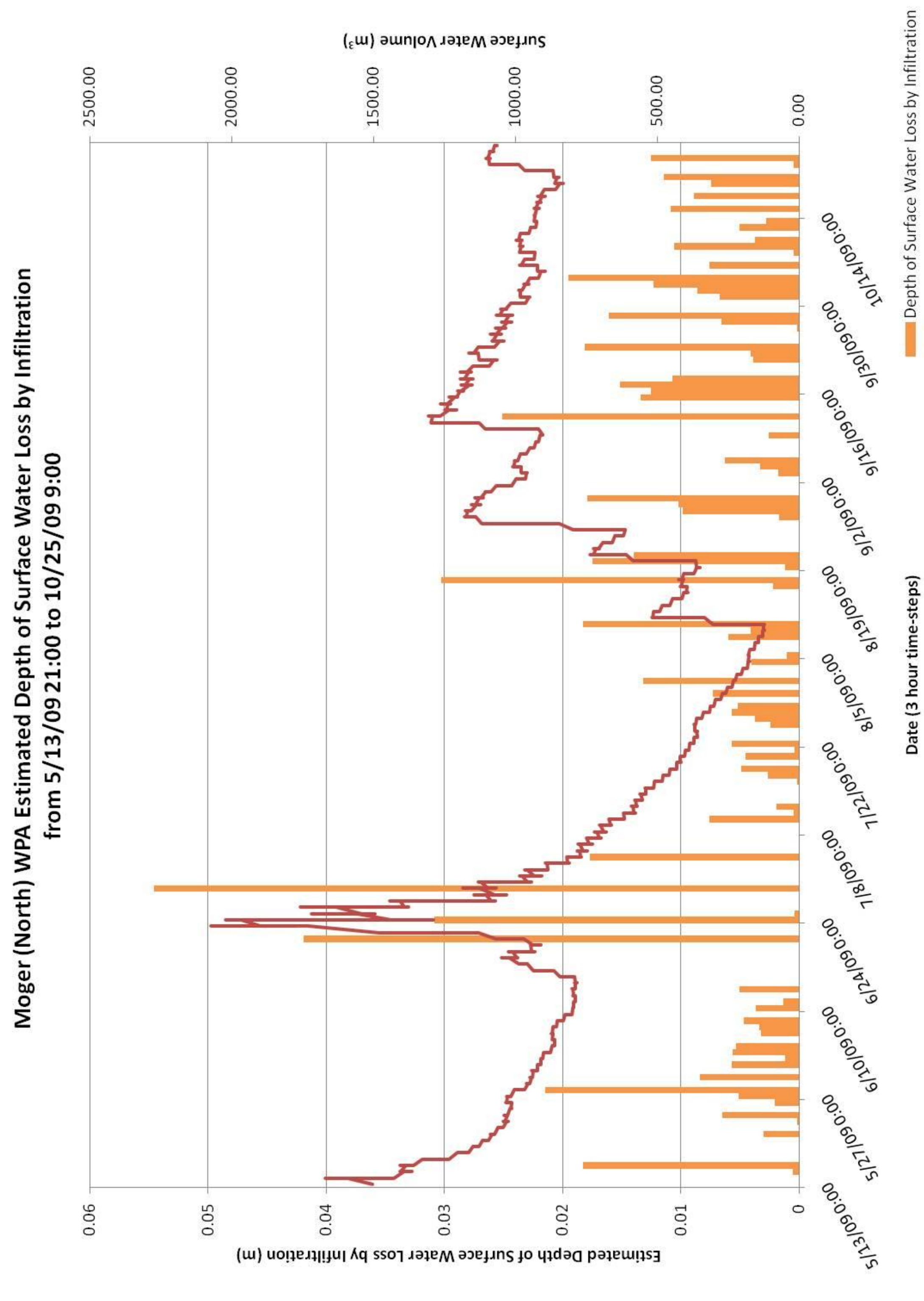


Figure 70: Estimated surface water loss depth to infiltration time-series for Moger (North) WPA.

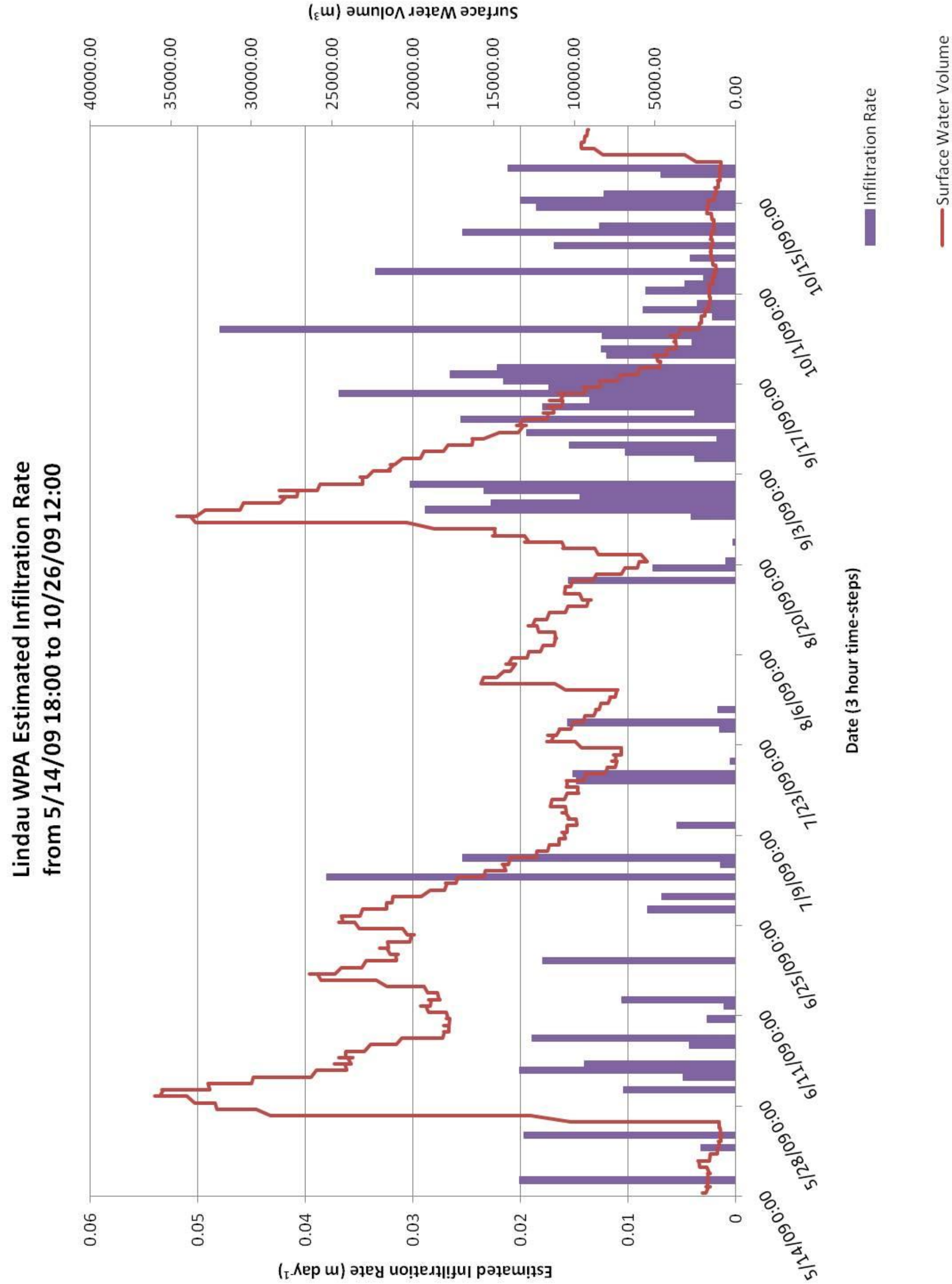


Figure 71: Estimated infiltration rate time-series for Lindau WPA.

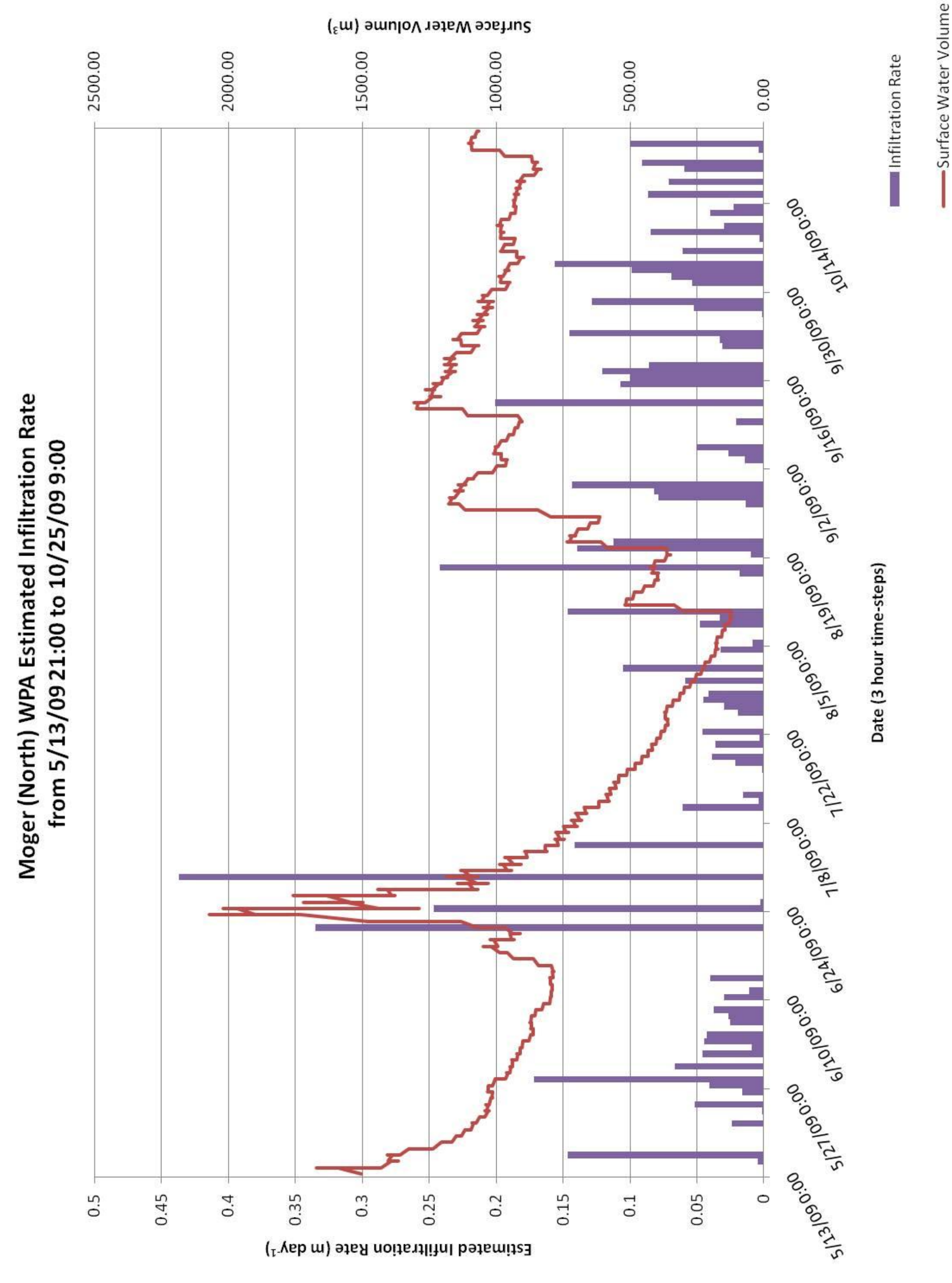


Figure 72: Estimated infiltration rate time-series for Moger (North) WPA.

