PLATTE RIVER RECOVERY IMPLEMENTATION PROGRAM

Peer Review Packet

Wet Meadows Hydrologic Monitoring Approach Chapters

PLATTE RIVER
RECOVERY IMPLEMENTATION PROGRAM

Prepared by staff of the Executive Director's Office for the Governance Committee of the Platte River Recovery Implementation Program

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PREFACE

This document was prepared by the Executive Director's Office (EDO) of the Platte River Recovery Implementation Program ("Program" or "PRRIP"). The objective of this publication is to describe the Program's wet meadows hydrologic monitoring approach that will guide the monitoring effort through 2019. The results of the monitoring effort will be presented in separate peer-reviewed documents. The information presented herein was developed to facilitate a peer review of the Program's wet meadow hydrologic monitoring approach to ensure the monitoring effort will meet the project's objectives. The Program began an extended monitoring effort focused on the dominant hydrologic process at wet meadow sites in 2013 and plans to continue monitoring through the end of the Program's First Increment in 2019. The Program's Executive Director's Office was directed to build upon previous research describing the hydrologic behavior of wet meadow sites to inform the Program's management of several hundred acres of wet meadow habitat in the Associated Habitat Reach (AHR).

This document is a compilation of four chapters describing various aspects of the monitoring approach. Chapter 1 was developed to provide an overview of the monitoring approach as well as background and context for the monitoring effort. Subsequent chapters provide additional information and description of various aspects of the monitoring approach. Chapter 2 provides additional background for the evapotranspiration (ET) monitoring described in Chapter 1. It presents various methods for determining ET that could be used at wet meadow sites and suggests several methods that are best suited to that endeavor. Chapter 3 expands upon the soil moisture monitoring approach and explains the role of soil moisture in the hydrologic monitoring effort. Chapter 4 documents the groundwater models developed to support the analysis of wet meadow hydrology and evaluate various management activities. Each chapter includes background information on the Program and the monitoring effort and thus may contain redundant content.

All four chapters in this peer review packet were developed in coordination with a working group comprised of members of the Program's Technical and Water Advisory Committees. The working group played an advisory role in the development of the monitoring plan and reviewed the four chapters to ensure the described monitoring approach would meet the project's objectives. After the working group review, the monitoring approach presented in these chapters was subjected to an external peer review facilitated by a third party neutral. Reviewers were selected based on their expertise in the areas of hydrologic monitoring, evapotranspiration, soil moisture, and groundwater modeling. The summary report from the external peer review process is included as Appendix A of this document. Program responses to external peer review comments and recommendations are included as Appendix B of this document. The independent external peer review process resulted in significant improvements to the chapters and the Executive Director's Office gratefully acknowledges the contributions all internal and external reviewers.

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EXECUTIVE SUMMARY

The Program began monitoring hydrologic processes at wet meadow sites in 2013 and will continue monitoring through the end of the Program's First Increment in 2019. The objective of the monitoring effort is to determine the groundwater response to changes in river stage, precipitation events, and evapotranspiration at wet meadow habitat sites in order to guide the Program's management activities. The monitoring effort focuses on groundwater elevations, river stage and discharge, liquid and solid precipitation, ET, soil moisture flux, off-site runoff, and surface water elevation at on-site wetlands and sloughs. The spatial and temporal density of the monitoring effort is set to capture hourly fluctuations in groundwater elevations. It is designed to determine the site-wide groundwater response, in both timing and magnitude, to changes in river stage, precipitation events, and ET. Data collected from the monitoring effort will be evaluated using a water budget approach as well as a variety of analytical and statistical tools and numerical models.

The chapters in this document describe specific aspects of the comprehensive hydrologic monitoring approach at the Program's wet meadow habitat sites. It has undergone internal review by Program's Technical and Water Advisory Committees as well as an external independent peer review to ensure the monitoring effort is set up to meet the project's objectives. The effort is focused on gathering data that are appropriate for the development of tools to inform the Program's management activities. The monitoring plan attempts to balance the spatial, temporal, and precision of the data collected with cost and use considerations. Results and conclusions stemming from the monitoring effort will be presented in future documents.

Several factors went into the design of the monitoring approach including the spatial and temporal density of monitoring needed as well as the precision required for each parameter monitored. The Program manages four main wet meadow habitat sites and selected differing levels of monitoring between the sites. Two sites receive a higher level of monitoring in terms of spatial density and

monitoring equipment used. The project's objectives and ultimate goal of the data to inform management decisions guided the decisions of which monitoring methods and equipment to employ. Methods for monitoring two parameters, ET and soil moisture, were expanded upon in separate chapters in light of the variety of possible monitoring approaches.

An extensive review of the common methods used to determine ET revealed several methods could successfully be employed on wet meadows sites. The Program selected a combination of mass balance and energy balance methods to estimate ET and will use a set of crop coefficients developed by the USGS on a nearby riparian grassland. Methods that measure rather than estimate ET were not chosen due to their high cost and data processing requirements and the suitability of other methods to the project's needs.

Water flux through soil moisture was identified as an important process in the hydrologic behavior of wet meadow habitat as shallow groundwater may quickly respond to precipitation events and ET may draw water from soil moisture and the shallow groundwater. The Program monitors soil moisture at points as well as over a large area on an hourly basis to provide additional insight into the connection between precipitation, ET, and groundwater table changes.

A suite of groundwater models was developed to simulate groundwater flow at two of the Program's wet meadow sites. The models were developed using observed river hydrology and calibrated using observed groundwater elevations to provide a faithful representation of wet meadow groundwater behavior. The models are used to inform the water budget analysis and can be used to evaluate the groundwater response to simulated hydrology of potential management actions.

CHAPTER 1 - WET MEADOW HYDROLOGIC MONITORING APPROACH

ABSTRACT

This document presents the hydrologic monitoring approach used by the Platte River Recovery Implementation Program to better understand the dominant hydrologic processes at wet meadow habitat sites. An overview of wet meadow hydrology is followed by a description of the conceptual model used to guide the monitoring effort. A description of the wet meadow sites is provided. Further detail is provided to outline the monitoring approach to each of the dominant hydrologic process, including groundwater, surface water, precipitation, evapotranspiration, and soil moisture content.

INTRODUCTION

This document describes the approach taken by the Platte River Recovery Implementation Program (PRRIP or the Program) to monitor the dominant hydrologic processes at wet meadow habitat sites. Understanding the hydrology of wet meadows is critical for effective management of Program water and land resources. This is true both for preserving existing wet meadow habitat areas and converting new areas to wet meadow habitat. The relationships between the dominant hydrologic processes of wet meadows, including groundwater levels, river stage, precipitation, evapotranspiration, and soil moisture flux have not been clearly described or quantified in the Central Platte Valley. The objective of the hydrologic monitoring project is to quantify these relationships in order to inform management decisions.

An overview of wet meadow hydrology, the monitoring project objectives, wet meadow hydrologic processes, the conceptual hydrologic model, a description of the wet meadow sites included in the monitoring effort, and an overview of the monitoring approach is provided in this section. Detailed descriptions of the monitoring approach for each of the dominant hydrologic processes are presented in the proceeding sections.

Wet Meadow Background and Hydrology

Wet meadow habitat areas are part of the Program's efforts towards the recovery of the whooping crane, an endangered species and one of the Program's target species. It is hypothesized that wet meadows are an important component of habitat on the Central Platte River used by whooping cranes for roosting and foraging during their migratory stopover in the spring and fall. Management of wet meadows through actions like flow releases to support the hydrologic functionality of wet meadow habitat may be considered as an important management action in the future.

The Program defines wet meadows in the Central Platte River Valley as "grasslands with waterlogged soil near the surface but without sanding water most of the year."[1] The Program hypothesizes that "Increasing wet meadows during migrational times will increase migration survival of whooping crane."[2] Wet meadow habitat areas are a specific element of the Program's land management plan[3] and the Program's adaptive management plan[4]. The Program seeks to increase wet meadow habitat by maintaining and enhancing the performance of existing wet meadow habitat and converting new areas to wet meadow habitat.

Further background information and a more thorough description of wet meadow habitat can be found in the Wet Meadow Literature and Information Review[5] and the PRRIP white paper "Platte River Wet Meadow Geohydrology and Management through Flow Releases."[6]

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[1] Ramirez, F.C., and Weir, E. 2010. *Wet Meadow Literature and Information Review*. Draft Report commissioned by the Governance Committee of the PRRIP, 2010.
[2] Platte River Recovery Implementation Program, Attachment 3. *Adaptive Management Plan*. PRRIP, 2006
[3] Platte River Recovery Implementation Program, Attachment 4. *Land Plan*. PRRIP, 2006
[4] Platte River Recovery Implementation Program, Attachment 3. *Adaptive Management Plan*. PRRIP, 2006
[5] Ramirez, F.C., and Weir, E. 2010. *Wet Meadow Literature and Information Review*. Draft Report commissioned by the Governance Committee of the PRRIP, 2010.
[6] PRRIP, 2012. *Platte River Wet Meadow Geohydrology and Management through Flow Releases*. White Paper compiled by the Office of the Executive Director of the PRRIP, 2012.

The importance of hydrologic processes in sustaining wet meadow habitat area, including vegetation and macroinvertabrate populations that provide whooping crane roosting and forage habitat, has been highlighted in several studies (Davis et al.[7], Meyers and Whiles[8], Simpson[9], Whiles and Goldowitz[10]). Dominant plant species found at the Binfield wet meadow site are included in APPENDIX D. Davis et al. captures a common sentiment among authors of these studies: "To maintain wet meadows and their biotic communities, flow management should focus on regaining as much as possible of the former hydrograph through properly timed flows that provide an adequate hydrologic regime for wet meadows." While these studies agree that hydrology is central to healthy wet meadow habitats, they do not provide much direction for managing existing and newly created wet meadows. Other studies have focused more specifically on the hydrology of wet meadows and have claimed a strong connection between groundwater levels and the river. For example, in his 1983 paper, Hurr[11] concludes after a seven month study of the groundwater hydrology of the Mormon Island wet meadow that river stage is the primary factor controlling groundwater levels. He notes that precipitation and evapotranspiration also have an effect on groundwater levels. Wesche et al.[12] came to a similar conclusion, stating "river stage, precipitation, and evapotranspiration were nearly always highly correlated with the groundwater level, with river stage usually the most highly correlated."

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[7] Davis, C.A., Austin, J.E., and Buhl, D.A. 2006. *Factors influencing soil invertebrate communities in riparian grasslands of the Central Platte River floodplain*. Wetlands 26(2): 438-454.
[8] Meyer, C. K., and Whiles, M.R. 2008. *Macroinvertebrate communities in restored and natural Platte River slough wetlands*. J. N. Am. Benthol. Soc. 27(3): 626-639
[9] Simpson, A. 2001. *Soil vegetation correlations along hydrologic gradient in the Platte River wet meadows*. Biology Department. Kearney, NE, University of Nebraska at Kearney. Master of Science: 136.
[10] Whiles, M. R., and Goldowitz, B.S. 2001. *Hydrologic influences on insect emergence production from central Platte River wetlands*. Ecological Applications 11(6): 1829–1842.
[11] Hurr, T. 1983. *Ground-water hydrology of Mormon Island Crane Meadows Wildlife Area near Grand Island Hall County, Nebraska.* In: 1277, USGS PP (ed.) Hydrologic and Geomorphic Studies of the Platte River Basin. Technical Report, University of Wyoming, Laramie, WY, USA. WWRC-94-07
[12] Wesche, T.A., Skinner, Q.D, and Henszey, R.J. 1994. *Platte River Wetland Hydrology Study: Final Report*. Submitted to U.S. Bureau of Reclamation, Mills, WY. Wyoming Water Resources Center Technical Report, University of Wyoming, Laramie, WY, USA. WWRC-94-07

The scientific literature does not provide a comprehensive description of Platte River wet meadow hydrology beyond recognizing the connection between river stage and groundwater levels. How water travels across a wet meadow from the time it falls as precipitation to the point it leaves the area as groundwater flow, surface runoff, or evapotranspiration from vegetation is not clear. The degree to which precipitation causes groundwater table elevations to increase or how evapotranspiration in the summer causes groundwater tables to lower is not known. How quickly groundwater table elevations respond to increases in river stage and how long this response lasts cannot be clearly determined based on the current understanding of wet meadow hydrology, nor can the degree and timing of a wet meadow's hydrologic connectivity to the Platte River. The hydrologic monitoring project aims to provide a more complete understanding of wet meadow hydrology in order to guide the Program's management of its water resources and the Adaptive Management Plan's effort to enhance and create wet meadow habitat areas.

Objectives

There are four principal objectives of the hydrologic monitoring plan. These objectives are based on the types of water management strategies that are being considered for creating, maintaining, and/or enhancing wet meadows environments in the Central Platte.

Objective 1: Quantify the amount and duration of groundwater response resulting from changes in river stage.

This objective includes determining groundwater response to rising river stage, determining how groundwater levels decrease over time after river stage decreases, and identifying the impact of antecedent conditions on groundwater response, all over a range of distances from the river. This objective relates to the question "What stage and duration of surface water flowing in river channels adjacent to wet meadow sites is required to raise wet meadow site groundwater levels to desired levels?"

and the Program's ability to manipulate wet meadow groundwater elevations through managed flow releases.

Objective 2: Quantify the amount and duration of groundwater response to precipitation events.

This objective includes estimating infiltration rates from precipitation events, determining how groundwater levels decrease over time after precipitation events, identifying the impact of antecedent conditions on groundwater response, and quantifying the amount of precipitation entering the groundwater that flows into the river. This objective relates to the question "What volume of water is required to raise groundwater levels in wet meadow sites to desired levels if that water is directly applied to the site, through flood irrigation, surface diversions into sloughs, or other methods?", with precipitation acting as a surrogate for overland application. This objective relates to the Program's ability to manipulate wet meadow groundwater elevations through surface water inputs.

Objective 3: Quantify the groundwater response to changes in evapotranspiration rates.

This objective includes determining the relationship between evapotranspiration and groundwater levels as a function of the depth of groundwater, and season and how evapotranspiration affects precipitation infiltration rates. This objective relates to the question "What conditions, in terms of river stage and water directly applied to the wet meadow site, are required to maintain desired groundwater levels in wet meadows once the desired groundwater levels have been achieved?" and the Program's ability to sustain wet meadow conditions once groundwater levels have reached the desired levels.

Objective 4: Investigate the impact of management strategy tests on groundwater levels.

The Program intends to test various management strategies to achieve desired groundwater levels at wet meadow sites. Management strategies may include flow releases or overland application of water through irrigation or pumping water into depressional areas. Pilot tests may be conducted as well as modeling of management strategies.

Wet Meadow Hydrologic Processes

The hydrologic processes that occur on wet meadow sites include river and groundwater interaction, precipitation, evapotranspiration, runoff, infiltration, and percolation, as shown in **Figure 1**.

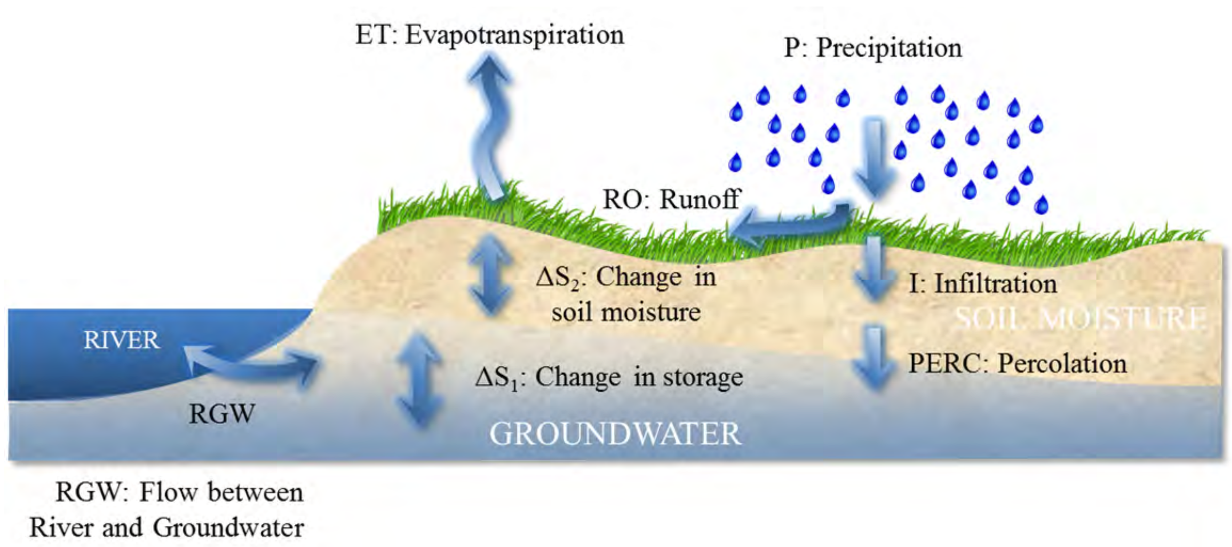

Figure 1. Hydrologic processes on a cross section of a typical wet meadow site.

River and groundwater interaction

The interaction between the river adjacent to wet meadow sites and the alluvial aquifer below the sites can be generally described as increases and decreases in river stage cause increases and decreases in groundwater elevations, respectively. The degree of influence river stage changes have on groundwater elevation decreases with increasing distance from the river. Wet meadow sites further from the river may not respond to smaller changes in river stage and may be influenced more by other hydrologic processes. The amount of water that passes between the river and the groundwater depends on the gradient between the river stage and the groundwater elevation as well as the hydraulic properties of the alluvial aquifer.

This gradient is impacted by changes in river stage as well as changes in groundwater elevation resulting from percolation, evapotranspiration, and regional groundwater elevation changes.

Precipitation

Precipitation plays an important role in wet meadow hydrology and constitutes a significant input of water into the system, with the Fox and Binfield sites receiving approximately 24 inches and 26 inches of rainfall annually, respectively[13]. The majority of precipitation is assumed to infiltrate into the soil or evaporate as surface runoff is assumed to be negligible at the wet meadow sites.

Evapotranspiration

A significant amount of water leaves wet meadow sites through evapotranspiration, which includes evaporation from dew, on-site surface water, soil moisture, and sublimation from snow as well as transpiration from vegetation. Water transpired by vegetation may have originated from soil moisture or directly from the groundwater when groundwater is at or above the vegetation's root zone. Evapotranspiration (ET) is highest during summer months and lowest during the winter and varies depending on a number of variables including the site's vegetation composition, weather parameters, vegetation cover stage, crop coverage versus bare soil, and available water.

Runoff

Due to the flat topography and sandy soils of the sites, it is assume there is no significant volume of runoff onto or off the sites. While some localized offsite runoff may occur, there is little evidence of erosion from concentrated surface runoff at the wet meadow sites. Sheet flow that might occur during high intensity events is assumed to accumulate in low lying areas onsite and not flow offsite. To test this assumption, any runoff that might occur will be monitored at low points along the site perimeters.

[13] NCDC/NOAA annual rainfall data from the Kearney and Wood River weather stations: http://www.ncdc.noaa.gov/

Infiltration

Sandy soils allow for the rapid infiltration of most of the precipitation that falls on the wet meadow sites. Water that infiltrates into the soil may continue to flow downwards and enter the groundwater table as percolation, be taken up by plant roots, evaporate into the atmosphere, or remain in the soil as stored soil moisture. The rate at which infiltration occurs depends on many factors, with antecedent soil moisture conditions being a primary factor. While the amount of water stored in soil moisture varies over time, the change in storage is assumed to be zero over long time scales.

Percolation

Percolation occurs when water that has infiltrated into the soil flows downward into the groundwater table. For the purposes of this study, percolation is synonymous to groundwater recharge. This water typically originates from precipitation and the portion of the total precipitation that enters the groundwater table depends on antecedent soil moisture conditions as well as evapotranspiration rates. We assume that there is percolation from the alluvial aquifer into the underlying Ogallala aquifer, but that it is negligible on the distance and time scale we are considering and is not investigated further.

Adjacent Groundwater Flow

Groundwater flow onto the site from adjacent land (not from the river) is not included in this conceptual model. Two of the wet meadow sites (the Binfield and Fox sites) are situated on islands in the Platte River and adjacent groundwater flow is assumed to have a minimal impact on groundwater below the sites. The Johns site is also situated between two river channels but does not have the same island configuration as the Binfield and Fox sites. Adjacent groundwater is not thought to have a significant influence on the site. The Morse site is located furthest from the river and may be impacted by adjacent groundwater. Several nearby wells will be monitored to determine the degree of influence adjacent groundwater flows have on groundwater behavior at the Morse site.

Conceptual Model

A conceptual model is developed to describe the relationships between the hydrological processes at wet meadow sites and guide the monitoring effort. A water budget approach is employed to balance inputs and outputs of water into and out of wet meadow sites. The domain boundaries for the conceptual model are determined by the site boundaries and by natural hydrologic features. Adjacent river channels function as hydrologic boundaries for the domain. The upper portion of the alluvial aquifer underlying the sites is in direct hydraulic communication with the river and serves to both store and transmit water. The Fox and Binfield sites are bounded to the north and south by river channels and the Johns and Morse site are bounded by a river channel to the north. The Johns site is bounded by the south channel of the Platte River; however the channel does not always contain water. When a river channel is dry, an arbitrary boundary is set to identify the impact of regional groundwater levels on local, on-site groundwater levels. A similar approach is used for the southern portion of the Morse site that lacks a natural hydrologic boundary. Regional groundwater monitoring wells are used to provide insight into regional groundwater levels near site boundaries.

The water budget equation for the wet meadow sites is stated in *Equation 1*, with all units in volume:

$$P \pm RGW - ET = \Delta S_1 + \Delta S_2 \qquad \textit{Equation 1}$$

where P=precipitation, RGW=the volume of water that passes between the river and the groundwater, ET=Evapotranspiration, ΔS_1=change in the volume of groundwater stored onsite, and ΔS_2=change in the volume of soil moisture stored onsite. **Figure 2** presents a schematic of each term in the water budget and shows the boundary of the conceptual model.

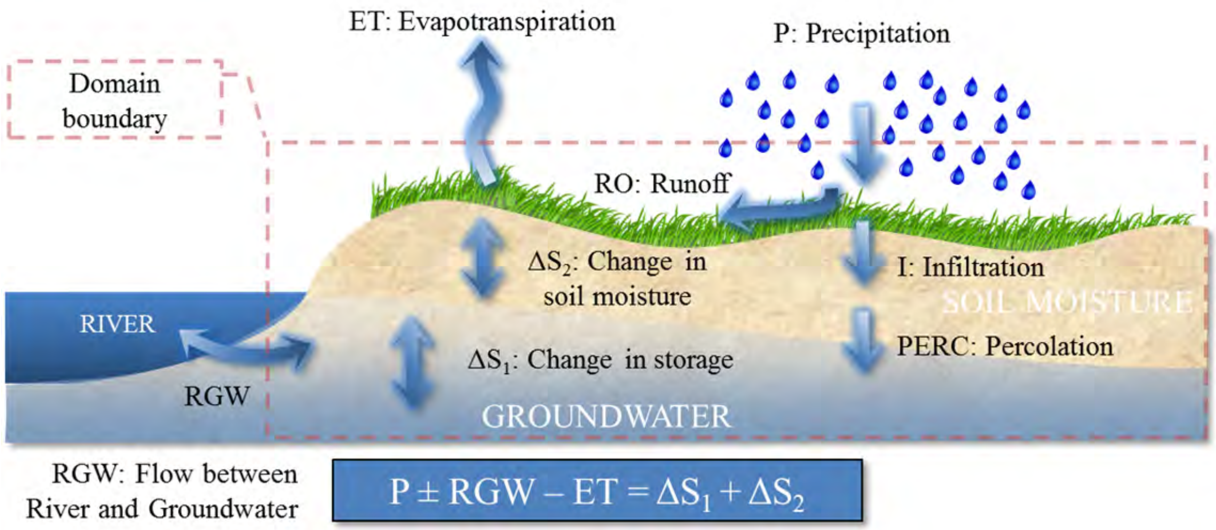

Figure 2. Schematic of wet meadow water budget

Infiltration, percolation, and runoff are process that occur internally to the model domain and are not stated in the water budget equation. The water budget contains two storage terms: a groundwater storage term to account for increases and decreases in the volume of groundwater beneath the site and a soil moisture storage term to account for change in soil moisture above the groundwater table. The storage terms are assumed to equal zero when the water budget is evaluated over long time scales; however, change in storage is likely to occur on smaller weekly, monthly, and possibly seasonal time scales.

The conceptual model represented by the water budget equation (*Equation 1*) provides a framework to identify the key hydrologic processes on the wet meadow sites. It also serves as a basis to determine which processes require monitoring.

Monitoring Overview

The wet meadow sites have been instrumented with monitoring equipment to measure all of the hydrologic processes described in the conceptual model. Monitoring equipment includes groundwater monitoring wells, river stage and discharge gages, precipitation gages, weather stations, and soil moisture sensors. The monitoring approach for each hydrologic process is discussed in the proceeding sections. All processes will be monitored on hourly to daily timescales to capture the interaction between precipitation, soil moisture, evapotranspiration, and groundwater levels resulting from rainfall events, rapid changes in river stage due to hydrocycling or rainfall-runoff events, and diurnal fluctuation in evapotranspiration.

The Binfield and Fox sites will receive a higher level of monitoring than the Johns and Morse site. The Binfield site was chosen for more extensive monitoring because it represents prototypical wet meadow habitat that has not been significantly altered through soil tilling. Data gathered from the Binfield site will be used to describe the hydrologic performance of a high functioning wet meadow habitat. Hydrologic processes at other wet meadow sites will be evaluated in light of hydrologic behavior observed on the Binfield site. The Fox site was chosen for more extensive monitoring to evaluate the site's functionality from a hydrologic perspective as it undergoes the transition process from an agricultural field into wet meadow habitat. The Binfield and Fox sites have more groundwater monitoring wells, weather stations, and area-averaged soil moisture sensors. The Johns and Morse sites do not and will not have as extensive of a groundwater monitoring well network, weather stations, or soil moisture monitoring. It is anticipated that a thorough understanding of wet meadow hydrologic processes can be gained from the Binfield and Fox sites and this information applied to the Johns and Morse site without the same density of monitoring equipment.

Monitoring began in 2013 on the Binfield and Fox site and in 2014 on the Morse site. Monitoring will begin in 2015 on the Johns site and additional equipment will be added to the Morse site in 2015. All monitoring will continue through the end of the Program's first increment in 2019.

Site Descriptions

The monitoring effort includes four wet meadow sites in the associated habitat reach of the Central Platte River, as seen in **Figure A1** of **Appendix A.** The sites are owned and managed by the Program and are part of larger habitat complexes. The sites represent a variety of site areas, proximities to the river, management histories, and functionalities as wet meadow habitat.

Binfield Site

The Binfield site is located near Wood River, Nebraska, and is part of the Shoemaker Island habitat complex. Shoemaker Island is bounded to the south by the main channel of the Platte River and to the north by the Platte River's north channel. Wet meadow habitat lies along the south channel and extends approximately half way across the island. The Binfield site has never been modified for agricultural or other purposes and maintains the shallow ridge and swale topography of a prototypical wet meadow. It is considered the most pristine of the four sites for this reason and whooping cranes have been observed using the Binfield wet meadow site occasionally during their migration.

A slough runs across the southern portion of the site that passes surface water during high flows and may intercept groundwater toward the eastern boundary of the site. During times of very high flow surface water may overtop the low banks on the western edge of the site and flow across the site.

Fox Site

The Fox site is located near Kearney, Nebraska, and is part of the Ft. Kearny habitat complex on Kilgore Island. Similarly to Shoemaker Island, Kilgore Island is bordered by the main channel of the Platte River to the south and the north channel of the Platte River to the north. The Fox site sits in the center of Kilgore Island and is separated from both the main and north channels by other properties. The site was previously in agricultural production until 2012. The Program excavated swales and built up ridges in an attempt to create site topography resembling the natural variation typical of wet meadow habitat. The swales were designed to expose groundwater during periods of whooping crane migration. The site was seeded with native vegetation and is managed to encourage the development of wet meadow habitat.

Johns Site

The Johns site is located near Elm Creek, Nebraska, and is part of the Elm Creek habitat complex. The site lies along the southern bank of the main channel of the Platte River. Several deep sloughs running parallel to the river channel that act as groundwater drains were excavated prior to the Program's purchase of the property. The Program plans to construct check dams in the drains to prevent groundwater from draining and improve the sites function as a wet meadow habitat.

The south channel of the Platte River runs to the south of the Johns site. The south channel is only connected to the main channel at its outlet and forms primarily from outflow from the Peterson drain. The channel may act as a groundwater drain at the site. The excavated drains are primarily fed by groundwater but may pass surface water during high flow in the river. The planned check structures are likely to limit surface flow through the drains; however, surface flow across the site is expected at very high flows.

Morse Site

The Morse site is located near Overton, Nebraska, and is part of the Cottonwood Ranch habitat complex. The site lies approximately one mile to the south of the main channel of the Platte River. The Peterson drain passes through the middle of the site and serves to drain groundwater and limit the sites ability to function as a wet meadow habitat.

The Program pumps a production well on the Morse site to create a series of wetlands on the property during whooping crane migration in the spring and the fall. To decrease the seepage from these wetlands, the Program installed check structures in the Peterson drain. The check structures raise groundwater elevation in the vicinity of the Peterson drain and lower the groundwater gradient between the ditch and the wetlands. The check structures are also thought to improve the sites functionality as a wet meadow habitat by bringing groundwater closer to the ground surface.

GROUNDWATER MONITORING APPROACH

Overview

As depth to groundwater plays a determining role in the function of wet meadow habitat, groundwater monitoring comprises a large portion of the monitoring effort. The focus of the groundwater monitoring is on the upper portion of the Platte Valley alluvial aquifer where interaction with other wet meadow hydrologic processes occurs. It is assumed that groundwater behavior deeper in the alluvial aquifer does not drive shallow groundwater behavior on daily or sub-daily timescales. Regional alluvial aquifer behavior likely has some impact on near surface groundwater behavior on seasonal timescales. It is also assumed the underlying Ogallala aquifer does not significantly affect shallow alluvial groundwater behavior. This assumption is consistent with the regional COHYST 2010[14] model and is based on the presence of a less permeable layer of silt between the alluvial aquifer and the Ogallala aquifer described in the COHYST Hydrostratographics Unit report.[15]

Groundwater is measured at points using groundwater monitoring wells. Wells are spaced across each site to form a network with a spatial density designed to capture groundwater behavior, such as gradient and flow direction, across the entire site. Groundwater behavior may be driven by changes in river stage, infiltration from precipitation, evapotranspiration, and changes in regional groundwater levels. The monitoring network may be denser near the river to capture groundwater response to river stage changes that may not propagate further inland. While precipitation is assumed to be fairly uniform over the area of the wet meadow sites, the groundwater response to precipitation may vary depending on topography

[14] Platte River Cooperative Hydrology Study (COHYST): http://cohyst.dnr.ne.gov/
[15] Cannia, J.C., Woodward, D., and Cast, L.D. 2006. *Cooperative Hydrology Study (COHYST) Hydrostratigraphic Units and Aquifer Characterization Report*. Cooperative Hydrology Study.

and antecedent soil moisture conditions. Similarly, even though vegetation is somewhat similar across the wet meadow sites, evapotranspiration may affect groundwater levels greater in areas of shallow groundwater than in areas with deeper groundwater. Monitoring wells are situated across each site to capture some of this variation. Wells situated near the edges of the sites provide information on regional groundwater behavior as do wells comprising a regional groundwater monitoring network. Additionally, site specific features such as groundwater drains or wetlands may drive local groundwater levels and monitoring wells placed near these features seek to capture their impact.

The Program navigated a number of constraints to determine the number and location of wells needed at each site to provide optimal data. Well locations were chosen to protect the monitoring equipment from grazing cattle, controlled burns, and haying equipment. Saturated soils at a few locations prevented drilling equipment access and required alternate well placement. Overall, locations were chosen to provide the most comprehensive data for each site as efficiently as possible.

Monitoring wells are primarily shallow wells ranging from 10 to 25 feet deep and are equipped with pressure transducers and data loggers that record hourly measurements. Some of the wells existed onsite before the start of the monitoring effort and others were installed by the Program. All Program wells were equipped with In-Situ Level Troll 500 pressure transducers and data loggers, for more information see **Table B1** in **Appendix B**. Several wells were connected to wireless telemetry systems to allow for real-time data access via the internet.

Binfield Groundwater Monitoring

Groundwater levels on the Binfield site are recorded along two transects of shallow monitoring wells running perpendicular to the Platte River, as seen in **Figure A2** in **Appendix A**. The transects are approximately 3,000 feet apart and the upstream or western transect contains nine wells while the downstream or eastern transect contains seven wells. Groundwater gradients across the site may be determined by comparing groundwater elevations in the upstream and downstream transects. Groundwater response to changes in river stage may be evaluated by comparing groundwater levels along a given transect. The spacing of wells along the two transects varies, with wells closer to the river positioned more closely together than wells further from the river. Well spacing and distances from the south channel are shown in **Table 1**.

Table 1. Binfield monitoring well information

Well	Transect	Distance from main channel (ft)	Pad Elevation (ft)	Well spacing (ft)
201	West	90	1939.24	90
202	West	298	1940.17	208
203	West	511	1939.36	213
204	West	827	1941.40	316
205	West	1360	1940.55	533
206	West	1924	1940.81	564
207	West	2650	1941.80	726
208	West	3467	1940.39	817
209	West	4180	1940.62	713
210	East	52	1937.32	52
211	East	203	1937.79	151
212	East	642	1937.69	439
213	East	1171	1937.28	529
214	East	1835	1936.68	664
215	East	2822	1936.39	987
216	East	3654	1936.34	832

All sixteen wells are drilled to 10 feet below the ground surface with their screened portion extending from 8 feet to 10 feet below the surface. Groundwater levels on the Binfield site range from 2 to 6 feet below the surface and In-Situ Level Troll 500 data loggers are installed just above the bottom of the wells. Wells are located to capture variations in topography across the site, with some wells located on ridges and others in lower swale regions.

Fox Groundwater Monitoring

Groundwater on the Fox site is monitored with a network of shallow monitoring wells in the four corners of the site and one in the middle of the site. In addition to these wells, a transect of monitoring wells runs perpendicular to the river from the main channel of the Platte river to the north channel along the western boundary of the site as well as on the neighboring Speidell property. Monitoring wells are shown in **Figure A3** in **Appendix A**. Wells 112 to 116 in the corners and the center of the site were installed on the site in 2011 and have a depth of 25 feet below the surface. Groundwater gradients may be determined by comparing groundwater elevations in these wells. Transect wells 101 to 111 were installed in 2013 and have a depth of 10 feet below the surface and provide information on groundwater response to changes in river stage. Similarly to the Binfield site, the spacing of wells along the two transects varies, with wells closer to the river positioned more closely together than wells further from the river. Well spacing and distances from the south channel are shown in **Table 2**.

Table 2. Fox monitoring well information

Well	Distance from Main channel (ft)	Distance from N. Channel (ft)	Pad Elevation (ft)	Well spacing (ft)	Depth (ft)
101	49	6540	2110.08	49	10
102	205	6330	2109.62	156	10
103	385	6090	2110.30	180	10
104	857	5479	2107.09	472	10
105	1711	4440	2107.65	573	10
106	2395	3540	2107.70	684	10
107	3089	2630	2107.69	694	10
108	3917	1425	2110.48	113	10
109	4597	525	2108.13	680	10
110	4800	255	2108.88	203	10
111	4939	75	2107.90	139	10
112	1138	5265	2107.42	281	25
113	3804	1660	2107.60	715	25
114	2360	3405	2105.62	2360	25
115	1050	5225	2105.89	1050	25
116	3950	1100	2104.96	2900	25

All sixteen wells are equipped with In-Situ Level Troll 500 data loggers are installed just above the bottom of the wells. The screened interval on wells 101 to 111 is 8 to 10 feet while the screened interval on wells 112 to 116 is 20 to 25 feet.

Johns Groundwater Monitoring

The Program plans to install 6 groundwater monitoring wells on the Johns site in 2015. The wells will be located to capture the overall groundwater gradient across the site as well as groundwater response to changes in river stage. Four wells will be located near the river and the excavated sloughs and two wells will be located on the southern boundary of the site to capture the behavior of groundwater in the vicinity of the south channel of the Platte River. The wells will be 20 feet deep and screened from 15 to 20 feet below the surface. All wells will be equipped with In-Situ Level Troll 500 data loggers. Proposed locations for the 6 monitoring wells are shown in **Figure A4** in **Appendix A** and well information is shown in **Table 3**.

Table 3. Proposed Johns monitoring well information

Well	Distance from Main channel (ft)	Distance from S. Channel (ft)	Depth (ft)
401	640	5050	20
402	2540	2940	20
403	5410	190	20
404	1870	2140	20
405	220	3860	20
406	3920	140	20

Morse Groundwater Monitoring

Several groundwater monitoring wells exist in the vicinity of the Morse site, with a transect of wells maintained by the Tri Basin Natural Resources District (TBNRD) to the west of the site as well as a nested monitoring well screened at shallow and deep depths located to the north of the Peterson drain. All of these wells are equipped with data loggers maintained by the TBNRD. An additional network of shallow monitoring wells lies to the west of the Morse site, none of the wells in this network is currently equipped with data loggers. The Program installed four monitoring wells to capture groundwater behavior near the wetland cells on the Morse site, as seen in **Figure A5** in **Appendix A**. **Table 4** provides well information and these four wells are equipped with In-Situ Level Troll 500 data loggers. The Program plans to instrument two additional existing groundwater monitoring wells with In-Situ Level Troll 500 data loggers in 2015.

Table 4. Morse monitoring well information

Well	Distance from Main channel (ft)	Distance from Peterson Drain (ft)	Pad Elevation (ft)	Depth (ft)
301	6910	1355	2287.45	20
302	7400	1460	2285.26	20
303	6760	490	2282.67	20
304	7020	700	2282.50	20

Regional Groundwater Monitoring

In addition to the monitoring wells installed on wet meadow sites, Program partners maintain several groundwater monitoring wells in the vicinity of the sites. The Central Nebraska Public Power and Irrigation District (CNPPID), the Central Platte Natural Resources District (CPNRD), and the TBNRD maintain monitoring wells on both the north and south side of the Platte River throughout the associated habitat reach. Some wells are deeper wells while others are shallow wells and some wells are equipped with data loggers but many are only read manually once or twice a year. Data from regional wells provides insight into regional groundwater behavior and allows for a comparison of shallow and deep groundwater elevations.

SURFACE WATER MONITORING APPROACH

Overview

Surface water is monitored to better quantify the hydrologic connection between groundwater and surface water at wet meadows habitat. River stage and discharge are the primary surface water processes monitored; however, pooled surface water, wetland stage, slough stage, and drain stage are also monitored at wet meadow sites containing those surface water features.

The Platte River has a braided structure with several smaller channels weaving between sandbars. The riverbed changes regularly as the smaller channels shift, sandbars are eroded, and new bars are formed. At high flows most or all of the smaller channels pass water and many lower sandbars are overtopped. At low flows, smaller channels with shallower thalwegs dry up and flow is concentrated in the deepest thalweg. Installing monitoring equipment in the deepest thalweg is often not practical unless a permanent structure, such as a bridge pier, is securely anchored well below the riverbed and installing permanent structures in the middle of the river is cost prohibitive. River stage monitoring equipment is installed on the riverbank of the subchannel closest to the wet meadow site. Riverbanks are prone to shift and gages may be buried in sediment or encounter significant erosion during high flow events. Monitoring equipment is anchored as best as possible but may require moving or adjusting with changes in the riverbank.

River Stage Monitoring Gages

River stage is currently monitored at the Binfield and Fox site in both the main and north channels of the Platte River. River stage gages will be installed on the Johns site and near the Morse site in 2015. Stage gages are comprised of a staff gage and a pressure transducer anchored to posts driven into the riverbed. Water surface elevation surveys are used to establish a stage-elevation relationship. The pressure transducers are In-Situ Level Troll 500 that capture and record stage at 15 minute intervals.

Stage gages are installed on the river bank nearest to the site, for example, the Fox south stage gage is installed on the north bank of the main channel and the Fox north stage gage is installed on the south bank of the north channel. It assumed that river stage does not vary significantly across the river channel and that the groundwater responds most directly to river stage at the nearest bank. It is also assumed that a single stage gage is sufficient to capture river stage changes in each channel at the wet meadow sites. River surface water gradient is assumed to be constant from the upstream end of the site to the downstream end of the site. Gradients are measured on a regular basis using survey-grade GIS equipment at the upstream and downstream ends of the site to test this assumption and results are compared to the Program's HECRAS[16] surface water models.

The pressure transducers used to monitor river stage must be protected from freezing. While the Platte River does not freeze over entirely during the winter, ice may form along the riverbanks where the gages are located. Additionally, ice flows in the river pose a threat to the gages as they are known to scour river banks. To prevent damage during the winter, the gages are removed from approximately mid-November until the end of February. If winter stage is deemed crucial to management decisions in the future, other equipment, such as automatic cameras focused on staff gages, may be installed to capture elevation changes and ice conditions during the winter months.

Binfield river stage monitoring

On the Binfield site, the main channel river stage gage is located at the southern end of the western monitoring well transect (see **Figure A2** in **Appendix A** for the gage's location). The gage is installed on the northern river bank of the main channel. The thalweg of the subchannel at the riverbank is not the deepest thalweg and is only able to capture river stage above flows of approximately 100 cubic feet per second (cfs). Due to property ownership limitations, the north channel stage gage is located downstream

[16] US Army Corps of Engineers Hydrologic Engineering Center (HEC): http://www.hec.usace.army.mil/software/hec-ras/

of the eastern monitoring well transect on the southern bank of the north channel (see **Figure A2** for the gage's location). The gage is not located in the deepest thalweg and is only able to measure river stage at flows above approximately 200 cfs. River elevation data captured at the two river stage gages can be compared to groundwater elevations recoded at the Binfield monitoring well transects to capture the timing and magnitude of groundwater response to river stage. The two gages also allow for a comparison of river elevation between the two channels.

Fox river stage monitoring

At the Fox site, the main channel river stage gage is located approximately 575 feet upstream from the monitoring well transect that spans Kilgore Island. The gage is located on the Speidell property on the north bank of the main channel. The thalweg of the channel that runs along the north bank is not the deepest thalweg and only passes flows above approximately 50 cfs. The north channel stage gages is located at the northern end of the monitoring well transect on the Speidell property. It is installed on the southern bank of the north channel and captures stage when flows are above approximately 100 cfs. The Kearney Canal return is located upstream of the north channel stage gage and the gage captures changes in stage resulting from canal returns.

Monitoring equipment was not installed at the bridge piers located along the hike-bike trail that crosses the river to the south of the Fox site as this location is not owned by the Program. Additionally, this location is popular recreation location and there are concerns of vandalism to monitoring equipment.

Morse and Johns stage monitoring

Stage in the Platte River at the Morse and Johns sites will be monitored beginning in 2015 using the same type of instrumentation installed on the Binfield and Fox sites. The stage gages will be installed on the south side of the channel at a location near the Morse site and another location on the Johns site. The south channel of the Platte River that forms from the Peterson drain and runs along the southern end of the Johns site will also be monitored using the same instrumentation as the other stage gage locations.

Discharge Monitoring

Platte River discharge provides a link between groundwater response to river stage and management decisions based on river flow. Discharge is monitored to quantify the volume of water associated with observed changes in groundwater at wet meadow sites. The wet meadow hydrologic monitoring effort relies primarily on discharge measurements from established gages maintained by other agencies. The US Geological Service (USGS) and the Nebraska Department of Natural Resource (DNR) manage several gages that capture river flow throughout the associated habitat reach, with gages located near each of the wet meadow sites as shown in **Figure A1** in **Appendix A**. While these gages are not located at the specific wet meadow sites, they provide reasonable estimates of river discharge at the sites. Discharge estimates may be improved by accounting for inflows from tributaries and canal returns and outflows to canal diversions that occur between the gage location and the site. **Table 3** lists the primary gages used for determining discharge at each wet meadow site.

Table 5. Distance from discharge gage to wet meadow site.

Gage (Managing agency)	Site	Distance (US: upstream, DS: downstream)
Platte River at Overton (USGS)	Morse	3.4 miles US
Platte River at Overton (USGS)	Johns	13.7 miles US
Platte River at Odessa (DNR)	Johns	6.3 miles DS
Platte River at Kearney (USGS)	Fox	6.8 miles US
Platte River at Shelton (DNR)	Binfield	13.6 miles US
Platte River at Grand Island (USGS)	Binfield	19.6 miles DS

Determining discharge at the Binfield and Fox site from nearby gage data requires additional calculations as the discharge gages are located above or below the channel splits that form Shoemaker and Kilgore Islands. The percentage of flow in each channel at a given stage is determined using the Program's HEC-

RAS[17] model of the associated habitat reach. These percentages are approximates as the river cross sections used in the HEC-RAS model date back to 2009. Shifts in the riverbed occurring after the model was created may change the percentage of total flow in the main and north channels. Discharges at these locations are checked with periodic field measurements of river discharge using a handheld flow meter.

USGS gages

The primary gages used for determining discharge at the wet meadow sites are the Overton, Kearney, and Grand Island gages. All three gages are installed on bridge piers on stretches of the river without islands. The gages have well established records and collect river stage and discharge on 15 minute intervals. The USGS provides provisional data in real-time via the internet and publishes approved data within approximately 6 months. Real-time data may not be available during the winter when ice may impact the gage readings. More details on the USGS gages can be found at the USGS website[18].

DNR gages

Two DNR gages are used in conjunction with the USGS gages to confirm discharge: the Odessa gage downstream of the Johns site and the Shelton gage upstream of the Binfield site. Discharge data from the Shelton gage is recorded on 30 minute intervals and is available to the Program via the internet. Data from the Odessa gage is not readily accessible online and is only available via email. The DNR provides emails on an erratic daily to weekly basis containing daily average flow data in a text file.

In addition to river discharge, the DNR collects discharge measurements at several tributaries and canals along the associated habitat reach. This data is available as daily average discharge via email and contains flow data for Strever Creek near Overton, Buffalo Creek near Elm Creek, Turkey Creek near Kearney, North Dry Creek near Kearney, Kearney canal diversions, and Kearney canal returns. Tributary

[17] US Army Corps of Engineers Hydrologic Engineering Center (HEC): http://www.hec.usace.army.mil/software/hec-ras/
[18] USGS Stream flow data website: http://waterwatch.usgs.gov/

and canal data is added to or subtracted from discharge measurements in the river to determine discharge at each wet meadow site.

Other Surface Water Gages

Additional surface water monitoring occurs at several hydrologic features on the wet meadow sites. Sandy soils at all four sites allow for rapid infiltration of pooled and flowing surface water and monitoring at surface water elevations provides insight into localized groundwater response.

Stage in the slough that runs along the southern portion of the Binfield site is monitored with a staff gage and an automated camera. The camera takes photos of the gage twice a day and photos are downloaded on a periodic basis. Staff gage readings can be compared to groundwater elevations in the nearby wells 202 and 203. Vegetation in the slough grows rapidly during summer months and the staff gage requires regular clearing so the camera's view of the staff gage is unimpeded.

A similar camera and staff gage are installed on the Fox site at the largest excavated swale near well 114. Water surface elevation readings can be compared to groundwater elevations to compare the relative impact of precipitation and evapotranspiration on surface and groundwater.

The excavated drains on the Johns site will not be initially monitored. If monitoring is deemed necessary it may be installed in 2016.

Surface water elevation is monitored at four locations on the Morse site using In-Situ Level Troll 500 pressure transducers and staff gages. Gages are installed at the two wetland areas the Program fills during whooping crane migration season as well as at two locations in the Peterson drain behind the two check structures. Surface water elevations can be compared to groundwater elevations to determine the impact of the wetlands and the check structures on the surrounding groundwater.

PRECIPITATION MONITORING APPROACH

Overview

Precipitation is a fundamental hydrologic process at wet meadow sites and is monitored to capture the timing and magnitude of precipitation events. Precipitation typically falls as rain from the spring through the fall and as snow during the winter. Separate gages are used to measure liquid precipitation and winter precipitation.

It is assumed that precipitation falls fairly uniformly across the wet meadow site areas and that one gage located near the center of the site accurately captures the spatial and temporal precipitation patterns across the entire site. This assumption may be tested on the larger Binfield and Morse sites using a temporary second precipitation gage if deemed necessary.

The assumption that precipitation can act as a surrogate for overland application of water identified in Objective 2 will be tested on the Fox site by comparing groundwater response to precipitation with groundwater response to water pumped onto the site.

Liquid Precipitation

Liquid precipitation is monitored using precipitation gages consisting of a Texas tipping bucket and data logger. At the Binfield and Fox sites, the precipitation gages are part of the High Plains Regional Climate Center (HPRCC) weather station. Precipitation data is collected on an hourly basis and is available in real time via the internet. Precipitation gages will be installed on the Johns and Morse sites in 2015 and will collect data on an hourly basis. Data loggers will be downloaded manually on a periodic basis.

Winter Precipitation

The Texas tipping buckets used to measure liquid precipitation are not able to fully capture precipitation that falls as snow or slush during colder times of the year. The amount of precipitation that falls from

November through February is much less than in other months and is not considered to influence groundwater behavior as significantly as precipitation during warmer months. Several aspects of winter precipitation impact how and when it infiltrates into the groundwater. Groundwater response to snow is typically delayed and less direct than rainfall. Snow may not melt for days or weeks after it first falls and it may be blown into drifts that result in a heterogeneous distribution of snow across a site. During especially cold periods, water present in the soil may freeze and create conditions that prevent rain or snowmelt from infiltrating into the groundwater. The presence of shallow groundwater may prevent extensive freezing of soil moisture.

Winter precipitation is monitored at the Binfield and Fox wet meadow sites. Winter precipitation gages may be added to the Johns and Morse sites if deemed necessary. Two types of winter precipitation gages are used. The first consists of an open cylinder partially filled with a combination of anti-freeze and a small amount of oil. Rain, snow, hail, and slush fall into the cylinder and melt in the anti-freeze. The oil floats on the surface of the antifreeze and prevents evaporation from the gage. The depth of the liquid is measured periodically to determine how much precipitation has fallen since the previous reading.

In addition to the total precipitation provided by the winter precipitation gage described above, an automated camera is trained at a staff gage and photographs snow levels twice a day. Changes in snow depth provides insight into when snow might be melting as well as the timing and magnitude of snowfall.

Several other pieces of monitoring equipment are used in conjunction with winter precipitation and snow camera data to aid in estimating the timing and distribution of snowmelt infiltration; specifically, if frozen soil is preventing infiltration of snowmelt or rainfall, and assess the impact of rapid snowmelt that might occur if rain falls on snow. Air temperature and solar radiation collected at the AWDN stations informs when snow might begin melting and how quickly it might melt. Wind speed and direction collected at the AWDN stations is used to determine if snow is likely to be blown into drifts on the site. Groundwater elevations in the groundwater monitoring well transects are used to see when and where snowmelt is infiltrating. Soil moisture content collected from the soil moisture probe array as well as the cosmic ray neutron probe is used to identify if snowmelt is infiltrating into the soil as well as if the soil is saturated or not. Soil temperatures collected at the AWDN stations inform when soil moisture is frozen. Groundwater temperatures are used to indicate if groundwater near the surface is freezing or remaining liquid.

The current monitoring approach is considered adequate to capture the impact of winter precipitation in light of its relatively small percentage of the total precipitation. If gaps or inconsistencies in the overall water budget arise as a result of inaccurate estimates of winter precipitation, the winter precipitation gages may be checked more frequently, especially after large snowfall events to more accurately estimate the amount of water that fell as snow during a given event. Snow depths across the sites may be taken if large snowfall and high winds routinely cause heterogeneous snowmelt that impacts the site-wide water budget. In general, additional equipment or supplemental measurements may be added to better capture the impact of winter precipitation if the current monitoring approach does not provide acceptable winter season water budget results.

EVAPOTRANSPIRATION MONITORING APPROACH

Overview

The term evapotranspiration (ET) combines evaporation from the soil and ground surface with transpiration from plants. ET is the upward flux of water from the site to the atmosphere and is driven by several meteorological processes. A variety of approaches for measuring and quantifying ET exist with varying degrees of complexity and accuracy. A review of applicable methods for determining ET is present in the Program's ET methods white paper[19].

ET varies over spatial and temporal scales. ET rates vary over the course of a day and typically drop significantly over night. ET depends on the season, with different vegetation stages and vegetation coverages resulting in differing ET rates. ET varies depending on the type of vegetation as well as the amount of moisture available. Many methods for determining ET assume a homogeneous vegetation type and coverage across the applicable monitoring area. These assumptions and their relevance to ET monitoring at the wet meadow sites is discussed in the ET methods white paper.

The monitoring of ET typically proceeds along one of two lines: an energy balance approach or a mass transfer approach. The energy balance approach measures the energy available to drive ET to estimate the amount of ET that occurs while the mass transfer approach seeks to quantify the amount of water that transfers from the site into the atmosphere. The Program has elected to use a combination of the energy balance and mass transfer approaches to estimate ET at wet meadow sites. Additional information on ET and the reasoning behind the approach details below can be found in the Program's ET methods white paper, the ET sensitivity analysis[20], and the ET Path Forward[21] documents.

Energy Balance Approach

The energy balance approach measures meteorological processes to calculate and estimate of reference ET. Automated weather data network (AWDN) weather stations maintained by the High Plains Regional Climate Center (HPRCC) are installed on the Binfield and Fox sites to monitor air temperature, relative humidity, solar radiation, wind speed and direction, plant canopy temperature, and soil temperature on an

[19] PRRIP, 2014. *Methods of Determining Evapotranspiration at Wet Meadow Sites*. White Paper compiled by the Office of the Executive Director of the PRRIP, 2014.
[20] PRRIP, 2014. *Evapotranspiration Sensitivity Analysis*. Memo from the Office of the Executive Director of the PRRIP, 2014.
[21] PRRIP, 2014. *Evapotranspiration Monitoring Path Forward*. Memo from the Office of the Executive Director of the PRRIP, 2014.

hourly basis. Soil temperature is measured at a depth of 4 inches (10 cm) below bare soil ground surface. See **Table B1** in **Appendix B** for additional information on the weather station equipment. The HPRCC uses the modified Penman equation to calculate an alfalfa reference ET from this data. Reference ET is an estimate of the ET used by a particular vegetative cover under ideal conditions. To estimate the ET for wet meadow vegetation, crop coefficients adjust reference ET to account for plant type, plant stage, and other factors. While a crop coefficient for wet meadow vegetation has not been explicitly developed, the USGS developed a set of crop coefficients for a riparian grassland located in the associated habitat reach[22]. The riparian grassland vegetation closely resembles wet meadow vegetation and the USGS crop coefficient is an improvement over other crop coefficients developed primarily for agricultural conditions.

The AWDN stations are equipped with additional equipment to monitor plant canopy temperature with an infrared temperature sensor. Plant canopy temperature can be used in combination with vegetation height measurements to develop coefficients needed for the Penman Monteith equation, another calculation used to estimate ET. The Program intends to compare ET calculated using the modified Penman equation with ET calculated using the Penman Monteith equation.

AWDN weather stations transmit data wirelessly via cellular phone telemetry and the Program partners with the HPRCC to maintain the weather stations.

In addition to the ET estimates from the AWDN weather stations, satellite data from January, 2014, through December, 2015, will be evaluated using a modified version of the Mapping EvapoTranspiration at high Resolution with Internalized Calibration (METRIC) algorithm. The METRIC algorithm will be enhanced by incorporating temporally and spatially dense soil moisture data collected on-sight into the

[22] Hall, B.M., & Rus, D.L. 2013. *Comparison of Water Consumption in Two Riparian Vegetation Communities along the Central Platte River, Nebraska, 2008-09 and 2011*. US Geological Survey Scientific Investigations Report 2013-5203.

soil water balance subroutine calculations to provide ET estimates at a 50 meter resolution[23]. These ET estimates will be compared to the AWDN ET estimates to further inform how well the modified Penman equation and USGS crop coefficient perform. The enhanced METRIC ET estimates will also provide valuable information about spatial variability in ET rates at the wet meadow sites.

Mass Transfer Approach

The mass transfer approach seeks to determine ET by measuring or estimating the amount of water that passes from the ground and plant canopy into the atmosphere. A fairly simple device used for this purpose is the modified atmometer. Consisting of a porous ceramic disc connected to a reservoir of water, the atmometer simulates the ET conditions of a surrounding field. ET is measured as the change in water level in the water reservoir over a given period of time. The modified atmometers used on the Program properties are instrumented with electronics and data loggers to read and store ET measurements on an hourly basis.

Modified atmometers estimate reference ET and require a crop coefficient to determine wet meadow ET. The USGS riparian grassland crop coefficients discussed above will be used to adjust the alfalfa reference ET to wet meadow vegetation ET.

Atmometers were chosen as an inexpensive way to check the ET measurements at the Binfield and Fox sites. Determining ET using both an energy balance method and a mass transfer method reduces the uncertainty associated with each approach and provides a cross check on the ET estimates from each method. Atmometers will be installed on the Johns and Morse sites in 2015. Atmometer data from the Binfield and Fox sites will be compared to ET estimates from the modified Penman equation to determine if any systematic adjustments need to be made to the atmometer readings at the Johns and Morse sites. Additionally, data from AWDN stations in Lexington and at the Fox site will be used as a metric of

[23] Franz, T.E. 2015. Combined analysis of remote and proximal sensing methods for high-resolution soil moisture, evapotranspiration, and recharge monitoring concept paper. UNL.

regional ET to compare with the ET estimates from the modified atmometers on the Johns and Morse sites.

Atmometers require regular filling of the water reservoir and clearing of debris from the evaporating disc. Atmometers are damaged by freezing temperatures and are only able to be used from approximately April through October. Data from data loggers recording atmometer readings are downloaded on a periodic basis throughout the spring, summer, and fall.

SOIL MOISTURE MONITORING APPROACH

Overview

Changes in soil moisture content provides the critical connection between hydrologic processes occurring above the ground surface and the groundwater table. Determining the fate of precipitation and the impact of ET on groundwater levels requires measurements of water flux through the unsaturated soil between the ground surface and the groundwater table.

Soil moisture content typically varies spatially on the horizontal plane depending on topography, vegetative cover, and other factors. Soil moisture also varies vertically from the ground surface to the groundwater table as soil wets and dries in response to precipitation and ET. Capturing vertical and horizontal variation necessitates a combination of soil moisture monitoring equipment. The Program's Soil Moisture Monitoring Plan memo[24] elaborates on the monitoring approach described below. The Program does not plan to monitor soil moisture on the Johns and Morse sites at this time. Soil moisture will be approximated based on observations at the Binfield and Fox site and precipitation and ET recorded onsite. Point arrays or CRNP sensors may be added to the sites at a later time if deemed necessary.

[24] PRRIP, 2014. *Wet Meadow Soil Moisture Monitoring Plan*. Memo from the Office of the Executive Director of the PRRIP, 2014.

Point Arrays

Soil moisture variations from the near the surface to a depth of 100 cm (3.3 feet) is measured using vertical soil moisture sensor arrays. Vertical arrays consisting of 4 sensors placed at depths of 10, 25, 50, and 100 cm (0.33, 0.82, 1.6, and 3.3 feet) are installed on the Binfield and Fox sites at the HPRCC weather stations. Sensors were installed by digging a pit near the base of the HPRCC weather station and inserting the sensors horizontally into the intact soil. Data from these sensors is recorded and transmitted via cellular telemetry as part of the HPRCC weather stations.

The vertical soil moisture sensor arrays are considered point measurements on the horizontal plane as soil moisture content may vary within a short distance from the sensors. While they provide useful insight into vertical variations in soil moisture, the point measurements are not likely representative of conditions across the entire site. Additional monitoring equipment is needed for determining site-wide soil moisture behavior.

CRNP Area-Averaged Sensors

Area averaged soil moisture measurements are taken at the Binfield and Fox sites with cosmic ray neutron probe (CRNP) sensors. The sensors determine soil water content by measuring changes in the ambient amount of low-energy neutrons above the land surface. The sensors capture soil moisture flux over a diameter of approximately 600 m (1,970 feet) and an area of 70 acres. Soil moisture content is measured to a depth ranging from 15 cm to 40 cm (0.5 to 1.3 feet). The CRNP sensor readings reflect the average soil moisture content over the horizontal area and vertical depth and record readings on an hourly basis. Data is transmitted via cellular telemetry and the equipment is maintained by HydroInnova, LLC, as part of a lease agreement with the Program. The sensors are installed on posts according to the methodology outlined in the CRNP field installation guide.[25] The CRNP sensors are installed near the HPRCC weather

[25] Franz, T. E. 2012. Installation and calibration of the cosmic-ray solar moisture probe. University of Arizona.

station and the vertical arrays of soil moisture sensors, and soil moisture content measured with the CRNP probes is compared to measurements from the sensor arrays.

The CRNP sensor measurements are used in conjunction with precipitation and ET measurements to estimate the amount of water that enters the groundwater table as percolation as well as the percentage of ET that originates from the groundwater table.

CRNP Rover Surveys

While the CRNP sensors capture soil moisture flux over an area of approximately 70 acres, the Binfield wet meadow site covers 944 acres and the Fox site covers 182 acres. To determine soil moisture on the portion of the sites not covered by the CRNP stationary sensors, mobile CRNP sensors mounted to a truck are driven across the Fox and Binfield sites. The mobile sensor unit (the "rover") determines soil moisture content over the entire site and several surveys are conducted over a range of wet and dry conditions. Rover surveys provide information on the variability in soil moisture across the wet meadow sites. After a full range of soil moisture conditions are surveyed, a relationship between soil moisture variability and the stationary CRNP sensor readings can be developed. Stationary CRNP readings are then used to estimate site-wide soil moisture content.

Rover surveys began on the Binfield and Fox sites in 2014 and will continue through 2015 to gather data over the necessary range of soil moisture conditions. Rover surveys are not planned for the Johns or Morse sites.

ADDITIONAL MONITORING

In addition to the monitoring of the hydrologic processes described above, other aspects of the wet meadow sites will be monitored over the course of the investigation.

Crest Stage Gages

To test the assumption that no significant off-site runoff occurs at the wet meadow sites, peak runoff stage is monitored at low lying areas along the perimeter of the Binfield and Fox site using a USGS Type A Crest-Stage Gages. These simple gages consist of a hollow steel pipe with a wooden rod inside and several holes drilled at its base. The Pipe is anchored to the ground and thin layer of granulated cork is placed at the bottom of the gage. Flow events cause the cork to float and adhere to the wooden rod inside of the pipe to record peak flow elevations. Crest stage gages are read manually on a periodic basis to determine if offsite runoff has occurred. While crest stage gages may not function properly when flowing water has a high mineral sediment load, they are assumed to provide reliable information for the quality of water anticipated with precipitation runoff. Crest gages are not installed on the Johns or Morse property but may be added if locations with significant runoff potential are identified.

Periodic Site Visits

During periodic visits to the wet meadow sites several pieces of data relating to hydrologic performance are recorded. Photographs are taken of site conditions, standing water after high flow or larger precipitation events, and site vegetation at different locations and at different times of year. Vegetation height is recorded manually at the weather stations using a tape measure.

LiDAR Flights

The Program conducts annual flights of the associated habitat reach to measure ground surface elevations using Light Detection and Ranging (LiDAR) . The LiDAR data has a 0.7 meter ground sample distance (GSD) data with an accuracy of 0.5 feet or better. Changes in riverbed topography are determined by comparing LiDAR data from successive years. LiDAR data is also used in conjunction with groundwater elevations at the monitoring wells to approximate average depth to water across the wet meadow sites.

GROUNDWATER MODELS

Groundwater models are developed for the Binfield and Fox sites to aid in the quantification of the hydrologic processes. The models are calibrated to observed groundwater behavior on the sites and incorporate the hydrologic data from the monitoring effort. The models are especially useful in quantifying the flow between the river and the groundwater. The models are described in the Wet Meadow Groundwater Model Description report[26].

Hypothetical scenarios will be used to test the model's ability to predict groundwater behavior during extreme stream flow, precipitation, and evapotranspiration conditions. Additionally, synthetic scenarios will be developed to determine what methods of water management most efficiently and effectively create desired groundwater levels at the wet meadow sites. These scenarios will investigate the impact of management strategies, including flow releases, irrigation of a portion or the entire wet meadow site, and pumping water into depressional areas. The river stage required to achieve desired groundwater levels under various conditions will be investigated as well.

Separate groundwater models developed for other Program projects cover the Johns and Morse sites. While not developed specifically to evaluate the sites' hydrologic performance, these models may be adapted and calibrated using observed groundwater elevations and other hydrologic data.

[26] PRRIP, 2014. *Wet Meadow Groundwater Model Description.* Report compiled by the Office of the Executive Director of the PRRIP, 2014.

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APPENDIX A: MONITORING EQUIPMENT LOCATION MAPS

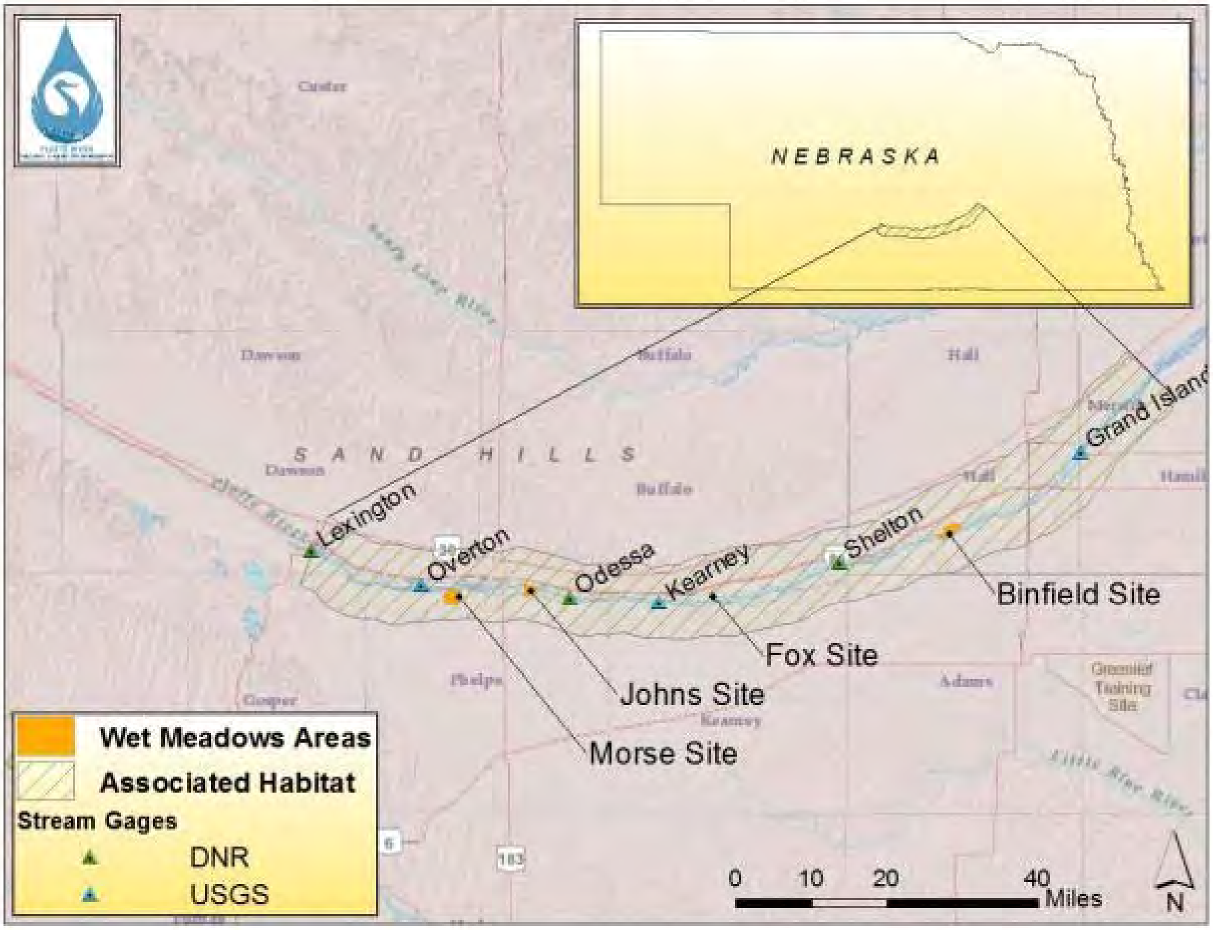


Figure A1. Overview map of wet meadow sites and stream gage locations.

Table A1. General wet meadow site information

Site	Size (acres)	Monitoring start date	Monitoring equipment
Fox	182	March, 2013	GW monitoring well transects, river stage, weather station, winter precipitation, soil moisture, crest-stage gage (for runoff), wetland pooled water elevation
Binfield	944	March, 2013	GW monitoring well transects, river stage, weather station, winter precipitation, soil moisture, crest-stage gage (for runoff), wetland pooled water elevation
Morse	595	September, 2014	GW monitoring wells, wetland stage Proposed equipment: precipitation gage, ET gage
Johns	667	Summer, 2015	Proposed equipment: GW monitoring wells, river stage, precipitation gage, ET gage

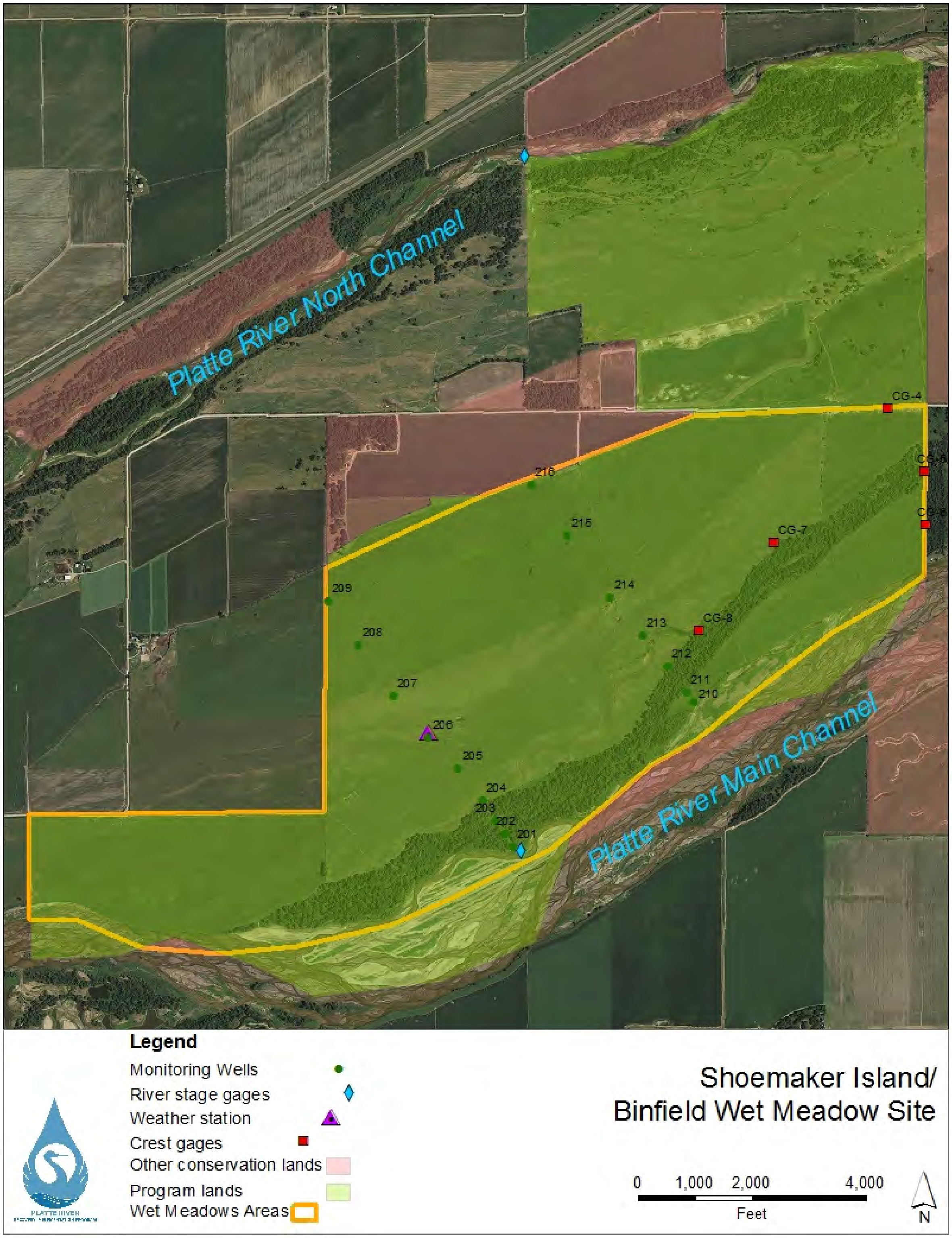


Figure A2. Binfield wet meadow site and instrumentation layout.

Figure A3. Fox wet meadow site and instrumentation layout.

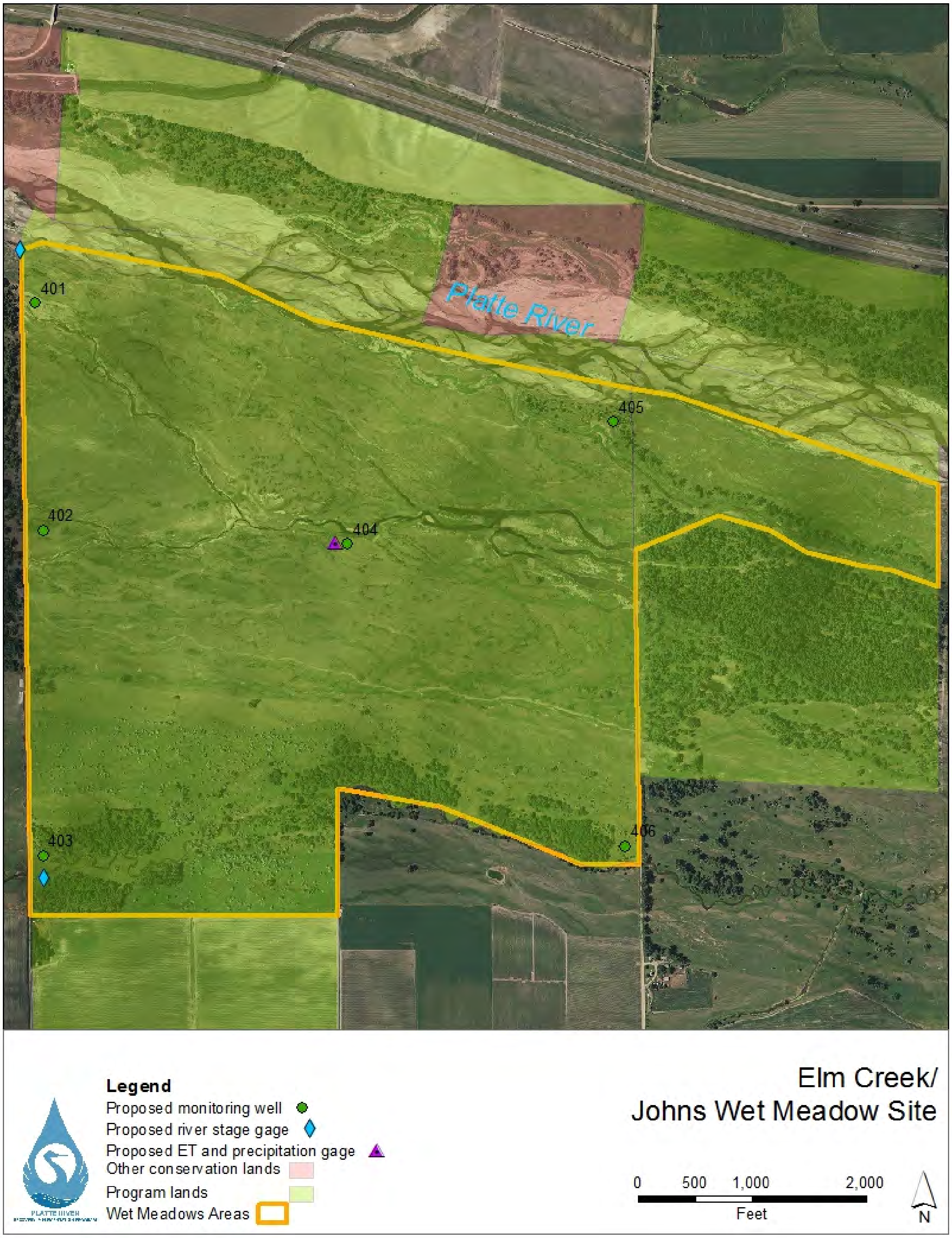


Figure A4. Johns wet meadow site.

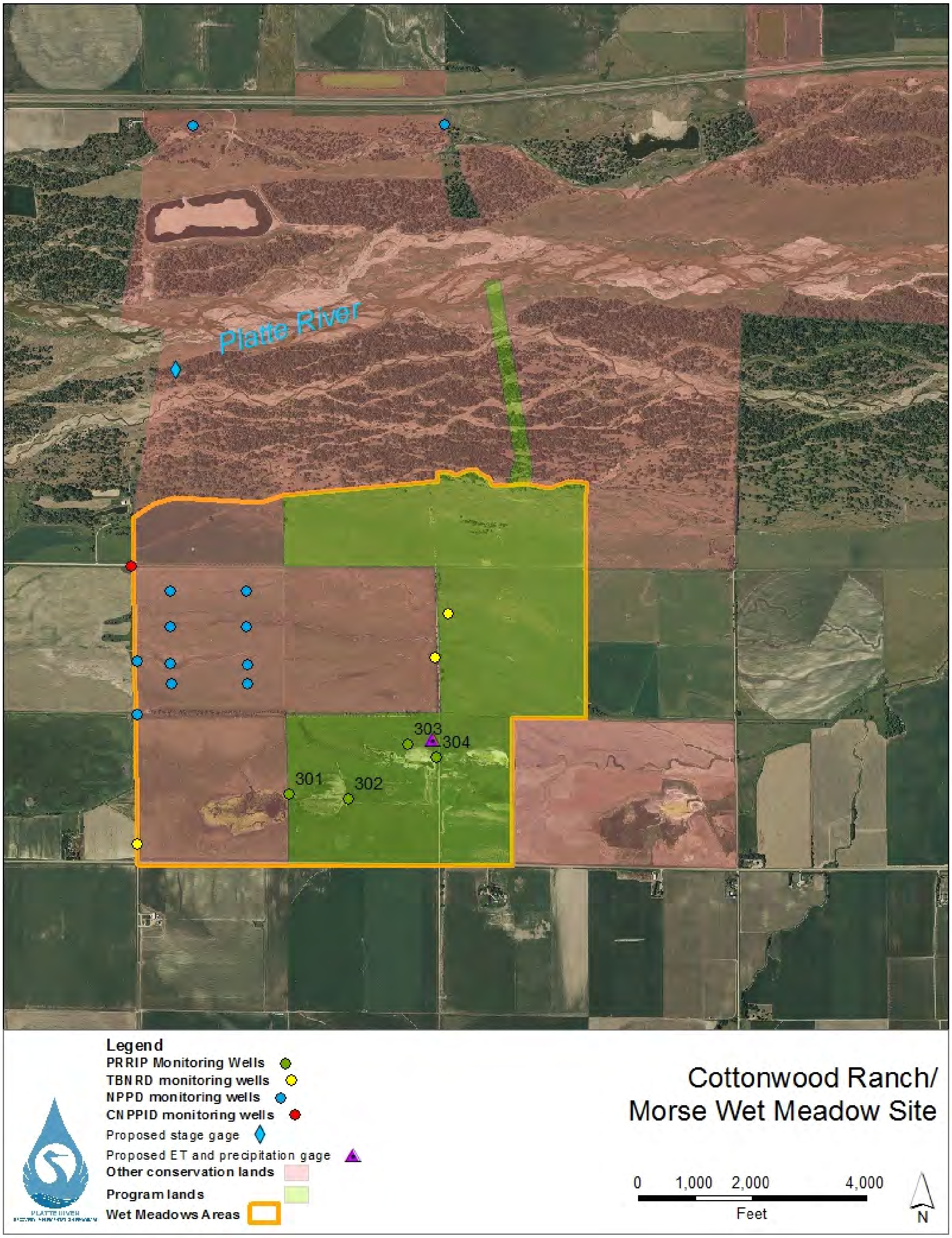
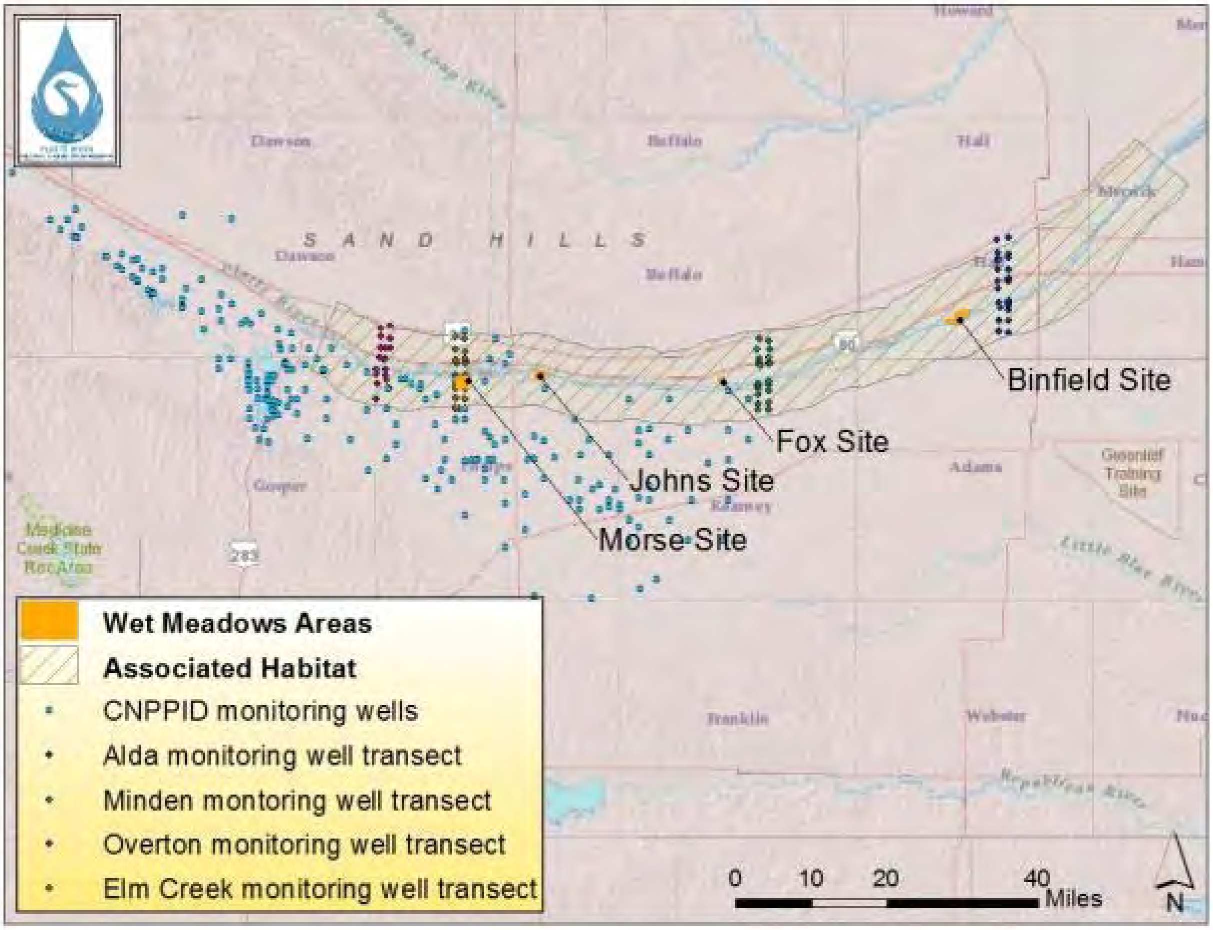


Figure A5. Morse wet meadow site and instrumentation layout.