5.0 DISCUSSION

The data obtained from Lindau WPA, Moger (North) WPA, and Griess WPA help provide insight on the hydrologic behavior of Rainwater Basin wetlands. Climate plays an important role in the hydroperiods of these wetlands. Water levels are highly dependent on precipitation occurring within the region. Since these three wetlands are closed basins, precipitation and runoff within the basin are typically the only sources of water. Snow melt and precipitation events in spring and fall can add significant volumes of water to a wetland site. During the dry months of July through September, precipitation was sporadic and limited. This allowed for the storage of water in the wetland to typically decrease. As can be seen between the years 2008 and 2009, the dichotomy of precipitation provided to a site had an enormous impact on the hydroperiod. During 2008, Moger (North) WPA and Griess WPA maintained high water volumes due to significant precipitation. However, in 2009 these two sites were either dry or had very low surface water volumes. Lindau WPA showed a different trend where less volume was maintained in the wetland during 2008 than in 2009. However, in the case with Lindau WPA, it does not appear to be how much water may be supplied to the wetland during the year, but the timing and magnitude of the precipitation event or events. A single event, such as what occurred on 8/26/09 at Lindau WPA, changed the dynamics of the wetland from a site which appeared to be on course to drying out into a site having a significant surface water volume in late August and early September.

ET is an important function at removing water from these wetlands. Based on the data obtained from Lindau WPA and Moger (North) WPA, ET will be most significant in May and June due to the increasing availability of solar radiation in these months. Water volume extraction by ET will be higher in May and June compared to the rest of the year considering if the water volume is maintained the same throughout the year with the same amount of surface area. However, changes to the water surface area can alter the volume of water extracted by ET. An increased surface water volume implies increased area at the air-water interface. This allows for more potential that water can be removed via ET. If surface water volumes decrease, which also decreases surface area exposed to the atmosphere; this will result in less water being directly removed from the wetland surface water body by ET.

Rapid increases of water volume can be related to most large, daily precipitation events. However, due to the dynamic nature of wetland sediments, a significant portion of the precipitation volume may rapidly infiltrate. The desiccated nature of dry sediments allows for extensive pores for rapid infiltration. The sediments may delay water ponding on the soil surface as well as delay runoff from higher in the basin. Once the sediments have become saturated, the soil cracks would “seal” and infiltration appeared to be governed by the hydraulic conductivity of the soil and the pressure head of the overlying water body. This phenomenon was most evident during the two precipitation events that occurred on Lindau WPA in October of 2008. The initial event lost a significant portion to rapid infiltration. This was evident by both the lack of volume being stored in the wetland water body and the rapid increase in the drive-point water levels. The event appeared to have saturated the soil sediments which aids in decreased infiltration and increases potential runoff. This was probably the mechanism that allowed for an increase in surface water volume as a result of the smaller, consecutive precipitation events. The infiltration process discussed here is documented in research from the Southern High Plains playa system. Gurdak and Roe (2009) summarized this research and discuss infiltration rates as three stages. Stage I is high infiltration due to desiccation cracks providing preferential flow. Stage II is where the cracks begin to close and soil moisture increases which causes infiltration rates to decrease. Stage III is where infiltration is considered to occur at a semi-constant flux that is governed by the saturated hydraulic conductivity of the sediments. Stage I infiltration is relatively short since increasing soil moisture causes the vertic soils to swell and eventually seal. During stage I infiltration, the cracks expose more of the soil matrix surface area to water. Saturation of the soil matrix may occur at the bottom and on the walls of the crack (Favre, Boivin, & Wopereis, 1997). According to Favre, Boivin, and Wopereis (1997) on crack closure in vertic soils, soil cracks sealed at about 4.5 hours after water application filled the cracks, initially, with the closure occurring from the soil surface and proceeding to the bottom of the crack. Even though crack closure occurred, the “soil islands” that were initially between cracks still remained unsaturated (Favre, Boivin, & Wopereis, 1997). This period where crack closure has occurred, but the soil matrix is still unsaturated may be indicative of stage II infiltration. Stage III infiltration is the dominant form of the three because it occurs when the soils are sealed and water is ponded on a site for long periods of time (Gurdak & Roe, 2009). Until further investigation into how infiltration is partitioned between these three stages in both magnitude and length of stage, it is assumed that the estimated infiltration that was model is representative of stage III.

The three stage infiltration model is common in soils and is well documented in hydrology textbooks (Dingman, 2002). However, the three stage infiltration model described for the Southern High Plains playas must account for the rapid infiltration in stage one for not only the soil matrix, but also for the bypass flow that can occur as a result of the desiccation cracks in the vertic soils (Gurdak & Roe, 2009; Favre, Boivin, & Wopereis, 1997).

Stage III infiltration may be evident as one of the components seen in the quasi-steady state rate of daily surface water volume change. Before this steady state is reached, the decrease of surface water volume is higher in magnitude when preceded by a significant precipitation event. The added volume from the precipitation event allows for more of the wetland floor to be covered by ponded water. In most cases, this added surface area incorporated sediments that had low water contents and were highly desiccated. Preferential flow through cracks probably occurs initially. Once the sediments “seal”, flow will be dictated by the saturated hydraulic conductivity of the sediments and the head pressures of the ponded water. Since this newly added surface area was having water ponded on it, it can be assumed that the soil moisture regime is not as developed as that of a depression that has had water ponded over it for a longer period of time. Scanlon and Goldsmith (1997) witnessed this behavior in their applied bromide tracer tests. At their site, areas further away from the playa center that were dry and had desiccation cracks showed preferential flow requiring more time to pond over the site and less time to drain it when compared to the playa center. Assuming piston flow through the sediments, hydraulic gradients may be larger for this periphery region due to ponded water on the surface and a shallow wetting front when compared to the depression. This increased hydraulic gradient may aid in rapid removal of water from the surface volume. As soil moisture increases, the wetting front gets deeper, and the surface water heads decrease, water losses to infiltration will decrease due to the decrease in the hydraulic gradient over these periphery sediments. However, this is one component to the rapid decrease in surface volume seen after a precipitation event. Increased pressure head would occur in parts of the wetland where water was already ponded before the precipitation event. This will increase hydraulic gradients at these spots which would increase infiltration flux. However, this may be minimal. Scanlon and Goldsmith (1997) noticed that water potential gradients were close to zero in their research playa. They concluded that the gradients are negligible and that flow is gravitationally driven. Thus, infiltration flux can be estimated by the hydraulic conductivity of the sediments. However, this does not take into account preferential flow (Scanlon & Goldsmith, 1997). The variability of the infiltration fluxes across the wetland floor at these Rainwater Basin sites has not been determined at this time nor have hydraulic conductivity measurements of the soils been performed. Another component that could result in the rapid decrease of surface water volume can be related to the added surface area over which ET has the ability to extract more water which was discussed earlier in the section.

The methodology used for obtaining infiltration estimates was a water balance approach. This approach has been criticized for the errors that can develop when trying to estimate infiltration or recharge to an aquifer (Gurdak & Roe, 2009). It appears that most of the error in the calculations is the result of the surface water volume and area estimation. To carry out the water balance approach, a highly accurate and precise survey of Rainwater Basin wetlands is necessary. Wetland floors can have very low relief. Thus, very minor changes in water levels can result in significant changes in water volume or surface area. Also, false readings of water surface levels can occur due to processes such as wave action. Oscillations of the water level that are being measured by a pressure transducer can have significant impact on the estimated volumes and surface areas when water is extended over the lower gradient portions of the wetland floor. To possibly overcome the issues of the pressure transducer measuring water level oscillations would be to locate the stilling well near vegetation of the wetland. The vegetation may act as a windbreak on the water surface which will create calmer waters. This may provide a more consistent water level reading than what would occur in open waters where undulation of the water surface may occur.

Modeled infiltration volumes follow a logical trend where high water volumes stored on the surface will result in more volume infiltrating. However, when trying to obtain water loss depths to infiltration, it appears some assumptions fail when carrying out the model. It is incorrect to assume that infiltration rate would be evenly distributed across the soil surface that has water ponded upon it. From the modeled water loss depths on Lindau WPA, it appears that infiltration magnitude is greater in the deeper portions of the site. This was evident by the increase in water loss depth when the volume of surface water decreased. It should be assumed that increased surface volumes would create increased water loss depths due to increased pressure heads. However, the depths were smaller under large surface volumes because of the assumption of evenly distributed infiltration. In reality, a significant portion of the infiltrated volume was probably occurring over a small portion of the wetland floor. The water loss depths determined during the periods when surface water volume was low may be more reflective of actual infiltration depths or rates. It is probable that the infiltration rates estimated at Lindau WPA may still underestimate true values. However, it is not known at this time how infiltration fluxes are distributed across the wetland sediment surface when ponded with water. It can only be assumed that the majority of water loss to infiltration was possibly occurring in the depressions found on Lindau WPA and Moger (North) WPA.