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780 **Figure A6.** Regional groundwater monitoring wells

CHAPTER 1 APPENDIX B: MONITORING EQUIPMENT SPECIFICAITONS

Table B1. Wet meadow monitoring equipment specifications

Abbreviations: In-Situ (IS), United States Geological Survey (USGS), Campbell Scientific (CS), High Plains Regional Climate Center (HPRCC).

Parameter monitored	*Instrumentation*	*Accuracy*	*Resolution*	*Data collection method*
Groundwater elevation	IS Level Troll 500, 5 psig	±0.0115 ft	0.000575 ft	Telemetry
River stage	IS Level Troll 500, 5 psig	±0.0115 ft	0.000575 ft	Telemetry
Fox wetland water elevation	Reconyx Hyperfire PC800 camera & WaterMark style "C" staff gage	±0.01 ft	±0.005 ft	Automated
Binfield slough water elevation	Reconyx Hyperfire PC800 camera & WaterMark style "C" staff gage	±0.01 ft	±0.005 ft	Automated
Liquid precipitation	CS tipping bucket (TE525-L)	±1% (up to 1 in/hr)	0.00083 ft	Telemetry
Frozen/winter precipitation	HPRCC winter precipitation gage	± 0.007 ft	0.002 ft	Telemetry
Snow depth	Reconyx Hyperfire PC800 camera & WaterMark style "C" staff gage	±0.01 ft	±0.005 ft	Automated
Wind speed	CS met-one wind set, 034B-L	±0.25 mph	0.002 mph	Telemetry
Wind direction	CS met-one wind set, 034B-L	±4°	0.5°	Telemetry
Solar radiation	CS silicon pyranometer, LI200X-L	±5% max	0.2 kW/(m^2mV)	Telemetry
Air temperature	CS temperature & humidity probe, HMP155A-L	±0.4°C	0.002°C	Telemetry
Relative humidity	CS temperature & humidity probe, HMP155A-L	±2%	0.6%	Telemetry
Plant canopy temperature	CS infrared radiometer, SI-111	±0.5°C	0.1°C	Telemetry
Soil temperature	CS temperature probe, 107L	±0.2°C	0.002°C	Telemetry
Reference evapotranspiration	ETgage company modified atmometer, Model E	±1% per day	±0.00083ft	Automated
Soil moisture, vertical array	Theta Probe soil moisture probe, MLX2	±1%	0.1%	Telemetry
Soil moisture, area-averaged	HydroInnova CRNP sensor, CRS 2000/B	±1%	0.1%	Telemetry
Soil moisture, Rover surveys	HydroInnova CRNP sensor, CRS 2000/B	±1%	0.1%	Manual
Runoff peak	USGS crest stage gage	±0.083 ft	0.021 ft	Manual

CHAPTER 1 APPENDIX C: DOMINANT PLANT SPECIES AT THE BINFIELD WET MEADOW SITE

The following tables summarize the findings of the vegetation assessment report conducted for the Program by Prairie Legacy, Inc., in July of 2013[27]. Results in **Tables C** to **Cx** show the plant species found on the Binfield wet meadow site during vegetation surveys and the percent cover for each species. Cover is shown as canopy cover; therefore, the total cover may exceed 100%.

Table C1. Cool season grass species

Exotic cool-season grass species		
Species	*Common name*	*% cover*
Agrostis gigantea	Redtop	1.43
Agrostis stolonifera	Creeping bentgrass	5.68
Bromus inermis	Smooth brome	8.68
Bromus japonicus	Japenese brome	1.71
Bromus tectorum	Downy brome	0.51
Poa compressa	Canada bluegrass	1.36
Poa pratensis	Kentucky bluegrass	7.00
Schedonorus pratensis	Meadow fescue	0.08
Total exotic cool-season grass species		**16.96**
Native cool-season grass species		
Species	*Common name*	*% cover*
Calamagrostis stricta	Northern reedgrass	6.42
Dichanthelium acuminatum	Western panicum	0.35
Dichanthelium oligosanthes	Scribner's panicum	0.29
Elymus canadensis	Canada wild-rye	0.50
Hordeum jubatum	Foxtail barley	4.61
Hordeum pusillum	Little barley	0.50
Koeleria macrantha	Junegrass	0.50
Leersia oryzoides	Rice cutgrass	1.03
Pascopyrum smithii	Western wheatgrass	0.89
Sphenopholis obtusata	Prairie wedge grass	0.08
Total native cool-season grass species		**6.85**
Total all cool-season grass species		**23.80**

[27] Prairie Legacy, Inc. 2013. PRRIP Grassland Vegetation Assessment Final Report. Buffalo, Dawson, Hall, Kearney, and Phelps Counties in Nebraska.

Table C2. Grass-like species

Species	*Common name*	*% cover*
Carex blanda	Woodland sedge	0.50
Carex brevior	Short-beak sedge	0.50
Carex gravida	Heavy-fruit sedge	0.08
Carex grisea	Gray wood sedge	0.08
Carex pellita	Woolly sedge	0.53
Carex spp.	Sedge	12.03
Carex vulpinoidea	Fox sedge	20.18
Eleocharis compressa	Flat-stem spikerush	5.20
Eleocharis palustris	Marsh spikerush	8.38
Eleocharis sp.	Spikerush	1.07
Schoenoplectus pungens	Three-square bulrush	4.25
Total grass-like species		**25.50**

Table C 3. Warm season grass species

Species	*Common name*	*% cover*
Andropogon gerardii	Big bluestem	4.85
Bouteloua curtipendula	Sideoats grama	3.55
Digitaria cognata	Fall witchgrass	0.17
Distichlis spicata	Saltgrass	7.84
Panicum virgatum	Switchgrass	7.27
Schizachyrium scoparium	Little bluestem	0.38
Sorghastrum nutans	Indian grass	1.38
Spartina pectinata	Prairie cordgrass	7.51
Sporobolus compositus	Tall dropseed	0.50
Total warm-season		**26.96**

794 **Table C4.** Exotic forb species

Species	*Common name*	*% cover*
Carduus nutans	Musk thistle	0.50
Lythrum salicaria	Purple loosestrife	0.50
Medicago lupulina	Black medick	1.06
Melilotus albus	White sweet-clover	1.62
Melilotus officinalis	Yellow sweet-clover	0.50
Morus alba	White mulberry	0.50
Rumex crispus	Curly dock	1.33
Taraxacum officinale	Common dandelion	0.99
Tragopogon dubius	Yellow goat's-beard	1.00
Trifolium fragiferum	Strawberry clover	0.50
Trifolium pratense	Red clover	0.75
Ulmus pumila	Siberian elm	0.50
Total exotic forbs		**5.78**

795 **Table C5.** Native forb species

Species	*Common name*	*% cover*
Allium canadense	Meadow garlic	0.59
Amaranthus retroflexus	Redroot pigweed	0.50
Ambrosia artemisiifolia	Common ragweed	0.08
Ambrosia psilostachya	Western ragweed	8.76
Apocynum cannabinum	Hemp dogbane	0.86
Arnoglossum plantagineum	indian-plantain	2.93
Asclepias speciosa	Showy milkweed	0.50
Asclepias syriaca	Common milkweed	0.38
Asclepias verticillata	Whorled milkweed	0.62
Asclepias viridiflora	Green milkweed	1.00
Callirhoe involucrata	Purple poppy-mallow	0.62
Cirsium altissimum	Tall thistle	0.50
Cirsium canescens	Platte thistle	0.50
Cirsium flodmanii	Flodman's thistle	1.03
Cirsium undulatum	Wavy-leaf thistle	0.50
Conyza canadensis	Horseweed	0.50
Cornus drummondii	Rough-leaf dogwood	11.83
Dalea candida	White prairie-clover	0.50
Dalea purpurea	Purple prairie-clover	1.01
Dalea villosa	Silky prairie-clover	0.50

796 **Table C5 (continued).** Native forb species

Species	*Common name*	*% cover*
Desmanthus illinoensis	Illinois bundleflower	0.62
Desmodium illinoense	Illinois tick-clover	0.88
Equisetum laevigatum	Smooth scouring-rush	0.97
Erigeron strigosus	Daisy fleabane	1.52
Euphorbia davidii	W. Toothed spurge	0.50
Euphorbia sp.	Spurge	0.50
Eustoma russellianum	Prairie-gentian	0.78
Euthamia gymnospermoides	Viscid goldentop	3.08
Galium aparine	Catch-weed bedstraw	0.08
Glycyrrhiza lepidota	Wild licorice	1.12
Hedeoma hispida	Rough false-pennyroyal	0.87
Helianthus maximiliani	Maximilian's sunflower	8.00
Iva annua	Annual marsh-elder	5.59
Juncus balticus	Baltic rush	1.03
Juncus dudleyi	Dudley's rush	1.03
Juncus nodosus	Knotted rush	1.00
Juncus torreyi	Torrey's rush	0.50
Juniperus virginiana	Eastern red-cedar	0.50
Lactuca ludoviciana	Western wild lettuce	0.29
Liatris punctata	Dotted gayfeather	0.50
Linum sulcatum	Grooved flax	1.31
Lithospermum incisum	Fringed puccoon	1.00
Lobelia spicata	Pale-spike lobelia	0.88
Lycopus americanus	American horehound	1.58
Lycopus asper	Rough bugleweed	4.67
Lythrum alatum	Winged loosestrife	1.75
Mentha canadensis	Canada mint	12.00
Oenothera curtiflora	Velvet butterfly-plant	0.50
Oenothera suffrutescens	Scarlet butterfly-plant	0.50
Packera plattensis	Prairie ragwort	0.08
Persicaria amphibia	Water smartweed	0.50
Phyla lanceolata	Northern fogfruit	5.22
Physalis longifolia	Common ground-cherry	0.08
Physalis virginiana	Virginia ground-cherry	0.29
Plantago patagonica	Woolly plantain	9.47
Potentilla paradoxa	Bushy cinquefoil	0.58
Prunella vulgaris	Self-heal	0.69

Table C5 (continued). Native forb species

Species	*Common name*	*% cover*
Pycnanthemum virginianum	Virginia mtn-mint	1.09
Ratibida columnifera	prairie-coneflower	1.33
Rosa arkansana	Dwarf prairie rose	0.75
Rosa woodsii	Western wild rose	5.55
Rudbeckia hirta	Black-eyed susan	2.90
Sisyrinchium montanum	Strict blue-eyed-grass	0.36
Solidago canadensis	Canada goldenrod	1.43
Solidago gigantea	Late goldenrod	1.23
Solidago mollis	Ashy goldenrod	0.50
Solidago rigida	Stiff goldenrod	1.60
Solidago sp.	Golgenrod	0.50
Symphoricarpos occidentalis	Wolfberry	2.04
Symphyotrichum ericoides	Heath aster	2.81
Symphyotrichum lanceolatum	Tall white aster	2.11
Teucrium canadense	American germander	0.50
Toxicodendron radicans	Eastern poison ivy	0.50
Triglochin maritima	Shore arrow-grass	1.40
Verbena stricta	Hoary vervain	0.37
Vernonia baldwinii	Western ironweed	0.58
Vernonia fasciculata	Prairie ironweed	1.33
Viola pedatifida	Prairie violet	0.62
Total native forb species		**59.13**

CHAPTER 2 – Methods of Determining Evapotranspiration at Wet Meadow Sites

ABSTRACT

A variety of methods used to determine evapotranspiration are described, compared, and evaluated on their applicability to determining evapotranspiration at wet meadow sites managed by the Platte River Recovery Implementation Program (PRRIP or the Program). Evapotranspiration comprises one hydrologic element of many being considered at two Program wet meadow sites as part of a wet meadow hydrology study to develop a quantitative water budget to aid in management decisions.

Mass transfer and energy balance approaches to determining wet meadow evapotranspiration are discussed with a focus on methods that measure evapotranspiration directly as well as methods that estimate evapotranspiration through other measurements. Lysimeters, Bowen ratio energy balance systems, and eddy covariance systems are summarized along with estimation methods including atmometers, evaporation pans, temperature-based equations, radiation-based equations, combination equations, and remote sensing approaches. The methods are compared based on their applicability to wet meadows, accuracy and precision, crop coefficient requirements, data processing requirements, operation and maintenance requirements, and cost. Their ability to be incorporated into the wet meadow hydrology study is evaluated. Several methods are identified as suitable for the purposes of the study and are sorted by their crop coefficient requirements, accuracy and precision, maintenance requirements, and total cost. Suggested approaches for determining evapotranspiration at wet meadow sites include using the Penman method, checking the Penman method with other energy balance estimation methods, checking the Penman method with modified atmometers, directly measure evapotranspiration using Bowen ratio energy balance systems, and directly measuring evapotranspiration using lysimeters. The crop coefficient requirements associated with reference evapotranspiration-based methods is discussed and approaches for determining wet meadow crop coefficients are identified.

INTRODUCTION

Purpose

This white paper summarizes a variety of applicable methods for estimating or measuring evapotranspiration at wet meadow sites managed by the Platte River Recover Implementation Program (PRRIP or the Program). The definition adopted by the Program describes wet meadows as "grasslands with waterlogged soil near the surface but without standing water most of the year" (PRRIP, 2012). The Program is developing a water budget for wet meadow sites through a combination of monitoring and modeling to better inform management decisions. Accurately determining wet meadow evapotranspiration is an integral part of this effort as evapotranspiration represents a primary term in the budget.

An overview of the various approaches to estimating and measuring evapotranspiration will be presented along with discussion of the advantages and disadvantages of each method in light of their applicability to wet meadow sites.

Wet Meadow Vegetation

Wet meadows have unique and varied vegetation characteristics. Some of the vegetation present at wet meadow sites includes mixed grass prairie species, emergent aquatic vegetation, and sedge meadows (Ramirez and Weir, 2010). When considering measuring evapotranspiration over wet meadow vegetation, it is important to realize that wet meadows differ from crop land in several key ways. Wet meadow vegetation does not consist of a monoculture; rather it has a range of plant species with varying heights and growth stages. Additionally, wet meadows may have standing water at various times of the year, further complicating evapotranspiration estimates. Further discussion of wet meadows vegetation can be found in the wet meadow literature review prepared for the Program (Ramirez and Weir, 2010). **Figure 1** shows standing water near a monitoring well and portrays some of the variety in vegetation present at wet meadow sites.

Wet Meadows Hydrology Study

The Program is currently conducting a hydrology study on two wet meadow sites along the Platte River in Central Nebraska. Monitoring includes groundwater levels, river stage, off-site runoff, and meteorological data collected using an Automatic Weather Data Network (AWDN) weather station. Liquid precipitation is measured with a rain gage and winter precipitation is measured with a winter precipitation gage as well as by photography to capture snow depth. Data collected as part of the study is analyzed to quantify each aspect of the wet meadow water budget.

Figure 1. Standing water near a monitoring well at a wet meadow site in the fall after abnormally high flows in the Platte River (image credit: PRRIP, October 2013)

The AWDN weather stations at the wet meadow sites are maintained by the High Plains Regional Climate Center (HPRCC) and monitor air temperature, relative humidity, solar radiation, wind speed and direction, plant canopy temperature, soil temperature, soil moisture, liquid precipitation on an hourly basis. The base cost for the HPRCC AWDN weather station equipment is about $9,340, including equipment to transmit data wirelessly via cellular phone telemetry. The HPRCC covered installation costs for the stations and station maintenance costs are less than $1000 per station per year. The Program requested the AWDN stations be equipped with additional equipment to monitor plant canopy temperature with an infrared temperature sensor, soil moisture, and frozen precipitation. Plant canopy temperature and soil moisture data are collected on an hourly basis and frozen precipitation is measured on a monthly to seasonal basis. Total AWDN weather station equipment costs are about $11,140 (HPRCC, 2013a).

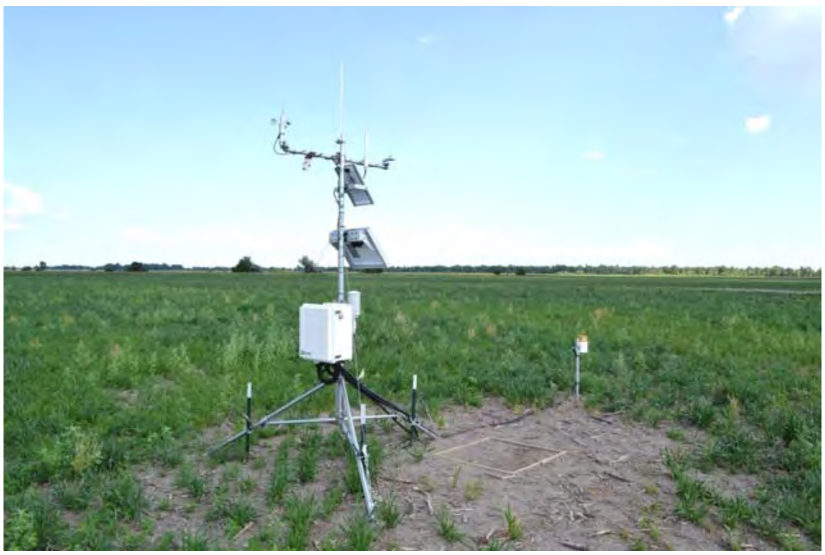


Figure 2. AWDN weather station (image credit: PRRIP, June 2013)

Any method used to determine evapotranspiration as part of the wet meadow hydrology study must provide evapotranspiration values on a daily basis at a minimum, with hourly values being preferred. Additionally, logistical considerations require automated data collection and a data download frequency of monthly or less. Similarly, the frequency of maintenance requirements for monitoring equipment should be monthly or less than monthly.

Evapotranspiration Overview

Evapotranspiration is defined in the ASCE Manual 70 as “the combined process by which water is transferred from the earth’s surface to the atmosphere; evaporation of liquid water from the soil surface and water intercepted by plants, plus transpiration by plants" (Jensen et al., 1990). It is a diffusive process driven by a difference in vapor pressures between an evaporating surface and the overlying air and perpetuated by wind (Dingman, 2008). Factors influencing evapotranspiration include water availability, solar radiation, soil properties such as hydraulic conductivity, vegetation properties such as leaf area, height, and maturity stage, and meteorological conditions such as air temperature, relative humidity, and wind speed (Jensen et al., 1990). Accurately determining evapotranspiration proves difficult due to the number of factors affecting evapotranspiration and the temporal and spatial variation in these factors. For further background information on evapotranspiration, refer to the Food and Agriculture Administration (FAO) Irrigation and Drainage Paper 56, "Crop Evapotranspiration" (Allen et al., 1998).

Methods

Methods for determining evapotranspiration are often divided into two categories: mass transfer approaches and energy balance approaches. Mass transfer approaches measure or estimate the amount of water that enters the atmosphere from an evaporating surface (for the purposes of this white paper, the evaporating surface will be vegetation, bare soil, and open water present at wet meadow sites). Energy balance approaches focus on latent-heat exchange during evaporation. Latent-heat (specifically, the latent-heat of vaporization) describes the amount of energy required for water to change phases from a liquid to a vapor. Evapotranspiration can be determined by balancing all energy input and output terms at an evaporating surface to quantify the energy associated with latent-heat. For further explanation of methods used to determine evapotranspiration, refer to ASCE Manual 70 (Jensen et al., 1990).

Evapotranspiration may be measured directly or estimated for both water balance and energy balance approaches. For the purposes of this white paper, a direct measurement involves equipment that is capable of determining evapotranspiration at a site without the use of empirical relationships and crop coefficients. Direct measurement of evapotranspiration is difficult and expensive and hydrologists have developed methods to estimate evapotranspiration based on measurements of meteorological data (Dingman, 2008). Estimation methods employ the physics of evapotranspiration and empirical relationships to calculate evapotranspiration from temperature, humidity, wind, solar radiation, and other data points collected on site or from a nearby location.

Reference Evapotranspiration

Due to the complexity involved with directly measuring evapotranspiration, many estimation methods calculate evapotranspiration using the concept of a reference crop. A reference crop is typically a common, well-studied crop, such as turf grass or alfalfa. The use of reference crops provides an evapotranspiration surface that is independent of crop type, crop development, soil factors, and management practices. Evapotranspiration estimation methods are calibrated to determine reference evapotranspiration for a specific reference crop. Reference evapotranspiration values calculated in different seasons or in different locations can be directly compared because they refer to the same evapotranspiration surface (Allen et al., 1998). Reference evapotranspiration serves as an evaporative index by which the actual evapotranspiration may be predicted for a range of vegetation, management, and surface conditions by applying crop coefficients, as illustrated by *Equation 1*:

$$ET = K_c ET_{ref} \qquad (Equation\ 1)$$

Where:

ET is evapotranspiration of the vegetation at the location of interest,

K_c is a dimensionless crop coefficient, and

ET_{ref} is the reference evapotranspiration (Jensen et al., 1990).

Crop coefficients are empirically derived for various crops and vegetative covers and account for crop transpiration at specific growth stages as well as soil evaporation (Jensen at al., 1990). For example, to calculate the evapotranspiration of soy beans, evapotranspiration for a reference crop such as alfalfa can be estimated using an appropriate method and then multiplied by a soy bean crop coefficient selected for the appropriate growth stage of the soy beans. Crop coefficients are not able to account for ET during times of vegetation dormancy, frozen soil, or for snow covered soils.

Crop coefficients have been identified for a wide range of agricultural crops and a few non-agricultural habitats; however, a specific crop coefficient does not exist for wet meadow vegetation. To estimate evapotranspiration with a reference crop method, a wet meadow crop coefficient could be approximated based on "surrogate" crop coefficients for similar vegetation or a crop coefficient could be developed for wet meadow vegetation. The variety in wet meadow vegetation makes the selection of a representative crop coefficient difficult and use of a surrogate crop coefficient will introduce additional error into evapotranspiration calculations.

Developing a wet meadows crop coefficient requires comparing direct measurements of evapotranspiration to calculated reference evapotranspiration as shown in *Equation 2*:

$$K_c = \frac{ET}{ET_{ref}} \qquad (Equation\ 2)$$

Where:

ET is evapotranspiration of the vegetation at the location of interest,

K_c is a dimensionless crop coefficient, and

ET_{ref} is the reference evapotranspiration.

Lysimeters, Bowen ratio energy balance systems, and eddy covariance systems are commonly used to directly measure evapotranspiration for the development of crop coefficients (Allen et al., 1998).

Reference crop methods for estimating evapotranspiration are primarily developed for agricultural crops. Wet meadows present unique challenges to the reference crop approach as they are not uniform monocultures. Wet meadow vegetation will have varying vegetation stage, vegetation height, and leaf area index, all of which are assumed constant for agricultural crops. Crop coefficients are most accurate when based on a regular irrigation pattern and will be less accurate when applied to wet meadows with irregular precipitation patterns and varying soil moisture content from fluctuating groundwater levels. The presence of open water on wet meadow sites further reduces the accuracy of reference crop methods as evaporation rates from open water differ from evapotranspiration rates from vegetated surfaces. The differences between wet meadow vegetation and agricultural crops must be accounted for if reference crop methods are used to determine wet meadow evapotranspiration.

Document structure

This document will present an overview of methods used to determine evapotranspiration, discussing the mass transfer approaches first followed by energy balance approaches. Direct measurement and estimation methods for both approaches will be presented. This document does not provide an exhaustive summary of every possible method for determining evapotranspiration, but focuses on widely used and accepted methods that may be applicable to wet meadow sites.

MASS TRANSFER APPROACHES

Overview of Mass Transfer Approaches

Mass transfer approaches to determining evapotranspiration do so by measuring the amount of water that evaporates from a container over a period of time. They quantify the mass of water that is transferred from an evaporating surface to the atmosphere. Atmometers and evaporation pans are relatively simple devices that measure evaporation from a container and determine evapotranspiration by applying a coefficient to the measured evaporation. Lysimeters are more complicated devices that measure the amount of water that enters and leaves a container of soil with established vegetation. Lysimeters are considered capable of directly measuring evapotranspiration, while atmometers and evaporation pans are considered to estimate evapotranspiration from measured evaporation.

Mass Transfer Measurement Methods

Highly sensitive weighing lysimeters offer the only method of precisely measuring water loss from soil and crop canopy surfaces. Because of this, lysimeter data have provided important input in the development and testing of other empirical methods for estimating evapotranspiration (Allen et al., 1996).

Lysimeters

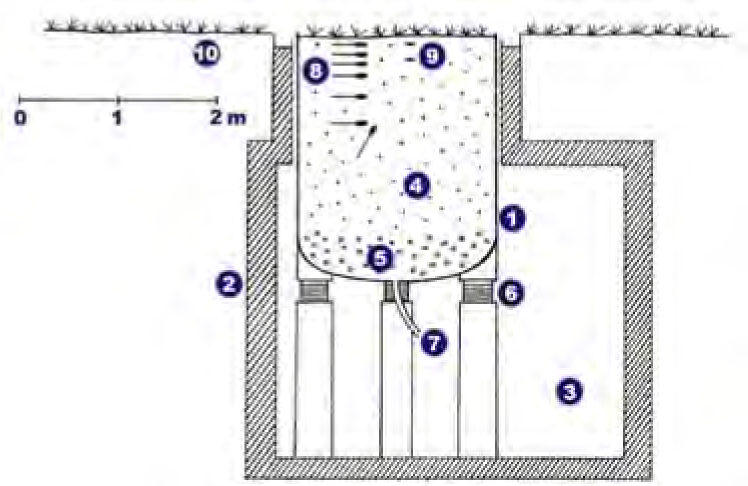
Description of method

Lysimeters consist of an inert container embedded in the ground and filled with soil volume as seen in **Figure 3**. Vegetation is grown in the lysimeter soil and water lost to evaporation and transpiration is measured by accounting for changes in the mass or volume of water in the container (Jensen et al., 1990). Lysimeters are usually classified as weighing or non-weighing and by whether the soil profile is monolithic or refilled (Howell et al., 1991). Additional discussion is included below that describes lysimeters designed to function in the presence of high groundwater tables, similar to those observed at wet meadow sites.

Figure 3: A lysimeter from above (image credit: http://www.iac.ethz.ch/groups/seneviratne/research/rietholzbach/instruments)

Weighing Lysimeters

Weighing lysimeters install scales below the lysimeter container to measure changes in the container's mass as shown in **Figure 4**. The amount of water lost by evapotranspiration is equal to the change in mass of the lysimeter after accounting for precipitation, drainage, and runoff (Allen et al., 2011). Mechanical, counterbalanced, and hydraulic scales can all be used, with mechanical scales providing the highest timescale resolution of sub hourly measurements (Jensen et al., 1990).



1 container

2 concrete wall

3 cellar

4 soil

5 filter (sand and gravel)

6 electronic scales

7 drainage outlet

8 moisture sensor

9 temperature sensor

10 grass

Figure 4: Weighing lysimeter cross section (image credit: http://www.iac.ethz.ch/groups/seneviratne/research/rietholzbach/instruments)

Weighing lysimeter scales counterbalance the dead weight of the soil and measure only the change in weight of water in the soil. The best weighable lysimeters are highly accurate and are capable of measuring evapotranspiration data for short time periods with a precision corresponding to changes in evapotranspiration rates of ±0.0254 millimeters (0.001 inches) per hour (Jones, 1992).

Weighing Groundwater Lysimeters

Standard weighing lysimeters do not function well in high groundwater conditions as they are isolated from the surrounding soil and cannot replicate groundwater levels above the base of the lysimeter container. In the presence of high groundwater, a groundwater lysimeter is used to simulate an artificial groundwater level. Groundwater lysimeters separate the soil in the lysimeter from the surrounding soil with an impermeable barrier. Groundwater levels in the surrounding soil are measured and the groundwater level in the lysimeter is lowered with a pump or raised by adding water from a supply tank until it matches the surroundings, as shown in **Figure 5**. The water added to or removed from the lysimeter is measured along with soil moisture content in the lysimeter and precipitation. Evapotranspiration is calculated as the sum of precipitation and the net change in groundwater minus the change in soil moisture in the lysimeter (Schwaerzel and Bohl, 2003).

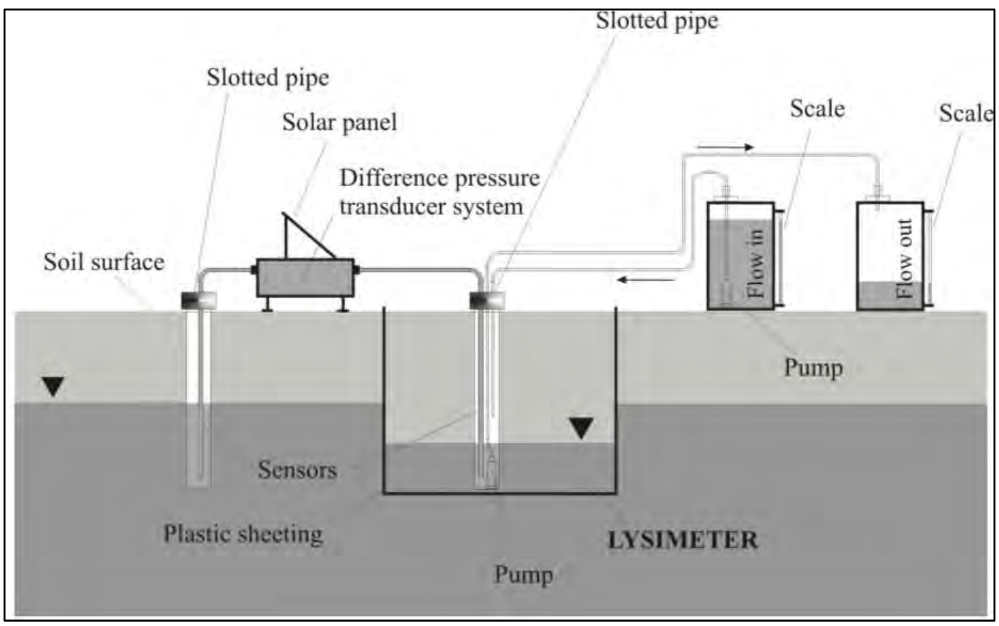


Figure 5. Groundwater lysimeter schematic (image credit: Schwaerzel and Bohl, 2003)

The accuracy and precision of groundwater lysimeters is slightly lower than that of standard weighing lysimeters due to the complexities introduced with maintaining groundwater levels in the lysimeter at the same elevation as the surrounding groundwater. The groundwater lysimeter developed by Schwaerzel and Bohl in 2003 reported evapotranspiration with a precision to the nearest 0.1 millimeter (0.004 inches) per hour (Schwaerzel and Bohl, 2003). An alternate groundwater lysimeter configuration was developed by Bethge-Steffens et al. in 2004 to monitor the soil water balance at floodplain sites and measured evapotranspiration with a precision to the nearest millimeter (0.04 inches) per day (Bethge-Steffens et al., 2004). The temporal resolution of the Schwaerzel and Bohl groundwater lysimeter was daily, while the Bethge-Seffens et al. reported evapotranspiration measurements every fifteen minutes.

Non-weighing Lysimeters

Non-weighing lysimeters determine evapotranspiration by collecting and measuring water that percolates through the lysimeter and measuring soil moisture content in the lysimeter, shown in **Figure 6**. After accounting for any runoff, the amount of water that leaves the lysimeter through percolation and changes in soil moisture is subtracted from precipitation to provide evapotranspiration values (Shukla et al., 2007).

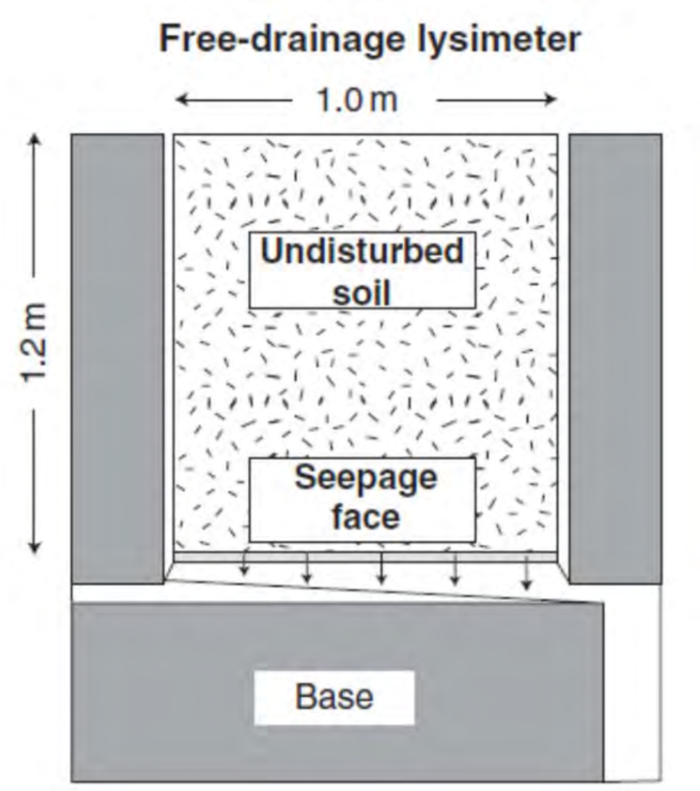


Figure 6. Free drainage lysimeter (image credit: Abdou and Flury, 2004)

Non-weighing lysimeters have a biweekly temporal resolution as measurable amounts of water must percolate through the lysimeter to be read (Dastane, 1978). Percolated water can often be measured to the nearest millimeter (0.04 inches) per week (Riley et al., 2009). While non-weighing lysimeters do not require significant maintenance once installed, readings are taken manually on a biweekly or weekly basis (Soil Moisture Equipment Corp., 2009). Non-weighing lysimeters can be made from parts available at a hardware store and are inexpensive compared to other types of lysimeters (Dastane, 1978).

Non-weighing Groundwater Lysimeters

Constant water table lysimeters are useful in locations where a high water table exists. With this kind of non-weighing lysimeter, the water table is maintained at a constant level inside the lysimeter and the water added to maintain water level is a measure of the actual evapotranspiration from the lysimeter (Van Bavel, 1961, Ward and Trimble, 2004).

Lysimeter Filling Methods

Two methods of filling lysimeters with soil are commonly employed. Lysimeters filled with loose soil are called refilled lysimeters and those filled with a cohesive block of soil are called monolithic lysimeters. Monolithic lysimeters seek to preserve existing vegetation and soil properties that are destroyed by excavation and backfilling; however, complex installation and high initial costs limit their use (Schneider and Howell, 1991). Rocky soils restrict the use of soil coring and do not allow for smooth walls for encasing a soil block. Sandy and unstructured soils can only be undercut with a continuous steel plate because the granular material will fall between pipes or rods driven under the monolith (Schneider and Howell, 1991). The refilling method must account for the time it takes for vegetation to establish a similar root structure and achieve a growth stage comparable to the surrounding vegetation.

Refilled lysimeters can be constructed to represent the surrounding soil properties. Quality installation of a refilled lysimeter requires precise excavation of soil layers, storage of the individual layers of soil, and careful backfilling of each soil layer to the same density as the natural soil (Jones, 1992). If the soil profile is complex, refilled lysimeters may require several years to reestablish soil properties and vegetation (Schneider and Howell, 1991) because root channels and soil fissures are removed during the back-fill process (Kohnke et al., 1940).

Lysimeter Assumptions

The basis of lysimetric measurements lies with the assumption that the sample of soil and overlying vegetation represents the surrounding area in terms of soil water content and vegetation growth. When this assumption is satisfied, lysimeter readings are widely accepted as an unparalleled standard against which to compare and validate other evapotranspiration measurements and models of crop evaporation. If the sample is unrepresentative, errors in evapotranspiration measurements can exceed actual values by more than ten percent (Shuttleworth, 2008). Lysimeters are not able to capture the complexity of native vegetation and soil structure that occur over large spatial and timescales. For example, lysimeters are likely too small for large vegetation with extensive root structure and establishing representative root structure for long lived plants may not be possible.

Lysimeter accuracy is directly proportional to the lysimeter area and the accuracy of the scale, but inversely proportional to the lysimeter mass (Schneider and Howell, 1991). Proper mass to area ratios must be applied to ensure assumptions of lysimeter accuracy prove appropriate.

Lysimeters are based on the assumption of one-dimensional (upward) evapotranspiration. This assumption is valid when lysimeters are designed correctly and lysimeter vegetation height closely matches that of the surrounding vegetation (Allen et al., 1991).

Lysimeter measurements are point measurements and typically apply to a surrounding area of less than 430 ft^2 (about one-hundredth of an acre). Lysimeter measurements are often extrapolated to larger areas and used to characterize evapotranspiration for several acres. This is appropriate when the vegetative and environmental conditions of the lysimeter system closely match that of the larger area (Allen et al., 1991).

Groundwater lysimeters attempt to match groundwater elevations in the lysimeter with the surrounding groundwater table. Any difference in groundwater elevations or time lag between changes in groundwater elevation matches will result in slightly different rates of evapotranspiration.

Cost

A wide range of lysimeter types results in a wide range of possible costs and increased lysimeter accuracy is typically accompanied by increased costs. Cost for the majority of precision weighing lysimeter installations have been in the $100,000 range due to the complexities in design and operation. Maintenance and operation costs over a continuous three-year period were low (Allen and Fisher, 1990).

Approximate equipment costs for a Decagon Devices weighing groundwater lysimeter amount to $25,000 (Decagon Devices, 2013). In addition to equipment costs, weighing groundwater lysimeters would require high installation costs associated with excavation, lysimeter compartment construction, and soil monolith extraction and lysimeter set up.

Non-weighing lysimeters can be inexpensive to construct and install using parts available from a hardware store.

Advantages of method

A significant advantage of lysimeters over other methods of determining evapotranspiration lies in their ability to provide actual evapotranspiration measurements rather than estimates that require additional coefficients and calculations. Lysimeters provide evapotranspiration measurements of site specific vegetation rather than a reference crop. When properly designed, constructed, instrumented, managed, operated, and interpreted, (Allen et al., 1991) lysimeters provide a direct measurement of evapotranspiration representative of their surroundings.

Weighing groundwater lysimeters can provide high quality evapotranspiration measurements for wet meadow sites on daily or less timescale that can be read by a data logger. They also provide insight into soil moisture content and quantify volume changes in the groundwater table.

Non-weighing groundwater lysimeters are relatively inexpensive and easy to install and may be used to verify evapotranspiration rates determined by other methods.

Disadvantages of method

While lysimeters provide accurate direct measurements of evapotranspiration, they are not without disadvantages. Lysimeters can be complicated to install and require field calibration to ensure proper evapotranspiration readings (Middleton and Jensen, 1969). Refillable lysimeters require time for vegetation to establish and may not provide accurate readings for as long as several years during this process. Lysimeters may never be able to fully represent the complexity of the natural vegetation found in diverse ecosystems such as wet meadows.

Weighing groundwater lysimeters are expensive and require extensive and complex installation while non-weighing groundwater lysimeters are less accurate and only measure evapotranspiration on weekly timescales. Non-weighing groundwater lysimeters also require manual operation and reading (Van Bavel, 1961). Weighing lysimeters are not able to capture lateral movement of groundwater and may not capture the effects of seasonal flooding.

Any type of lysimeter requires routine maintenance to check the condition of the vegetation on and around the lysimeter. The lysimeter may need to be occasionally tilled, fertilized, and sprayed to ensure accurate measurements (Fisher, 2012).

Applicability to wet meadows

Wet meadow evapotranspiration could be measured using groundwater lysimeters. Weighing groundwater lysimeters could provide high quality evapotranspiration measurements on sub-daily timescales, but they do so at a high cost and involve complex installation and operation. Non-weighing groundwater lysimeters are not able to provide evapotranspiration measurements on a daily basis but could be valuable in confirming evapotranspiration values determined by another method. They are cheap and fairly easily installed but require regular readings.

Mass Transfer Estimation Methods

Estimating evapotranspiration from measured evaporation rates provides an appealing alternative in light of the high cost and complexity of weighing groundwater lysimeters. Atmometers and evaporation pans are two measurement methods commonly used to estimate evapotranspiration. Atmometers measure the evapotranspiration of water from the instrument surface and evaporation pans measure evaporation from an open pan. Coefficients are used to obtain evapotranspiration estimates from atmometer and evaporation pan measurements.

Atmometer

<u>Description of method</u>

Atmometers are some of the oldest devices used to measure evaporation, with early designs dating back to the 1800's (Livingston, 1908), and have been updated in recent times to provide estimates of evapotranspiration of water into the atmosphere. Recent updates for modified atmometers consist of a porous ceramic cup covered with a green fabric that simulates the canopy of a grass or alfalfa reference crop. The cup is mounted on top of a cylindrical water reservoir as shown in **Figure 7** (Colorado State University Cooperative Extension, 1999). As evaporation from the fabric's surface draws water from the reservoir, the decline in reservoir water level is measured to determine evaporation from the atmometer. Rain water cannot enter the modified atmometer because a membrane impervious to liquid water is utilized on top of the ceramic cup.

Figure 7. ETgage[tm] Modified Atmometers (image credit: http://www.etgage.com/)

Modified atmometer readings are approximations of actual evapotranspiration and are based on reference crops (Kettridge and Baird, 2006). Actual evapotranspiration from the surrounding vegetation (ET) are obtained by multiplying atmometer readings by a crop coefficient which is empirically derived, as shown in *Equation 3*:

$$\mathrm{ET} = \mathrm{K_c ET_{atmometer}} \qquad \text{(Equation 3)}$$

Where:

ET is evapotranspiration of surrounding vegetation,

K_c is a crop coefficient, and

$ET_{atmometer}$ is evapotranspiration from the atmometer. Atmometers have been shown to closely agree closely to reference evapotranspiration estimated from weather station data and are well suited irrigation scheduling (Gleason et al., 2013).

Modified atmometers may be automated or read manually. Automated atmometers can provide evapotranspiration readings on a sub-daily timescale with a precision of 0.254 millimeters (0.01 inches) per day and accuracy of ±1.0% of evaporated water per day. Manual atmometers read by a sight glass can provide weekly evapotranspiration readings with precisions of approximately 0.254 millimeters (0.01 inches) per week. Atmometers must be refilled with distilled water about every two months, require regular cleaning of the evaporating surface if dirty, and cannot operate in below freezing temperatures (ET_{gage} Company, 2013a).

Evapotranspiration measurements from modified atmometers for estimating surrounding vegetation evapotranspiration assume plants have an unlimited supply of water. This assumption does not hold true during dry conditions or with incomplete ground cover and may result in over-prediction of evapotranspiration unless crop coefficients for such situations are developed and utilized in *Equation 3*.

Cost

Atmometers are inexpensive, with the manual ETgage Model A atmometer costing about $200 and the automated ETgage Model E atmometer costing about $620 (ETgage Company, 2013b).

Advantages of method

Atmometers are easily installed, inexpensive, and require little maintenance. In the absence of a nearby weather station, atmometers can provide water use information for a radius of a few miles (Irmak et al., 2005). Additionally, numerous studies suggest a good correlation between reference evapotranspiration estimated by combination energy balance equations and evaporation rates from modified atmometers (Irmak et al., 2013). Automated atmometers can be connected to data loggers, allowing evapotranspiration readings to be stored electronically and accessed remotely via telemetry.

Disadvantages of method

Atmometer measurements are based on reference crop coefficients which may not be capable of capturing the variability in wet meadow vegetation unless appropriate coefficients are developed. Atmometers must also be drained during the winter to prevent the reservoir water from freezing and cannot provide year-round readings at wet meadow sites.

Applicability to wet meadows

Modified atmometers could provide cost effective estimation of evapotranspiration on wet meadow sites if appropriate coefficients are developed and utilized. Atmometers must be used in conjunction with another method of determining evapotranspiration due to their inability to collect evapotranspiration measurements during the winter but could provide a reasonableness check for other methods.

Pan Evaporation

Description of method

The other common mass transfer method used for estimating evapotranspiration is pan evaporation. Evaporation pans measure evaporation from a large open container filled with water exposed to the atmosphere. The difference between observed water levels on two consecutive days provides evaporation information, which can be converted to evapotranspiration using pan coefficients (Jensen et al., 1990).

Three common evaporation pan types include the U.S. Class A Evaporation Pan, the Colorado Sunken Pan, and the U.S. Geological Survey (USGS) Floating Pan. The Class A pan sits above the ground on a wooden platform and the water surface level is measured in a stilling well, as shown in **Figure 8**. The Colorado pan is buried with the pan water surface at ground level to better simulate radiation and aerodynamic characteristics of a water body (Allen et al., 1998). The USGS pan is set afloat in a lake to simulate the characteristics of a large reservoir.

Figure 8. Class A evaporation pan (Eijkelkamp Agrisearch Equipment, 2009).

Discussion below focuses on the Class A pan as it is the standard evaporation pan used in the United States (Viessman and Lewis, 2003). The pan equipment is comprised of a stainless steel cylinder set on a wooden platform half an inch above the ground. The pan must be located in a grassy area away from obstacles such as trees, bushes, and buildings, in order to best represent open water evaporation. Each pan evaporation station is equipped with an anemometer, a thermometer to measure the daily minimum and maximum water surface temperature, and a rain gage.

Water level readings in the pan are recorded manually on a daily basis (National Weather Service, 2006). Evaporation pans may be automated but additional development is needed to improve the accuracy of automated evaporation pans (EPA, 2008). Class A pan require maintenance of well irrigated short grass turf between heights of 38 to 102 millimeters (1.5 to 4 inches) (Jensen et al., 1990). They also require weekly cleaning of leaves, litter, sediment, and oil films and monthly inspection for leaks (WMO, 2010).

To account for the differences between evaporation measured with an evaporation pan and evapotranspiration, pan evaporation is multiplied by an empirically determined pan coefficient (Jensen et al., 1990). The pan coefficient is based on a reference crop, such as turf grass, and the method for calculating reference evapotranspiration is shown in *Equation 4*:

$$ET_{ref} = K_{pan}E_{pan} \qquad (Equation\ 4)$$

Where:

ET_{ref} is the reference evapotranspiration,

K_{pan} is the pan coefficient, and

E_{pan} is the measured change in water level of the pan.

The pan coefficient is dependent on the type of pan, the pan environment in relation to nearby surfaces and obstructions, and climatic factors (Jensen et al., 1990). For Class A pans, pan coefficients range from a low value of 0.4 in dry and windy areas to a high value of 0.9 in calm, humid areas, with a national average of 0.7 (Dingman, 2008). Other factors affecting pan coefficient values include vegetation presence and type, solar radiation, wind speed, temperature, relative humidity, pan color, pan position, water level within the pan, and the presence of screens (Allen et al., 1998). The accuracy of the pan coefficient is often determined for a site by comparing pan evaporation with estimations based on a combination equation (NOAA, 1982). Suggested values for Class A pan coefficients are tabulated in the Food and Agriculture Organization Irrigation and Drainage Paper No. 56 along with descriptions of coefficient adjustment methods (Allen et al., 1998).

Assumptions concerning the accuracy of pan evaporation methods are based on the accuracy of the pan coefficient. Evaporation pans do not provide any resistance to evaporation, but when water evaporates from plant surfaces, some water has to travel through the plant before it is transpired as water vapor. The plant shows some resistance to evaporation that limits evapotranspiration in a way that is not represented by the open water surface of the evaporation pan (Irmak et al., 2005). This discrepancy is assumed to be addressed by the pan coefficient. On the whole, mean monthly reference evapotranspiration estimates based on pan evaporation should be predictable to within ±10 percent with a precision of 0.254 millimeters (0.01 inches) per month in the absence of strong, dry-wind conditions (Jensen et al., 1990 and Harwell, 2012).

Cost

A total pan evaporation station including a Class A pan, fixed point Stillwell, rain gage, totalizing anemometer, and submersible min-max thermometer costs about $2,380 (Forestry Supplies Inc., 2013).

Advantages of method

Evaporation pans have been used for many years with proven ability to determine evapotranspiration through use of appropriate coefficients. Pan coefficients make reference evapotranspiration calculations straightforward and evaporation pans are relatively inexpensive to purchase and install.

Disadvantages of method

Pan evaporation relies on the reference crop approach which is not easily able to account for the vegetative heterogeneity present on wet meadows sites. They require regular manual readings and maintenance. Additionally, pan evaporation is not suitable for low-radiation, winter-time conditions (Jensen et al., 1990), and algae growth can be an issue during warmer seasons (Jones, 1992).

Applicability to wet meadows

While evaporation pans are capable of determining evapotranspiration at wet meadow sites, their requirement of manual daily readings and weekly maintenance make them infeasible as part of the wet meadow hydrology study.

Summary of Mass Transfer methods

Of the mass transfer methods discussed above, lysimeters provide the most accurate and precise measurements of evapotranspiration on the timescale required at wet meadow sites. Weighing groundwater lysimeters could provide high quality evapotranspiration data at a high cost, while non-weighing groundwater lysimeters could provide lower quality data used to validate other methods at a very low cost. Atmometers could be used to check evapotranspiration data obtained with another method at a very low cost but would not be functional during the winter. Evaporation pans are capable of determining evaporation with a fair degree of accuracy, but their ability to determine evapotranspiration is limited by the pan coefficient used and their recording and maintenance requirements are too extensive for this monitoring project. Mass transfer methods for determining evapotranspiration are applicable to wet meadows and may be most valuable if used as a way to verify evapotranspiration data obtained through an energy balance approach.

ENERGY BALANCE APPROACHES

Overview of Energy Balance Approaches

While mass transfer approaches seek to quantify the amount of water that passes from an evaporating surface into the atmosphere, energy balance approaches determine evapotranspiration by quantifying the amount of energy used in the evapotranspiration process. The transfer of energy associated with the phase change from liquid water to gaseous vapor or the condensation of water vapor to liquid water is called the latent heat flux (NASA, 2012). When evapotranspiration is occurring, water molecules are absorbing energy and the latent heat flux is positive. During condensation, the latent heat flux is negative because the water molecules are releasing energy to the surrounding air. Latent heat flux is difficult to measure directly but can be determined by balancing all other energy inputs and outputs. The energy budget equation for evapotranspiration provides a foundation for relating the various energy inputs and outputs and is shown in *Equation 5*:

$$R_n - G = H + \lambda E \qquad (Equation\ 5)$$

Where:

R_n is the net solar radiation ($MJ/m^2 \cdot d$),

G is sensible heat flux into the soil ($MJ/(m^2 \cdot d)$),

H is the sensible heat flux ($MJ/(m^2 \cdot d)$), and

λE is the latent heat flux ($MJ/(m^2 \cdot d)$).

Equation 5 does not include an energy term accounting for change in temperature at the surface of a body of water as is commonly included in energy balance equations for evaporation from an open water surface. In the context of evapotranspiration, this term is generally regarded to be negligible. Several other miscellaneous fluxes such as flux from heat storage within foliage and flux related to photosynthesis are neglected in *Equation 5* as they are generally insignificant relative to magnitudes of the other fluxes (Allen, 2005).

Evapotranspiration is related to the latent-heat flux component of *Equation 5* as shown in *Equation 6*:

$$\lambda E = \rho_w \lambda_v ET \qquad (Equation\ 6)$$

Where:

λE is the latent heat flux (MJ/(m^2·d)),

ρ_w is the density of the water (kg/m^3),

λ_v is the latent heat of vaporization of water (MJ/kg), and

ET is the evapotranspiration rate (m/d). Combining *Equations 5* and 6 and solving for *ET* allows for estimations of evapotranspiration when all other energy terms are known. The energy balance methods below discussed employ various techniques to measure or estimate the energy terms in order to provide evapotranspiration values.

Energy Balance Measurement Methods

Energy balance measurement methods determine evapotranspiration by measuring turbulent flux. Turbulent flux is the total energy available for sensible and latent heat fluxes, shown as the left hand terms in *Equation 5* (Litvak, 2010). While latent heat flux describes the energy required for phase changes, sensible heat flux describes the energy that causes changes in temperature. For evapotranspiration calculations, sensible heat flux is identified as the heat transferred between the evaporating surface and the air resulting from a temperature difference. When the evaporating surface is warmer than the air above, heat will be transferred upwards into the air as a positive sensible heat flux. If the air is warmer than the surface, heat is transferred from the air to the surface creating a negative sensible heat flux (Christopherson, 2011).

Measuring the latent and sensible heat fluxes proves difficult and requires specialized equipment. The Bowen ratio energy balance and the eddy covariance methods apply different techniques to overcome the challenges associated with measuring turbulent flux. These methods are referred to as direct measurement methods because they measure the flow of water vapor into the atmosphere using meteorological sensors (Shuttleworth, 2008).

Bowen Ratio Energy Balance

Description of method

The Bowen ratio energy balance method measures gradients in vapor pressure and temperature above an evaporating surface to determine evapotranspiration. Measurements of vapor pressure are used to determine latent heat flux and measurements of temperature are used to determine sensible heat flux. The method employs the ratio between sensible heat flux and latent heat flux known as the Bowen ratio, shown in *Equation 7*:

$$H = B(\lambda E) \qquad (Equation\ 7)$$

Where:

H is the sensible heat flux (MJ/(m^2·d)),

B is the dimensionless Bowen ratio, and

λE is the latent heat flux (MJ/(m^2·d)) (Bowen, 1926). By substituting the Bowen ratio into energy balance shown in *Equation 5*, rearranging terms, and applying the definition of λE from *Equation 6* as seen in *Derivation 1*, evapotranspiration can be defined as:

$$R_n - G = H + \lambda E$$

$$R_n - G = B(\lambda E) + \lambda E$$

$$R_n - G = (B + 1)\lambda E$$

$$R_n - G = (B + 1)\rho_w \lambda_v ET \qquad (Derivation\ 1)$$

$$ET = \frac{R_n - G}{\rho_w \lambda_v (B + 1)} \qquad (Equation\ 8)$$

Where:

ET is the actual evapotranspiration rate (mm/day),

R_n is the net radiation flux ($W/m^2 \cdot d$),

G is sensible heat flux into the soil ($MJ/(m^2 \cdot d)$),

ρ_w is the density of water (kg/m^3),

λ_v is the latent heat of vaporization of water (MJ/kg), and

B is the dimensionless Bowen ratio.

The Bowen ratio energy balance method measures net solar radiation with a pyranometer and sensible heat flux to the soil with soil temperature probes. To quantify the Bowen ratio, temperature and vapor pressure gradients are measured and the Bowen ratio is determined using *Equation 9*:

$$B = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} = \gamma \frac{T_1 - T_2}{e_1 - e_2} \qquad (Equation\ 9)$$

Where:

B is the dimensionless Bowen ratio,

H is the sensible heat flux ($MJ/m^2 \cdot d$)),

λE is the latent heat flux ($MJ/(m^2 \cdot d)$),

γ is the psychrometric constant (kPa/°C), defined below in *Equation 12*,

ΔT is the temperature gradient,

T_2 and T_1 are the air temperatures (°C), at heights z_2 and z_1 (m), and

e_2 and e_1 are the vapor pressures (kPa) at heights z_2 and z_1 (m). *Equation 9* assumes a stable atmosphere without turbulence; the validity of this assumption is discussed later in this section.

Measurements of temperature and vapor pressure gradients can be taken with Bowen Ratio Energy Balance Systems (BREBS), which consist of towers set up over an area of interest and monitoring equipment mounted at different heights, as seen in **Figure 9**. A BREBS tower uses temperature and relative humidity probes at two heights to determine temperature and vapor pressure gradients. The BREBS towers also include radiometers and pyranometers, soil temperature probes and soil heat flux plates, anemometer, and barometer (Hay and Irmak, 2009). The towers must be installed in locations that allow wind to move over a sufficient distance of similar vegetation and terrain before it reaches the sensors. This distance is termed fetch, and it is generally considered to be 100 times the height of the sensors (Campbell Scientific, 2005). BREBS towers are fully automated and typically calculate the Bowen ratio every 30 minutes based on averages from data collected as frequently as every 30 seconds (Allen et al., 2011). The specialized equipment of a BREBS tower requires careful installation, calibration, and regular supervision and maintenance (Hay and Irmak, 2009).

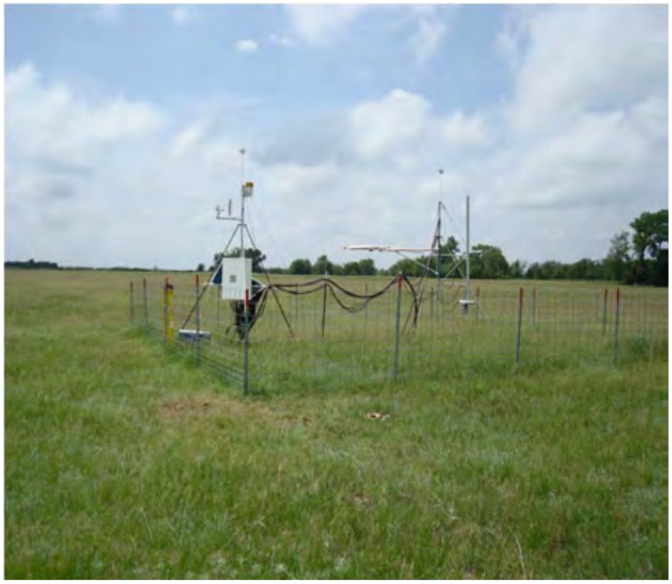


Figure 9 BREBS tower (Irmak, 2010)

BREBS towers can measure evapotranspiration with a precision to the nearest 0.1 millimeter (0.004 inches) per hour (Hay and Irmak, 2009). Comparisons between evapotranspiration values determined using the Bowen ratio energy balance method and lysimeter methods show differences of less than 10% per day (Prueger et al., 1997). The accuracy of the Bowen ratio method heavily depends on the accuracy of net radiation and soil heat flux measurements (Allen et al., 2011).

Several assumptions underpin the Bowen ratio energy balance method and the method's accuracy diminishes when these assumptions fail. One key assumption is that of atmospheric stability. Sensible and latent heat flux are affected by atmospheric turbulence, and turbulence is included in calculations of heat fluxes using turbulent transfer coefficients, shown in *Equation 10*:

$$B = \frac{H}{\lambda E} = \gamma \frac{k_h \Delta T}{k_v \Delta e} \qquad (Equation\ 10)$$

Where:

B is the dimensionless Bowen ratio,

H is the sensible heat flux (MJ/($m^2 \cdot$d)),

λE is the latent heat flux (MJ/($m^2 \cdot$d)),

γ is the psychrometric constant (kPa/°C), defined below in *Equation 12*,

k_h is the turbulent transfer coefficient for sensible heat flux,

k_v is the turbulent transfer coefficient for latent heat flux, and

ΔT is the temperature gradient (°C), and

Δe is the vapor pressure gradient (kPa) (Prueger et al., 1997).

The coefficients k_h and k_v are difficult to determine under turbulent conditions but are equal under stable (turbulent-free) atmospheric conditions. *Equation 10* simplifies to *Equation 9* under these conditions as $k_h = k_v$ (Halliwell and Rouse, 1989). The assumption of atmospheric stability does not hold during periods of high wind and storms.

Additionally, the Bowen ratio energy balance method is not applicable under very dry conditions when latent heat flux approaches zero and the Bowen ratio approaches infinity. Sufficient latent heat flux must be assumed in order to produce numerically meaningful evapotranspiration measurements. In semi-arid areas, the potential errors of the Bowen ratio method have been found between 5% and 15% during daylight hours and 25% to 45% overnight compared with lysimeter method, with the greatest bias occurring during hot, dry, and windy days (Xing et al., 2008).

<u>Cost</u>

The equipment costs associated with a BREBS system is $40,000, not including installation costs or data analysis costs (Irmak, 2012). Additionally, BREBS systems require approximately $5,000 in annual maintenance costs.

<u>Advantages</u>

A primary advantage of the Bowen energy ratio balance method is the ability to obtain direct measurements of evapotranspiration for whatever vegetation type a BREBS tower is placed over. Crop coefficients and estimates of other vegetation properties are not required and evapotranspiration over heterogeneous vegetation can be determined. BREBS towers can collect evapotranspiration data year round with high precision and accuracy (Allen et al., 2011). The method also provides estimates of evapotranspiration over larger areas than estimates made with lysimeters (Prueger et al., 1997). BREBS towers have been proven appropriate for a range of vegetation types in the region surrounding the wet meadow sites, with an extensive network of BREBS towers comprising the Nebraska Water and Energy Flux Measurement, Modeling, and Research Network (NEBFLUX) (Irmak, 2010). NEBFLUX towers have been used to determine crop coefficients for riparian vegetation in the region and could be used to determine crop coefficients for wet meadow vegetation (Irmak et al., 2013). Determining a crop coefficient for wet meadow vegetation would allow for more accurate determination of evapotranspiration at other wet meadow sites using less complicated and less expensive methods.

Disadvantages

Evapotranspiration measurements from Bowen ratio energy balance systems involve expensive, sensitive equipment. Installation is complex and BREBS towers require regular maintenance and surveillance. Equipment is also susceptible to freezing, damage from high winds, and hail damage (Halliwell and Rouse, 1989). The Bowen ratio methodology involves several assumptions that can reduce the accuracy of measurements when not properly addressed.

Applicability to wet meadows

The Bowen ratio energy balance method would be able to produce high quality evapotranspiration measurements at wet meadow sites. Installing a BREBS tower would come at a considerable cost and require an ongoing contract for data processing and tower maintenance. If a tower is installed on one wet meadow site, evapotranspiration data gathered from it could be used to develop a crop coefficient for wet meadow vegetation which could improve the accuracy of evapotranspiration measurements made on other wet meadow sites using other methods.

Eddy Covariance

<u>Description of method</u>

The eddy covariance method, also called the eddy correlation method, determines evapotranspiration by measuring heat and water vapor fluxes associated with atmospheric vapor transport (Burba, 2013). The primary transport mechanism by which heat and water vapor move from vegetation to the atmosphere is by the turbulent motion of air near the ground surface (Harrington et al., 2000). The eddy covariance method measures the properties of eddies in turbulent airflow, and the product of the vertical wind speed and water vapor concentration of these eddies yields a direct evaluation of evapotranspiration (Twine et al., 2000). Airflow fluxes change rapidly near the earth surface and require rapid measurements to accurately quantify heat and vapor fluxes (Burba, 2013). Measurements are on the order of tenths to hundredths of a second and require highly sensitive equipment and significant computational processing to produce evapotranspiration measurements (Burba, 2013).

A typical eddy covariance installation includes a three-dimensional sonic anemometer, a water vapor analyzer, a fine-wire thermocouple, a data logger, and a power supply. The sonic anemometer measures wind speed several times per second. The wind speed measurements are then transformed and recorded as orthogonal wind speed components. The speed of sound is calculated as a function of the orthogonal wind speeds to solve for the virtual sonic temperature which is required for boundary-layer calculations. The water vapor analyzer measures the vapor flux density in the vertical axis and the thermocouple measures the true air temperature (Campbell Scientific, 2012). An eddy covariance installation is shown in **Figure 10**.

Figure 10. An eddy covariance installation (Burba, 2013)

Short time-constant (hundredths of seconds) vertical anemometers and vapor pressure sensors are used in conjunction with a microprocessor for sensing, multiplying, and summing data to provide evapotranspiration measurements. The collected data is averaged over a specific time period (e.g. 30 minutes) and used to calculate the mean vertical flux of water vapor. Temperature data is used to indicate, on average, whether updrafts or downdrafts are warmer and indicate if evaporation or condensations is occurring (USGS, 2009).

Accuracy of the eddy covariance method is approximately 10% per hour due to the stochastic nature of turbulence and the natural variability of the environment (Meyers and Baldocchi, 2005). Eddy covariance instruments are capable of measuring evapotranspiration with a precision of 0.01millimeters (0.0004 inches) per hour (Tomlinson, 1996). Precision and accuracy of evapotranspiration measurements are determined by the precision and accuracy of each component of the eddy covariance system and proper maintenance of the system (Burba, 2013). Additionally, eddy covariance stations do not function well in the presence of heavy rain, hail, and snow and dew or frost on the sonic transducers can lead to errors (Burba, 2013).

The eddy covariance method assumes the uninterrupted distance over which the wind flows, called fetch, is sufficient to represent the surface energy exchange. An upwind fetch on the order of 100 meters for each meter of tower height above the vegetative canopy is generally considered adequate (Burba, 2013).

Use of the eddy covariance measurements assumes fully turbulent fluxes. This requires most of the net vertical vapor transfer to be done by eddies that can be detected by eddy covariance sensors. When there is no mixing of heat or water vapor, such as in humid areas with stable atmospheric conditions, eddy covariance systems do not measure evapotranspiration (Burba, 2013).

Cost

Equipment for eddy covariance systems ranges in price from $30,000 to $45,000 (Li-Cor, 2013 and Campbell Scientific, 2013). Additional costs include initial installation costs and annual maintenance, operation, and data processing costs. Annual costs are estimated to be on the order of $10,000 to $20,000 based on high maintenance requirements, the complexity of the system and professional judgment.

Advantages

Similar to the Bowen ratio energy balance method, eddy covariance systems provide direct measurements of evapotranspiration at a site with high accuracy and precision without the use of crop coefficients. A distinct advantage of the eddy covariance method over the Bowen ratio energy balance method is that evapotranspiration calculations are reliable under both stable and unstable atmospheric conditions. Additionally, the eddy covariance method measures evapotranspiration in semi-arid and arid locations better than the Bowen ratio energy balance method (Tomlinson, 1996).

Disadvantages

The main disadvantages of the eddy covariance method are the high cost, the fragility of sensitive instrumentation, and processing requirements associated with high frequency data readings. The eddy correlation method requires personnel who are well-trained in electronics, turbulent theory, and biophysics due to mathematical complexity and the significant care required to assemble and process data (Allen et al., 2011). At a minimum, weekly maintenance must be provided (Irmak, 2010). Equipment can be impaired or damaged by rain, hail, snow, dew, and frost. The method requires a number of corrections that are often empirical and not well defined (Allen et al., 2011).

Applicability to wet meadows

Eddy covariance systems are capable of providing high quality measurements of evapotranspiration at wet meadow sites. They do so at a high cost and involve significant maintenance, operation, and data processing involvement. While eddy covariance systems may perform slightly better than BREBS towers, the have the highest maintenance, operation, and data processing requirements of any method.

Energy Balance Estimation Methods

An alternative to direct measurement methods is to estimate evapotranspiration rates using local meteorological data in empirical and analytical equations (Shuttleworth, 2008). Estimation methods are organized below on the basis of their data requirements (Jensen et al., 1990):

- Temperature-based (Thornthwaite and Blaney-Criddle) methods use only air temperature and day length to estimate evapotranspiration.
- Radiation-based (Priestly-Taylor) methods use net radiation and air temperature to estimate evapotranspiration.
- Combination (Penman and Penman-Monteith) methods are based on the Penman-Monteith combination equation and use net radiation, air temperature, wind speed, and relative humidity to estimate evapotranspiration.

- Remote Sensing methods use aerial and satellite imagery to estimate evapotranspiration.

With the exception of remote sensing, the methods above commonly employ data collected from automated weather stations used in agricultural and environmental studies. The primary meteorological parameters measured include solar radiation, air temperature, wind speed, and humidity (Allen, 2008). The Automated Weather Data Network (AWDN) weather stations installed on the wet meadow sites are examples of weather stations used as a data source for energy balance estimation calculations. The AWDN weather stations at the wet meadows sites are operated by the High Plains Regional Climate Center (HPRCC, 2013b).

Two terms common to many of the methods described below merit a brief description. The slope of the saturation vapor pressure curve, Δ, is approximated by *Equation 11*:

$$\Delta = \frac{e_s^0 - e_a}{T_s - T_a} \qquad Equation\ 11$$

Where:

e_s^0 is the vapor pressure at the vegetated surface (kPa),

e_a is the vapor pressure of air at a reference height (kPa),

T_s is the temperature of the vegetated surface (°C), and

T_a is the temperature of air at a reference height (°C) (Dingman, 2008).

Several methods have been developed to calculate Δ using only temperature measurements (Jensen et al., 1990).

The psychrometric constant, γ, relates the partial pressure of water vapor to the air temperature as shown in *Equation 12*:

$$\gamma = \frac{c_p P}{0.622\lambda_v} \qquad Equation\ 12$$

Where:

c_p is the specific heat of dry air (~$1.013X10^{-3}$ MJ/(kg·°C)),

P is the atmospheric pressure (kPa), and

λ_v is the latent heat of vaporization (MJ/kg) (Jensen et al., 1990). *Equation 12* assumes surface temperature is equal to wet-bulb temperature.

Temperature Methods (Thornthwaite and Blaney-Criddle)

Description of method

The Thornthwaite and Blaney-Criddle methods of estimating evapotranspiration do so using temperature as the sole meteorological data input. The methods assume temperature to be the dominant factor in evapotranspiration and recognize temperatures averaged over long time periods provide a good estimate of total solar radiation (Blaney-Criddle, 1962). The two methods were developed under different climactic conditions, with the Thornthwaite method developed in humid valleys of the eastern United States and the Blaney-Criddle method developed in the drier western United States.

Thornthwaite method

The Thornthwaite method is based on the correlation between mean monthly air temperature and evapotranspiration, as seen in *Equation 13*:

$$ET_{pot} = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10 \cdot T_{mean}}{I}\right)^{a} \qquad Equation\ 13$$

Where:

ET_{pot} is the potential evapotranspiration adjusted to a standard month of 30 days, each having 12 hours of possible sunshine,

L is the average day length of the month being calculated (hours),

N is the number of days in the month being calculated,

T_{mean} is the mean daily temperature (°C) for the month given as $T_{mean}=(T_{max}+T_{min})/2$, *I* is a heat index, and

a is a climate coefficient.

The monthly heat index *I* is calculated by summing monthly heat indices. The coefficient *a* varies with a factor that is small in cold climates and large in hot climates (Thornthwaite, 1948). The Thornthwaite method assumes uniform values of wind and humidity, so the method may be invalidated during strong seasonal changes. This assumption is usually inconsequential because the evapotranspiration estimate is strongly dependent on site-specific mean monthly temperature. The Thornthwaite method was developed for temperature measured under humid conditions and it represents the evapotranspiration when there is no soil moisture stress (Jensen et al., 1990). Because temperature is the only measurable parameter, the method tends to overestimate the evapotranspiration during dry conditions.

Blaney-Criddle method

The Blaney-Criddle method also uses temperature and applies a crop coefficient along with a different method for determining the amount of daylight received, as shown in *Equation 14*:

$$ET_{ref} = kp(0.46\,T_{mean} + 8.13) \qquad (Equation\ 14)$$

Where:

ET_{ref} is the monthly reference crop evapotranspiration (mm),

k is a consumptive use crop coefficient,

p is the monthly percentage of daytime hours of the year, and

T_{mean} is the mean daily temperature (°C) for the month given as $T_{mean}=(T_{max}+T_{min})/2$ (Blaney and Criddle, 1962).

The Blaney-Criddle method was improved upon to include relative humidity, wind speed, and an elevation correction. The resulting method, referred to as the FAO-24 Blaney-Criddle method, provides more accurate evapotranspiration measurements on shorter timescales (Jensen et al., 1990).

The simplicity of the Blaney-Criddle method limits its accuracy. The reference evapotranspiration tends to be underestimated by up to 60% in dry, windy areas with clear skies and tends to be overestimated by up to 40% in calm, humid areas with less sunshine (Natural Resource Management and Environment Department, 1986). The Blaney-Criddle equation assumes an actively growing crop with adequate soil moisture and may be inaccurate when soil moisture limits evapotranspiration (Jensen et al., 1990). Additionally, it takes time for air temperature to respond to solar radiation. This time lag causes evapotranspiration to be underestimated during heating periods and overestimated during cooling periods, so the temporal resolution of temperature methods is limited to average daily values (Jensen et al., 1990).

The only equipment requirement for the Thornthwaite and Blaney-Criddle methods is a thermometer to measure the mean temperature (daily or monthly). It is preferable to also measure the sunlight hours, but the duration of daylight may be obtained from astronomical charts. The FAO-24 Blaney-Criddle method also requires the relative humidity. Though measured values would be more accurate, in the absence of humidity data the relative humidity may be estimated as a function of temperature.

<u>Cost</u>

Temperature methods only require a thermometer, making them the cheapest method for determining evapotranspiration. Additional instrumentation, including relative humidity probes and anemometers, will improve the accuracy and reduce the timescale when using the FAO-24 Blaney-Criddle method. The Campbell Scientific thermometer for the AWDN station costs about $100 and the Campbell Scientific relative humidity probe costs about $690 (HPRCC, 2013a). Additional equipment would be required for remote data access via cellular telemetry, but total costs for automatic data logging and cellular telemetry are less than $5,000 (HPRCC, 2013a).

<u>Advantages</u>

The Thornthwaite and Blaney-Criddle methods require minimal data inputs to provide estimates of evapotranspiration. The methods have been used for over sixty years and have been shown to provide useful evapotranspiration data at a low cost and without significant installation or maintenance requirements.

Disadvantages

Temperature methods rely on empirical crop coefficients which are not easily able to fully capture the variability in vegetation cover present at wet meadow sites. In general, temperature methods tend to underestimate evapotranspiration in arid regions while overestimating in humid regions and their reliability depends on local calibration of empirical coefficients.

The Thornthwaite and Blaney-Criddle methods were developed to provide average monthly evapotranspiration. Though there are modified equations to estimate daily values of evapotranspiration using mean daily values, temperature methods are not suitable for hourly estimates (Jensen et al., 1990).

Applicability to wet meadows

Temperature methods are not suitable as the sole method of determining evapotranspiration from wet meadow applications due to their low temporal resolution. Weather stations measuring several meteorological parameters in addition to temperature are present on the wet meadow sites involved in this study. These stations allow for application of other methods that require more data and provide more accurate evapotranspiration estimates. Temperature methods may prove useful for comparing evapotranspiration trends on larger time scales with evapotranspiration values calculated using other methods or for basic evapotranspiration estimates on wet meadow sites where weather stations have not been installed.

Radiation Methods (Priestley-Taylor)

Description of method

The Priestley-Taylor method calculates evapotranspiration for a reference crop using only temperature and solar radiation measurements. The method assumes the portion of evapotranspiration resulting from advection is much lower than the amount of evapotranspiration caused by solar radiation (Priestly and Taylor, 1972). The method is a simplification of the Penman combination equation discussed in the next section and uses a coefficient to account for advection, as shown in *Equation 15*:

$$ET_{ref} = \alpha \frac{\Delta}{\Delta + \gamma} \frac{(R_n - G)}{\lambda_v} \qquad (Equation\ 15)$$

Where:

ET_{ref} is the reference evapotranspiration (mm/d)

α is an empirical coefficient with a typical value of 1.26,

Δ is the slope of the saturation vapor pressure-temperature curve (kPa °C-1),

γ is the psychrometric constant (kPa/°C),

R_n is the calculated net radiation at the crop surface (MJ/(m^2·d)),

G is the soil heat flux density at the soil surface (MJ/(m^2·d), and

λ_v is the latent heat of vaporization (MJ/kg) (Priestley and Taylor, 1972, and Jensen et al., 1990).

All terms in *Equation 15* can be determined from temperature measurements with the exception of R_n, which requires measurements of solar radiation. Soil temperature measurements will improve the estimation of *G* but are not necessary. The method produces daily estimates of evapotranspiration for a reference crop.

The assumption of low advective evapotranspiration generally proves valid, and the energy portion of the Penman equation has been found to frequently exceed the advective term during the growing season by a factor of 4 (Irmak et al., 2008). In vegetated areas with no or small water deficit, approximately 95% of the annual evaporative demand was supplied by radiation (Singh and Frevert, 2002). Evapotranspiration from advection occurs when wind removes humid air from an evaporating surface and replaces it with drier air. Advection driven evapotranspiration is greater in the presence of high winds or steep gradients in the moisture content of air that occur under drier conditions. The Priestly-Taylor method underestimates evapotranspiration in hot, dry, and windy conditions and the value of the coefficient α may be calibrated to improve its accuracy (Jensen et al., 1990). The method performs best when evaluating large-scale, well-watered surfaces (Irmak et al., 2008).

Cost

The Priestley-Taylor method requires a minimum of a thermometer and a pyranometer (an instrument used to measure solar radiation) and may provide more accurate estimates with soil temperature probes. The method does not require wind or humidity measurements typically associated with a full weather station, making it a cheaper alternative to combination methods. A Campbell Scientific thermometer costs about $100 and a Campbell Scientific pyranometer costs about $470, for a total price of about $570. Additional costs for automatic data collection and remote data access through cellular phone telemetry are on the order of $5,000 (HPRCC, 2013a).

Advantages

The Priestley-Taylor method provides daily evapotranspiration estimates without the need for wind speed or relative humidity measurements.

Disadvantages

The Priestley-Taylor method does not perform well in dry and windy conditions and the coefficient α would require calibration under these conditions. It relies on reference crop coefficients which are not able to fully capture the variability in vegetation cover present at wet meadow sites.

Applicability to wet meadows

The Priestley-Taylor method would require calibration of the coefficient α to provide reliable evapotranspiration estimates at wet meadow sites. The method is not ideally suited to the hot, semi-arid, and windy summers typically occurring at wet meadows. Other methods would likely provide better estimates of evapotranspiration and the Priestly-Taylor method could be employed as means of comparison.

Combination Method (Penman)

Description of method

The Penman equation accounts for the two drivers of evaporation, advective air transfer and solar radiation, and was the first method to combine them in a single equation. The method eliminated the need for surface temperature measurements previously required by other methods was the first to allow theoretical estimates of evaporation rates from standard meteorological data (Penman, 1948). The method was developed to calculate evapotranspiration over open water and applies empirical coefficients to determine reference crop evapotranspiration. Various versions of the Penman equation have developed over the years to account for different reference crops and climates, a general version is shown in *Equation 16*:

$$\lambda_v ET_{ref} = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 6.43 W_f (e_z^0 - e_z) \qquad (Equation\ 16)$$

Where:

$\lambda_v ET_{ref}$ is the evaporative latent heat flux for a well-watered grass reference crop (MJ/(m^2·d)),

Δ is the slope of the saturation vapor pressure curve as defined in *Equation 10* (kPa/°C),

γ is the psychrometric constant as defined in *Equation 11* (kPa/°C),

R_n is the net radiation flux (W/m^2·d),

G is sensible heat flux into the soil (MJ/(m^2·d)),

W_f is a wind function as defined by *Equation 14* (mm/(d·kPa)),

e_z^0 is the saturation vapor pressure at height z (kPa),

e_z is the actual vapor pressure at height z (kPa) (Jensen et al., 1990). The wind function depends on reference crop characteristics and the height of wind speed measurements as described by *Equation 17*:

$$W_f = a_w + b_w u_s \qquad (Equation\ 17)$$

Where:

a_w and b_w are empirical coefficients, and

u_s is wind speed at a reference height (m/s) (Jensen et al., 1990). The coefficients a_w and b_w are developed for individual reference crops under various climatic conditions.

The Penman equation requires measurement of mean air temperature, a measurement or estimate of vapor pressure, a measurement or estimate of solar radiation, a measurement of wind speed, and a measurement of soil temperature. The method can be calculated on an hourly or daily basis, depending on available data. Preferred equipment for the method includes a thermometer for measuring air temperature, a barometer for measuring atmospheric pressure, a hygrometer for measuring humidity, an anemometer for measuring wind speed, soil temperature probes, and a rain gage for measuring liquid precipitation. Alternate methods for calculating vapor pressure and solar radiation exist if comprehensive data is not available (Jensen et al., 1990). If soil temperature data is not available, the effect of soil heat flux may be ignored for daily calculations.

The Penman method assumes open water evaporation may be related to evapotranspiration from a vegetated surface under the same weather conditions through the use of coefficients. These coefficients are based on reference crops and are not able to capture site specific vegetation heterogeneity. The accuracy of the method depends on the time step used. While soil temperature can vary widely throughout a day, the magnitude of the temperature change for a 24-hour period is relatively small. Using hourly time steps captures the range of soil temperatures through the day better than daily time steps, resulting in better estimates of evapotranspiration (Allen et al., 1998).

The accuracy of the Penman method depends on the specific form of the equation used. The modified Penman equation used by the HPRCC for AWDN weather station data was shown to have an accuracy of 20% per day when compared to evapotranspiration measured with eddy covariance equipment. The precision of evapotranspiration values calculated using the modified Penman equation and AWDN station data is on the order of 0.5 millimeters (0.02 inches) per day (Hubbard, 2013).

A recent study by the United States Geological Survey (USGS) developed monthly crop coefficients for a grassland site located between the north and south channels of the Platte River near the two wet meadow study sites (Hall and Rus, 2013). The study used reference evapotranspiration estimations calculated by the HPRCC and evapotranspiration measurements from an eddy covariance system. The modified Penman equation used by the HPRCC to calculate reference evapotranspiration from AWDN station data is based on a well-watered alfalfa reference crop of uniform height. The grassland crop coefficients are shown in **Table 1** and relate grassland evapotranspiration to reference evapotranspiration as shown in *Equation 1* (restated below).

$$ET = K_c ET_{ref} \qquad (Equation\ 1, \text{restated})$$

Where:

ET is evapotranspiration of the grassland vegetation,

K_c is a dimensionless crop coefficient, and

ET_{ref} is the reference evapotranspiration for the modified Penman method used by the HPRCC.