It has been hypothesized by individuals living in the region that ET is the dominant mechanism for removing surface water from Rainwater Basin wetlands. This was based on the assumption that wetland sediments retard flow which allows for the ET rate to be several orders of magnitude greater than infiltration. Based on this thesis' methodology, it appears that surface water losses occur as infiltration more than ET. At Moger (North) WPA, ET had some influence at removing water in early spring and summer. However, as available energy decreases as the year progresses, most surface water loss occurred as infiltration. This could also be a result of the limited surface area of water exposed to the atmosphere. The water was maintained within the depression during most of the monitoring period. A combination of the limited surface area and the larger depths that could be provided while still keeping the water volume within the depression allowed for decreased ET while potentially increasing infiltration. It was also more apparent that water loss by infiltration is greater than ET at Lindau WPA. This was based on the ratios of infiltrated water volume to total surface water volume loss being more frequently above 0.5 throughout the monitoring period.

6.0 CONCLUSIONS

This study determined and investigated the hydroperiods and the impacts of precipitation, ET, and infiltration on Rainwater Basin wetlands in south-central Nebraska. The wetlands are located in closed basins where the wetland floor is the terminus for runoff from the upland. With no stream input or outputs and significant depths to groundwater, these basins are highly dependent on precipitation to maintain surface water levels. Increases of surface water volumes are dependent on the timing and magnitude of the precipitation event as well as the sediment's soil water content. Dry, desiccated wetland sediments can retain significant portions of water and focus it deep into the sediments due to preferential flow along the cracks. Depending on the extensiveness of these cracks as well as the magnitude of the precipitation event will determine how much water may be maintained at the surface.

It has been assumed that these wetlands were losing water primarily by ET alone. Due to the low conductivity of the wetland sediments when saturated, it was believed that the rate of ET was several orders of magnitude greater than infiltration. However, from this research, it appears that infiltration can remove a significant portion of water from surface storage compared to ET. ET may dominate water removal in early spring and summer due to increased solar radiation, but becomes limited in late summer and early fall because solar radiation is decreasing. However, water loss by ET is not just energy based, but also a product of the wetland shape. Wetland shape influences the surface area of the water. Reduction of surface area exposed to the atmosphere will decrease the impact of water loss by ET while a larger surface area will cause greater water loss. This was the case of the larger, flat wetland of Lindau WPA having more water loss by ET than the deeper, bowl-shaped wetland of Moger (North) WPA.

Infiltration seems to be a large sink for surface water when compared to ET. At the deepest points of the wetland site, infiltration appears to be occurring, but possibly at a flux similar to the hydraulic conductivity of the sediments. Hydraulic gradients underneath the low point of the wetland may have time to mature where flow becomes gravitational. Infiltration on the periphery may have initially higher fluxes when ponded upon after a significant period of lacking moisture. Unlike the deep portions of the wetland, hydraulic gradients may be steep in these periphery sediments initially due to the shallow depth that may occur between a ponded water head (positive) and the drier soil pressure head (negative). This theory may account for the rapid water loss from the surface water after a large increase resulting from a precipitation event. Over time the hydraulic gradient of the periphery portions of the site may develop which will decrease infiltration to a rate similar to the hydraulic conductivity of the sediments. Based on the modeling of infiltration at Lindau WPA, infiltration volume is not distributed evenly across the surface water area. A significant portion of infiltrated volume may be focused in the deeper portions of a site. Potential gradients and an understanding of infiltration fluxes across the wetland floor will aid in separating these processes.

7.0 RECOMMENDATIONS FOR FURTHER STUDY

After completing this study of the Rainwater Basin wetlands, new questions have developed about the processes at work. Further study and analysis of these new research perspectives as well as processes not studied in the initial project should occur. This chapter will highlight some important aspects that should be looked at in order to obtain a greater understanding of the hydrologic behavior of these sites.

7.1.0 Evapotranspiration

This study only discussed ET for a period in 2009. Data will be collected on weather stations through August 2010. This added data should be analyzed in order to determine how ET trends may vary from year to year. Also, vegetative cover can dramatically change from site to site as well as from year to year. These changes could have a major impact on the rate of water loss by ET. Does the rate of open-water evaporation exceed, equal, or be less than the transpiration rate of wetland vegetation? How does vegetation affect the transfer of energy near the air-water interface? Partitioning of evaporation and transpiration rates may aid in the understanding of how these systems react to atmospheric stimuli causing water loss. The impact of grazing or burning of these sites may limit or increase the potential of water loss to the atmosphere if there are dynamic changes to vegetation in coverage and species because of these practices. Also, according to Sánchez-Carrillo et al. (2004), there is a correlation between water volume and vegetation type present. The wetland water volume in early spring may dictate the dominant vegetation for the growing season and the resulting transpiration rate.

7.2.0 Water Balance Approach

The water balance approach was used to try to estimate infiltration. However, runoff from the uplands was not quantified. This reduced the water balance to only periods when precipitation had not occurred. Instituting methods to get a grasp of runoff rates will aid in the water balance approach and allow more data to be analyzed and allow for better models to be developed. Due to the dynamic nature of soils on the wetland floor and dry soil conditions in the uplands that sometimes occur, runoff rates may be highly variable. Several studies may need to occur when measuring runoff to account for the changes that can occur with vertic soils. The runoff discussed here involves both precipitation derived and irrigation derived. As was seen in the data for surface water volumes, most of the increases were attributed to precipitation and its assumed runoff. However, several of these basins have irrigation occurring in the uplands or have groundwater pumped onto the sites directly. A better understanding of how much irrigation runoff reaches the wetland may help in the understanding of how each site's water volume is being maintained anthropogenically. This will also aid in understanding agriculture contaminant runoff from adjacent cropped fields and the timing of possible contaminant pulses.

7.3.0 Infiltration

Infiltration was modeled by using surface water volumes and ET data in the water balance approach. However, independent verification of infiltration values still need to occur. Infiltrometer studies will be useful in focusing in on a range of values that may represent the wetland floor sediments. These tests should try to cover the whole range of infiltration that can occur from a dry, desiccated soil to a wet, "sealed" soil. It should be determined what magnitudes are arising between the stage I infiltration and stage III infiltration. Along with understanding the rate of infiltration in stage I, it is important to understand when this stage ends. When will crack closure occur and at what soil moisture may be necessary for this to happen? This could be an important tool for managers of the site who pump groundwater in order to maintain surface water volumes. It may aid in their calculations of water loss to infiltration or how long they will need to pump to meet their storage limits. During stage II and III infiltration, it would be interesting to see how hydraulic gradients change due to influences of the overlying water body and the changes of soil moisture that may result from the presence of that water body. The use of matric potential sensors could be inserted vertically into the sediments at various points throughout the wetland. This will aid in the understanding of unsaturated flow through the sediments and may help in understanding wetting front development. It could be used to calculate infiltration fluxes and determine when or if flow into the sediments approaches the hydraulic conductivity of the soils.

During this study, data was collected from soil moisture sensors that were vertically inserted into the soil profile at Lindau WPA and Moger (North) WPA. The data were not presented in this thesis. However, it appears that there might be a time where there is significant infiltration that may occur when soil moisture thaws out. Deeper sensors saw rapid soil moisture increases when a surface soil layer increased above the freezing point. This occurred in early March 2009 for both sites. Infiltration may be low or even negligible due to frozen soils in these basins. Over the winter, sediments below the frozen surface layer may have become drier due to redistribution of the soil water there. Hydraulic gradients may be large between the dry sediments and the ponded surface water body, but flow is restricted by the frozen soil layer. Once thawing of the soil occurs, this restriction was removed which allowed for initial rapid infiltration. This could be an important infiltration phenomenon occurring within these wetlands and may be necessary to understand when determining recharge to the underlying aquifer.

7.4.0 Recharge

The major intent of the overall research project was to quantify recharge to the underlying aquifer. Due to the large unsaturated zone, the estimated infiltration rates from this study do not necessarily equate to a recharge rate. It is important to understand the redistribution properties within the unsaturated zone. The infiltrated water may be taken up by vegetation, move laterally to drier sediments on the wetland periphery, be removed by direct soil evaporation, or it could move deep into the soil profile. A physical and chemical approach may be used concurrently to derive a solution for flow beneath the wetlands. The matric potential sensors mentioned previously may aid in understanding this redistribution process. Direction of water flow could be inferred from these sensors. They may be key in understanding whether water flow is downwards (drainage), upwards (ET), or is lateral. Next, excavation of several intact sediment columns using a Geoprobe® near the wetland center, on the wetland edge, and possibly in the uplands will also help in understanding the flow dynamics within and outside the wetland floor. Measuring water potentials in the lab based on the method described by Scanlon and Goldsmith (1997) may give an indication of if flow is directed downward or upward. Along with the water potential analysis, the chloride mass-balance approach and isotope data of pore water from these sediment columns could aid in determining possible rates of recharge to the aquifer.

The research to this point will only be able to describe shallow processes of the wetland floor. The previous suggestions can be future routes for investigations within the Rainwater Basin wetlands. Implementing these techniques will aid in the understanding of the wetlands and to validate outputs that were obtained from this research study.

8.0 REFERENCES

Autodesk, Inc. 2011. *AutoCAD Civil 3D 2011 User's Guide*. Retrieved from http://docs.autodesk.com/CIV3D/2011/ENU/indexMadRiverCUG.html?url=./filesMadRiverCUG/WS1a9193826455f5ff5cf1d02511b1d00097820b3.htm,topicNumber=MadRiverCUGd0e93575 (Accessed July 2010).

Bagarello, V., M. Iovino, & W.D. Reynolds. 1999. Measuring Hydraulic Conductivity in a Cracking Clay Soil Using the Guelph Permeameter. *American Society of Agricultural Engineers* 42, no. 4: 957-964.

Brakke, T.W., S.B. Verma, & N.J. Rosenberg. 1978. Local and Regional Components of Sensible Heat Advection. *Journal of Applied Meteorology* 17: 955-963.

Bronswijk, J.J.B., W. Hamminga, & K. Oostindie. 1995. Field-scale solute transport in a heavy clay soil. *Water Resources Research* 31, no. 3: 517-526.

Burba, G.G., S.B. Verma, & J. Kim. 1999. Surface energy fluxes of *Phragmites australis* in a prairie wetland. *Agricultural and Forest Meteorology* 94: 31-51.