Table 1. Riparian grassland crop coefficients (dimensionless) (Hall and Rus, 2013).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Crop Coefficient	0.05	0.12	0.14	0.28	0.46	0.61	0.64	0.63	0.49	0.40	0.20	0.13

(K_c)												

The crop coefficients are based on monthly averages of measured evapotranspiration and reference evapotranspiration which may limit their ability to capture daily variations in evapotranspiration. These crop coefficients represent a far more appropriate crop coefficient than a generalized grassland crop coefficient as they were developed for similar vegetation in a nearby location. They can be reasonably applied to wet meadow sites.

<u>Cost</u>

The minimum equipment requirements for the Penman method are instrumentation to measure temperature, relative humidity, and wind speed. Adding a pyranometer for measuring solar radiation and soil temperature probes improves the accuracy of the method. Instruments capable of hourly readings will also improve accuracy. The equipment listed above is typically included in a standard weather station, such as the AWDN station at the wet meadow sites. The Penman method requires more equipment than the Priestley-Taylor, Blaney-Criddle, and Thornthwaite methods and thus involves higher equipment and maintenance costs. Sensor costs, automatic data collection costs, and cellular phone telemetry costs for the AWDN stations are about $9,340 (HPRCC, 2013a).

<u>Advantages</u>

The Penman equation accounts for the two processes that drive evapotranspiration and uses readily available meteorological data to estimate evapotranspiration for a reference crop. The method has been employed for a wide variety of vegetation types and locations over the past sixty years. It is used by the HPRCC to provide evapotranspiration estimates from AWDN weather station data at the wet meadow sites as well as many other weather stations throughout Nebraska and the Mid-West (HPRCC, 2013b).

The availability of this crop coefficient presents a significant advantage as it eliminates the need for further development of a wet meadow crop coefficient for this method.

Disadvantages

The Penman equation estimates the open water evaporation and uses reference crop coefficients to determine evapotranspiration. The method is less accurate for conditions outside of the early stages that arise after thorough wetting of the soil by rain or irrigation, when soil type and crop type are of little importance (Penman, 1948). While the USGS crop coefficients show promise, they were developed based on a total of three years' worth of data and may not fully capture the range of meteorological conditions experienced at wet meadow sites.

Applicability to wet meadows

The Penman method is able to provide hourly evapotranspiration estimates for wet meadow sites. The method is currently employed by the HPRCC and the AWDN weather stations provide data that allows for hourly estimates. The recently developed crop coefficient makes this an appealing method as a wet meadow crop coefficient would not need to be developed.

Combination Method (Penman-Monteith)

Description of method

As noted above, the Penman method was primarily developed to calculate open water evapotranspiration and was modified to provide evapotranspiration estimates. Monteith improved upon Penman by recognizing vegetative surface have a higher resistance to evaporation than open water. He also took into account the complex aerodynamics of advection over vegetated surfaces (Allen, 2005). The resulting equation, called the Penman-Monteith equation, adds a surface resistance term and a more rigorous aerodynamic resistance term as seen in *Equation 18*:

$$ET_{ref} = \frac{\Delta(R_n - G) + \frac{\rho_a c_p (e_s - e_a)}{r_a}}{\lambda_v\left(\Delta + \gamma(1 + r_s/r_a)\right)} \qquad (Equation\ 18)$$

Where:

ET_{ref} is the reference evapotranspiration (mm/d)

R_n is the net radiation flux (W/m^2·d),

G is sensible heat flux into the soil (MJ/(m^2·d)),

ρ_a is the density of air (kg/m3),

c_p is the specific heat of dry air (~1.013X10^{-3} MJ/(kg·°C)),

e_s is saturation vapor pressure of the air at some height above the surface (kPa),

e_a is the actual vapor pressure of the air (kPa),

λ_v is the latent heat of vaporization (MJ/kg),

Δ is the slope of the saturation vapor pressure curve as defined in *Equation 11* (kPa/°C),

γ is the psychrometric constant as defined in Equation 11 (kPa/°C),

r_s is the canopy surface resistance (s/m), and

r_a is aerodynamic resistance for water vapor (s/m), (Allen, 2005).

Canopy resistance, r_s, is calculated using a variety of methods that account for vegetation properties and canopy coverage (Allen, 2005). Aerodynamic resistance, r_a, can be estimated from wind speed and vegetation height (Jensen at al., 1990).

Similar to the Penman method, the Penman-Monteith method requires measurement of mean air temperature, a measurement or estimate of vapor pressure, a measurement or estimate of solar radiation, a measurement of wind speed, and a measurement of soil temperature. The method can be calculated on an hourly or daily basis, depending on available data. Additional data requirements for the Penman-Monteith equation above those of the Penman equation are mean plant height, leaf area index (LAI), and information about crop spacing and orientation, if available. Mean plant height is used to determine r_a and LAI and crop information is used to calculate r_s (Allen, 2005).

Measuring or estimating characteristics of the vegetative surface proves challenging and calculations used to develop r_a and r_s add complexity to the method (Allen et al., 1998). Variations of the Penman-

Monteith equation have been developed to avoid these challenges.

The FAO-56 Penman-Monteith method bases calculations on a clipped grass reference crop as defined in a report for the Food and Agriculture Organization (FAO) of the United Nations (Allen et al., 1998). The method assumes a constant for the latent heat of vaporization to simplify the air density term, applies a constant canopy surface resistance, and simplifies the aerodynamic resistance for water vapor (Howell and Evett, 2004). The method eliminates the need for additional crop or vegetation data, reducing equipment and data requirements to those of the Penman method.

The ASCE Penman-Monteith method builds on the FAO-56 Penman-Monteith equation and was developed to define a benchmark reference evapotranspiration equation to standardize the calculation of reference evapotranspiration and to improve transferability of crop coefficients. The method is applicable for a reference crop of clipped grass or alfalfa and can employ daily or hourly data. The ASCE method includes preferred methods for calculating the components of the equations and estimation of missing climatic data (Allen et al., 2005b).

The accuracy of evapotranspiration estimates made using the Penman-Monteith methods depends on the quality of the meteorological data used in calculations (Allen et al., 2005b). The method has been shown to have an accuracy of 20% per hour with a precision 0.1 millimeter (0.004 inches) per hour in some cases (Allen, 2005).

Cost

Equipment requirements of the Penmen-Monteith methods are similar to those of the Penmen method. The AWDN stations at the wet meadow sites are capable of providing required meteorological data. As with the Penman method, equipment requirements are greater than those of the Priestley-Taylor, Blaney-Criddle, and Thornthwaite methods and involve higher equipment and maintenance costs. AWDN station equipment costs are about $9,340, including cellular phone telemetry (HPRCC, 2013a).

Advantages

The Penman-Monteith methods represent the most thorough calculation method for estimating evapotranspiration. The Penman-Monteith methods are considered an improvement over the Penman method because they account for vegetative resistance. The physically-based parameters of canopy surface resistance and aerodynamic resistance may be altered to represent characteristics of the surface or vegetation type in question and allow the objective characterization of a surface via visual observation (Allen et al., 1996).

Disadvantages

The Penman-Monteith methods were developed primarily for agricultural applications, uniform cover, and the coefficients used to capture vegetation properties are based on aspects of crops, such as row spacing and row orientation. These properties are not easily determined for heterogeneous vegetation present on wet meadow sites and require estimates and assumptions that limit the method's accuracy (Allen, 2005). While the Penman-Monteith method captures vegetation resistance, both sparse vegetation and non-uniform forest present challenges to the method's approach to determining canopy surface resistance and aerodynamic resistance coefficients (Allen et al., 1996). The FAO and ASCE Penman-Monteith methods both employ reference crops which limit their ability to capture the variation in wet meadow vegetation.

Applicability to wet meadows

The Penman-Monteith method is assumed to be able to estimate evapotranspiration data on wet meadow sites and data collected by the AWDN weather stations allows for hourly calculations. Determining vegetation properties to calculate canopy surface resistance and aerodynamic resistance coefficients may prove difficult for the varied vegetation at wet meadow sites. For the FAO and ASCE methods the application of crop coefficients may limit the methods accuracy.

Remote Sensing Methods

Description of method

The final method of determining evapotranspiration discussed in this paper is remote sensing. This method uses data from meteorological satellites in addition to topographic and vegetation aerial imagery from airplanes or satellites to estimate evapotranspiration over field, catchment, and watershed scales. The method is able to provide accurate estimates of evapotranspiration for regions without reliable weather data (Campbell and Wynne, 2011).

Meteorological satellites observe electromagnetic signals from the earth's surface and atmosphere. While the process of evapotranspiration does not produce a direct electromagnetic signal, the other components of the energy balance may be estimated from satellite data and used in the energy balance equation stated in *Equation 4* to estimate evapotranspiration. Electromagnetic surface radiances are converted into surface properties such as albedo, vegetation indices, surface emissivity and surface temperature (Mkhwanazi and Chavez, 2013).

Two of the most common algorithms used to calculate evapotranspiration from satellite data are the Surface Energy Balance Algorithm for Land (SEBAL) and the Mapping Evapotranspiration at High Resolution using Internalized Calibration (METRIC) method. Both methods require data collected from surface-based weather stations in addition to satellite imagery to accurately determine evapotranspiration.

The SEBAL method measures solar radiation to determine net solar radiation and sensible heat flux to the soil, the R_n and G terms in *Equation 4*. Sensible heat flux, H, is determined using satellite temperature measurements and surface based wind speed measurements from common weather stations. The method is capable of estimating evapotranspiration without prior knowledge of the soil, crop, or management conditions (Bastiaanssen et al., 2005). A chief assumption in SEBAL is that the evaporative fraction, defined as the portion of turbulent flux associated with latent heat flux, $\lambda E/(\lambda E+H)$, remains constant during daytime hours (Bastiaanssen et al., 2005). This assumption allows data collected during a single daily satellite overpass to be applied to the entire day. Evaporative fraction is rarely constant, especially during hot and windy conditions (Mkhwanazi and Chavez, 2013). The SEBAL method requires significant data processing to determine evapotranspiration. Extreme wet and extreme dry pixels must be manually identified by trained personnel in each image used to development evapotranspiration estimates. Daily estimates require the processing of daily images (Bastiaanssen et al., 2005).

The METRIC method is based on the SEBAL method and was developed to avoid the assumption of a constant evaporative fraction. The method replaces evaporative fraction with a calculation of alfalfa reference evapotranspiration using the ASCE-EWRI standardized Penman-Monteith equation (Allen et al., 2005b) using surface-based weather station data (Allen et al., 2005a). This innovation establishes a ground reference for the satellite-based evapotranspiration estimate and allows the method to provide better estimates for arid and semi-arid areas (Allen et al., 2007). In order to calculate reference evapotranspiration, high quality hourly weather data consisting of air temperature, relative humidity, wind speed, incoming solar radiation, and precipitation are required for the operation of the METRIC model (Kamble et al., 2013).

Remote sensing data is collected in pixels which are squares of data corresponding to areas on the earth’s surface. Typical pixel resolution varies from 30 square meters (323 square feet) from satellites to 5 square meters (54 square feet) from airplanes (Garcia et al., 2013). The energy balance equation may be applied at each pixel, allowing evapotranspiration to be determined at many locations across and a given area. This contrasts with other methods that determine evapotranspiration based on data collected at a single point and applied to a larger area. Remote sensing is able to capture changes in vegetation type over an area better than other methods (Allen et al., 2011). The method has been shown to agree with evapotranspiration measurements from lysimeters with less than 1% difference over a growing season, although higher variations in agreement ranging from -5% to 22% existed on individual days (Allen et al., 2005a). The method is capable of determining evapotranspiration with an accuracy of 0.1 millimeter (0.004 inches) per day.

Both the SEBAL and METRIC method require significant processing time. The METRIC method reduces the processing time requirement of the SEBAL method somewhat by using reference evapotranspiration estimates from weather stations. Even so, processing time for one image is on the order of 2.5 hours (Allen et al., 2005a). Assuming a single image would cover an entire wet meadow site, annual data processing times for daily evapotranspiration estimates would be greater than 900 hours (2.5 hours * 365 images = 912.5 hrs).

Cost

The cost of remote sensing is minimal when compared to costs required by other field measurement methods to provide the same spatial coverage (Bastiaanssen et al., 2005). Remote sensing is cost effective for large areas, with the costs associated with monitoring water use using remote sensing estimated to be one fifth of the costs based on standard evapotranspiration data for the Snake River Plain (Allen et al., 2005a).

Much of the meteorological data required for remote sensing is provided for free from the Earth Science Office of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) (NASA, 2013 and NOAA, 2013). Landsat imagery required for vegetation classification costs $50 per square kilometer (Landsat, 2013). Data processing time requirements must be factored into the cost of the method as high trained personnel are required. The METRIC method also includes weather station costs associated with determining reference evapotranspiration.

Assuming a private contractor were hired to process data at a billing rate of $40/hour, the annual cost to process 365 images at 2.5 hours/image would be $36,500 (365 images * 2.5 hours/image * $40/hour = $36,500). Image processing time may decrease as technology improves and might reduce costs of remote sensing in the future.

Advantages

This method is capable of producing high quality estimates of evapotranspiration with high accuracy and precision. Remote sensing estimates actual evapotranspiration rather than reference evapotranspiration and does not require detailed data on crop types, irrigation water diversions, or pumping (Burkhalter et al., 2013). Additionally, remotely sensed estimates apply to areas of small areal extent corresponding to the footprint of an imagery pixel and are able to capture vegetation heterogeneity. Another clear advantage of remote sensing method is the ability to estimate evapotranspiration over areas where high quality data is not available (Effendi, 2012).

Disadvantages

A primary disadvantage of the remote sensing method is its data processing requirements. The method requires significant time and skill to produce evapotranspiration estimates. The SEBAL method's applicability may be limited by hot, dry, and windy conditions that occur at wet meadow sites during the summer. The METRIC method requires additional calculations as well as a weather station to provide evapotranspiration estimates.

Applicability to wet meadows

Remote sensing is capable of providing high quality evapotranspiration estimates at wet meadow sites. The data processing requirements associated with this method would require outside contractors to complete, greatly increasing costs and diminishing the methods appeal as a useful tool for this study.

Summary of Energy Balance Methods

Several of the energy balance methods discussed above are able to provide evapotranspiration data for wet meadow sites. They vary widely in their degree of complexity, precision, and cost. The Bowen ratio energy balance and eddy covariance approaches represent the most accurate methods as well as the most complex and costly ones. Estimation methods have a range of complexity, data requirements, and equipment requirements. All of the estimation methods with the exception of remote sensing rely on crop coefficients and may not fully capture evapotranspiration at wet meadows due to the variety of vegetation present at the sites. The Bowen ratio energy balance method and the Penman method stand out as the two methods best suited for determining evapotranspiration for this study. The Penman method can be applied without further need for crop coefficient development, while other estimation methods would require a crop coefficient to be developed. Other estimation methods may be used in conjunction with either the Penman calculation or a Bowen ratio energy balance installation to provide a means of validating evapotranspiration values. Eddy covariance and remote sensing do not appear to be favorable alternatives due to their high cost, complexity and data processing requirements.

CONCLUSION

Comparison of Methods

While all the methods described in this white paper have been used to determine evapotranspiration, their ability to do so at wet meadow sites varies. **Table 2** lists several aspects common to all the methods and ranks each method accordingly. The ratings are discussed below:

Applicability to Wet Meadows: A rating of “Primary” indicates the method is capable of satisfying all evapotranspiration requirements for wet meadow site study and can be used as the primary method for determining evapotranspiration. A rating of “Validation” indicates the method may provide useful information to validate or check a primary method but cannot be relied upon as the sole method for evapotranspiration determinations.

Accuracy & Precision: A rating of “High” indicates the method provides evapotranspiration estimates with a precision of 0.1 millimeter (0.004 inches) per hour and an accuracy of ±10% per day. A rating of “Moderate” indicates the method provides evapotranspiration estimates with a precision of 0.5

millimeters (0.02 inches) per day and an accuracy of ±20% per day. A rating of "Low" indicates the method provides evapotranspiration estimates with a precision of 2.5 millimeters (0.1 inches) per week and an accuracy of ±30% per week. It is important to note all three methods of directly measuring evapotranspiration (lysimeters, Bowen ratio energy balance systems, and eddy covariance systems) have high accuracy compared to other methods based on crop coefficients. Estimation method accuracy depends on the crop coefficients used to calculate actual evapotranspiration from reference transpiration. A given method with less general accuracy but a well-defined crop coefficient may perform better than a more accurate method with an assumed or inaccurate crop coefficient. The accuracy and precision of the equipment used in data collection directly impacts the accuracy of any method based on that data. Higher accuracy could potentially be obtained using the Priestly-Taylor method with very precise equipment than the Penman-Monteith equation with poor quality or poorly maintained equipment.

It is difficult to apply a uniform accuracy to a given method because the processes that drive evapotranspiration vary widely depending on local climate, vegetation type, and time of year. A given method may perform well in humid climates and poorly in arid climates. Many of the methods discussed were developed to determine evapotranspiration of monoculture agricultural crops and their reported accuracy may diminish if applied to the heterogeneous wet meadow vegetation. Accuracy in evapotranspiration measurements is also influenced by measurement equipment quality and operator knowledge. The accuracy and precision ratings shown in **Table 2** should be seen primarily as a comparison between methods rather than a final determination of a given method's accuracy and precision.

Equipment Requirements: Two categories of equipment requirements are shown: total and additional. Total equipment requirements do not account for the AWDN stations the Program has already installed on wet meadow sites while additional equipment requirements are those beyond the AWDN station equipment. "High" equipment requirements indicate specific and/or highly sensitive equipment is required with complex installation. "Moderate" equipment requirements indicate standard equipment is required with relatively straightforward installation. "Low" equipment requirements indicate readily available equipment with easy installation. Several methods do not require any additional equipment.

Crop Coefficient: The crop coefficient column is divided into two categories: required and available. The required category indicates if the method requires a crop coefficient, while the available category indicates if a crop coefficient exists or if it would need to be developed. For the "Required" category, a "Yes" indicates a given method requires the use of a crop coefficient and a "No" indicates the method does not need a crop coefficient. For the "Available" category, a "Yes" indicates a crop coefficient exists for the method, while a "No" indicates a crop coefficient would need to be developed for the method.

Data Processing or Operation & Maintenance Requirements: "High" maintenance and operation requirements indicate the need for regular equipment maintenance and/or data collection and processing. "Moderate" requirements indicate maintenance, operation, and data collection is not needed more frequently than every two months. "Low" requirements indicate little maintenance, data collection, or equipment operation needs.

Cost: Two categories of costs are shown: total and additional. Total costs are the costs involved for determining evapotranspiration using a given method while additional costs take into account the AWDN stations the Program has already installed on wet meadow sites. Total costs reflect the cost of using a method at a new wet meadow site while additional costs reflect the cost of using a method at one of the wet meadow sites the Program is currently monitoring. "High" equipment costs are greater than $25,000, "Moderate" costs are around $10,000, and "Low" costs are under $5,000. Several of the energy balance estimation methods require no additional costs beyond the weather stations already present at the wet meadow sites.

Table 2. Method comparison table

Method	Applicability to Wet Meadows	Accuracy & Precision	Coefficient (Required/ Available)	Equipment Requirements (total/ additional)	Data Processing or Operation & Maintenance Requirements	Cost (total/ additional)
Mass Transfer Methods						
Lysimeter (Weighing)	Primary	High	No/No	High/High	High	High/High
Lysimeter (Non-weighing)	Validation	Low	No/No	Low/Low	Moderate	Low/Low
Atmometer	Validation	Moderate	Yes/No	Low/Low	Moderate	Low/Low
Evaporation Pan	Validation	Moderate	Yes/No	Low/Low	High	Low/Low
Energy Balance Methods						
Bowen Ratio	Primary	High	No/No	High/High	High	High/High
Eddy Covariance	Primary	High	No/No	High/High	High	High/High
Thornthwaite	Validation	Low	Yes/No	Low/None	Low	Low/None
Blaney-Criddle	Validation	Low	Yes/No	Low/None	Low	Low/None
Priestley-Taylor	Validation	Low	Yes/No	Low/None	Low	Low/None
Penman	Primary	Moderate	Yes/Yes	Moderate/None	Low	Moderate/ None
Penman-Monteith	Primary	Moderate	Yes/No	Moderate/None	Low	Moderate/ None
Remote Sensing	Primary	Moderate	No/No	Moderate/None	High	High/High

Of the methods that may be used as the primary or sole method for determining evapotranspiration on wet meadows, weighing lysimeters, Bowen ratio energy balance systems, and the Penman method are the most attractive. Weighing groundwater lysimeters and Bowen ratio energy balance systems would provide high quality evapotranspiration measurements with high costs while the Penman method would provide good estimates of evapotranspiration at no additional costs. The Penman method does not require developing a crop coefficient and reference evapotranspiration is already calculated by the HPRCC, allowing this method to be used with current monitoring equipment. The eddy covariance method has high cost, equipment, maintenance, and operation requirements, making it less appealing than other methods.

Of the mass transfer methods appropriate for validation applications, modified atmometers appear more attractive than non-weighing lysimeters. The cost of both methods is similar and modified atmometers provide automated readings while non-weighing lysimeters require manual readings. A mass transfer estimation method would provide good validation if the primary method for determining evapotranspiration is an energy balance method as it would allow for evapotranspiration to be characterized by both dominant approaches. Any of the three energy balance estimations methods appropriate for validation applications would provide useful information without additional cost or equipment. Calculations for all three equations could be made with data collected at the AWDN weather stations and compared to evapotranspiration measured using the Penman-Monteith equation or another primary method.

The maintenance and data processing requirements of pan evaporation and remote sensing methods limit their applicability for this study.

Suggestions For Determining Wet Meadow Evapotranspiration

Several options for determining evapotranspiration at wet meadow sites exist and vary in cost and complexity. These include using only the Penman method, checking the Penman method with temperature, radiation, or the Penman-Monteith methods, checking the Penman method with modified atmometer data on one or both sites, installing Bowen ratio energy balance systems on one or both sites to directly measure evapotranspiration, and installing lysimeters on one or both sites to directly measure evapotranspiration.

Penman Only

The most simple and least expensive method involves applying the Penman equation to calculate evapotranspiration values from data collected by the AWDN stations already in place. The grassland crop coefficient developed by the USGS would ideally be verified on wet meadow sites to ensure accurate evapotranspiration estimates. The primary drawback to determining evapotranspiration with this estimation method is the additional uncertainty associated with the application of crop coefficients. Direct measurements would reduce this uncertainty, but the reduction comes at a cost.

Checking with Other Estimation Methods

Estimates of evapotranspiration made using the Penman method could be validated by estimates based on temperature and radiation methods. Any of the Thornthwaite, Blaney-Criddle, Priestly-Taylor, or Penman-Monteith methods could be used at no additional expense as they all rely on data from the AWDN weather stations. Crop coefficients for these methods would need to be developed if they were to be used as a means of validation.

Checking with Modified Atmometers

An additional step to ensure accurate evapotranspiration data involves installing modified atmometers on one or both wet meadow sites. Modified atmometers base their evapotranspiration estimates on measurements of mass transfer and would provide a useful check and comparison to the energy balance-based estimates of the Penman method. The crop coefficients developed by the USGS are anticipated to work well with the modified atmometers. Installing modified atmometers would cost less than $1,000 per site.

Direct Measurement with Bowen Ratio Energy Balance Systems

Evapotranspiration could be measured directly with a BREBS tower on one or both wet meadow sites. The BREBS tower would provide high quality evapotranspiration measurements and could be used to develop wet meadow crop coefficients. The towers would require a contractor to perform the complicated installation and operation associated with the systems. Costs for BREBS towers are in the range of $60,000 per installation, including operations and maintenance and data processing.

Direct measurement with Lysimeters

Installing weighing groundwater lysimeters on one or both of the wet meadow sites would likely provide the highest quality direct measurements of evapotranspiration. Lysimeters could be used to develop accurate wet meadow crop coefficients for general use. Installing lysimeters would involve significant design, construction, and over site to ensure proper function and may require the services of a contractor. Accurate lysimeter data may not be available for one or two years after installation as vegetation becomes established. Estimated costs for weighing groundwater lysimeters are on the order of $100,000 for equipment and installation per site.

Combinations

Any of the methods mentioned above could be used in combination with one another and additional methods and equipment can be installed to provide several methods for measuring evapotranspiration and validating calculations. Cost, maintenance requirements, operational requirements, and the level of accuracy needed will guide further discussion of how to best determine evapotranspiration at wet meadow sites.

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CHAPTER 3 – Soil Moisture Monitoring Plan

ABSTRACT

The Platte River Recovery Implementation Program's approach to monitoring soil moisture at wet meadows sites is described. This document provides an overview of soil moisture behavior and the conceptual model used to guide the monitoring efforts followed by a description of the monitoring plan to capture changes in soil moisture content over a variety of spatial and temporal scales.

INTRODUCTION

Background

The Platte River Recovery Implementation Program (Program) is conducting a hydrologic monitoring effort at several wet meadow sites with the objective of quantifying groundwater response to changes in river stage, precipitation, and evapotranspiration. The flux of water through unsaturated soil between the ground surface and the groundwater table plays a critical role in the accurate quantification of groundwater response to precipitation and evapotranspiration. Monitoring soil moisture flux allows for an estimation of the amount of water entering the groundwater as percolation from precipitation and leaving the groundwater due to evapotranspiration.

The soil moisture monitoring plan employs a combination of stationary point measurements and area-averaged measurements to estimate soil moisture flux across the Fox and Binfield wet meadow sites. In addition to the stationary sensors, non-stationary sensors will be used to assess the spatial variability in soil moisture across the sites.

Objectives

The objective of the soil moisture monitoring plan is to quantify the amount of water that passes between the ground surface and the groundwater table through the unsaturated soil zone. Soil moisture flux will be used to estimate percolation from precipitation events as well as the portion of evapotranspiration that originates from the groundwater table.

SOIL MOISTURE OVERVIEW

Soil Moisture Overview

The term soil moisture refers to water present in the unsaturated zone between the ground surface and the groundwater table (**Figure 1**). Water fills void spaces between soil particles below the groundwater table causing saturated conditions. Water may be present above the groundwater table by adhering to soil particles due to capillary forces (**Figure 2**).

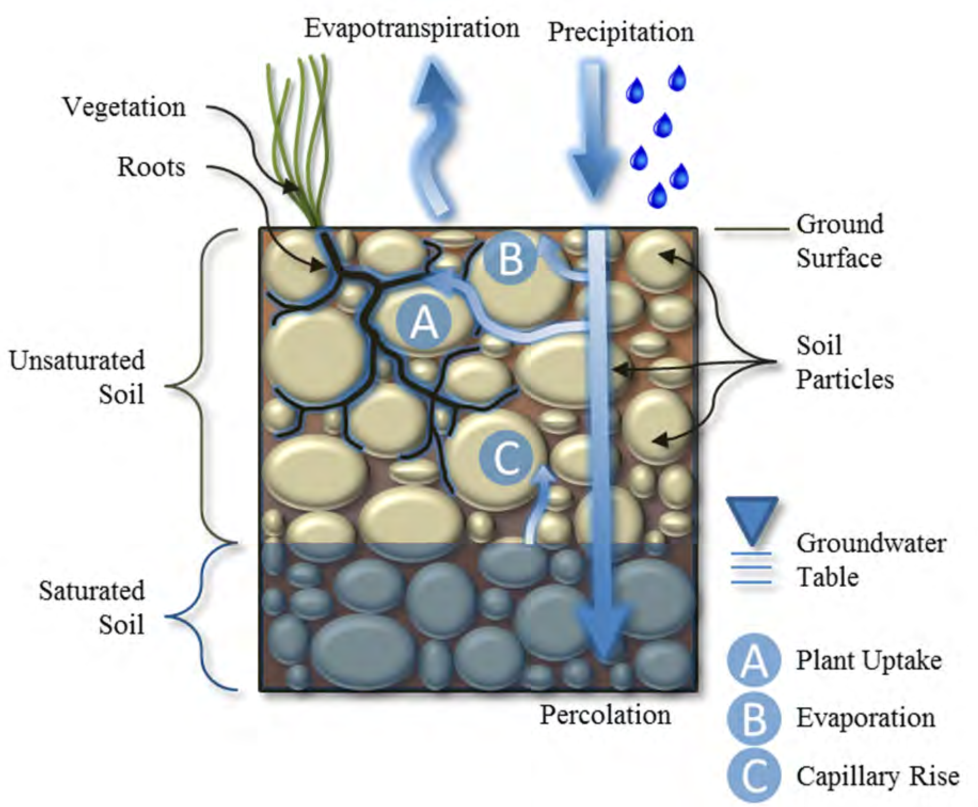

Figure 1. Soil cross section showing water movement from the ground surface to the groundwater table.

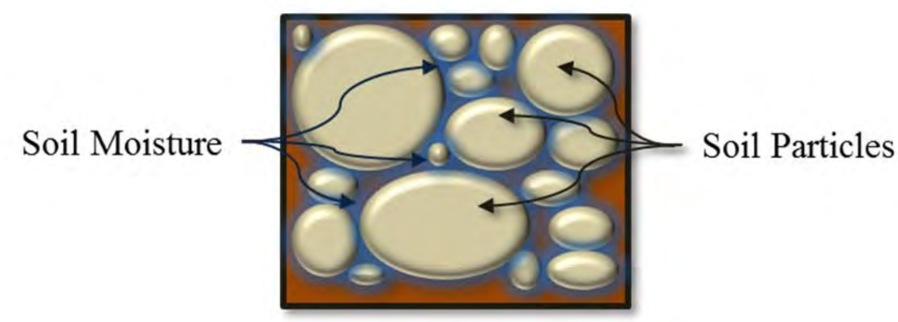

Figure 2. Water adhering to soil particles in the unsaturated zone

Water Movement Through the Unsaturated Zone

At wet meadow sites, water primarily enters the unsaturated zone as infiltration from precipitation events and from below as capillary rise. Water leaves as percolation into the groundwater table (for the purposes of this study, percolation is considered synonymous to groundwater recharge), evaporation into the atmosphere, or from uptake by plant roots (**Figure 1**). The unsaturated zone at wet meadow sites may become saturated from above due to occasional surface flooding or from below if groundwater levels rise in response to high river stage. While water is subject to an array of forces in the unsaturated zone, including hydrostatic and air pressure, the dominant upward force is due to capillary forces from soil particles and the dominant downward force is due to gravity. When gravity forces are larger than upward capillary forces, water will flow downward. Capillary forces dominate in soils that have drained to the point that gravity can no longer remove water from the soil pores, also called a soil's field capacity. Upward flow from capillary pull occurs near the groundwater table and may extend inches to feet above the groundwater table, depending on the soil material[1]. Water may flow laterally from an area of higher

[1] Dingman, S. L. 1994. *Physical Hydrology*. New York: Macmillan.

soil moisture to an area of lower soil moisture over smaller scales; however, lateral flow is assumed to be negligible over the larger scale of this monitoring effort.

While the volume of water present in the unsaturated zone may be much less than other aspects of the hydrologic cycle, it represents a key interface between groundwater and the atmosphere[2]. Measuring the flux of water through the unsaturated zone provides a means of connecting groundwater behavior with observed precipitation and evapotranspiration.

Spatial and Temporal Variations in Soil Moisture

Soil moisture content varies across vertical and horizontal distances as well as over time. Changes in soil texture and structure lead to variances in soil moisture content both horizontally and vertically. Soil moisture is rarely uniform in the vertical direction especially in the active root zone which typically extends two feet below the ground surface for many wet meadow species but can extend up to 6 feet for native grasses[3]. Precipitation, evaporation, and transpiration determine soil moisture content in the active root zone and may cause large variations over the course of hours. At greater depths, soil moisture is largely influenced by changes in groundwater table elevations which often occur on longer timescales of days and weeks[4].

Soil moisture varies spatially in the horizontal direction due to varying rates of wetting and drying over a given area. For example, water may collect in low-lying areas and drainages after precipitation events, resulting in lower soil moisture content on hills and ridges and greater soil moisture content in depressions and drainages. Terrain does not play as large a role in soil moisture variations during dry conditions, especially at relatively flat sites like the wet meadow sites. Spatial variability in soil moisture

[2] Robinson, D. A., et al. 2008. *Soil moisture measurement for ecological and hydrological watershed-scale observations*. Vadose Zone Journal. Vol. 7, No. 1
[3] Weaver, J. E. 1926. *Root Development of Field Crops.* New York: McGraw-Hill
[4] Western, A.W., Grayson, R.B., Bloschl, G., 2002. *Scaling of soil moisture: a hydrologic perspective*. Annu. Rev. Earth Planet. Sci. 30 (1), 149-180

content is also influenced by spatial variations in vegetation, soil properties, and precipitation. Horizontal variations in soil moisture content may occur on short or long timescales[5].

Soil Moisture Water Balance

The water balance at wet meadow sites is shown in **Figure 3**, with the domain boundary extending from the south to the north river channel horizontally and from just above the ground surface to below the groundwater table vertically. Water enters and leaves the domain from flow between the river and the groundwater as well as from precipitation and evapotranspiration (runoff outside of the domain is considered negligible).

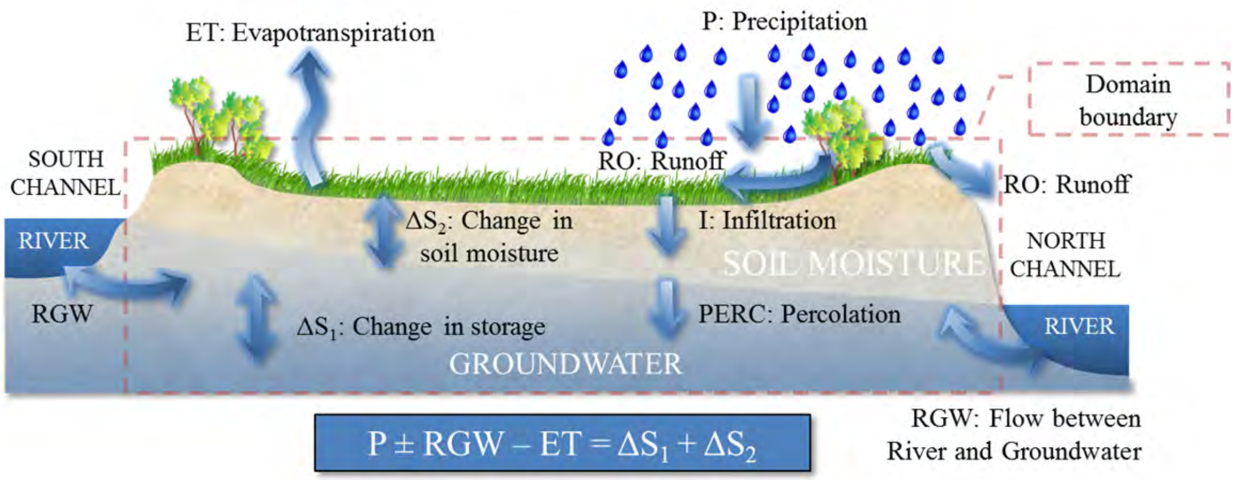

Figure 3. Wet meadow water balance

Several intermediate processes occur inside the domain shown in **Figure 3**, including infiltration, percolation, and changes in soil moisture content. These intermediate processes connect groundwater behavior to atmospheric processes and are not easily estimated. Soil moisture monitoring seeks to determine the change in soil moisture volume in order to calculate percolation. Percolation is a key process in determining the impact precipitation and evapotranspiration have on groundwater levels. To

[5] Western, A.W., Grayson, R.B., Bloschl, G., 2002. *Scaling of soil moisture: a hydrologic perspective*. Annu. Rev. Earth Planet. Sci. 30 (1), 149-180

calculate percolation, a smaller domain, shown in **Figure 4**, is outlined within the larger water budget domain to account for the intermediate processes occurring in the unsaturated soil zone.

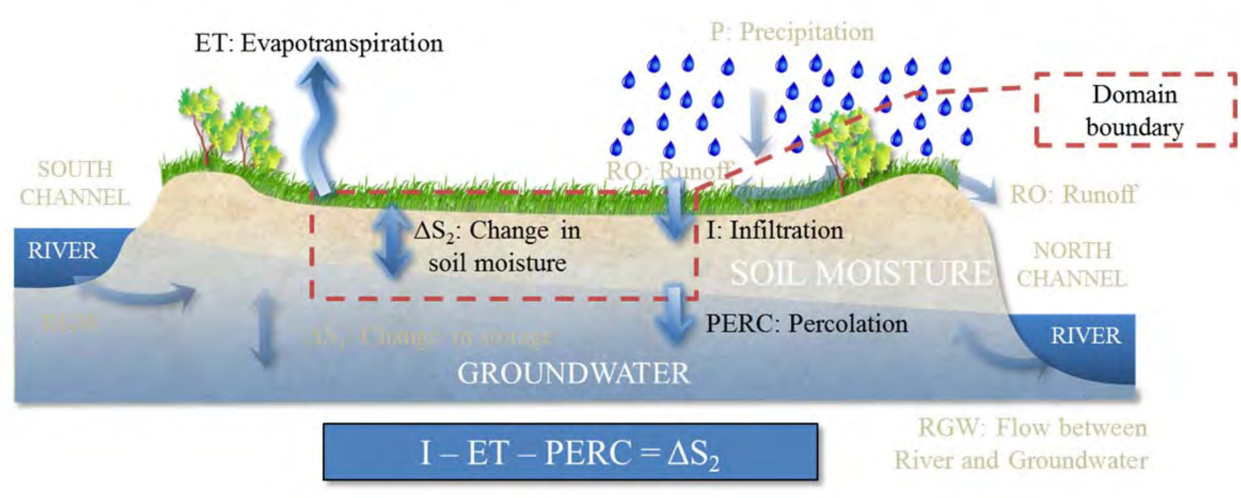

Figure 4. Soil moisture water balance

The domain boundaries extend from the ground surface to the top of the groundwater table vertically. The bottom of the domain is not static but changes as the groundwater table rises and falls. The horizontal extent of the domain boundary is somewhat arbitrary as it is assumed the primary direction of soil moisture flow is vertical. Water may enter the domain as infiltration from precipitation or as capillary rise; however, capillary rise is thought to only impact the lower 10 to 25 cm of this boundary based on the capillary rise associated with the medium to coarse sand present onsite.[6] For the purposes of this investigation, capillary rise is considered negligible. Water leaves the domain upward through evapotranspiration (including both direct evaporation from the soil surface and uptake through plant roots) or downward as percolation into the groundwater. *Equation 1* states the water balance within the soil moisture domain.

$$I - ET - PERC = \Delta S \qquad \textit{Equation 1}$$

[6] Lohman, S. W. 1978. Ground-water hydraulics. U.S. Geological Survey Prof. Paper 708

Where:

I is infiltration

ET is evapotranspiration

PERC is percolation, and

ΔS is change is soil moisture volume.

Infiltration is assumed to equal precipitation as both wet meadow sites are relatively flat and do not experience significant runoff. The sandy soils at the wet meadow sites allow for precipitation to infiltrate quickly, minimizing evaporation of pooled water.

If precipitation, evapotranspiration, and change in soil moisture volume are measured, percolation can be calculated by rearrange *Equation 1* so that $PERC = I - ET - \Delta S$.

Soil Moisture Measurements

Soil moisture measurement methods can be divided into remote sensing methods and ground based methods. Remote sensing methods include airborne and satellite remote sensing and generally measure soil moisture at resolutions of 100 m to 1000 km over periods of days to months[7]. Remote sensing techniques are only able to measure near surface soil moisture and often require additional information about vegetation and soil roughness[8].

Ground based methods include thermogravimetric determination, neutron scattering, and measurements of dielectric properties of the soil. Ground based methods may be point measurements at horizontal and vertical scales of 1 cm to 100 cm or area averaged measurements at scales of 10 m to 100 m horizontally

[7] Robinson, D. A., et al. 2008. *Soil moisture measurement for ecological and hydrological watershed-scale observations*. Vadose Zone Journal. Vol. 7, No. 1

[8] Western, A.W., Grayson, R.B., Bloschl, G., 2002. *Scaling of soil moisture: a hydrologic perspective.* Annu. Rev. Earth Planet. Sci. 30 (1), 149-180

and 10 mm to 10 cm vertically. Networks of point measurements are commonly used to capture soil moisture behavior across a larger area. Point and area-averaged measurements capture soil moisture over periods from seconds to months[9].

MONITORING PLAN

Monitoring Approach Overview

The wet meadow soil moisture monitoring plan is designed to capture the vertical, horizontal, and temporal variations in soil moisture and provide estimates of the change in soil moisture over time. The change in soil moisture will be used in conjunction with other data collected at the wet meadow sites to quantify percolation into the groundwater. Percolation will be used in water budget calculations and as an input in the groundwater model.

To obtain change in soil moisture, both point and area-averaged measurements are used. Point measurements provide information on changes in the vertical soil moisture profile while area averaged measurements indicate the average flux of soil moisture across large areas of the wet meadow sites. Hourly measurements account for rapid changes in soil moisture from precipitation and evapotranspiration. Electronic data loggers record hourly measurements. To limit the need for frequent field visits, the monitoring system requires minimal maintenance and will send data via telemetry to allow for real-time analysis. Rover surveys inform the degree to which area averaged measurements capture soil moisture behavior across the entire site.

Point Measurements

[9] Western, A.W., Grayson, R.B., Bloschl, G., 2002. *Scaling of soil moisture: a hydrologic perspective*. Annu. Rev. Earth Planet. Sci. 30 (1), 149-180

An array of four soil moisture probes are installed at the High Plains Regional Climate Center (HPRCC) Automated Weather Data Network (AWDN) weather stations on the Fox and Binfield site at depths of 10, 25, 50, and 100 cm. The arrays are equipped with ThetaProbe ML2x soil moisture probes (**Figure 5**) and measure volumetric soil moisture content using time-domain reflectometry (TDR). The horizontal extent of the probe's measurements is small and the measurements are considered point measurements. The probes measure soil water content (SWC) on an hourly basis as a volumetric percentage. Subtracting the previous hour's SWC from the current SWC provides the change in soil moisture. SWC measurements can be averaged on a daily basis to determine the daily change in SWC. The probes have an accuracy of ±1% and a resolution of 0.1% of the volumetric water content[10]. The probes are connected to data loggers that capture hourly readings and telemetry that make data available for remote access.

The ThetaProbe data loggers were installed by excavating a pit to a depth of 1 meter (100 cm), and inserting the probes horizontally into the adjacent undisturbed soil. Cables from the probes were connected to data loggers on the weather station and the pit was filled back in. The top of the pit was not seeded and vegetation has not fully established on the bare sand. The disturbed soil in the pit and the lack of vegetation may impact the soil moisture readings of the ThetaProbes somewhat, but it is assumed that the probes are situated deep enough in undisturbed vegetation to provide reasonable soil moisture measurements. ThetaProbes were calibrated according to manufacturer recommendations.

Figure 5. Theta Probe ML2x soil moisture probe

[10] Delta-T Devices, Ltd., 1999. *ThetaProbe soil moisture sensor type ML2x user manual*.

While soil moisture from point measurements may not be extrapolated across the entire site, they provide information about vertical variation in soil moisture as water passes from the ground surface to the groundwater table. Because the arrays are located adjacent to the weather stations (**Figures 6** and **7**), their measurements capture response to precipitation and evapotranspiration measured at the weather staitons.

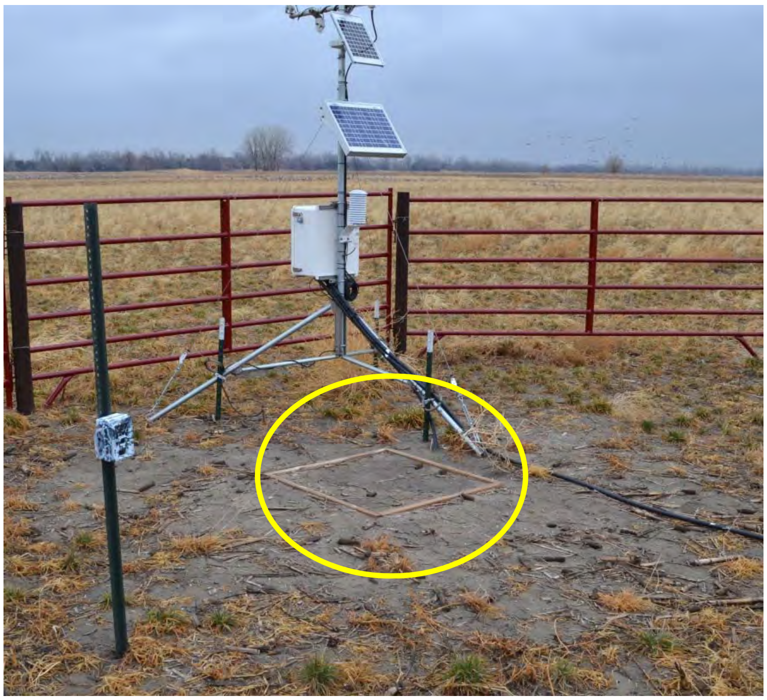

Figure 6. Soil moisture profile (circled in yellow) at the Fox AWDN weather station

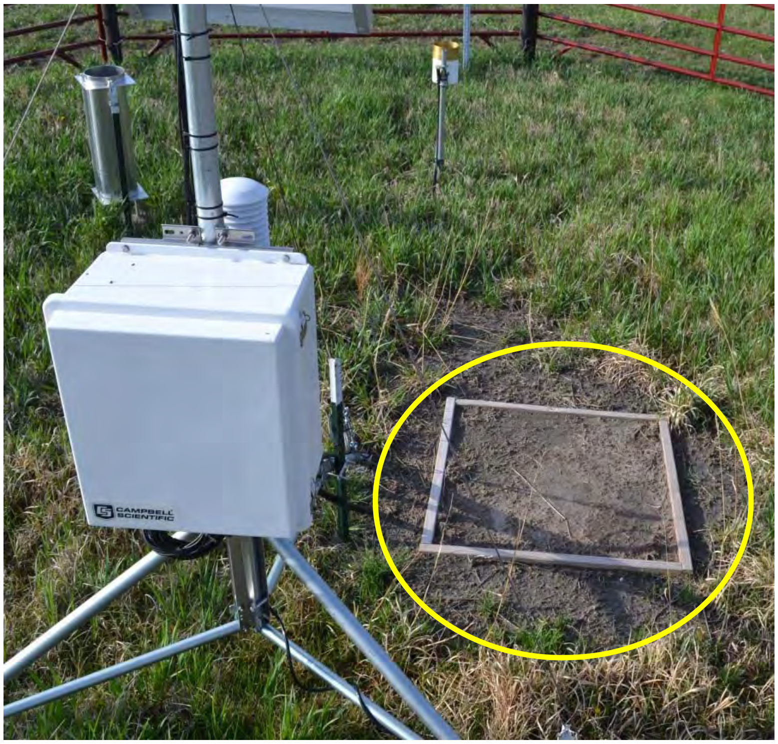

Figure 7. Soil moisture profile (circled in yellow) at the Binfield AWDN weather station

Area-Averaged Measurements

Area-averaged soil moisture measurements are taken using cosmic-ray neutron probes, CRNP (model # CRS 2000/B, HydroInnova LLC, Albuquerque, NM). Both stationary and vehicle mounted probes are used to capture soil moisture behavior across larger areas of the sites.

CRNPs determine soil moisture content by measuring the changes in the ambient amount of low-energy neutrons above the land surface. Soil moisture is inversely correlated with the density or count rate of low-energy neutrons. The probes provide average soil moisture over a circle with a diameter of approximately 600 m (1,970 ft) and an area of 70 acres[11]. The depth of measurement typically ranges

[11] Zreda, B., et al. 2012. *COSMOS: the cosmic-ray soil moisture observing system*. Hydrology and Earth System Sciences, 16, 4079-4099, 2012

from 15 cm to 40 cm[12] and measurements are typically recorded over one hour intervals. The CRNPs SWC measurements can be used to determine hourly or average daily change in SWC. The accuracy of the probes depends on several factors, but soil moisture measurements typically have accuracies of ±1% and resolutions of 0.1% of the volumetric water content[13]. The probes are mounted on poles shown in **Figure 8**. They are powered by solar panels, and upload data to the internet via satellite modems. Additional CRNP equipment and installation details can be found on the Hydroinnova website.[14]

Figure 8. CRNP at a site in Colorado (Photo credit: Trenton Franz)

The Fox wet meadow site has a roughly square shape with an area of 180 acres. The CRNP covers approximately 39% of the site's area. The Binfield site has an irregular shape with an area of 937 acres. The CRNP only covers 7.5% of the Binfield site. To quantify the variation across the portions of the wet

[12] Franz, T. E., et al. (2012), *Measurement depth of the cosmic-ray soil moisture probe affected by hydrogen from various sources*. Water Resources Research, 48.
[13] Franz, T. E., M. Zreda, R. Rosolem, and P. A. Ferre (2012), *Field validation of cosmic-ray soil moisture sensor using a distributed sensor network.* Vadose Zone Journal, 11(4).
[14] http://hydroinnova.com/main.html

meadow sites covered by the CRNP as well as those not covered, vehicle mounted probes will be used to collect soil moisture across the entirety of the sites.

The cosmic-ray rover consists of a large CRNP (~30 times larger than the stationary CRNP, allowing for soil moisture measurements collected every 1 minute instead of 1 hour) mounted in a pickup truck, shown in **Figure 9**, or an all-terrain vehicle (ATV). The rover drives across the site collecting soil moisture data and pairs this data with GPS information. The rover surveys indicate how soil moisture changes across the site and quantifies the degree of spatial variability in soil moisture[15]. Approximately ten rover surveys will be collected during 2014 and 2015 to capture a range of wetting and drying soil conditions. Site-wide soil moisture obtained from rover surveys will be compared to soil moisture in the area of the stationary CRNP to determine how closely the stationary probe represents the entire site. Rover results will also provide information on the overall variance and spatial correlation of soil moisture across the site.

[15] Chirsman, B., and Zreda, M., 2013. *Quantifying mesoscale soil moisture with the cosmic-ray rover*. Earth System Sciences, 17, 5097-5108, 2013

Figure 9. Truck-mounted rover soil moisture probes (Photo credit: Trenton Franz)

After rover surveys have capture soil moisture patterns over a range of wet and dry conditions, a regression equation can be developed between the stationary CRNP probe and the rover results. This will allow for site-wide estimates of soil moisture to be derived from the stationary CRNP soil moisture measurements.

Monitoring Timeline

The installation of the soil moisture monitoring equipment and rover surveys will continue through 2015. The TDR soil moisture probe arrays were installed at the Fox and Binfield weather stations in May of 2012. Rover surveys of the sites are scheduled to begin in the fall of 2014 and will continue through the fall of 2015. Stationary CRNP will be installed in the fall of 2014. Data will be collected through the end of the Program's first increment in 2019 with the possibility of continuing beyond 2019.

Monitoring Cost

The cost of the TDR soil moisture probes was included in the total cost of the AWDN weather station. The CRNP stationary probes will be leased from HydroInnova on an annual basis for a cost of $5,000 which includes equipment, installation, maintenance, telemetry, and web-based data access. To instrument both sites through the remaining 5 years of the Program's first increment would cost $50,000.

The rover surveys cost $1,600 each, with a single survey covering both sites. Approximately 8 to 10 surveys are needed to capture the full range of wet and dry conditions at the sites. The current approach will be to conduct 2 surveys in the fall of 2014 and an additional 8 surveys in 2015 for a total cost of $16,000.

The total budget for soil moisture monitoring is $66,000 through the end of the first increment. An annual breakdown of costs is shown in **Table 1**. The 2018 stationary probe lease would extend through the fall of 2019 and no additional costs would be incurred in 2019.

Table 1. Soil moisture monitoring costs

Year	**Description**	**Cost**
2014	Stationary Probe lease, Fox and Binfield site Rover Surveys (2) Subtotal (2014)	$10,000 $3,200 $13,200
2015	Stationary Probe lease, Fox and Binfield site Rover Surveys (8) Subtotal (2015)	$10,000 $12,800 $22,800
2016	Stationary Probe lease, Fox and Binfield site	$10,000
2017	Stationary Probe lease, Fox and Binfield site	$10,000
2018	Stationary Probe lease, Fox and Binfield site	$10,000
Total		$66,000

CONCLUSIONS

The soil moisture monitoring approach outlined above captures spatial and temporal variations in soil moisture to aid in water budget calculations and general understanding of hydrologic processes at wet meadow sites. Accurate soil moisture measurements are needed to develop estimates of percolation into the groundwater. Percolation is needed to determine the groundwater response to precipitation and evapotranspiration.

Point measurements with vertical arrays of soil moisture probes provide useful insight into the behavior of soil moisture between the ground surface and the groundwater table. Because point measurements are only applicable to small horizontal areas, area-averaged measurements from the CRNP stationary probes will confirm the point measurements and provide soil moisture data over a larger area on a real time basis. Several rover surveys will be conducted to capture soil moisture behavior across the entirety of the wet meadow sites. Rover surveys will also serve to confirm the CRNP stationary probe measurements and provide insight into spatial variations in soil moisture across the sites.

Area-averaged soil moisture flux determined by CRNP stationary probes paired with precipitation and evapotranspiration data is used to quantify percolation into the groundwater. Percolation is an important aspect of the wet meadow water balance and will improve water budget calculations and groundwater model results.

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Franz, T. E., Zreda, M., Rosolem, Y., and Ferre, P. A. (2012), *Field validation of cosmic-ray soil moisture sensor using a distributed sensor network*, Vadose Zone Journal, 11(4).

Lohman, S. W. 1978. Ground-water hydraulics. U.S. Geological Survey Prof. Paper 708

Robinson, D. A., Campbell, C.S., Hopmans, J.W., Hornbuckle, B.K., Jones, S.B., Knight, R., Ogden, F., Selker, J., Wendroth, O. 2008. *Soil moisture measurement for ecological and hydrological watershed-scale observations.* Vadose Zone Journal. Vol. 7, No. 1

Weaver, J. E. 1926. Root Development of Field Crops. New York: McGraw-Hill

Western, A.W., Grayson, R.B., Bloschl, G. 2002. *Scaling of soil moisture: a hydrologic perspective*. Annu. Rev. Earth Planet. Sci. 30 (1), 149-180

Zreda, B., Shuttleworth, W.J., Zeng, X., Zweck, C., Desilets, D., Rosolem, R. 2012. *COSMOS: the cosmic-ray soil moisture observing system.* Hydrology and Earth System Sciences, 16, 4079-4099, 2012

CHAPTER 4 – WET MEADOW GROUNDWATER MODELS

ABSTRACT

A suite of numerical groundwater models were constructed to capture groundwater response to changes in river stage, precipitation, and evapotranspiration at two wet meadow sites managed by the Platte River Recovery Implementation Program (PRRIP or the Program). The models are part of a larger hydrologic modeling effort at the wet meadow sites and will be used to aid in quantification of groundwater response to hydrologic changes and to test a variety of management scenarios. River stage gages, groundwater monitoring well transects, and weather station data were used to develop the models and evaluate their performance. Seasonal groundwater behavior was evaluated using annual models with monthly stress periods and short duration events were evaluated using event models with daily stress periods. The models were developed using hydrologic data from the spring of 2013 through the spring of 2014. This period captures a wide range of hydrologic conditions including two high flow events as well as a drying of the river during late summer.

The models were calibrated and underwent sensitivity testing. The models faithfully reproduce observed groundwater response to a wide range of hydrologic conditions. They match observed groundwater elevations with sufficient accuracy to provide useful quantification of groundwater response to a variety of hydrologic conditions. The models provide insight into groundwater response across the wet meadow sites to historical and simulated river flows and management scenarios.

INTRODUCTION

Overview

A suite of numerical groundwater models was built to aid in the analysis of data collected as part of the wet meadow hydrologic monitoring effort conducted by the Platte River Recovery Implementation

Program (PRRIP or the Program). Monitoring is currently conducted at two wet meadow sites, the Fox site, near Kearney, NE, and the Binfield site, near Wood River, NE. The models were developed for the Fox and Binfield sites to simulate flow in the shallow alluvial aquifer below the sites. The models were run using MODFLOW 2000[1] and Groundwater Vistas[2] was used as a graphical user interface (GUI) to aid in model set up and processing of results. The models were designed to quantify the volume of flow passing from the river into the groundwater and from the groundwater into the river as well as investigate the hydrologic system's sensitivity to changes in various aspects of the water budget. Annual models were developed for each site to capture seasonal variations and event models were developed for each site to capture short duration events such as spring runoff, a Short Duration High Flow (SDHF) release, or a flood event. The annual and the event models of each site share the same domain, aquifer properties, boundary conditions, and model components. The annual models cover a time span of 13 months with monthly stress periods while the event models cover a time span of 2 months with daily stress periods.

This memo discusses the domain, aquifer properties, boundary conditions, model components, calibration, and sensitivity testing of the groundwater models. It also presents model performance for the annual and event models based on spring 2013 through spring 2014 hydrology.

Model Objectives

The groundwater models have two primary objectives:

- **Quantify groundwater response to changes in river stage, precipitation, and evapotranspiration.** The complex interaction between the Platte River and groundwater below wet meadow sites makes quantifying the effect of river stage changes on groundwater response using a simple water budget approach difficult. The numerical models track the amount of water

[1] McDonald, M.G. and Harbaugh, A.W. 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*. Book 6, Chapter A1, Techniques of Water-Resources Investigations of the U. S. Geological Survey.
[2] Environmental Simulations Incorporated: Groundwater Vistas, version 6. www.groundwatermodels.com

that passes from the river into the groundwater and from the groundwater into the river as well as the amount of precipitation and evapotranspiration that occur within the models.

- **Test water management scenarios.** The groundwater models will be used to evaluate various management scenarios aimed at maintaining desired groundwater levels at wet meadow sites. Two primary scenarios identified thus far include increasing river stage through flow releases to raise and maintain groundwater levels and directly applying water to wet meadow sites through flood irrigation or other methods to maintain groundwater levels.

MODEL DOMAIN

Model Domain Overview

The model domains for the Fox and Binfield sites are designed to capture groundwater flow behavior below the wet meadow sites by accounting for the influence of river levels, precipitation, and evapotranspiration. The domains extend beyond the wet meadow site areas and are bounded by the Platte River channels. The model domains are comprised of rectilinear grids that are roughly aligned with the cardinal directions. The dominant direction of river flow on both sites is from southwest to northeast. It is assumed the direction of groundwater flow roughly aligns with the dominant direction of river flow. **Figures 1** and **2** provide an overview of the sites, with the wet meadow area outlined in orange and arrows indicating the direction of river flow. **Figures 3** and **4** show the groundwater domain for the Fox and Binfield sites, with inactive (no-flow) cells shown in black, river boundary cells shown in green, and specified head boundary cells shown in blue. Boundary conditions are discussed in **SECTION 3** below. **Table 1** lists several general domain attributes of both models.

Table 1. Model domain characteristics

Model	*Cell Size*	*Rows*	*Columns*	*Layers*	*Total Cells / Area (acres)*	*Active Cells / Area (acres)*
Fox	100’ x 100’	90	240	1	21,600 / 4,959	10,797 / 2,479
Binfield	100’ x 100’	160	258	1	41,280 / 9,477	17,313 / 3,975

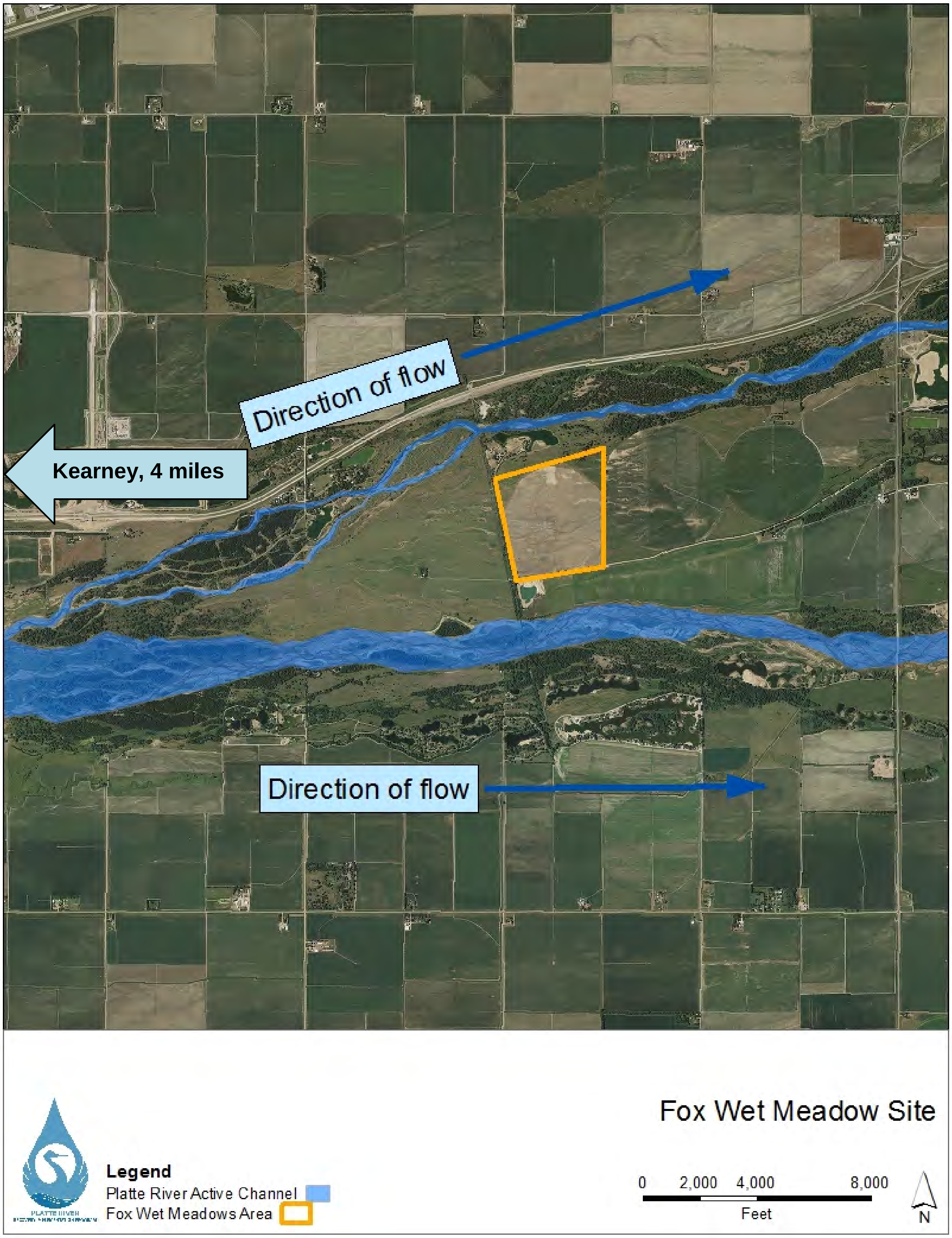

Figure 1. Fox site overview and river flow direction.

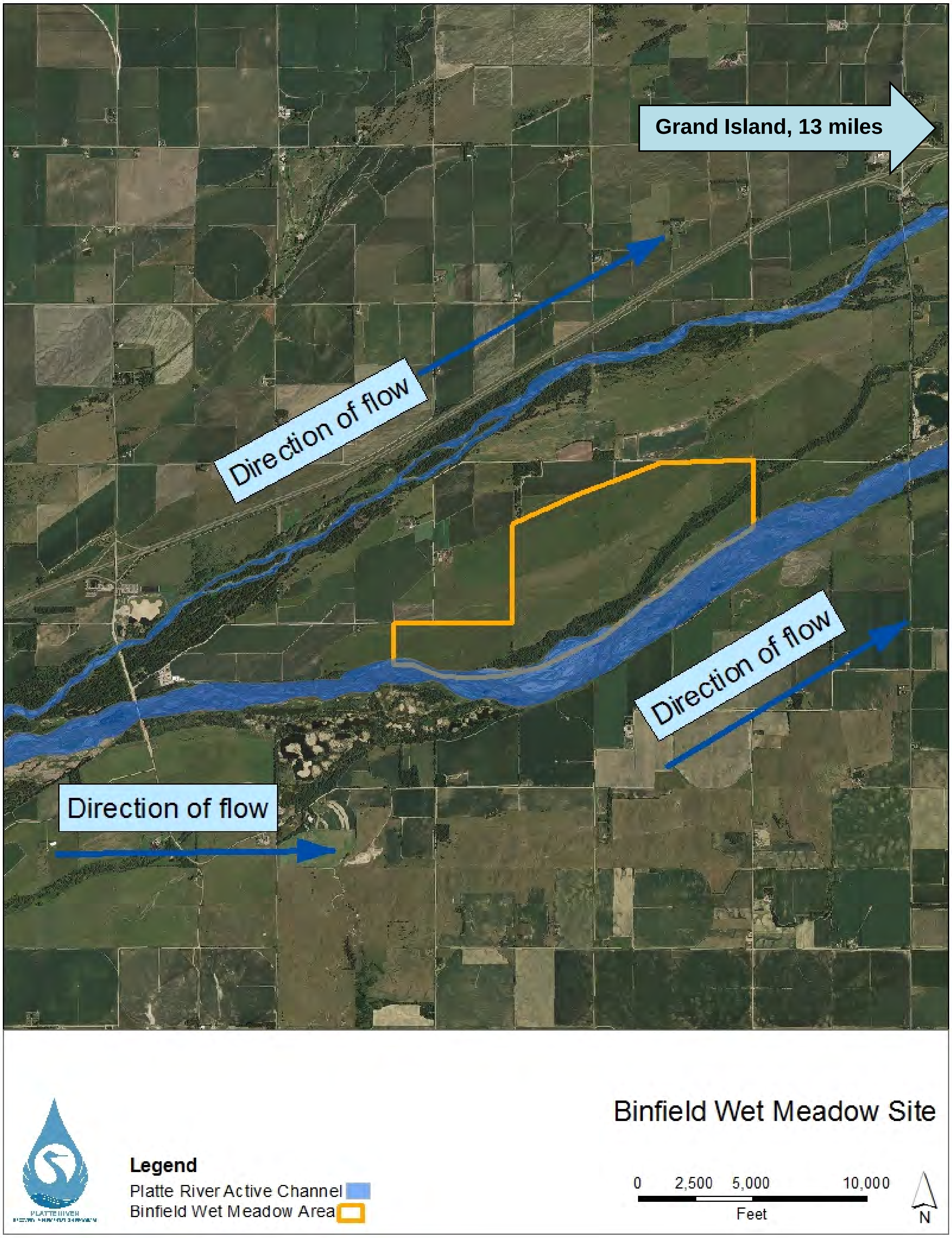

Figure 2. Binfield site overview and river flow direction.

Figure 3. Fox model domain with site area outlined in orange and inactive (no flow) cells shown in black

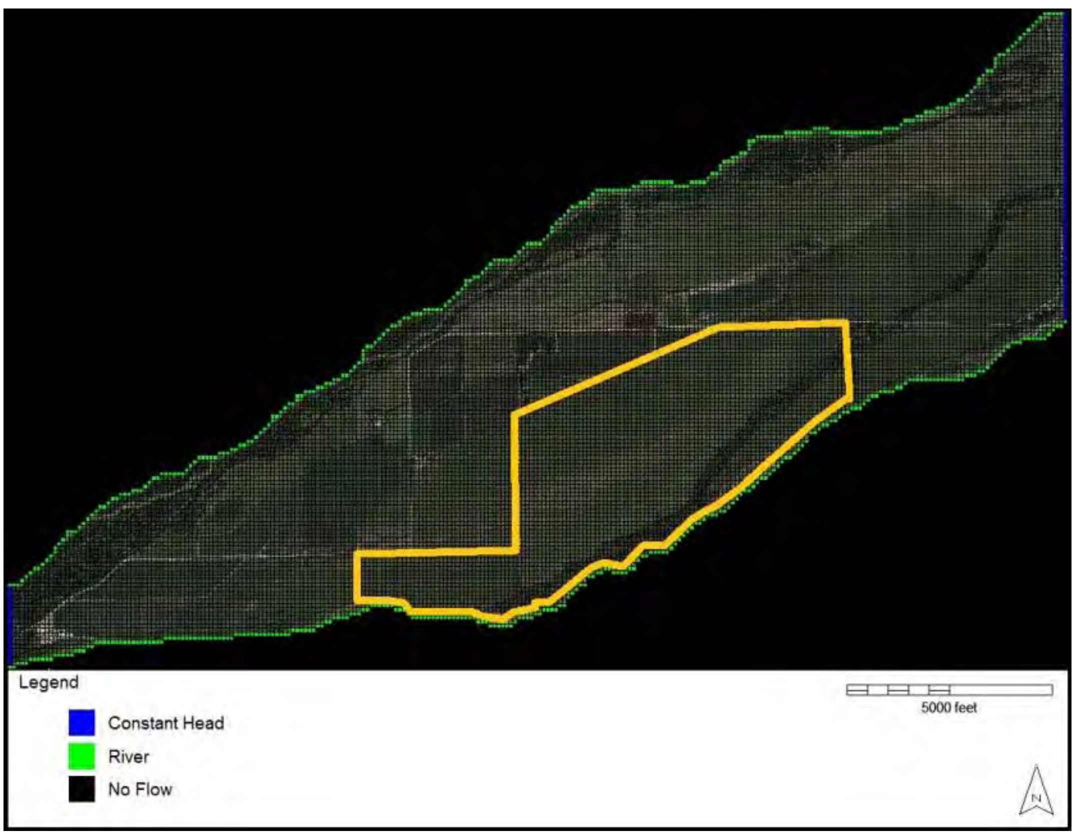

Figure 4. Binfield model domain with site area outlined in orange and inactive (no flow) cells shown in black

Active Boundary

The total domain of the Fox models is 9,000 feet from north to south and 24,000 feet from east to west and the total domain Binfield models is 16,000 feet from north to south and 25,800 feet from east to west. The area of interest for both models lies in between the north and south channels of the Platte River. Because the model domains are rectangular, the domain extends beyond this area of interest. The portions of the models that lie outside the area of interest are made inactive by assigning the cells in these areas "no-flow" boundary conditions. Groundwater is not simulated in these areas, shown in black in **Figures 3** and **4**.

The active portion of the models covers the islands between the north and south channels of the Platte River. The islands extend several miles to the east of both sites and the eastern boundary of the models was chosen to exclude areas unlikely to influence groundwater behavior at the wet meadow sites. The models are terminated several thousand feet beyond the eastern edge of the wet meadow sites at road crossings. The Fox models extend approximately 13,500 feet upstream from the western edge of the wet meadow area and 7,800 feet downstream from the eastern edge. The Binfield models extend approximately 8,500 feet upstream from the western edge of the wet meadow area and 5,400 feet downstream from the eastern edge.

Temporal Discretization

Annual and event models were developed for the Fox and Binfield sites. The annual models span approximately 13 months while the event models span approximately two months. While all models use days for the units of time, the annual models use monthly stress periods and the event models use daily stress periods with the exception of an initial 7-day stress period designed to allow the model to stabilize. The annual models have 13 stress periods coinciding with the number of months in the simulation, and 30 time steps per stress period, coinciding with the average number of days per month. The annual models cover 390 days and typically begin in the late winter and end in early spring as groundwater levels are relatively stationary in the late winter before spring runoff. The annual models used for calibration and sensitivity testing are based on hydrology and observed groundwater levels from February 26th, 2013 to March 22nd, 2014.

The event models have an initialization stress period with 7 time steps that simulate seven daily time steps followed by 51 stress periods (days) containing 24 hourly time steps each. The initialization stress period allows the models a short run-up time to reach initial conditions before simulating the desired hydrologic event. The span of the event models is about two months which is typically enough time to capture the rise and fall of a hydrologic event. The development of the event models used spring 2013 river conditions and fall 2013 high flow hydrology and groundwater response. The spring 2013 period lasted from March 18th through May 13th for both the Fox and Binfield models and the fall 2013 period lasted from September 14th through November 10th for the Fox model and from September 16th through November 12th for the Binfield model.

Temporal parameters for the annual and event models are show in **Table 2**. Other variations of these models can be developed if modeling is desired for longer periods of time to compare one year to another or long-term effects of management scenarios.

Table 2. Model stress periods and time steps

Model	*Total time*	*Stress Periods*	*Time Steps*
Fox annual	~13 months (390 days)	13	30
Binfield annual	~13 months (390 days)	13	30
Fox event	58 days	52	SP[*] 1: 7 SP 2-52: 24
Binfield event	58 days	52	SP 1: 7 SP 2-52: 24

[*]SP: Stress Period

Spatial Discretization

The cell dimensions for both the Fox and Binfield models are a uniform 100 feet by 100 feet (both models use feet for units of length). Model grids have uniform size and orientation throughout both model domains. Cell size was chosen to allow the models to capture localized variations in groundwater without introducing excessive model computation times. The models have one layer simulating the alluvial aquifer with the surface elevation acting as the layer's top elevation and the underlying aquitard between the Ogallala aquifer and the alluvial aquifer acting as the layer's bottom elevation.

Surface Elevation

Surface elevations for both models were developed from a 0.7 meter ground sample distance (GSD) Light Detection and Ranging (LiDAR) data with an accuracy of 0.5 feet or better. Lidar was collected for the Program in November, 2013 for the Fox site and November, 2012 for the Binfield site. The Spatial Analyst tool in ArcGIS was used to calculate the average elevation at the center of each model cell from LiDAR data within the cell area. Surface elevations of monitoring wells were confirmed with Real Time Kinetic (RTK) Global Positioning System (GPS) surveys with an accuracy of ± 0.05 ft.

Aquifer Bottom Elevation

The elevation of the bottom of the alluvial aquifer was approximated based on the termination depth of irrigation wells in the areas surrounding the wet meadow sites. It is assumed that well termination elevations roughly correspond to the bottom of the alluvial aquifer and the top of the Ogallala aquifer. The average of the surrounding well depths was obtained from the Nebraska Department of Natural Resources well data base[3] and the bottom elevation of the model was set to that average. Bottom

[3] Obtained via the internet at http://dnr.nebraska.gov/groundwater-data

elevations were set uniformly at an elevation of 2,000 feet at the Fox site and 1,860 feet at the Binfield site, representing an approximate aquifer depth of 80 feet for both sites.

AQUIFER PROPERTIES

Aquifer Properties Overview

The alluvial aquifer was modeled as a homogeneous, isotropic, unconfined aquifer. Well logs, geotechnical analysis, and pumping tests were analyzed to estimate the hydraulic properties of the aquifer. The findings from these analyses are presented in the Alluvial Aquifer Properties memo[4]. Overall, the aquifer is composed of fine to coarse sand with interspersed gravel and small amounts of clay. Most of the aquifer originated from river sediment deposits with some wind-blown deposits near the surface. The aquifer below both sites is composed of similar material and can be considered homogeneous; see the Alluvial Aquifer Properties memo for further figures and calculations.

Hydraulic Conductivity

A uniform hydraulic conductivity was used for each model domain as well logs indicated the aquifer had a largely homogeneous make up. Hydraulic conductivity values in the “x” and “y” directions were set equal and vertical hydraulic conductivity was set equal to horizontal hydraulic conductivity to reflect isotropic conditions ($K_x = K_y = K_v$). The value of hydraulic conductivity was determined through the calibration process described in **SECTION 6**, with a hydraulic conductivity of 400 ft/d at the Fox site and 375 ft/d at the Binfield site. This value is appropriate for the medium to coarse sand observed throughout both sites. Hydraulic conductivity values determined from sediment grain size analyses were 225 ft/d for the Fox site and 375 ft/d for the Binfield site. While the hydraulic conductivity used in the Fox model is slightly higher than the average hydraulic conductivity determined through sediment analysis, the

[4]PRRIP, 2014. *Alluvial Aquifer Properties*. Memo from the Office of the Executive Director of the PRRIP, 2014

sediment analysis had a large range of values. The calibrated value used in the Fox model falls within the range of values for medium to coarse sand described by Heath (1983)[5] as 10 to 1,000 ft/d.

Although the assumption of a homogeneous aquifer at both the Fox and Binfield sites is reasonable, using a variable rather than a uniform hydraulic conductivity over the model domain may improve the model's ability to predict observed heads. Parameter estimation tools such as the PEST[6] tool could be used to further refine hydraulic conductivity.

Specific Yield

Similarly to hydraulic conductivity, a uniform specific yield was used for each model domain. The value of specific yield was determined through the calibration process described in **Section 6.** A specific yield of 0.2 was used for the Fox model and a specific yield of 0.16 was used for the Binfield model. These specific yields fall into the range of specific yield described by Morris and Johnson[7] for medium sand, where they suggest specific yield values ranging from 0.16 to 0.46.

BOUNDARY CONDITIONS

Overview of Boundary Conditions

The Fox and Binfield groundwater models employ three types of boundary conditions: specified head, river, and no-flow boundaries. **Table 3** summarizes the number of boundary conditions for both models. **Figures 3** and **4** show the location of the boundary conditions for the Fox and Binfield models, respectively.

[5]Heath, R.C. 1983. *Basic Ground-Water Hydrology*. USGS Water Supply Paper 2220. U. S. Geological Society.
[6]PEST: Model Independent Parameter Estimation and Uncertainty Analysis software, http://www.pesthomepage.org/PEST.php
[7]Morris, D.A. and Johnson, A.I. 1967. *Summary of Hydrologic and Physical Properties of Rock and Soil Material, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60.* U.S. Geological Survey Water-Supply Paper 1893-D.

Table 3. Boundary conditions

Model	*Specified Head cells*	*River cells*	*No-Flow cells*
Fox	87	487	10,803
Binfield	94	529	23,967

Specified Head Boundaries

Specified head boundaries are used on the eastern edge of the Fox model and the western and eastern edge of the Binfield model and extend from the north channel to the south channel in both models. The constant head package (CHD) in MODFLOW is used to assign boundary cell heads. Heads vary linearly between the north and south channels based on the water surface elevation in the channels. River surface elevations are determined using measured river stage at the wet meadow sites and translating this elevation upstream and downstream using a channel gradient determined from RTK survey measurements. The specified head boundaries are varied every stress period to account for changes in river surface elevations.

River Boundaries

The MODFLOW River package (RIV) is used to represent boundary conditions along the north and south channels of the Platte River for both the Fox and Binfield models. River surface elevations were determined from river stage gages located on the north and south channel near both sites. Water surface elevations were translated upstream and downstream from the observation point using water surface gradients determined from an RTK GPS survey. River stage varies every stress period to simulate the hydrology of the modeled period. The water surface gradient is assumed to be constant regardless of river stage. The elevations of the river channel bottom were based on the zero reading of the river stage gage and translated upstream and downstream using the water surface gradient. While model river channel bottom elevations may not reflect the actual topographic variation in the channel bottom, this method ensures river cells do not go dry unless the river stage gage shows a zero reading.

Vertical flow across the riverbed (i.e. flow between the river and the underlying aquifer) is governed by the riverbed conductance term in the RIV package, defined in Equation 1 as

$$C_{riv} = \frac{K_{rb} L W}{b} \qquad Equation\ 1$$

Where:

C_{riv} is riverbed conductance (ft^2/day),

K_{rb} is riverbed hydraulic conductivity (ft/d),

L is channel length per cell (ft),

W is channel width (ft), and

b is riverbed thickness (ft).[8]

K_{rb} values were determined using the calibration procedure described in **SECTION 6** to arrive at a K_{rb} of 10 ft/d for both channels in both models. Riverbed hydraulic conductivity typically ranges from 0.1 to 10 ft/d depending on bed material. The riverbed experiences a high degree of sediment transport resulting in existing material scoured and replaced with upstream sediment. Little organic material builds up along the riverbed and the bed material is very similar to the underlying sandy soil. The use of a higher K_{rb} values is reasonable due to the lack of organic matter or other fine sediment that would reduce K_{rb}.

A value of 100 ft (the cell length) is used for the channel length per cell and riverbed thickness is assumed to be 0.1 foot. The relatively thin riverbed reflects the similarity in riverbed material and the underlying soil. River width is determined using a stage-width relationship developed from a HEC-RAS[9] model of the associated habitat reach. The Platte River has a wide, braided channel structure and river widths can vary greatly from periods of low flow to high flow. As river stage increases, the width used to calculate

[8] McDonald, M.G. and Harbaugh, A.W. 1988. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model.* Book 6, Chapter A1, Techniques of Water-Resources Investigations of the U. S. Geological Survey.
[9] US Army Corps of Engineers Hydrologic Engineering Center (HEC): http://www.hec.usace.army.mil/software/hec-ras/

riverbed conductance increases as well. River widths for the north channel of the Fox model vary from 10 ft to 197.5 ft and widths for the south channel of the Fox model vary from 10 ft to 839 ft. River widths for the north channel of the Binfield model vary from 10 ft to 250 ft and widths for the south channel of the Binfield model vary from 10 ft to 720 ft. Table 4 summarizes the parameter values used in the RIV package for the Fox and Binfield models.

Table 4. River package parameters

Parameter	***Fox Model***	***Binfield Model***
Channel Gradient, N. channel/ S. Channel (ft/ft)	0.00136 / 0.00120	0.00135 / 0.00133
K_{rb}, N. channel/S. channel (ft/d)	10 / 10	10 / 10
Channel Length, per cell (ft)	100	100
Bed Thickness (ft)	0.1	0.1
Channel Width, N. channel/ S. channel, (ft)	10 to 197.5 / 10 to 839	10 to 250 / 10 to 720
Conductance, N. channel/ S. channel, (ft^2/d)	100,000 to 1,980,000 / 100,000 to 8,390,000	100,000 to 2,500,000 / 100,000 to 7,200,00

During dry summers, one or both channels of the Platte River can go dry. In these instances, the river channel(s) does not act as a hydraulic boundary. The river package is still used for the model boundary but the head in the river cells is based on the head in the well nearest the river gage, not the river stage gage. For example, when the south channel at the Fox site is dry, river stage is set based on observed heads at well 101. Resulting model heads are compared to observed heads used to calibrate the input river head if necessary when the river is dry. The river bottom elevation is set 0.1 ft below the river stage in these instances.