Conservation and Survey Division (CSD). 2010. *UNL School of Natural Resources Conservation and Survey Division website*. Retrieved from http://snr.unl.edu/csd/ (Accessed January 2010).

Dingman, S.L. 2002. *Physical Hydrology (2nd ed.)*. Long Grove, IL: Waveland Press, Inc.

Ekstein, J.D., S.E. Hygnstrom. 1996. Fate of Wetlands Associated with the Central Nebraska Irrigation Canal System. *Great Plains Research* 6: 41-60.

Favre, F., P. Boivin, & M.C.S. Wopereis. 1997. Water movement and soil swelling in a dry, cracked Vertisol. *Geoderma* 78: 113-123.

Foster, S. 2010. Temporal and Spatial Variations of Ions, Isotopes and Agricultural Contaminants in Surface and Groundwaters of Nebraska's Rainwater Basin Wetlands. M.S. thesis, Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Nebraska, 171 p.

Global Energy Concepts, Inc. 1999. *Nebraska Wind Energy Site Data Study: Final Report.* Retrieved from http://www.nlc.state.ne.us/epubs/E5700/B047-1999.pdf (Accessed May 2010).

Gurdak, J.J. & C.D. Roe. 2009. Recharge Rates and Chemistry Beneath Playas of the High Plains Aquifer – A Literature Review and Synthesis. *U.S. Geological Survey Circular* 1333, 39 p.

Haukos, D.A. & L.M. Smith. 2003. Past and Future Impacts of Wetland Regulations on Playa Ecology in the Southern Great Plains. *Wetlands* 23, no. 3: 577-589.

High Plains Regional Climate Center (HPRCC). 2010. *Online Data Service*. Retrieved from http://www.hprcc.unl.edu/ (Accessed January 2010).

Keech, C.F. & V.H. Dreeszen. 1959. Geology and Ground-Water Resources of Clay County, Nebraska. *U.S. Geological Survey Water-Supply Paper* 1468, 163 p.

Keech, C.F. & V.H. Dreeszen. 1968. Geology and Ground-Water Resources of Fillmore County, Nebraska. *U.S. Geological Survey Water-Supply Paper* 1839-L, 34 p.

Kuzila, M.S. & D.T. Lewis. 1993. Properties and Genesis of Loessial Soils across a South-Central Nebraska Basin. *Soil Sci. Soc. Am. J.* 57: 155-161.

Kuzila, M.S. 1994. Inherited Morphologies of Two Large Basins in Clay County, Nebraska. *Great Plains Research*. 4:51-63.

LaGrange, T. 2005. *Guide to Nebraska's Wetlands and Their Conservation Needs (2nd Ed.)*. Nebraska Game & Parks Commission Publication.

Lugn, A.L. & L.K. Wenzel. 1938. Geology and Ground-Water Resources of South-Central Nebraska: With Special Reference to the Platte River Valley Between Chapman and Gothenburg. *U.S. Geological Survey Water-Supply Paper* 779, 275 p.

McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, & I.M. Verstraeten. 2003. Water in Storage and Approaches to Ground-Water Management, High Plains Aquifer, 2000. *U.S. Geological Survey Circular* 1243, 56 p.

McMahon, P.B., K.F. Dennehy, B.W. Bruce, J.K. Böhlke, R.L. Michel, J.J. Gurdak, & D.B. Hurlbut. 2006. Storage and transit time of chemicals in thick unsaturated zones under rangeland and irrigated cropland, High Plains, United States. *Water Resources Research* 42, W03413: 18 p.

Mitsch, W.J. & J.G. Gosselink. 2007. *Wetlands (4th Ed.)*. New Jersey: John Wiley & Sons, Inc.

Murkin, H.R. 1998. Freshwater Functions and Values of Prairie Wetlands. *Great Plains Research*. 8:3-15.

Nebraska Game & Parks Commission (NGPC) Proposal. 2007. Investigation of the role of Rainwater Basin wetlands in contributing to the functions of groundwater quality improvements and wildlife habitat, including an analysis of the impact of sediment on these functions. *EPA Region 7 Wetland Program Development Grant proposal*: FY 2007.

NEBRASKAland. 1996. *Nebraska's Rainwater Basin*. Nebraska Game & Parks Commission Publication.

Parkhurst, R.S., T.C. Winter, D.O. Rosenberry, & A.M. Sturrock. 1998. Evaporation from a Small Prairie Wetland in the Cottonwood Lake Area, North Dakota – An Energy-Budget Study. *Wetlands* 18, no. 2: 272-287.

Perez, P.J., F. Castellvi, M. Ibañez, & J.I. Rosell. 1999. Assessment of reliability of Bowen ratio method for partitioning fluxes. *Agricultural and Forest Meteorology* 97: 141-150.

Sánchez-Carrillo, S., D.G. Angeler, R. Sánchez-Andrés, M. Alvarez-Cobelas, & J. Garatuza-Payán. 2004. Evapotranspiration in semi-arid wetlands: relationships between inundation and the macrophyte-cover: open-water ratio. *Advances in Water Resources* 27: 643-655.

Saur, J.F.T. & E.R. Anderson. 1955. The Heat Budget of a Body of Water of Varying Volume. *U.S. Navy Electronics Laboratory Contributions Number* 41.

Scanlon, B.R. & R.S. Goldsmith. 1997. Field study of spatial variability in unsaturated flow beneath and adjacent to playas. *Water Resources Research* 33, no. 10: 2239-2252.

Schwab, G.O., D.D. Fangmeier, & W.J. Elliot. 1996. *Soil and Water Management Systems* (*4th ed.*). New York, NY: John Wiley & Sons, Inc.

Smith, L.M. 2003. *Playas of the Great Plains*. Austin, TX: University of Texas Press.

Sparks, D.L. 2003. *Environmental Soil Chemistry (2nd ed.)*. San Diego, CA: Academic Press.

Stannard, D.I., D.O. Rosenberry, T.C. Winter, & R.S. Parkhurst. 2004. Estimates of Fetch-induced Errors in Bowen-ratio Energy-budget Measurements of Evapotranspiration from a Prairie Wetland, Cottonwood Lake Area, North Dakota, USA. *Wetlands* 24, no. 3: 498-513.

Starks, P.J. 1984. Analysis of the Rainbasin Depressions of Clay County, Nebraska. M.S. thesis, University of Nebraska-Omaha, Nebraska, 90 p.

USDA-NRCS. 1999. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys (2nd ed.)*. Agriculture Handbook Number 436.

USDA-NRCS. 2010a. *Hydric Soils*. Retrieved from http://soils.usda.gov/use/hydric/ (Accessed January 2010).

USDA-NRCS. 2010b. *Official Soil Series Descriptions (OSD) with series extent mapping capabilities.* Retrieved from http://soils.usda.gov/technical/classification/osd/index.html (Accessed January 2010).

Wood, W.W., & W.E. Sandford. 1995. Chemical and Isotopic Methods for Quantifying Ground-Water Recharge in a Regional, Semiarid Environment. *Ground Water* 33, no. 3: 458-468.

Wood, W.W., K.A. Rainwater, & D.B. Thompson. 1997. Quantifying Macropore Recharge: Examples from a Semi-Arid Area. *Ground Water* 35, no. 6: 1097-1106.

Zartman, R.E., P.W. Evans, & R.H. Ramsey. 1994. Playa lakes on the Southern High Plains in Texas: Reevaluating infiltration. *J. Soil and Water Cons.* 49, no. 3: 299-301.

9.0 APPENDICES

Appendix A: Sensor Information

Site Name	DW1	DW2	DW3	DW4	DW5	SW
Lindau WPA	99°2'30.2"W 40°24'0.0"N	99°2'14.4"W 40°24'5.8"N	99°2'4.8"W 40°24'16.3"N	99°2'20.7"W 40°24'15.0"N	99°2'6.3"W 40°24'5.3"N	99°2'14.3"W 40°24'5.9"N
Moger (North) WPA	97°59'28.0"W 40°29'23.9"N	97°59'23.1"W 40°29'18.7"N	97°59'18.4"W 40°29'16.9"N	97°59'25.6"W 40°29'18.8"N	97°59'17.5"W 40°29'20.0"N	97°59'23.1"W 40°29'18.7"N
Griess WPA	97°46'35.2"W 40°34'57.9"N	97°46'31.8"W 40°35'1.3"N	97°46'29.3"W 40°35'5.4"N	97°46'33.0"W 40°35'5.6"N	97°46'30.1"W 40°34'57.0"N	97°46'31.8"W 40°35'1.3"N

A-1: Location of drive-point and stilling wells on each wetland.

Site Name	New DW2 (4/23/09)	New SW (4/23/09)
Moger (North) WPA	97°59'19.0"W 40°29'20.0"N	97°59'19.0"W 40°29'20.0"N

A-2: New location of DW2 and SW at Moger (North) WPA.

Wetland	Well	Screen Mid-Point Relative to Surface (m)
Lindau WPA	DW1	-0.76
	DW2	-0.74
	DW3	-0.76
	DW4	-0.76
	DW5	-0.76
	SW	0.09
	SW 3/17/09	0.06
Moger (North) WPA	DW1	-0.76
	DW2	-0.76
	DW3	-0.76
	DW4	-0.67
	DW5	-0.76
	SW	0.08
	DW2 4/24/09	-0.76
	SW 4/24/09	0.03
Griess WPA	DW1	-0.76
	DW2	-0.76
	DW3	-0.76
	DW4	-0.76
	DW5	-0.76
	SW	0.06

A-3: Mid-point depths of well screens relative to soil surface.

			Accuracy		Precision	
Sensor Type	**Sensor Model**	**Full Scale (FS)**	Level	Temperature	Level	Temperature
Solinst Levelogger Gold	LT F15/M5	5 m	+/- 0.3 cm	+/- 0.05°C	0.001% FS	0.003°C
Solinst Barologger Gold	LT F5/M1.5	1.5m	+/- 0.1 cm	+/- 0.1°C	0.002% FS	0.001°C

A-4: Pressure transducer type, accuracy, and precision information.

Instrument	Measurement	Real-Time Kinematic Surveying Precision
Epoch 25 L1/L2 RTK GPS System	Horizontal	+/- 10 mm + (1 ppm * baseline length)
	Vertical	+/- 20 mm + (1 ppm * baseline length)

A-5: Survey system type and measurement precision.