No-Flow Boundaries

No-flow boundary conditions are used on the north side of the north channel and the south side of the south channel for both models. The Platte River is assumed to function as regional control for groundwater levels and groundwater levels across the river from the model domain do not significantly influence groundwater behavior in the domain. A comparison of groundwater levels in wells adjacent to the Platte River show this assumption to be valid. When the Platte River goes dry, regional groundwater levels do play a role in groundwater behavior inside the domain and this assumption does not hold. Observed groundwater elevations at wells adjacent to the river are used to determine to what degree regional groundwater levels impact groundwater behavior in the domain.

An implicit no-flow boundary condition is also applied to the bottom of the alluvial aquifer. This boundary is based on the assumption that the model's area of interest (the upper ten feet of the aquifer) is influenced by surface and near-surface hydrologic conditions such as river stage, evapotranspiration, and rainfall, to a much greater extent than conditions in the underlying aquifer. While the models simulate groundwater flow through the entire alluvial aquifer, their focus is only on the upper portion of the aquifer. Assigning a no-flow boundary to the bottom of the alluvial aquifer essentially assumes no significant flow takes place between the alluvial aquifer and the underlying Ogallala aquifer. This assumption is consistent with the regional COHYST 2010[10] model.

OTHER MODEL COMPONENTS

The groundwater models incorporate several other components to simulate the hydrology and groundwater flow at the wet meadow sites.

Initial Groundwater Elevations

Initial groundwater elevations, called initial heads in MODFLOW, were determined by running a steady state version of the Fox and Binfield groundwater models. The river stages used in the steady state models correspond to river stage at the beginning of the transient models. The specified head boundary conditions are based on water surface elevations at the north and south channels. The groundwater heads determined by the steady state simulation are used as initial head inputs to the transient models.

[10] Platte River Cooperative Hydrology Study (COHYST): http://cohyst.dnr.ne.gov/

Evapotranspiration

MODFLOW simulates evapotranspiration (ET) with the EVT package which requires inputs of the maximum ET rate, typically equal to the ET rate when the water table lies at the surface, and an extinction depth, or the depth of the groundwater table below which ET can no longer occur. The ET rate is estimated at the wet meadow sites using meteorological data collected from a weather station on site. The weather stations were installed in June, 2013. For models beginning before June 2013, data is used from nearby weather stations in Kearney for the Fox model and Shelton for the Binfield model. The extinction depth is set to the approximate average rooting depth of the vegetation on the sites. An extinction depth of 5 feet was used to account for the deep rooting depth of several grasses present on both sites. The EVT package varies the ET rate based on groundwater elevations. When groundwater is at the surface, the full ET rate is removed from the groundwater. When groundwater is at or below the extinction depth, the model assumes no ET occurs. MODFLOW treats the relationship between ET rate and depth to water as linear. The linear variation in ET rate with groundwater depth may not reflect the actual behavior of ET with changing depth to water. ET rates were uniformly applied across the model domains and were varied from stress period to stress period to coincide with changing meteorological conditions recorded at the weather stations. ET rates are shown in **Tables G1** and **G2** in **APPENDIX G**.

Precipitation

Recharge from precipitation was modeled using MODFLOW's recharge (RCH) package. The amount of water infiltrating into the groundwater from precipitation is entered as the recharge rate. Precipitation was monitored on both wet meadow sites using automated rain gages installed with the onsite weather stations. Precipitation data prior to the installation of the onsite rain gages in June, 2013, was obtained from nearby rain gages in Kearney for the Fox model and Shelton for the Binfield model. The pre June 2013 precipitation data was modified to better reflect the timing of the observed groundwater response.

This approach was not used for the data obtained from the onsite weather stations from June 2013 onwards and will not be used in the future.

The precipitation rate was reduced by a factor of 0.3 or 0.6 to account for differences between the amount of precipitation that fell on the site and the amount of water that actually reached the water table. This factor was estimated through calibration, based on observed model response. The value was also varied depending on climatic conditions, with less precipitation reaching the water table during hot and dry periods and more precipitation reaching the water table during cool wet periods. A factor of 0.3 was used from June through September and a factor of 0.6 was used October through May. A uniform recharge rate was applied across the model domains and the rate was varied from stress period to stress period to reflect changes in precipitation.

Groundwater across the Binfield site has a dramatic response due to precipitation events, especially when initial groundwater levels are high as seen in the spring and the fall of 2013. Capturing the observed response to precipitation proved difficult, especially with the annual models, as discussed in the performance and conclusions sections below.

Wells

No pumping occurred on the wet meadow sites and pumping wells were not incorporated into either the Fox or Binfield models. Pumping may occur at nearby fields with center pivot irritation, but monitoring wells at both sites show no indication of groundwater levels being affected by pumping.

MODEL CALIBRATION

Calibration Overview

The annual groundwater models were calibrated by comparing modeled groundwater elevations to observed groundwater elevations at several monitoring wells located on the sites. The groundwater models were calibrated using a trial and error approach rather than an automated calibration process. Hydraulic conductivity, specific yield, riverbed hydraulic conductivity, and recharge multipliers were adjusted to improve the model's simulation of observed groundwater behavior. Parameter calibration was first performed on the annual models and calibrated parameter values were input into the event models to confirm the calibration. The calibration sought to match modeled and observed groundwater behavior as well as minimize the error between observed and modeled groundwater heads. Calculations used to quantify error included Mean error (*ME, Equation 2*), absolute mean error (*AME, Equation 3*), and root mean squared error (*RMSE, Equation 4*).

$$ME = average(\, x_{observed} - x_{modeled}) \qquad Equation\ 2$$

$$AME = average\big(absolute\ value(\, x_{observed} - x_{modeled})\big) \quad Equation\ 3 RMSE$$

$$= \sqrt{average(\, x_{observed} - x_{modeled})^2} \qquad Equation\ 4$$

Error values were calculated by comparing daily average observed groundwater elevations at each monitoring well with the modeled groundwater elevation for the corresponding time.

Calibration Targets

Observed groundwater heads at onsite monitoring well locations were used as calibration targets. The Fox and Binfield sites have sixteen monitoring wells each that collect groundwater elevation data on an hourly basis. Thirteen monitoring wells on the Fox site form a western transect and the remaining three wells provide groundwater elevations for the central and eastern portion of the site (**Figure 5**). The Binfield site has two transects crossing the site, with nine wells in the eastern transect and seven wells in the western transect (**Figure 6**).

Once the groundwater models were run, modeled heads were compared to observed heads to calculate ME, AME, and RMSE. **Figure 7** shows an example of the observed heads to modeled heads comparison using RMSE. As seen in **Figure 7**, the annual model has month-long stress periods and is only able to predict groundwater behavior on a monthly basis. It does not capture daily variations in groundwater elevations.

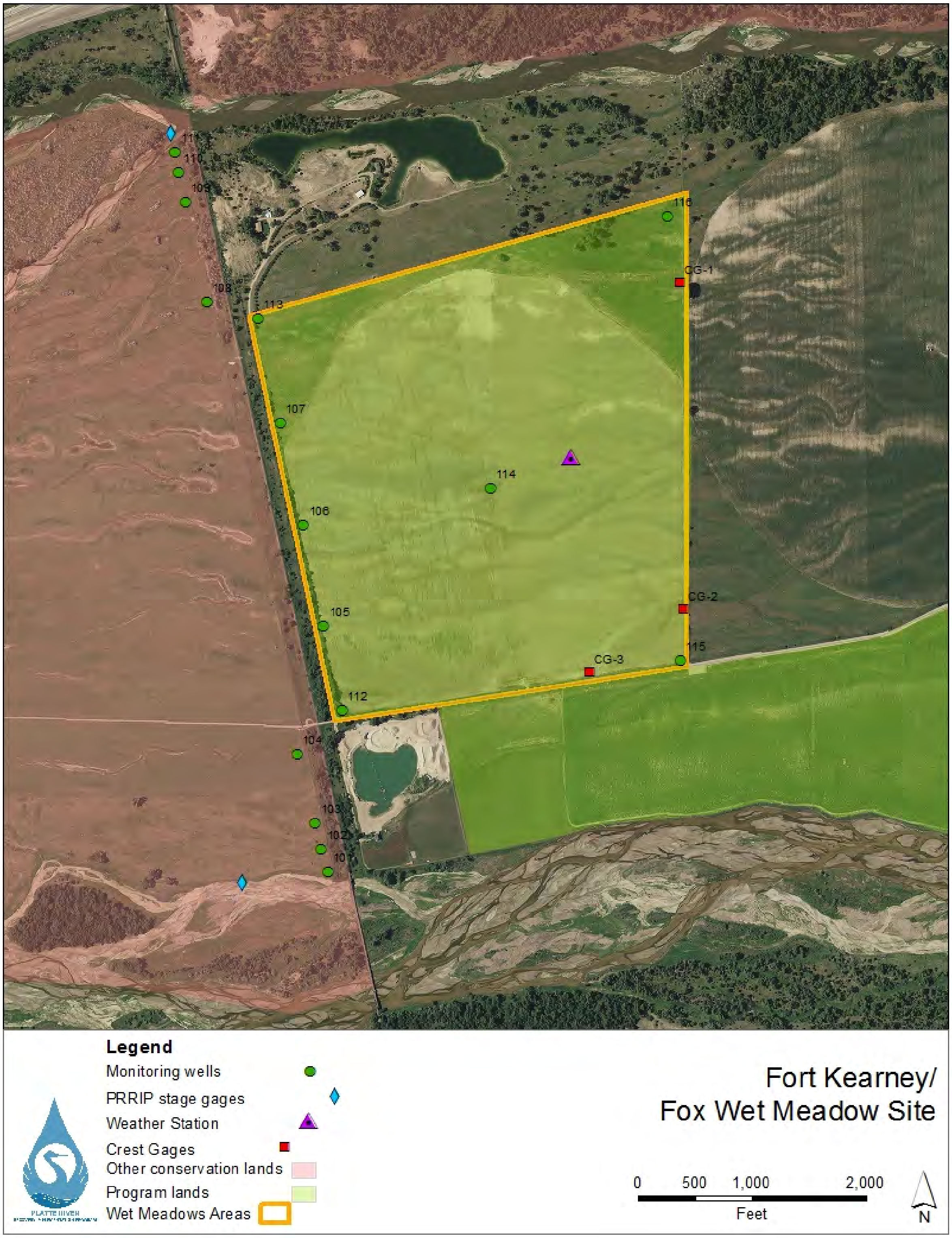

Figure 5. Monitoring wells and other monitoring equipment on the Fox site

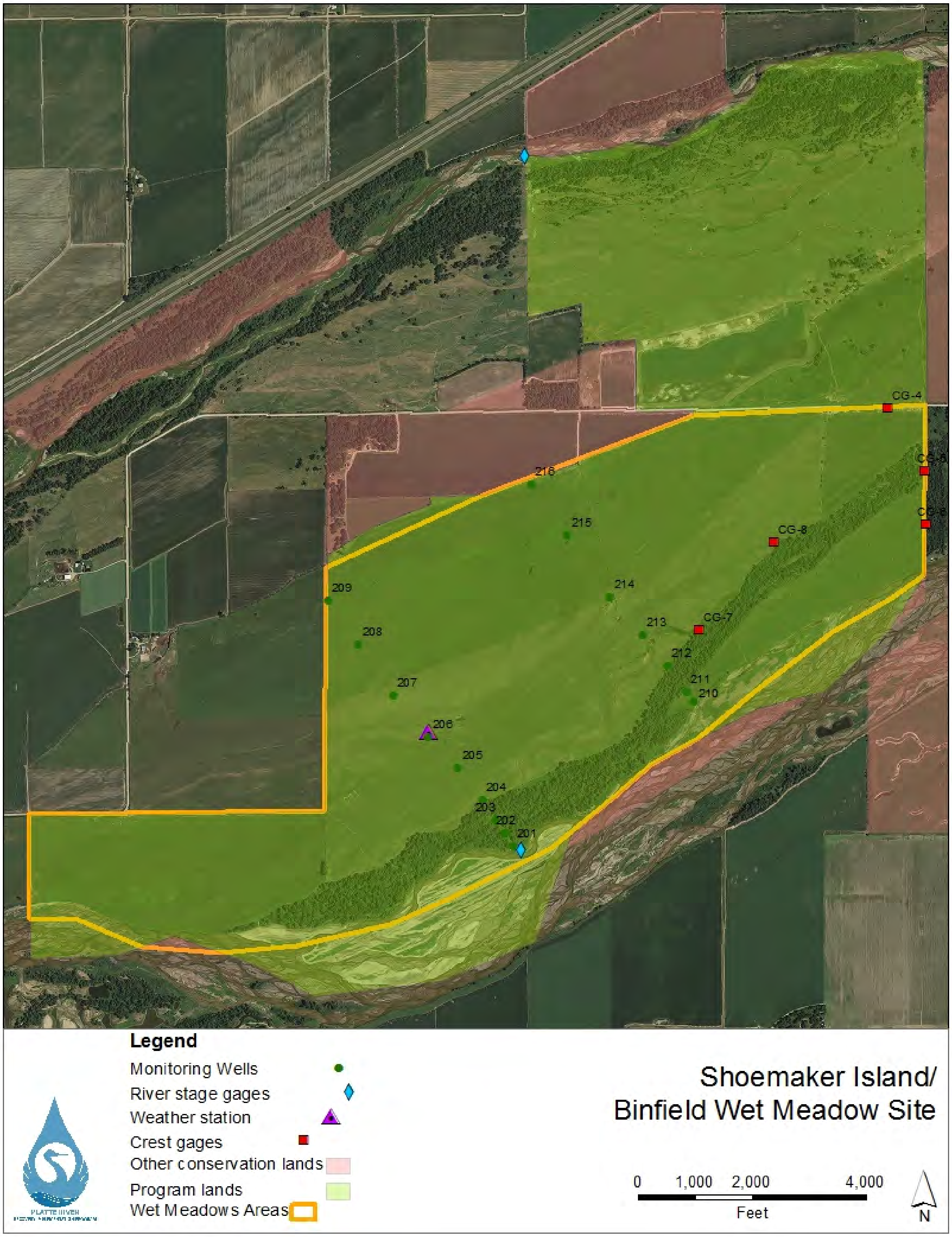

Figure 6. Monitoring wells and other monitoring equipment on the Binfield site

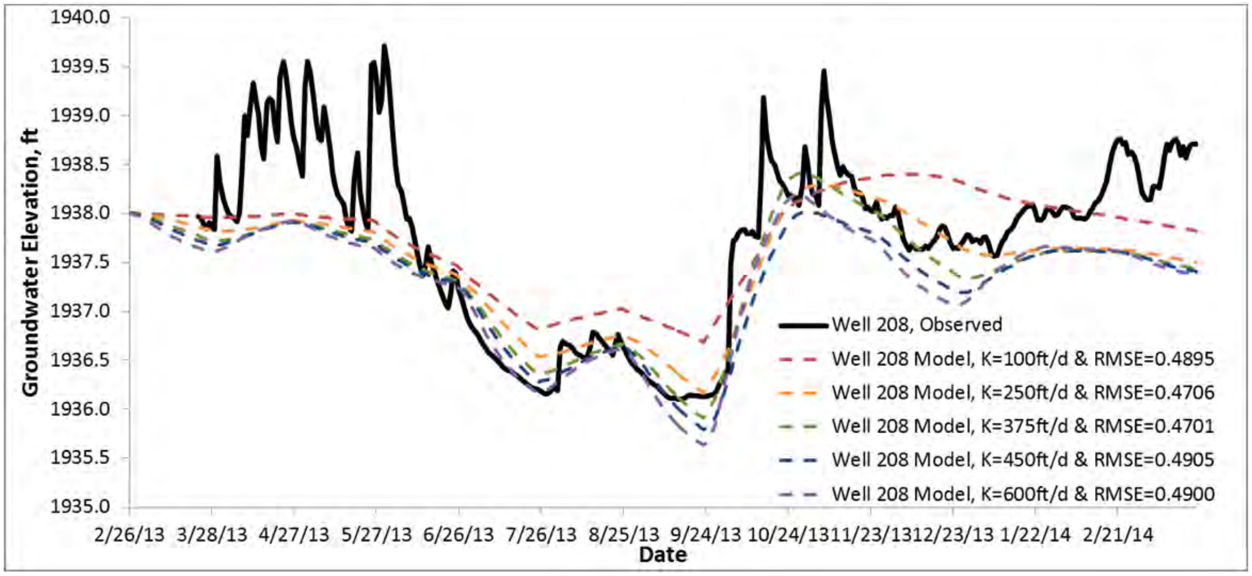

Figure 7. Binfield well 208 observed and modeled heads for a range of hydraulic conductivity values

Hydraulic Conductivity Calibration

Hydraulic conductivity was the first parameter to be calibrated. While steady state models are often used to calibrate hydraulic conductivity, this was not done for the Fox and Binfield models. Matching observed groundwater elevations proved difficult with steady state models because observed groundwater levels were nearly constantly in flux (**Figures 8 and 9**), responding to changes in river stage, recharge, and snowmelt. For this reason, the transient models were used to calibrate hydraulic conductivity rather than steady state models.

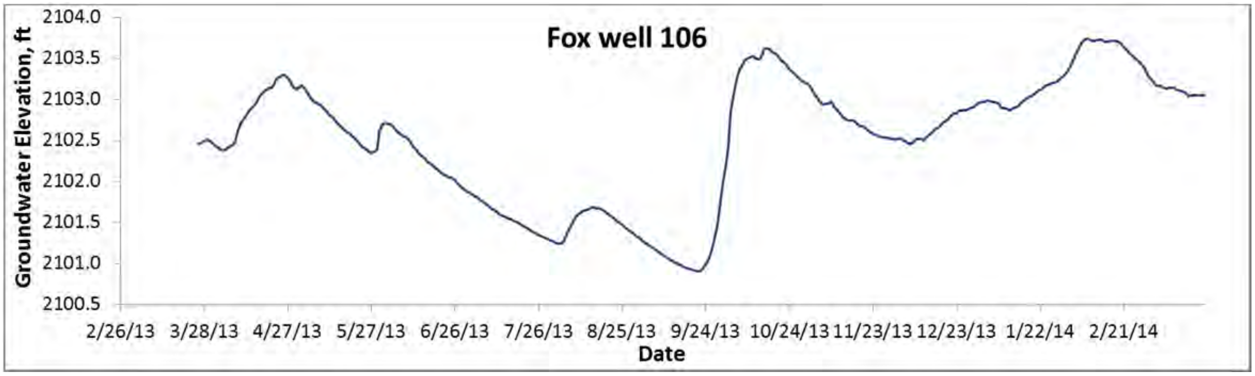

Figure 8. Example of transient behavior typical in monitoring wells at the Fox site.

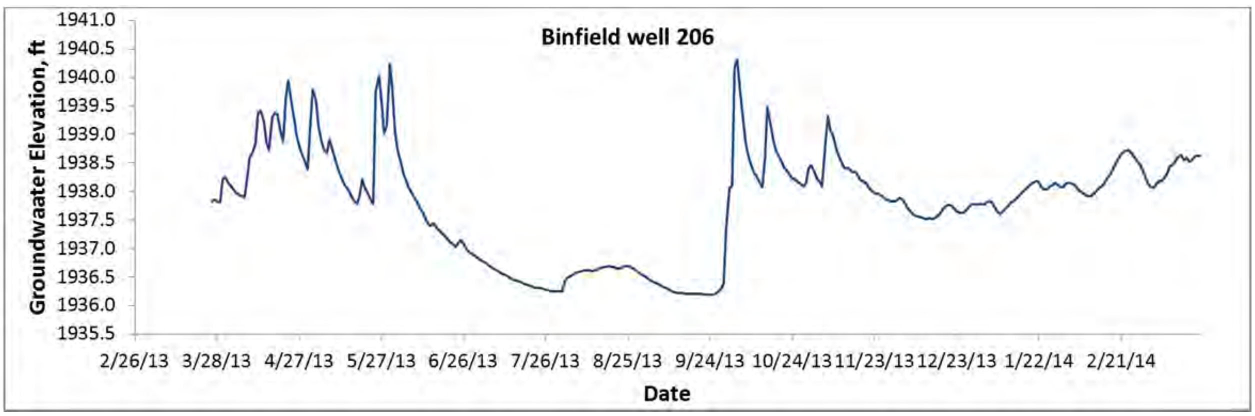

Figure 9. Example of transient behavior typical in monitoring wells at the Binfield site.

An initial hydraulic conductivity value of 500 ft/d was used for both the Fox and Binfield models. This value was increased and decreased and the resulting modeled heads compared to the observed heads to see what value produced the best fit based on RMSE, keeping in mind the range of hydraulic conductivity for medium sands of 10 to 1,000 ft/d[11]. **Figure 7** shows an example in of the response of modeled heads to various hydraulic conductivity values. The final calibrated value of hydraulic conductivity was 400 ft/d for the Fox site and 375 ft/d for the Binfield site.

[11] Heath, R.C. 1983. *Basic Ground-Water Hydrology*. USGS Water Supply Paper 2220. U. S. Geological Society.

Specific Yield Calibration

Once hydraulic conductivity had been calibrated satisfactorily, specific yield was calibrated using the same method. An initial specific yield of 0.2 was used for both models and specific yields were kept within the appropriate range for medium sands as reported by Morris and Johnson[12] of 0.16 to 0.46. **Figure 10** shows an example of the modeled head over a range of specific yield values.

The observed heads of well 208 seen in **Figures 7** and **10** show the groundwater's response to precipitation events, shown in **Figure 11**, on the Binfield site evident by dramatic spikes in groundwater elevation in April and May as well as October and November. When groundwater is high on the Binfield site even small precipitation events can lead to sharp rises in groundwater elevation. The models were not able to capture these sudden rises that occur on a smaller timescale (hours to days) than the model's monthly stress period. Rather than trying to match the exact observed groundwater behavior, the calibration sought to capture the general behavior of the groundwater.

[12] Morris, D.A. and Johnson, A.I. 1967. *Summary of Hydrologic and Physical Properties of Rock and Soil Material, as Analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60.* U.S. Geological Survey Water-Supply Paper 1893-D.

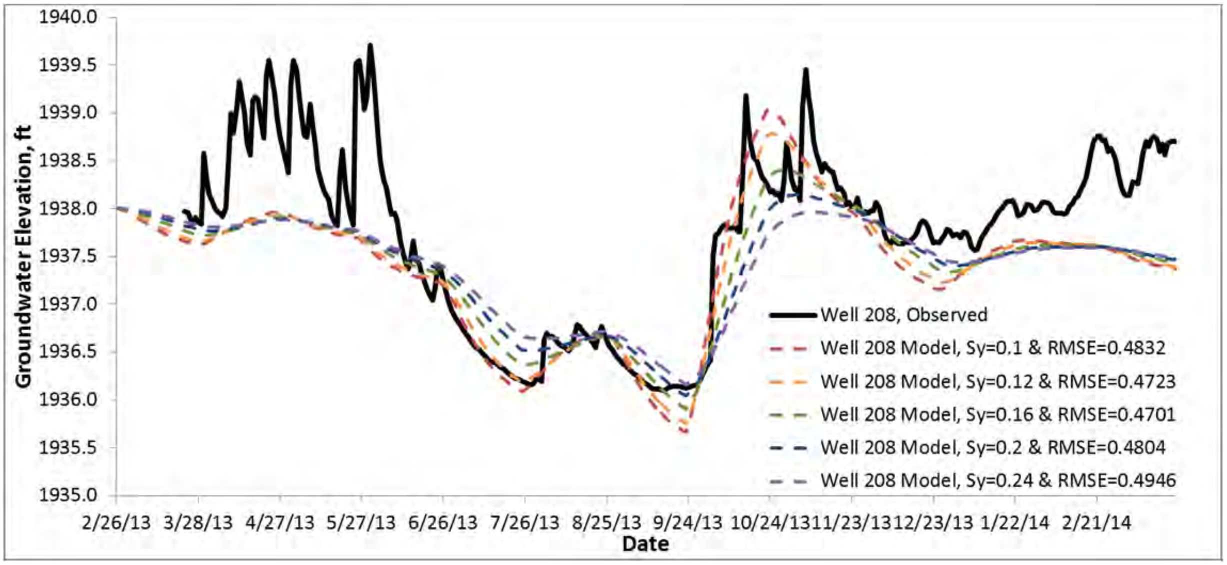

Figure 10. Binfield well 208 observed and modeled heads for a range of specific yield values

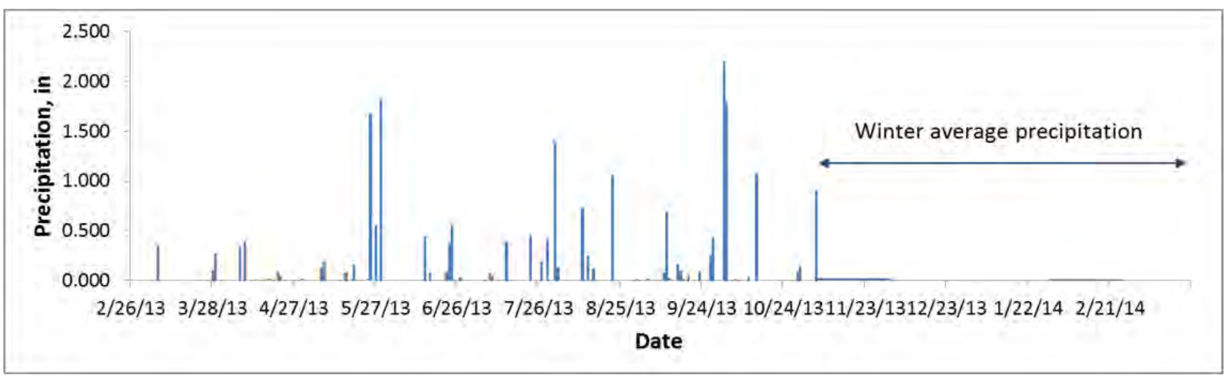

Figure 11. Precipitation at the Binfield site

Riverbed Hydraulic Conductivity

Riverbed hydraulic conductivity was calibrated using the same methods as hydraulic conductivity and specific yield. A riverbed hydraulic conductivity of 10 ft/d resulted in a good fit between the model and observed behavior. This value was used during the calibration of the other model parameters.

Recharge Multiplier Calibration

Recharge was calibrated by multiplying the observed precipitation rate by recharge multipliers ranging from 0 to 1. Rather than adjust the multipliers for each stress period, a period of higher recharge and a period of lower recharge were used. The higher recharge period corresponds to the fall, winter, and spring when soil moisture conditions are typically wetter and a larger percentage of precipitation enters the groundwater table as recharge. The lower recharge corresponds to the summer to reflect the hotter and drier conditions that typically lead to less precipitation entering the groundwater table as recharge. A higher recharge multiplier of 0.6 was used for fall, winter, and spring and a lower multiplier of 0.3 was used during the summer. These values were used during the calibration of other model parameters.

Calibration Challenges

While the calibration of the model achieved a good match between modeled heads and observed heads across the domain of both models, observed heads during certain periods of time were difficult to match. The high flows in the fall of 2013 caused dramatic rises in river stage and groundwater levels. Finding aquifer parameters that allowed the model to capture the observed groundwater response proved difficult. **Figure 12** shows the model over predicts the observed groundwater response in late October through mid-December, 2013.

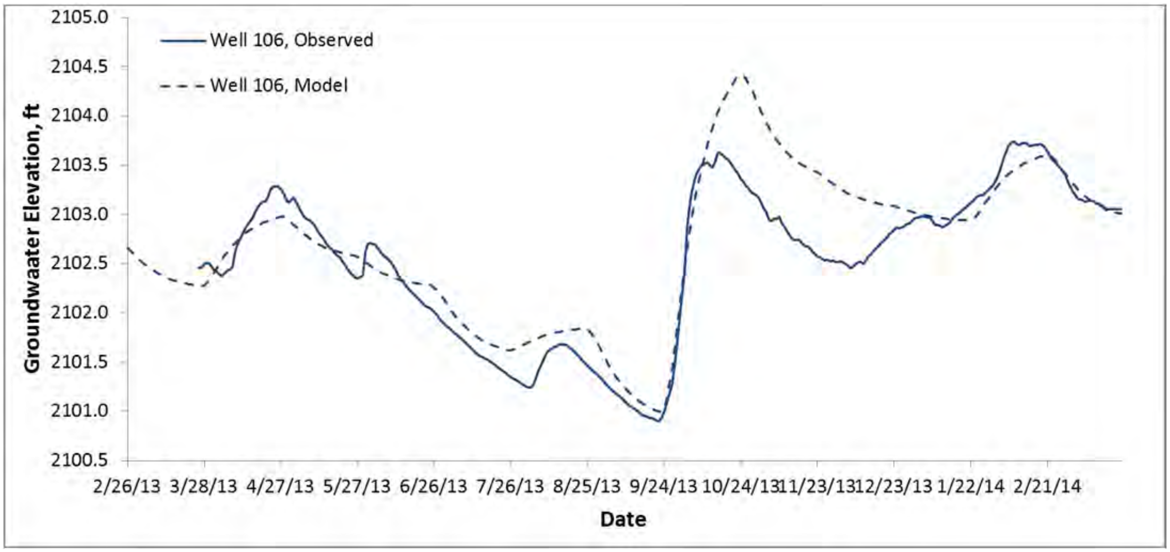

Figure 12. Modeled and observed heads at Fox well 106

SENSITIVITY TESTING

Overview

The sensitivity of the model to variations in hydraulic conductivity, specific yield, recharge multipliers, extinction depth, and riverbed hydraulic conductivity was evaluated by running the models over a range of parameter values above and below the baseline parameter values shown in **Table 5**. Only one parameter was evaluated at a time. The parameter was increased and decreased and the change in ME, AME, and RMSE from baseline was recorded to quantify the model's sensitivity to that particular parameter. The modeled heads were compared to observed heads as well to provide a qualitative sense of the model's sensitivity.

Table 5. Baseline parameter values

Parameter	***Fox Model***		***Binfield Model***	
	Value	*Range*	*Value*	*Range*
Hydraulic Conductivity, ft/d	400	40 to 800	375	37.5 to 750
Specific Yield	0.2	0.02 to 0.4	0.16	0.016 to 0.32
Recharge Multipliers	0.6/0.3	0.3 to 0.9	0.6/0.3	0.3 to 0.9

Extinction Depth, ft	5	2.5 to 7.5	5	2.5 to 7.5
Riverbed Hydraulic Conductivity, ft/d	10	1 to 20	10	1 to 20

Sensitivity Testing Results

Results of the sensitivity testing are shown in **Figures 13** to **17**, with mean error (ME), absolute mean error (AME), and root mean square error (RMSE) values shown for each parameter range. The error values plotted in **Figures 13** to **17** are the average value for all monitoring wells over the modeled time period. The slope of the lines in **Figures 13** through **17** indicates the degree of the model's sensitivity to changes in the parameter value. Steeper slopes indicate greater sensitivity and low or no slope indicates little or no sensitivity. All of the model's calibrated values fall in the low slope or flat line portions of the parameter ranges shown below. Lower values for AME and RMSE indicate the model is capturing observed behavior well. ME values are not absolute and periods when the model under predicts observed results may cancel out periods when the model over predicts observed results when the ME is averaged. Negative ME values reflect the model consistently over predicting observed results. ME values capture general model error while AME and RMSE provide a better sense of model performance.

Hydraulic Conductivity

Both models showed an increase in model error for lower hydraulic conductivity values and little sensitivity to changes in hydraulic conductivity above 400 ft/d.

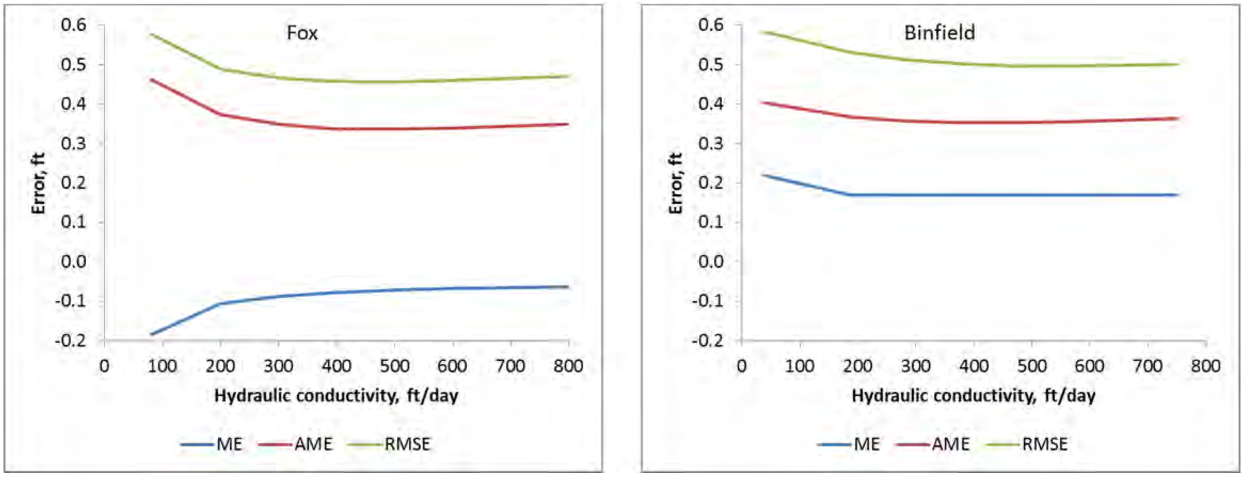

Figure 13. Hydraulic Conductivity sensitivity results

Specific Yield

A range of specific yields from 0.02 to 0.4 for the Fox site and 0.016 to 0.32 for the Binfield site resulted in a difference in RMSE value of just less than 0.1 ft. The Binfield site showed greater sensitivity to specific yield than the Fox site.

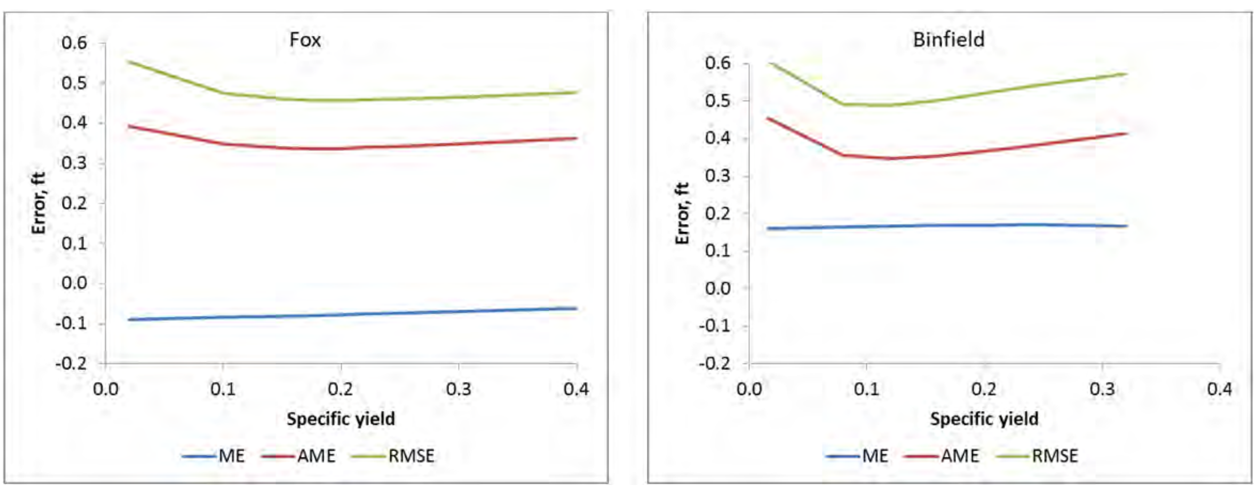

Figure 14. Specific yield sensitivity results

Recharge Multiplier

The recharge multipliers shown in **Table 5** and **Figure 15** correspond to the higher recharge season (fall, winter, and spring). The recharge multiplier during the lower recharge season was also varied with values half that of the values shown and showed similar sensitivities.

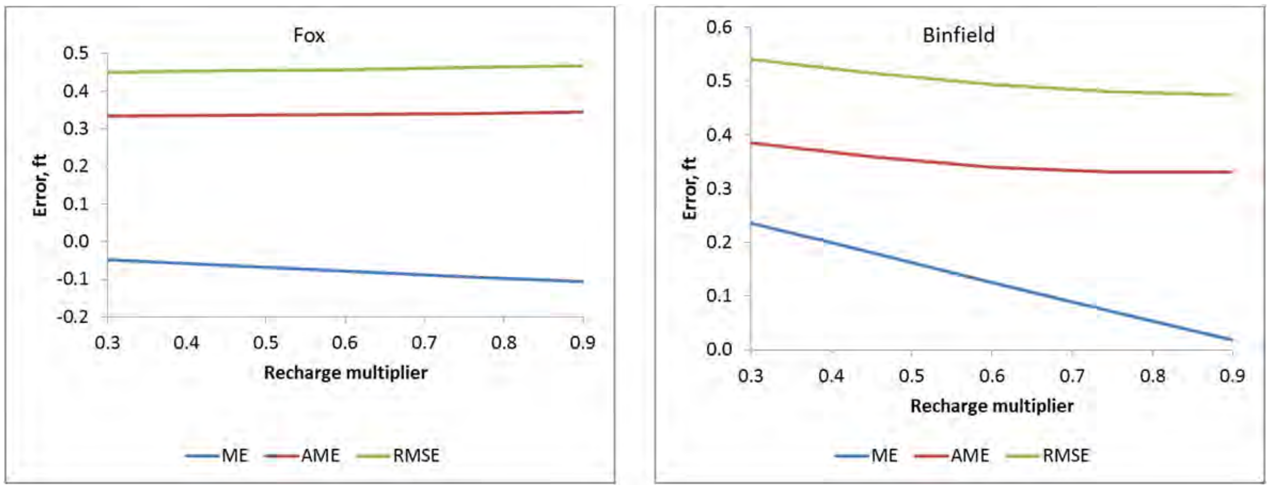

Figure 15. Recharge multiplier sensitivity results

Extinction Depth

The Fox site showed little sensitivity to changes in extinction depth values. Groundwater levels across much of the Fox site are at a depth of 4 to 7 feet below the surface during the modeled time period. Increasing extinction depth did not significantly alter the model's performance because the resulting increase in ET was small. The Binfield site showed a larger sensitivity to changes in extinction depth as groundwater levels are closer to the surface across the site.

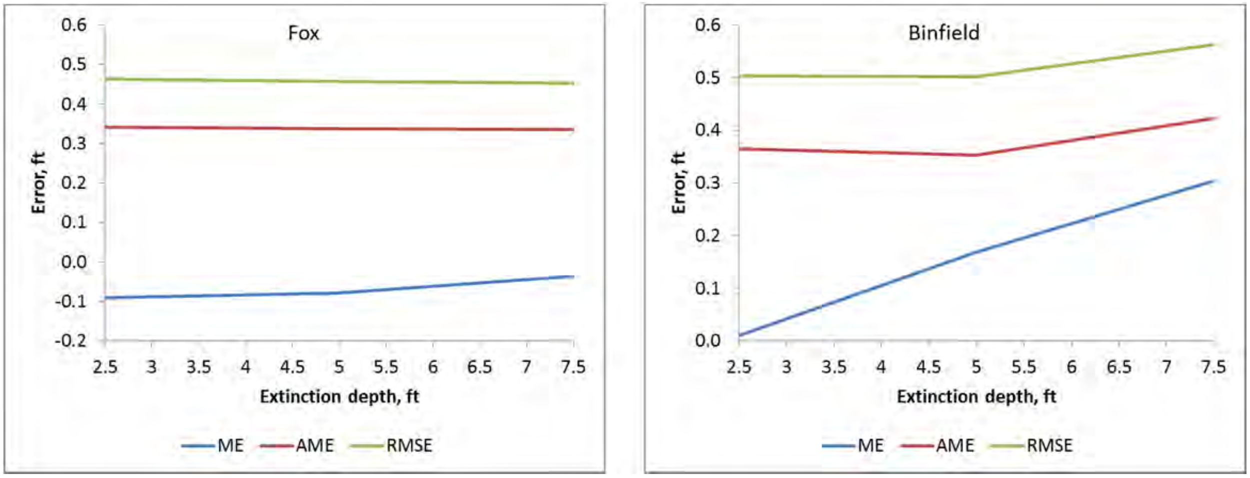

Figure 16. Extinction Depth sensitivity results

Riverbed Hydraulic Conductivity

Both models showed very little sensitivity to changes in riverbed hydraulic conductivity. Some of the lack of sensitivity may be due to the way the RIV package in MODFLOW incorporates riverbed hydraulic conductivity into the riverbed conductance term (see *Equation 1* in **SECTION 4**). The conductance term combines riverbed hydraulic conductivity with river width and length. The small changes in hydraulic conductivity may be obscured by river width and river length values shown in **Table 4, SECTION 4**.