	Lindau	Moger (North)	Griess
Base Station Location	99°2'33.8"W 40°24'10.2"N	97°59'30.2"W 40°29'19.6"N	97°46'35.3"W 40°34'57.9"N
Base Station Surface Elevation (m)	640.3	508.3	490.7

A-6: Survey system base station location and measured surface elevation.

Sensor	Moger (North) WPA	Lindau WPA
Soil Temp. Probe	-10 cm	-10 cm
Temp./RH Probe 1	1.52 m	2.29 m
Temp./RH Probe 2	2.44 m	1.22 m
Wind Gage	1.83 m	1.83 m
Infrared Sensor	2.44 m	2.29 m
Pyranometer	2.44 m	2.29 m
Net Radiometer	2.44 m	2.29 m
Rain Gage	1.37 m	1.22 m
Location	97°59'19.4"W 40°29'20.8"N	99°2'14.0"W 40°24'7.8"N
Operational	5/13/09	5/14/09

A-7: Weather station sensor elevation (relative to soil surface), location, and operational date.

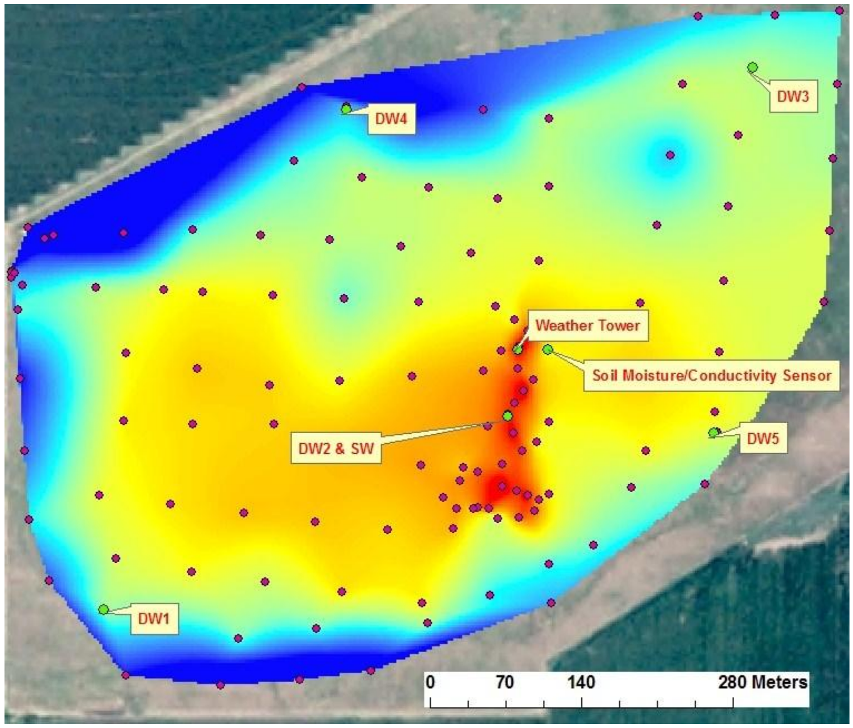
Degree Range Measured by Wind Vane		
From	**To**	**Direction**
337.51°	22.50°	North
22.51°	67.50°	Northeast
67.51°	112.50°	East
112.51°	157.50°	Southeast
157.51°	202.50°	South
202.51°	247.50°	Southwest
247.51°	292.50°	West
292.51°	337.50°	Northwest

A-8: Directional degree output of Met One Windset 034B vane and associated direction.

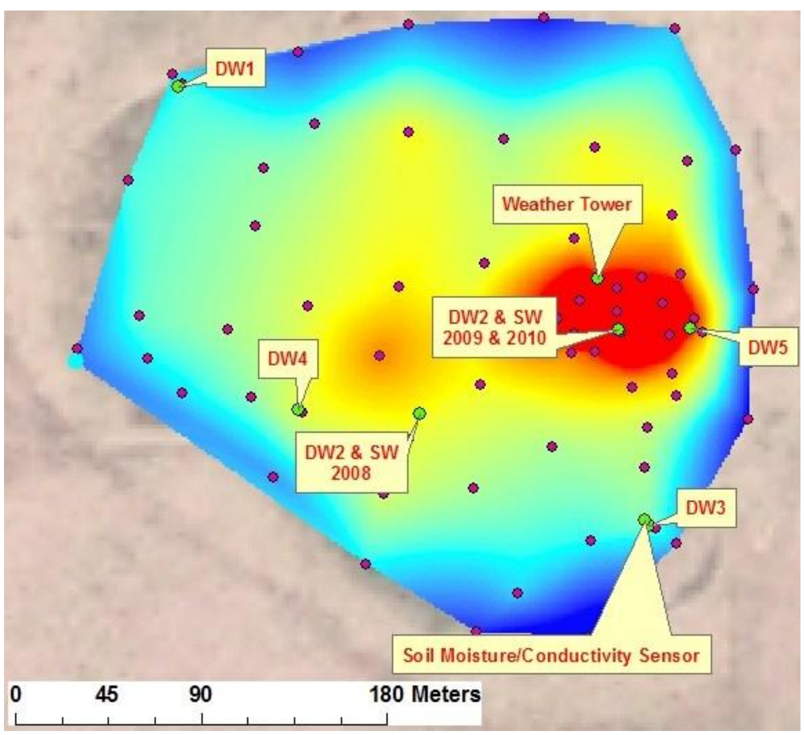
Measured Variable	Instrument	Range	Accuracy/Precision	Threshold
Wind Velocity/Direction	Met One Wind Set 034B Anemometer & Vane	0 to 50 m s^{-1}; 0 to 360°	+/- 0.11 m s^{-1}; +/- 4°	0.4 m s^{-1}
Air Temperature & Relative Humidity	Vaisala Temp./RH probe HMP45C	-40 to +60°C; 0 to 100%	+/- 0.2°C; +/- 1%	
Atmospheric Pressure	Setra 278 Barometer CS100	600 to 1100 mb	+/- 0.5 mb	
Soil Temperature	Campbell Scientific Temperature Probe 107-L	-35 to +50°C	+/- 0.01°C	
Water Surface Temperature	Apogee Infrared Radiometer IRR-P	-55 to +80 °C	+/- 0.2°C	
Incoming Solar Radiation	Kipp & Zonen Pyranometer CMP3	0 to 2000 W m^{-2}	5 to 20 µV per W m^{-2}	
Net Radiation	Kipp & Zonen Net Radiometer CNR2	0 to 2000 W m^{-2}	10 to 20 µV per W m^{-2}	
Precipitation	Texas Electronics Rain Gage TE525MM	> 0 mm	+/- 1%	0.1 mm per tip
Precipitation	Texas Electronics Rain Gage TE525	> 0 mm	+/- 1%	0.254 mm per tip
Datalogger	Campbell Scientific CR1000			
Power System	Campbell Scientific 65 W Solar Panel; Morning Star SunSaver-10 regulator; 12 V lead-acid battery			

A-9: Type, range, accuracy, precision, and threshold information for sensors used on weather station

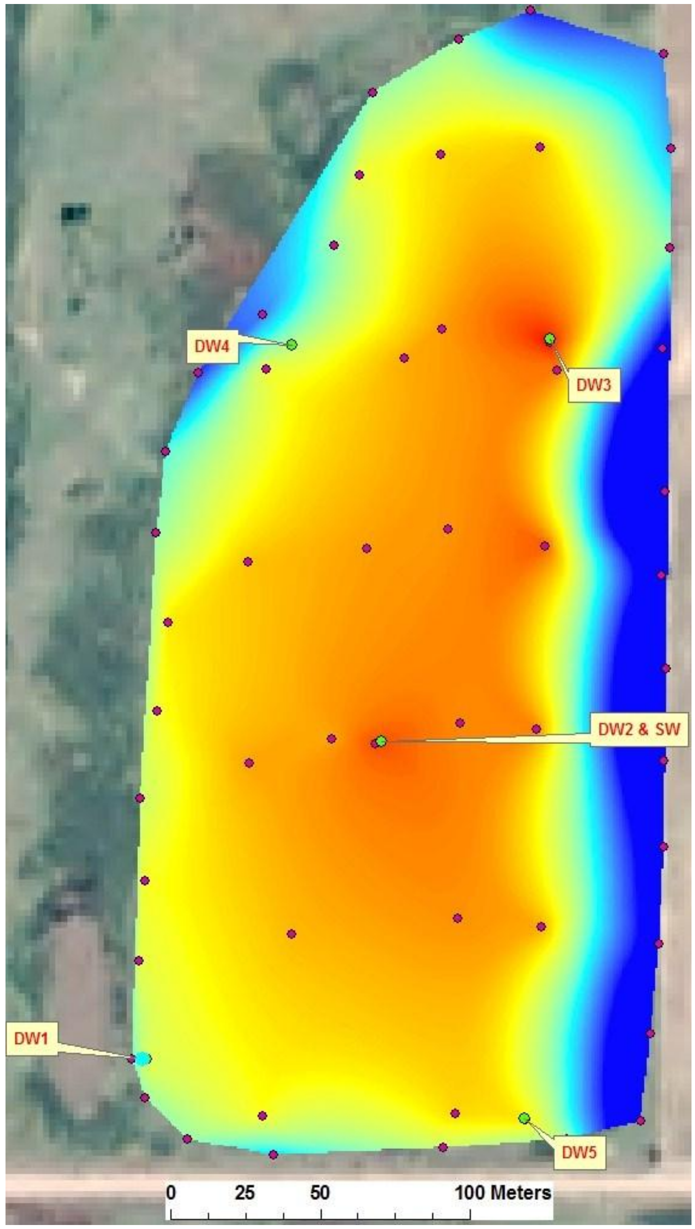
Appendix B: Wetland Stage-Storage Curves & Equations



B-1: Survey points on Lindau WPA.



B-2: Survey points on Moger (North) WPA.



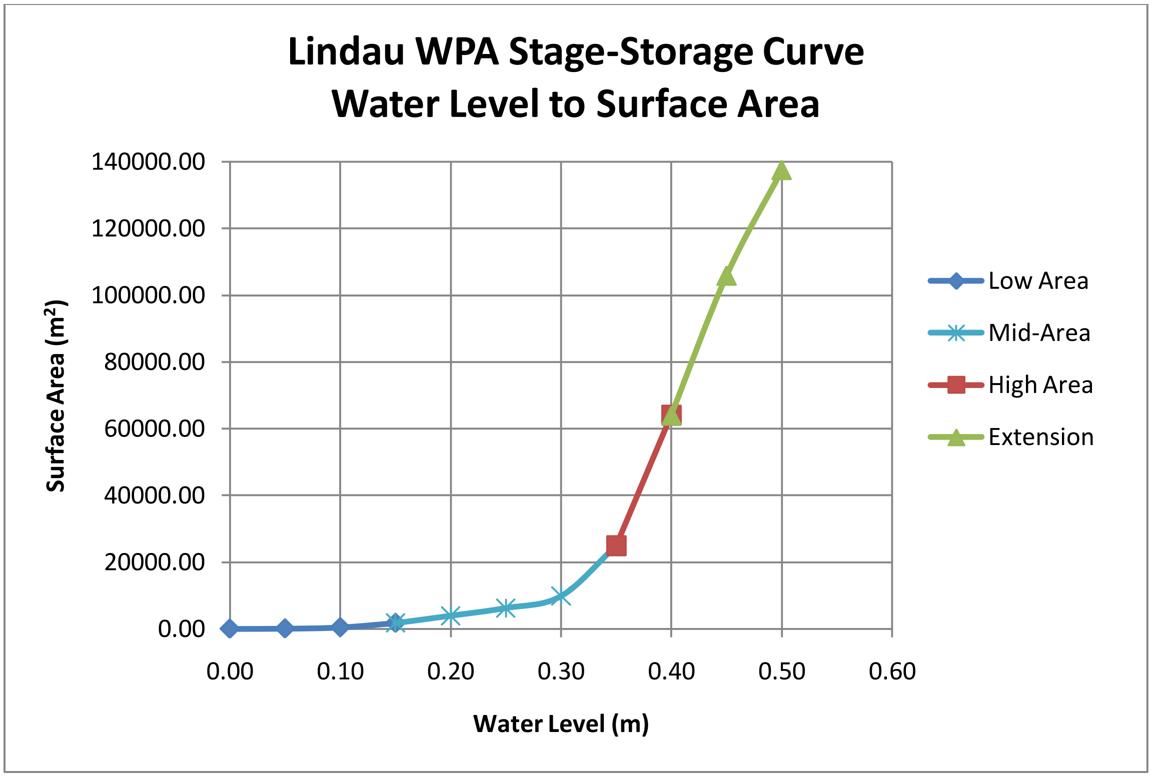
B-3: Survey Points on Griess WPA.

Water Level to Surface Area Stage-Storage Curve Equations				
Wetland	**Curve**	**Fitting Equation f(water level)**	**Water Level (m)**	**r^2**
Lindau WPA	Low Area	$125139x^2-7580.8x+32.363$	x ≤ 0.15	0.9894
	Mid-Area	$770498x^2-280910x+27557$	0.15 < x ≤ 0.35	0.9577
	High Area	782979x-249143	0.35< x ≤ 0.40	1
	Extension	735526x-228451	0.40 < x	0.9936
Moger (North) WPA	Low Area	$6360.3x^2+1320.8x-1.6377$	x ≤ 0.65	0.9916
	Mid-Area			
	High Area	$395917x^2-514971x+171027$	0.65 < x ≤ 0.95	0.9953
	Extension	197808x-149462	0.95 < x	0.9978
Griess WPA	Low Area	$225738x^2-2770.3x+(5E-13)$	x ≤ 0.04	1
	Mid-Area	$(9E6)x^2-775645x+17339$	0.04 < x ≤ 0.08	1
	High Area	$(-2E6)x^2+733731x-36475$	0.08 < x ≤ 0.14	1
	Extension	199879x+4132.4	0.14 < x	0.9927

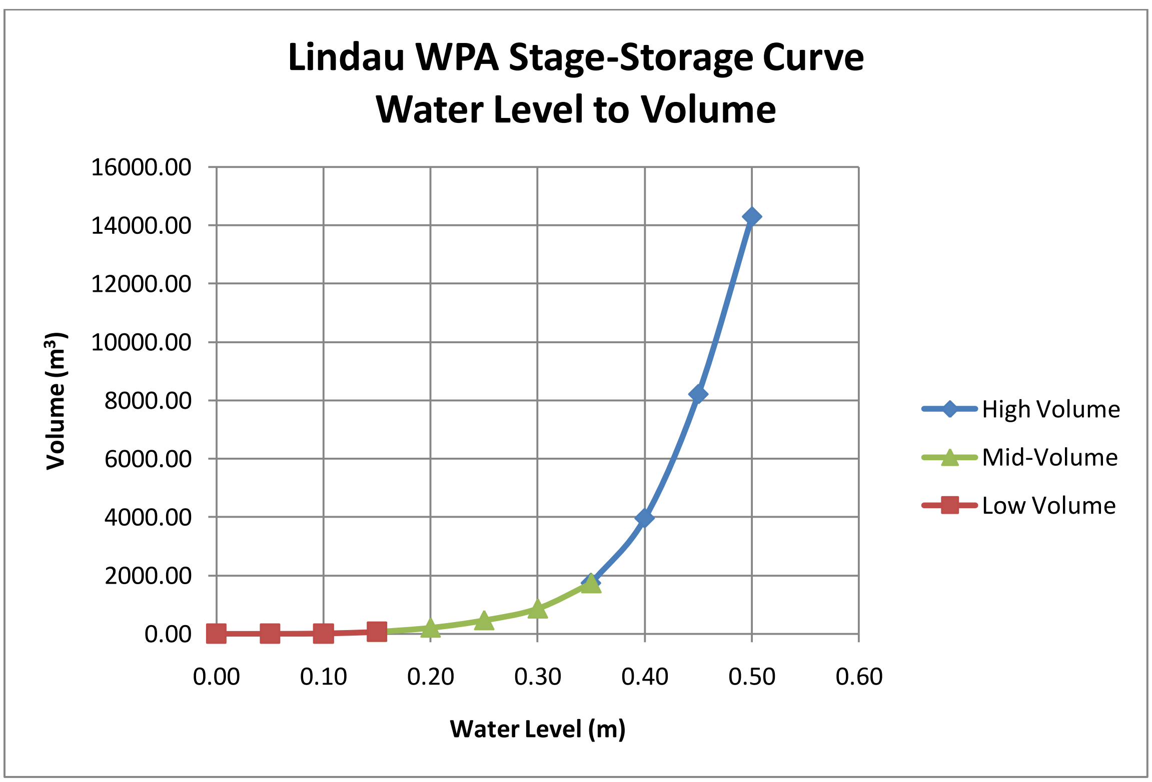
B-4: Surface area stage-storage curve equations

Water Level to Volume Stage-Storage Curve Equations				
Wetland	**Curve**	**Fitting Equation f(water level)**	**Water Level (m)**	**r^2**
Lindau WPA	Low Volume	$5271.4x^2-357.08x+1.5642$	x ≤ 0.15	0.9842
	Mid-Volume	$45629x^2-14825x+1296.4$	0.15 < x ≤ 0.35	0.9924
	High Volume	$386525x^2-244669x+40012$	0.35 < x	1
Moger (North) WPA	Low Volume	$3267.7x^2-806.63x+43.663$	x ≤ 0.75	0.9926
	High Volume	$90124x^2-132353x+49976$	0.75 < x	0.9999
Griess WPA	Low Volume	$14837x^2-466.61x+0.9366$	x ≤ 0.06	0.9661
	High Volume	$158196x^2-13193x+225.46$	0.06 < x	0.9995

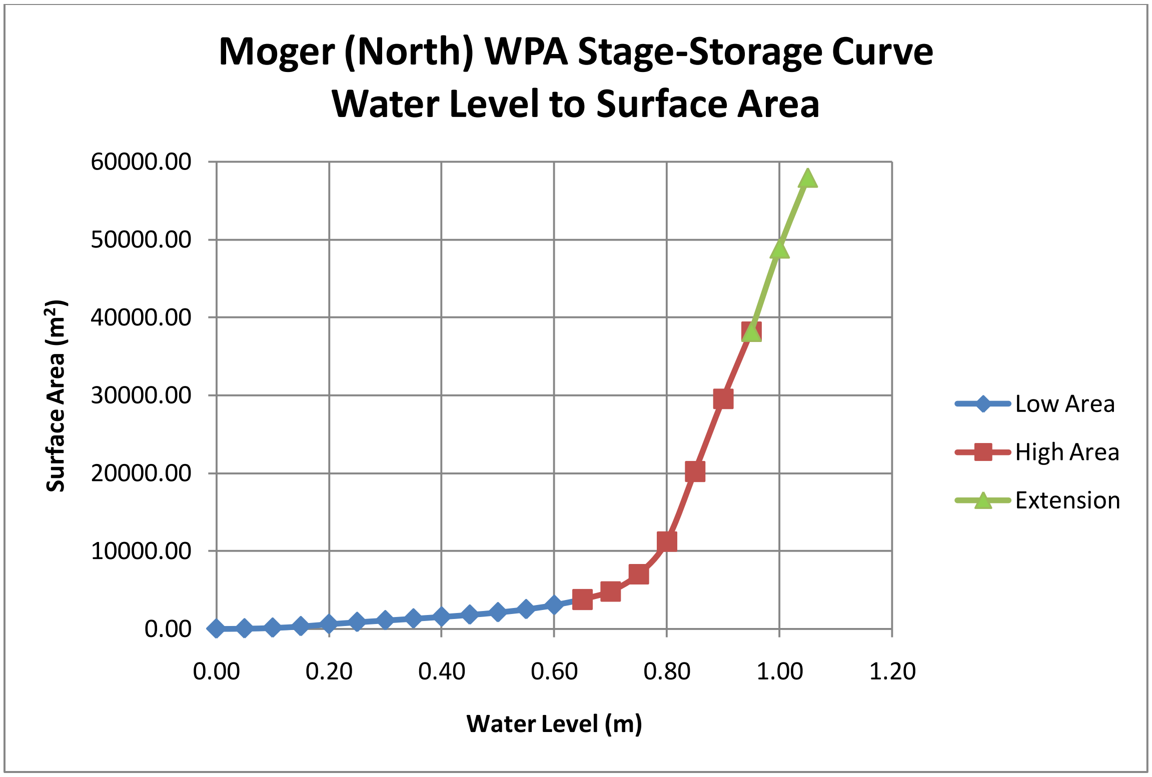
B-5: Surface volume stage-storage curve equations



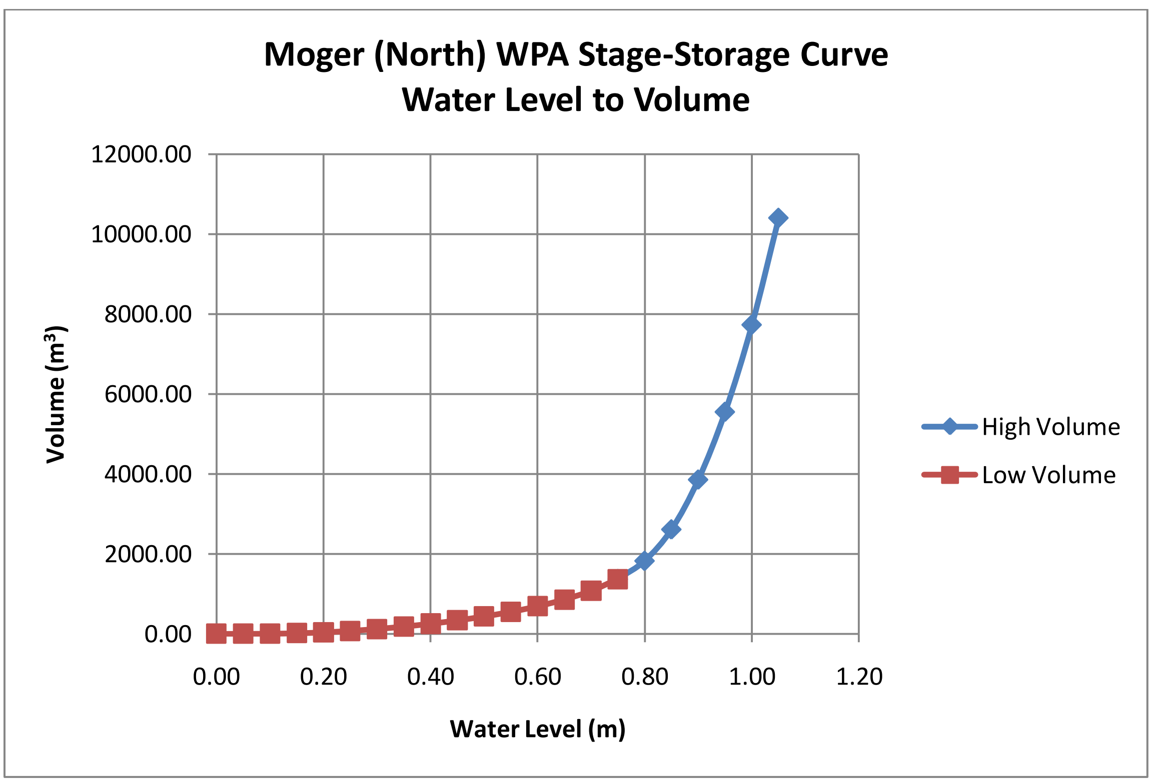
B-6: Lindau WPA water level to surface area relationship.



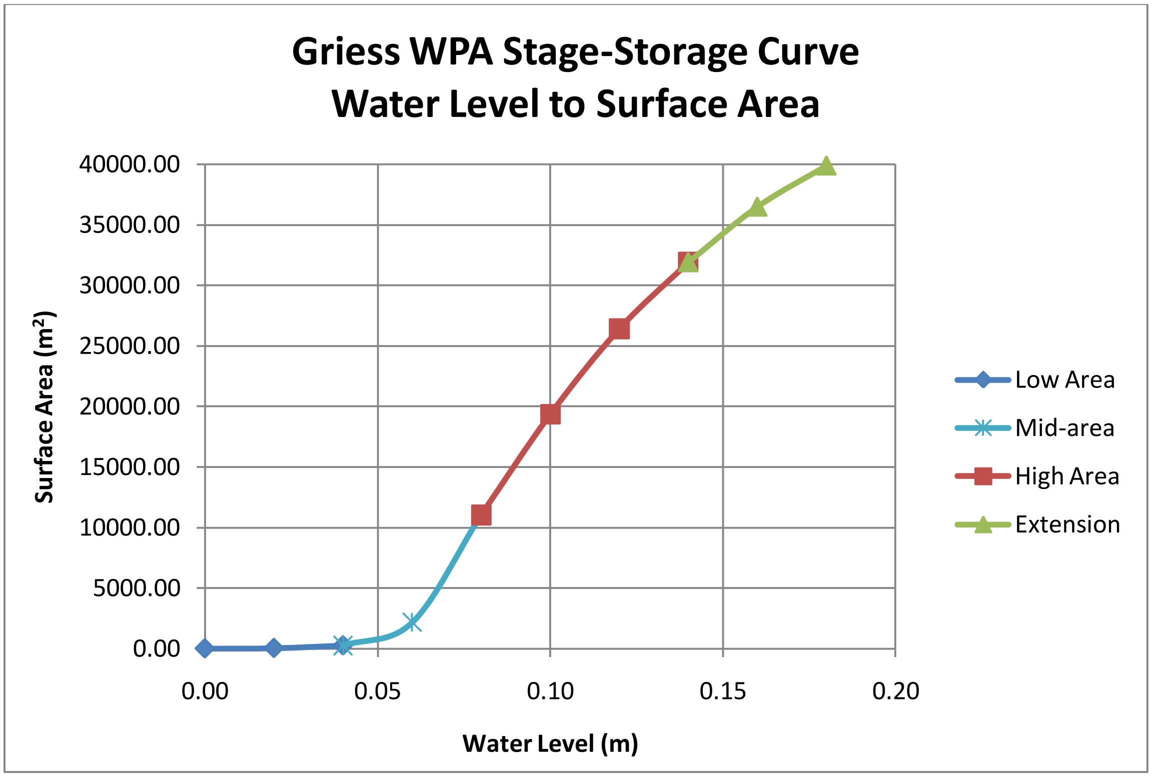
B-7: Lindau WPA water level to surface volume relationship.



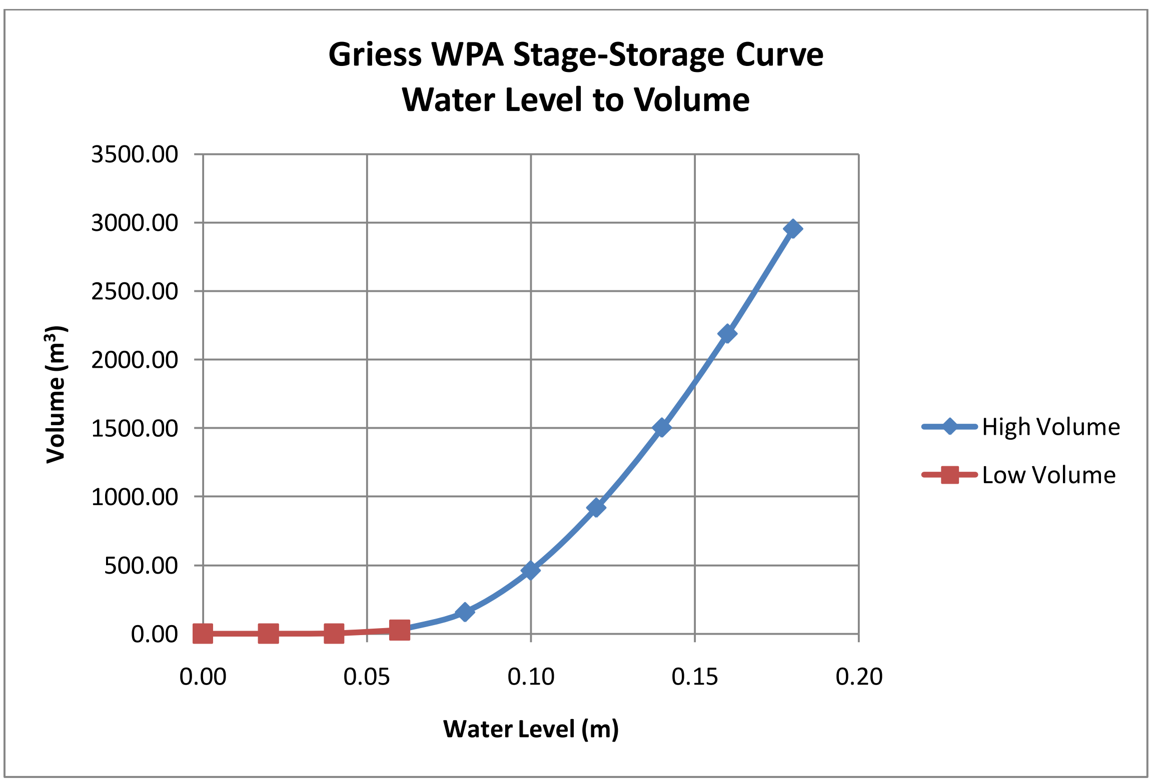
B-8: Moger (North) WPA water level to surface area relationship.



B-9: Moger (North) WPA water level to surface volume relationship.



B-10: Griess WPA water level to surface area relationship.



B-11: Griess WPA water level to surface volume relationship.

Appendix C: Soil Series Information (USDA-NRCS, 2010b)

C-1: MASSIE SERIES

The Massie series consists of very deep, very poorly drained, very slowly permeable soils formed in alluvium derived from loess. They are in the lowest parts of upland depressions and are ponded during most of the growing season, often with as much as 6 inches or more of water. Slopes are less than 1 percent. Mean annual precipitation is about 23 inches, and mean annual temperature is about 52 degrees F at the type location.

TAXONOMIC CLASS: Fine, smectitic, mesic Vertic Argialbolls

TYPICAL PEDON: Massie clay on a less than 1 percent concave slope under vegetation of giant sedge, perennial smartweed, and other water-tolerant plants. (Colors are for dry soil unless otherwise stated.)

A1--0 to 3 inches; very dark gray (10YR 3/1) clay, black (10YR 2/1) moist; moderate medium granular structure; slightly hard, very friable; on the surface is a layer of partially decayed leaves and stems; medium acid; clear smooth boundary.

A2--3 to 7 inches; dark gray (10YR 4/1) silty clay loam, black (10YR 2/1) moist; weak fine and medium platy structure parting to weak fine granular; slightly hard, very friable; moderately acid; abrupt wavy boundary. (Combined thickness of A horizon 3 to 16 inches.)

E--7 to 9 inches; light gray (10YR 6/1) silt loam, gray (10YR 5/1) moist; few fine faint brownish yellow (10YR 6/6) iron masses in the matrix; moderate medium platy structure parting to weak fine granular; soft, very friable; slightly acid; abrupt wavy boundary. (1 to 9 inches thick)

Bt1--9 to 13 inches; dark gray (10YR 4/1) silty clay loam, black (10YR 2/1) moist; light gray coating on faces of peds; many fine and medium distinct brownish yellow (10YR 6/6) iron masses in the matrix; moderate medium prismatic structure parting to moderate fine subangular blocky; hard, firm; many fine to large dark concretions (iron-manganese oxides); slightly acid; clear wavy boundary.

Bt2--13 to 25 inches; dark gray (10YR 4/1) silty clay, black (10YR 2/1) moist; few to common fine distinct brownish yellow (10YR 6/6) iron masses in the matrix; strong coarse prismatic structure parting to strong medium angular blocky; very hard, very firm; shiny surfaces on faces of peds; many fine to coarse dark concretions (iron-manganese oxides); neutral, gradual wavy boundary.

Bt3--25 to 65 inches; gray (10YR 5/1) silty clay, very dark gray (10YR 3/1) moist; strong coarse prismatic structure parting to strong coarse angular blocky; very hard, very firm; shiny surfaces on faces of peds; many fine to coarse dark concretions (iron-manganese oxides); neutral; diffuse smooth boundary. (Combined thickness of the Bt horizon 19 to 64 inches.)

BC--65 to 85 inches; dark grayish brown (2.5Y 4/2) silty clay, very dark grayish brown (2.5Y 3/2) moist; moderate coarse prismatic structure parting to moderate medium angular blocky; very hard, very firm; neutral; gradual smooth boundary. (8 to 30 inches thick)

C--85 to 96 inches; grayish brown (2.5Y 5/2) silty clay, dark grayish brown (2.5Y 4/2) moist; weak coarse prismatic structure parting to weak medium subangular blocky; hard, firm; few line soft segregated accumulations of calcium carbonates; slight effervescence; slightly alkaline.

C-2: FILLMORE SERIES

The Fillmore series consists of very deep, somewhat poorly drained soils formed in loess. They are in depressions on uplands and stream terraces. Slopes are 0 to 2 percent. Mean annual precipitation is about 58 centimeters (23 inches) and mean annual temperature is about 11 degrees C (52 degrees F), at the type location.

TAXONOMIC CLASS: Fine, smectitic, mesic Vertic Argialbolls

TYPICAL PEDON: Fillmore silt loam on a less than 1 percent concave slope in native rangeland. (Colors are for dry soil unless otherwise stated.)

A--0 to 23 centimeters (0 to 9 inches); gray (10YR 5/1) silt loam, very dark gray (10YR 3/1) moist; weak medium subangular blocky structure parting to weak medium granular; slightly hard, friable, slightly acid; abrupt smooth boundary. (18 to 43 centimeters) 7 to 17 inches thick)

E--23 to 33 centimeters (9 to 13 inches); gray (10YR 6/1) silt loam, gray (10YR 5/1) moist; weak medium platy structure parting to weak fine granular; soft, friable; slightly acid; few hard 1 to 2 mm (ferro-manganese) pellets; abrupt smooth boundary. (8 to 31 centimeters) 3 to 12 inches thick)

Bt1--33 to 61 centimeters (13 to 24 inches); gray (10YR 5/1) silty clay, very dark gray (10YR 3/1) moist; strong coarse and medium angular blocky structure; very hard, very firm; shiny faces on most peds; many hard 1 to 2 mm (ferro-manganese) pellets; neutral; clear smooth boundary.

Bt2--61 to 81 centimeters (24 to 32 inches); grayish brown (10YR 5/2) silty clay, very dark grayish brown (10YR 3/2) moist; strong coarse and medium angular blocky structure; very hard, very firm; shiny faces on most peds; slightly alkaline; clear smooth boundary. (Combined thickness of Bt horizons is (38 to 127 centimeters) 15 to 50 inches.)

BC--81 to 112 centimeters (32 to 44 inches); grayish brown (10YR 5/2) silty clay loam, very dark grayish brown (10YR 3/2) moist; moderate coarse and medium subangular blocky structure; hard, firm; slightly alkaline; gradual smooth boundary. (13 to 38 centimeters) 5 to 15 inches thick)

C--112 to 152 centimeters (44 to 60 inches); grayish brown (2.5Y 5/2) silty clay loam, dark grayish brown (2.5Y 4/2) moist; weak coarse prismatic structure parting to weak medium subangular blocky; slightly hard, friable; slight effervescence; moderately alkaline.

C-3: SCOTT SERIES

The Scott series consists of very deep poorly and very poorly drained soils. They formed in loess in depressions on uplands and stream terraces of the Central Loess Plains (MLRA 75). Slope ranges from 0 to 1 percent. Mean annual temperature is 13 degrees C. (55 degrees F) and mean annual precipitation is 58 centimeters (23 inches) at the type location.

TAXONOMIC CLASS: Fine, smectitic, mesic Vertic Argialbolls

TYPICAL PEDON: Scott silt loam with a slope of less than 1 percent in pasture. (Colors are for moist soil unless otherwise stated.)

A--0 to 13 centimeters (0 to 5 inches); very dark gray (10YR 3/1) silt loam, gray (10YR 5/1) dry; moderate medium granular structure; slightly hard, friable; slightly acid; abrupt smooth boundary. (5 to 15 centimeters (2 to 6 inches) thick)

E--13 to 20 centimeters (5 to 8 inches); gray (10YR 5/1) silt loam, gray (10YR 6/1) dry; moderate thin and medium platy structure parting to moderate fine subangular blocky; slightly hard, friable; slightly acid; abrupt smooth boundary. (3 to 13 centimeters (1 to 5 inches) thick)

Bt1--20 to 51 centimeters (8 to 20 inches); very dark gray (N 3/0) silty clay, dark gray (N 4/0) dry; common medium prominent yellowish brown (10YR 5/4) iron masses; strong coarse prismatic structure parting to strong medium angular blocky; very hard, very firm, shiny surfaces on faces of most peds; many hard 1 to 2 mm, spherically shaped iron-manganese concretions; neutral; clear smooth boundary.

Bt2--51 to 86 centimeters (20 to 34 inches); very dark gray (N 3/0) clay, dark gray (N 4/0) dry; few fine prominent yellowish brown (10YR 5/4) iron masses; strong coarse prismatic structure parting to strong fine angular blocky; very hard, very firm; shiny surfaces on faces of most peds; many hard 1 to 2 mm, spherically shaped iron-manganese concretions; neutral; clear smooth boundary. (Combined thickness of the Bt horizon is 41 to 102 centimeters (16 to 40 inches) thick)

BC--86 to 117 centimeters (34 to 46 inches); dark grayish brown (2.5Y 4/2) silty clay loam, light brownish gray (2.5Y 6/2) dry; moderate medium subangular blocky structure; hard, firm; neutral; gradual smooth boundary. (13 to 36 centimeters (5 to 14 inches) thick)

C1--117 to 142 centimeters (46 to 56 inches); brown (10YR 4/3) silt loam, pale brown (10YR 6/3) dry; weak coarse prismatic structure; slightly hard, friable; slightly alkaline; gradual smooth boundary. (20 to 51 centimeters (8 to 20 inches) thick)

C2--142 to 152 centimeters (56 to 60 inches); brown (10YR 4/3) silt loam, pale brown (10YR 6/3); moist; weak coarse prismatic structure; slightly hard, friable; carbonates disseminated throughout matrix; violent effervescence; slightly alkaline.

C-4: BUTLER SERIES

The Butler series consists of very deep, somewhat poorly drained, very slowly permeable soils formed in loess or mixed loess and alluvium. They are flat or in slightly concave swales on uplands and high stream terraces. Slopes are 0 to 2 percent. Mean annual precipitation is about 27 inches, and mean annual temperature is about 55 degrees F, at the type location.

TAXONOMIC CLASS: Fine, smectitic, mesic Vertic Argiaquolls

TYPICAL PEDON: Butler silt loam with a slope of less than 1 percent in a cultivated field. (Colors are for dry soil unless otherwise stated.)

Ap--0 to 10 inches; dark gray (10YR 4/1) silt loam, very dark brown (10YR 2/2) moist; moderate medium subangular blocky structure parting to moderate medium granular; slightly hard, friable; moderately acid; abrupt smooth boundary. (6 to 14 inches thick)

E--10 to 12 inches; gray (10YR 5/1) silt loam, very dark gray (10YR 3/1) moist; weak fine platy structure; soft, friable; moderately acid; abrupt smooth boundary. (0 to 3 inches thick)

Bt1--12 to 23 inches; very dark grayish brown (10YR 3/2) silty clay, black (10YR 2/1) moist; strong coarse prismatic structure parting to strong medium subangular blocky; very hard, very firm; thin dark coatings on faces of peds; few fine dark brown soft rounded masses (iron-manganese); neutral; gradual smooth boundary.

Bt2--23 to 32 inches; dark gray (10YR 4/1) silty clay, black (10YR 2/1) moist; strong coarse prismatic structure parting to strong medium subangular blocky; very hard, very firm; thin dark coatings on faces of peds; many fine dark brown soft rounded masses (iron-manganese); slightly alkaline; clear smooth boundary. (Combined thickness of the Bt horizon is 12 to 50 inches.)

BC--32 to 38 inches; dark gray (5Y 4/1) silty clay loam, dark olive gray (5Y 3/2) moist; moderate coarse prismatic structure parting to moderate medium subangular blocky; hard, firm; few fine masses of calcium carbonate; strong effervescence; few fine distinct yellowish brown (10YR 5/6) soft masses (iron-manganese); moderately alkaline; gradual smooth boundary. (6 to 15 inches thick)

C1--38 to 50 inches; gray (5Y 6/1) silt loam, dark olive gray (5Y 3/2) moist; massive; slightly hard, friable; strong effervescence; moderately alkaline; gradual smooth boundary. (0 to 20 inches thick)

C2--50 to 60 inches; gray (5Y 6/1) silt loam, olive gray (5Y 5/2) moist; massive; slightly hard, friable; strong effervescence; moderately alkaline.