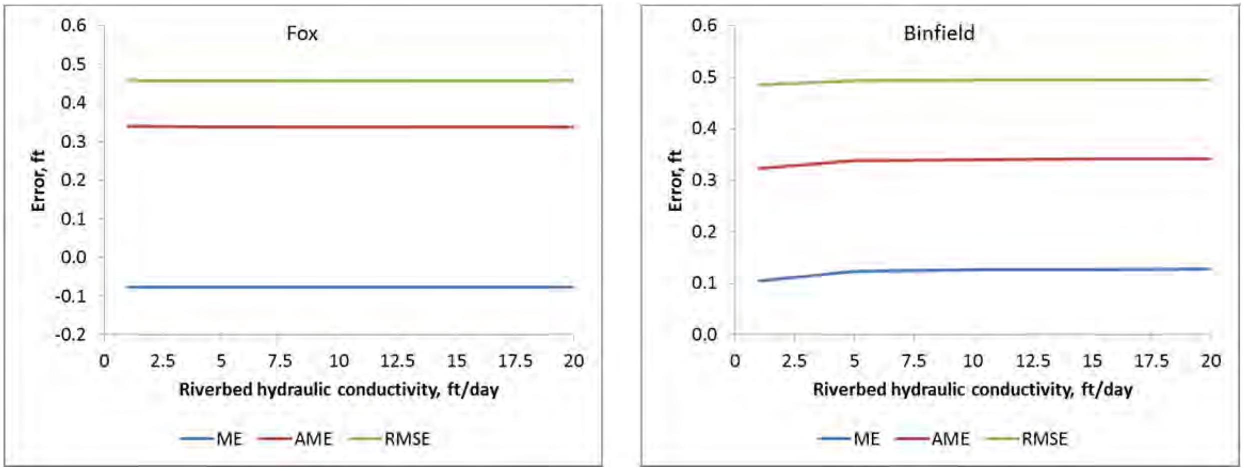

Figure 17. Riverbed hydraulic conductivity sensitivity results

MODEL PERFORMANCE

Performance Overview

Model performance is shown in **APPENDICIES A** through **F**, with water budget values discussed in **APPENDIX A**, a comparison of modeled and observed heads presented in **APPENDICIES B, C,** and **D** for a selection of wells for both sites, spatial variation of RMSE shown in **APPENDIX E**, and maps of modeled groundwater heads and depth to groundwater in **APPENDIX F**.

An important distinction is made in the discussion of model performance between a model’s ability to match the observed elevations and a model’s ability to match the observed behavior, such as increasing and decreasing trends and response times. Matching the observed elevation is important especially in meeting the model’s first objective: to quantify groundwater response to changes in river stage, precipitation, and evapotranspiration. The better a model is able to match observed elevations the more accurate the quantification of groundwater response is likely to be.

The model may over predict or under predict the observed elevation and still capture the observed behavior of the groundwater as it responds to changes in river stage and precipitation. A model’s ability to capture observed behavior indicates how well it will be able to accomplish the model's second objective: to test water management scenarios. Water management scenarios are tested by comparing a modeled scenario to a baseline model run. Scenario testing focuses on the change between the baseline and the scenario results rather than the exact groundwater elevations. If a model captures the observed groundwater behavior well it will likely prove useful for scenario testing.

APPENDICIES B through **D** compare modeled and observed heads using three comparison methods: a time series comparison of observed and modeled heads in the first plot, a percent exceedance comparison in the second plot, and an observed-verses-modeled scatter plot comparison in the third plot. See **Figures 18** and **19** for examples. The percent exceedance plot shows the percentage of observed and modeled groundwater elevation values that exceed a given elevation. The plot provides insight into how well the model matches observed values as well as behavior. In some instances, the model may under or over predict the observed values but capture the observed slope or trend in the exceedance plots. The scatter plots compare observed elevation to modeled elevation with each point representing a unique observation time. When the model matches the observed elevation, the point will lie along the 1 to 1 slope line. If the modeled elevation is greater than the observed elevation, the point will lie above this line and, conversely, if the modeled elevation is lower than the observed elevation the point will lie below the 1 to 1 slope line. Scatter plots indicate if the model captures observed behavior and whether any errors in the model are random or reflect a bias in the model. Several wells have patterns in model errors, with the model consistently under predicting or over predicting observed elevations, especially at higher elevations. Wells nearer to the river also show distinct patterns as they are more directly affected by the constant river elevation during a given stress period. This shows up as horizontal patterns with little variation in modeled elevation over a range of observed elevations.

Figures in **APPENDIX B** through **D** are presented in south to north order, with wells in the western transects shown first followed by wells in the eastern transects. Comparisons of modeled and observed heads for the annual model are in **APPENDIX B**, comparisons for the event model run with spring 2013 hydrology are in **APPENDIX C**, and comparisons for the event model run with fall 2013 hydrology are in **APPENDIX D**. Performance comparisons are not available at all wells because certain wells were instrumented at later times than others, with installation dates shown in **Table 6**.

Table 6. Data logger installation dates

Installation date	***Fox Site Wells***	***Binfield Site Wells***
May 2011	112, 113, 114, 115, 116	
March 2013	101, 103, 106, 109, 111	201, 203, 206, 208, 210, 213, 216
June 2013	102, 104, 105, 107, 108, 110	202, 204, 205, 207, 209, 211, 212, 214, 215

Average error values for the models are shown in **Table 7**. Error values for the annual model are calculated by comparing the daily average of observed groundwater elevations with the modeled elevation for the corresponding daily time step at each monitoring well location. Error values for the event models are calculated by comparing hourly observed groundwater elevations with the modeled groundwater elevations for the corresponding hourly time step at each monitoring well location. Monitoring wells that were not instrumented in the spring of 2013 were not included in the error calculations. The performance of each model is discussed in detail below.

Table 7. Average error values for the Fox and Binfield models

Model	***Fox Error (ft)***	***Binfield Error (ft)***
Annual model	ME: -0.078 AME: 0.337 RMSE: 0.457	ME: 0.065 AME: 0.321 RMSE: 0.470
Event model: Spring 2013	ME: 0.160 AME: 0.246 RMSE: 0.249	ME: -0.033 AME: 0.211 RMSE: 0.314
Event model: Fall 2013	ME: -0.425 AME: 0.535 RMSE: 0.505	ME: -0.110 AME: 0.380 RMSE: 0.457

The error values in **Table 7** should be evaluated in the context of the model's cell size. Modeled groundwater elevations are calculated at the center of a 100' x 100' cell and represent an average of the groundwater elevation over the cell area. Observed groundwater elevations are measured at a single point that does not correspond to the center of the model cell. Some of the difference between the modeled and observed heads results from the difference between the spatially averaged modeled heads and the point specific observed heads. Overall, average differences between observed and modeled elevations are on the order of 0.5 feet over an area of 10,000 square feet and indicate the model does a good job of capturing both observed elevation and observed behavior.

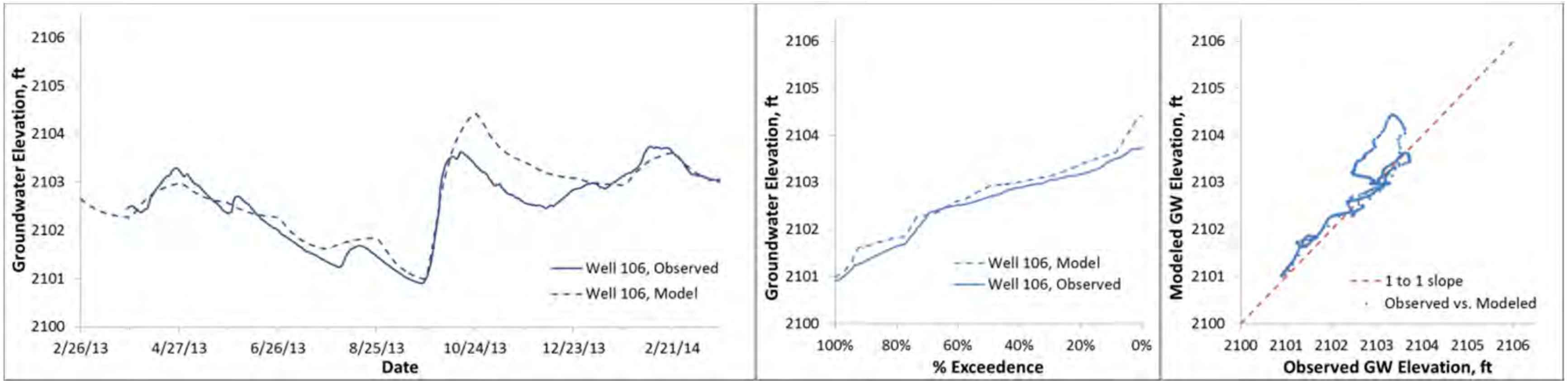

Figure 18. Modeled and observed heads 2013-2014, Fox well 106

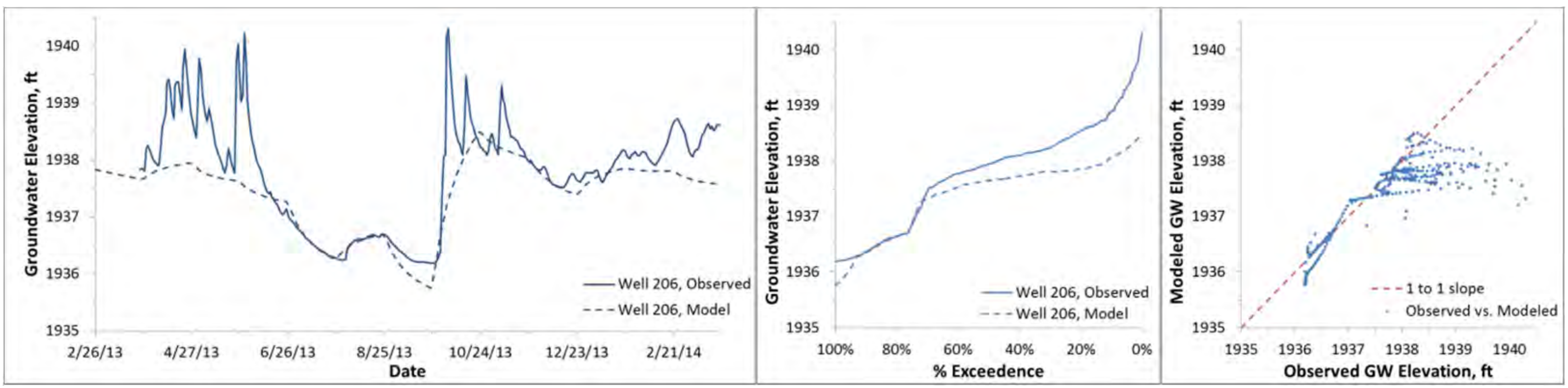

Figure 19. Modeled and observed heads 2013-2014, Binfield well 206

Fox Annual Model Performance

Overall, the Fox annual model performs well when compared to observed groundwater elevations, as seen in **Figure 18**. The model captures the overall behavior of the observed groundwater response with an average RMSE value of 0.457. The model slightly under predicts the groundwater response to high flows in the spring of 2013 and over predicts the response to the high flows in the fall of 2013. The model performs better at the western transect of monitoring wells than it does at the eastern transect of monitoring wells.

As an annual model with monthly stress periods, the Fox annual model is not able to (nor is it intended to) capture the fluctuations in groundwater elevations that occur on a sub-monthly timescale. Daily and weekly variations in groundwater elevations are more evident at wells nearer to the river, such as wells 101 to 103 and 109 to 111 (**Figures B1** to **B3** and **B11** to **B13**). These portions of the model show a step pattern as the river stage shifts up or down in each stress period. Errors are fairly uniform across the site, shown as RMSE in **Figure E1**, with wells in the north of the sites (110, 111, and 116) showing slightly higher error values than those in the south of the sites. Overall, the model matches observed elevations and behavior over the majority of the domain.

Binfield Annual Model Performance

The Binfield annual model captures the general behavior of the observed groundwater with an average RMSE value of 0.470. The model is not able to capture the sharp rise and fall in groundwater elevations resulting from spring and fall precipitation events, as seen in **Figure 19**. Groundwater at the Binfield is particularly responsive to precipitation, especially when groundwater is high at wells 205 to 209 and 215 to 216 during the spring and the fall. Ground water response occurs on a daily timescale and the annual model is only able to capture the general trend of the groundwater. The model under predicts the observed response to precipitation events at these wells.

The annual model also slightly under predicts groundwater response during the spring 2013 runoff as well as during the dry period in August and September of 2013 at wells 206 and 208 (**Figures B10** and **B11**). The modeled groundwater elevations at wells near the river (wells 201 to 203 and 210 to 212, **Figures B17** to **B19** and **B26** to **B28**) show a clear influence from the river boundary, with sharp changes in elevation corresponding to river stage changes between stress periods. These sharp changes are dampened in wells further from the river. The model consistently over predicts observed groundwater elevations in the area of wells 210 and 211 in the south eastern portion of the domain. Wells 210 and 211 are located between the main channel of the Platte River and a slough that runs across the Binfield site. It is suspected that the slough plays a role in lowering groundwater elevations in the area of wells 201 and 211 as it acts as a drain during periods of higher groundwater. While the model does not match the observed elevations at these wells, it does capture the observed behavior of the groundwater in this area.

RMSE is distributed reasonably uniformly across the site with the RMSE at well 206 showing an RMSE of about 0.2 higher than the wells around it. This is due to the model's inability to capture precipitation spikes that occur in observed groundwater elevations at well 206. Overall, the model matches observed behavior well and matches observed elevations to a lesser degree of accuracy.

Fox Spring 2013 Model Performance

The Fox spring 2013 model captures the rise and fall seen in groundwater elevations resulting from spring runoff and the Short Duration Medium Flow (SDMF) release that occurred in April of 2013. The model has a RMSE value of 0.249, the lowest of all the models. The model captures the behavior of the observed groundwater response and closely matches the observed groundwater elevations in many places. The model under predicts groundwater response by approximately 0.5 feet or less across the eastern transect (wells 114-116, **Figures C8** to **C10**) and to a lesser degree in parts of the western transect (wells 103, 112, and 106, **Figures C2** to **C4**).

Error is not distributed evenly across the site, as seen in **Figure E3**, with wells in the middle and eastern portions of the site showing higher errors than in other locations.

Binfield Spring 2013 Model Performance

The Binfield Spring 2013 model captures the general response of the observed groundwater but is not able to capture the sharp rise and fall in groundwater elevations resulting from precipitation. The model has an RMSE of 0.314, which is lower than the Binfield annual and fall 2013 models.

As evident by the dramatic spikes in observed groundwater elevation in **Figures C13**, **C14**, **C16,** and **C17**, precipitation dominates groundwater behavior at the Binfield site over short timescales, especially during periods of high groundwater. Precipitation is modeled through recharge input into the model. The Binfield spring 2013 recharge inputs were based on observed precipitation at the Shelton rain gage located ten miles to the northwest (the Binfield precipitation gage was not installed until the end of May, 2013). While the Shelton gage provided a general sense of how much precipitation fell in the area, it did a poor job of matching the timing and magnitude of precipitation at the Binfield site based on observed groundwater response. The observed Shelton gage values were modified to better match the timing and magnitude of groundwater response at the Binfield monitoring wells. Precipitation in future models will be based on observed precipitation at the Binfield gage.

The model can match the sudden rise in groundwater elevation by increasing recharge inputs; however, the model is not able to simulate the sharp drop in groundwater elevations following precipitation events. Because of this, higher recharge multipliers lead to increasing overall groundwater elevations with each precipitation event and over prediction of groundwater response. To avoid this, recharge multipliers were selected to match the observed groundwater elevation following a precipitation event rather than the peak groundwater elevations during or immediately following precipitation events.

Similarly to the annual model, the spring event model over predicts the groundwater response at well 210 (**Figure C15**) but the model's predictions improve at wells 213 and 216 (**Figures C16** and **C17**). The RMSE values are not distributed very evenly across the site, as seen in **Figure E4**. Errors are low in the south of the western transect and increase toward the middle of the site. Conversely, errors are high in the south of the eastern transect due to the poor performance in the area around well 210 and decrease toward the middle of the site. Overall, the model captures observed behavior better than it matches observed elevations.

Fox Fall 2013 Model Performance

The Fox fall 2013 model captures the rise in groundwater elevations resulting from the fall 2013 flood flows but does not model the following decrease in groundwater elevations seen in the monitoring wells. The model captures the general behavior of the observed groundwater across the site but over predicts the groundwater elevations after the sharp rise. The model has a RMSE value of 0.505, the highest of all the models, largely due to the modeled heads which exceed observed heads by close to 1 foot in many places.

The model performs better on eastern transect and follows the same pattern as the Fox spring 2013 model with higher heads in the western portion of the model and lower heads in the eastern portion of the model.

RMSE values are distributed fairly evenly across the site from south to north, as seen in **Figure E3**, but errors in the western portion of the site are much greater than the errors seen in the eastern transect.

Binfield Fall 2013 Model Performance

The observed groundwater response to the fall 2013 flood flows and subsequent precipitation events proved difficult to model at the Binfield site. The sudden rise in river stage was closely followed by several large precipitation events. Additionally, river stage rose to the point where surface water was flowing across the Binfield site at wells 205 and 206 and water was flowing in the Binfield slough between wells 202 and 203 as well as 211 and 212. Surface water flows across the site were not modeled, nor were flows in the slough. Overall, the model was able to capture the general response of observed groundwater during the fall 2013 time period, but it was not able to capture the sudden rise and falls in groundwater elevations caused by precipitation and surface water flow across the site. The model had an average RMSE value of 0.457

The model showed an interesting sensitivity to recharge inputs for the Binfield fall 2013 model. Modeled heads responded sharply to recharge prior to October 4 then showed a muted response to recharge inputs after October 4. A recharge multiplier of 0.3 was used to capture the general observed response to precipitation occurring prior to October 4. The multiplier was then increased to a value of 1, simulating 100% of precipitation entering the model as recharge, after this date. Despite the high recharge multiplier, the model was not able to simulate the observed response in groundwater elevation changes resulting from precipitation events.

Similarly to the other Binfield models, the fall 2013 model over predicts groundwater elevations at wells 210 and 211 (**Figures D26** and **D27**).

The average RMSE values varied across the site (**Figure E6**), with wells 205 and 206 having higher RMSE values than other wells in the western transect, likely due to the model's inability to capture surface flow that occurred at these locations. Errors were higher at wells 210 and 211 and decreased moving northward along the eastern transect.

MODEL SCENARIOS

In addition to quantifying the groundwater response to changes in surface water and precipitation, a second objective of the model is to evaluate scenarios to inform management activities. The groundwater models described in this report will be used to run a series of scenarios to gain a better understanding of the hydrologic behavior at wet meadow sites. Scenarios will focus on the groundwater response to changes in one or more hydrologic components of the system. Some scenarios will seek to identify key river stage needed to obtain desired groundwater levels while others will simulate alternative management activities. Extreme events, such as high streamflow, large precipitation, or very dry conditions and the resulting groundwater response will be investigated. The scenarios will primarily be run by comparing the impact of a change in one aspect of the model, such as river stage, precipitation, or recharge, to a baseline model. The baseline models will be based on observed hydrology.

CONCLUSIONS

The Fox and Binfield models faithfully reproduce observed groundwater behavior on an annual and event timescale. They match observed groundwater elevations with sufficient accuracy to provide useful quantification of groundwater response to changes in river stage, precipitation, and evapotranspiration.

The models have been calibrated and all calibrated parameters fall within reasonable and commonly accepted ranges. The sensitivity of the models to changes in parameter values has been evaluated to test the effect of small changes in model parameter values on model performance.

While periods exist when the models over or under predict the observed groundwater elevations, these errors are typically within half a foot across the majority of the model domains. While current model performance is considered sufficient for its intended uses, it may be improved with further adjustments. Recharge multipliers could be adjusted in both magnitude and seasonal timing in an attempt to improve the model’s ability to capture groundwater response to precipitation. The slough that runs through the southern portion of the Binfield site could be modeled as a drain in an attempt to improve model performance in the southeastern portion of the model.

The wet meadow groundwater models are an integral part of the larger wet meadows hydrologic monitoring project. As additional monitoring equipment is added to the wet meadow sites, the models will be updated. Equipment capable of providing average soil moisture flux is expected to be installed at both the Fox and Binfield wet meadow sites in 2015. Soil moisture flux will be used in conjunction with precipitation and evapotranspiration measurements to determine recharge into the groundwater with greater accuracy. These values will be used in the recharge package and will likely result in improved model performance. As the recharge values already account for evapotranspiration, the ET package will not be needed, eliminating inaccuracies that may arise from the ET package's estimates of evapotranspiration.

The Fox and Binfield models are well suited for use in testing changes from an established baseline for a variety of management scenarios. For example, the models may be used to test how a flow release resulting in higher river stage will increase groundwater elevations across the sites or how increasing recharge through some type of irrigation or other artificial means will impact groundwater elevations. The models provide useful insight into groundwater response across the entirety of the wet meadow sites for both historical events and simulated scenarios.

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CHAPTER 4 APPENDIX A: WATER BUDGET VOLUMES

A water budget is used to compare the relative volumes of the various sources and sinks of water into and out of the model domain. The water budget balances flows into and out of the model domain according to *Equation A1*:

$$(RIV_{in} - RIV_{out}) + R_{in} - ET_{out} + (CH_{in} - CH_{out}) + (S_{in} - S_{out}) = Error \qquad Equation\ A1$$

Where:

RIV_{in} represents inflows from the river,

RIV_{out} represents outflows to the river,

R_{in} represents inflows from recharge,

S_{in} represents inflows from storage,

S_{out} represents outflows to storage,

ET_{out} represents outflows to evapotranspiration,

CH_{in} represents inflows from the constant head boundary,

CH_{out} represents outflows to the constant head boundary, and

Error represents the error in the model's water balance.

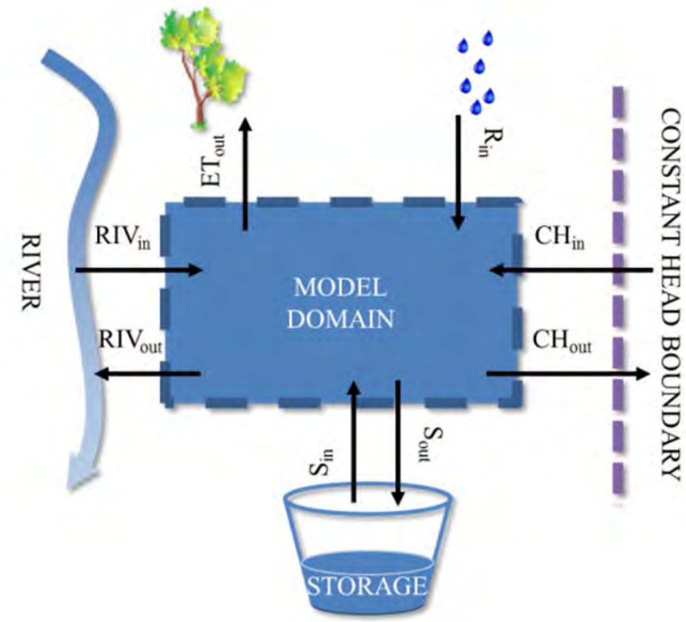


Figure A1. Conceptual model water balance

$RIV_{in} – RIV_{out}$ is referred to as river leakage and accounts for the volume of water that passes between the river and the groundwater. Positive river leakage values indicate water is flowing from the river into the groundwater (“losing” river reach) and negative values indicate water is flowing from the groundwater into the river (“gaining” river reach). Recharge volume is always positive as negative recharge values were not modeled. Conversely, evapotranspiration (ET) volume is always negative as water is removed (not added to) the model domain through ET. Constant head volume ($CH_{in} – CH_{out}$) accounts for the amount of water that entered and left the model domain across the constant head boundary. Similarly to river leakage, a positive constant head volume indicates water flowed from the boundary into the model domain and a negative value indicates water flowed from the domain to the boundary.

For the purposes of the water balance, storage should be thought of as a source or sink of water that can flow into or out of the model domain. Inflows from storage, S_{in}, do not reflect an increase in storage but rather a decrease in the volume of water in the storage “bucket.” On the other hand, outflows to storage,

S_{out}, reflect an increase in storage as water is leaving the model domain and entering the storage “bucket”. For change in storage volume ($S_{in} – S_{out}$), positive values indicate a decrease in storage water (more water entered the model domain from storage than left the model domain to storage) and negative values indicate an increase in storage.

The error term in the water budget captures the numerical error in the model’s balancing of the inflow and outflows from the model domain. The error volume is calculated as the difference between total volume of flow into the model and the total flow out of the model (total volume in – total volume out). While the error volume represents the absolute error in the model, it is also helpful to evaluate the error in light of the total volume of water passing through the model. Dividing the error by the total volume of flow into or out of the model domain provides the percent error. The error is an indication of how well the model is performing numerically; high percent error indicates poor model convergence while low error typically indicates the model is numerically stable and converges.

Figures A2 to **A7** show the total volume of water in acre-feet (AF) associated with each component of the model’s water budget. River leakage indicates the total river leakage ($RIV_{in} – RIV_{out}$) for the entire model domain at the end of the model’s run, constant head represents the total flow across all the constant head boundaries ($CH_{in} – CH_{out}$), and storage represents the total flow from storage or into storage ($S_{in} – S_{out}$).

Fox Annual Model

Water primarily entered the Fox model domain from river leakage and left the site across the constant head boundary along the eastern edge of the model. The positive river leakage volume indicates this stretch of river is a losing reach during the modeled time period; however, the high flows in September 2013 are largely responsible for the magnitude of water entering the site from the river. The model gained about two and a half times more water from recharge than was lost from evapotranspiration.

Storage increased slightly over the modeled time period. The low percent error indicates good model convergence.

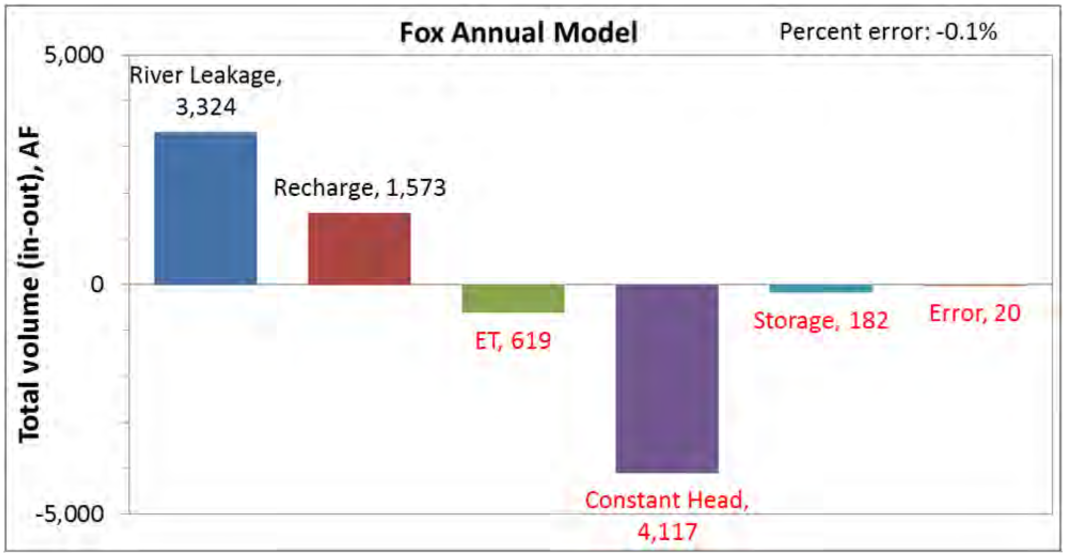


Figure A2. Fox annual model water budget

Binfield Annual Model

Water entered the Binfield model through both recharge and the constant head boundary at the western (upstream) end of the model. Storage decreased somewhat during the modeled time period. More water was lost to ET in the Binfield model than the Fox model due to groundwater depths being closer to the surface at Binfield. River leakage made up the largest component of the water budget, indicating this section of the river to be a gaining reach during the modeled period. The model gained over 1,200 AF of water from the river during the high flows in September; however it lost water to the river during the majority of the modeled time period. The error volume for the Binfield annual model was -3 AF, less than 0.02% of the total volume, indicating good model convergence.

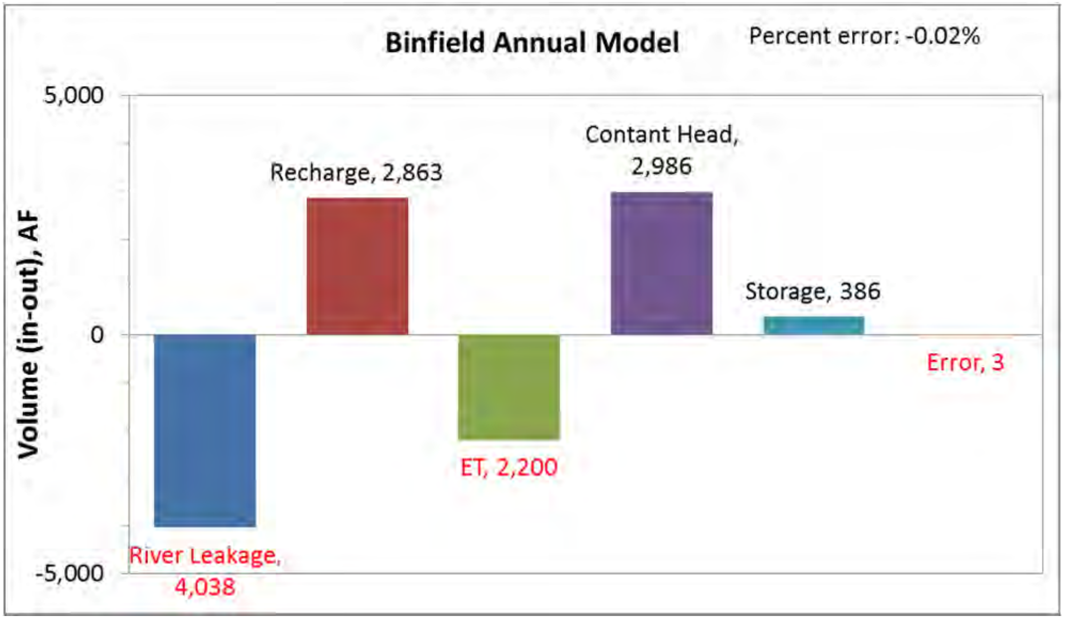
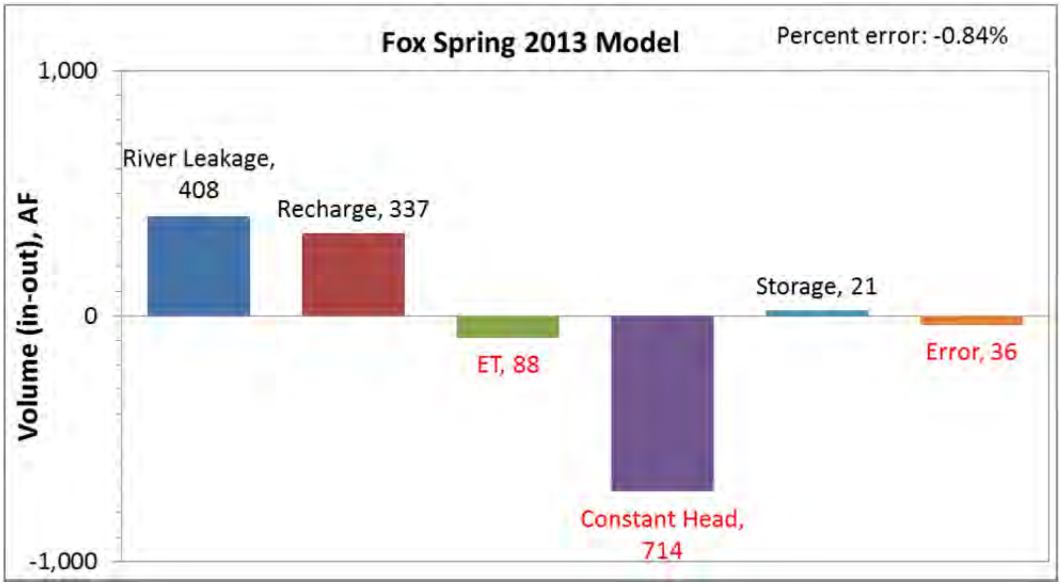


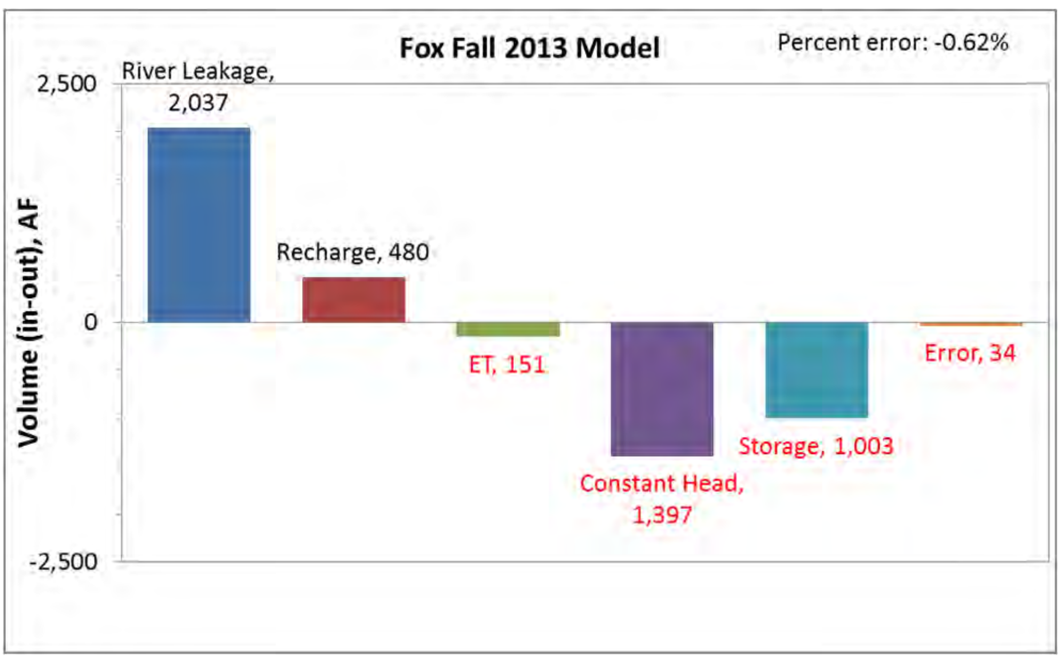
Figure A3. Binfield annual model water budget

Fox Event Models

The components of the water budgets for the Fox event modes follow the same general distribution as the annual model's water budget. The Spring 2013 model showed less water entering the site from river leakage and the Fall 2013 model showed a larger portion of water entering storage. Volume discrepancy was -36 AF for the Fox Spring 2013 model and -34 AF for the Fox Fall 2013 model, both less than 1% of the total volume, indicating good convergence.

738 

739 **Figure A4**. Fox spring 2013 event model water budget

740 

741 **Figure A5**. Fox fall 2013 event model water budget

Binfield Event Models

Recharge provided the majority of water to the Binfield event models, with the Fall 2013 model also receiving some water from river leakage. The Spring 2013 model lost approximately equal portions of water to river leakage, storage, ET, and constant head. The fall 2013 model lost a larger portion of water to storage than the Spring model. Volume discrepancy was -26 AF for the Binfield Spring 2013 model and -37 AF for the Binfield Fall 2013 model, both less than1% of the total volume, indicating good convergence.

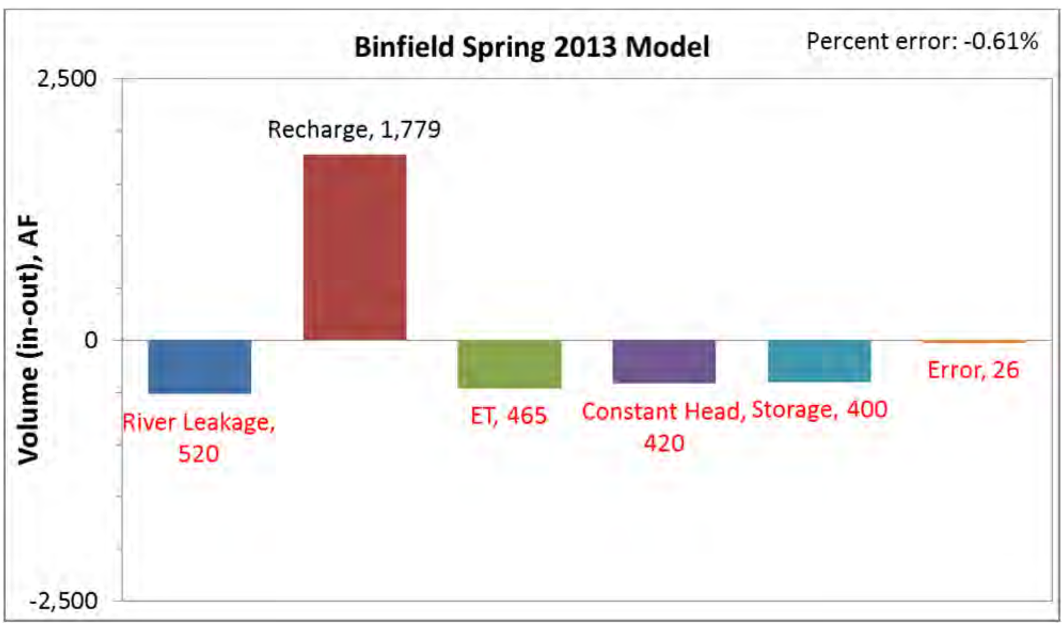


Figure A6. Binfield spring 2013 event model water budget

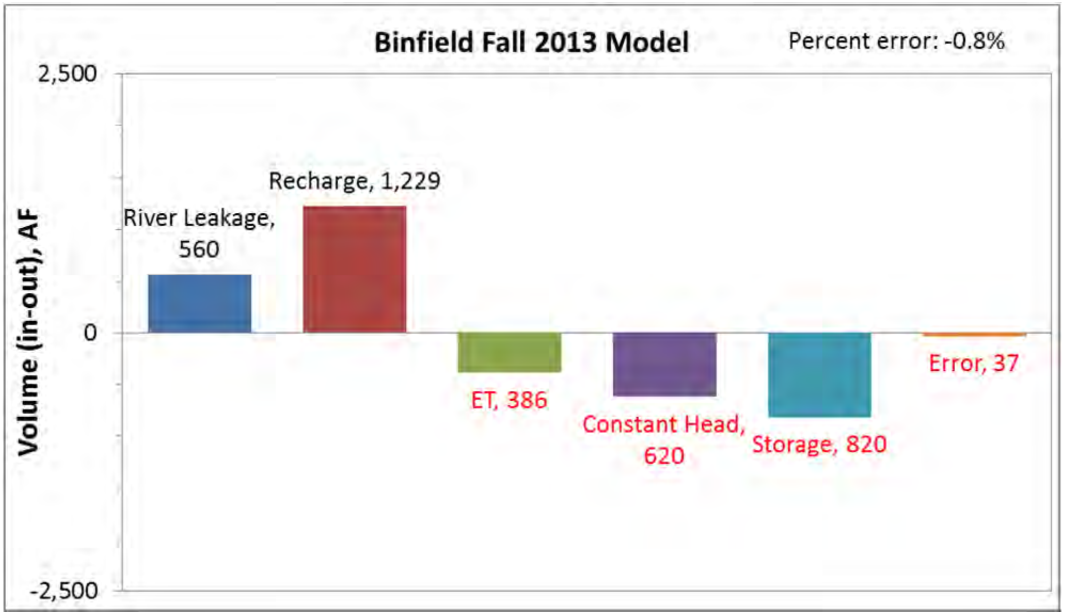


Figure A7. Binfield fall 2013 event model water budget

CHAPTER 4 APPENDIX B: MODELED AND OBSERVED HEADS, ANNUAL MODELS

Modeled and observed heads are shown below for the Fox and Binfield sites, refer to **Figures 5** and **6** for well locations. Figures are presented in south to north order and discussed in **SECTION 8** of the report.

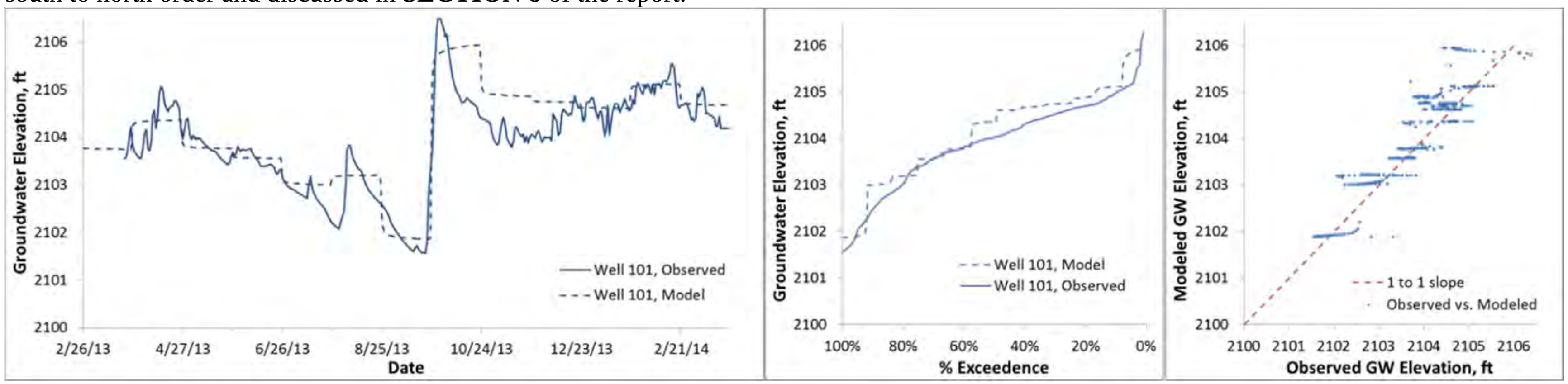


Figure B1. Modeled and observed heads 2013-2014, Fox well 101 (ground surface elevation 2110.1 ft)

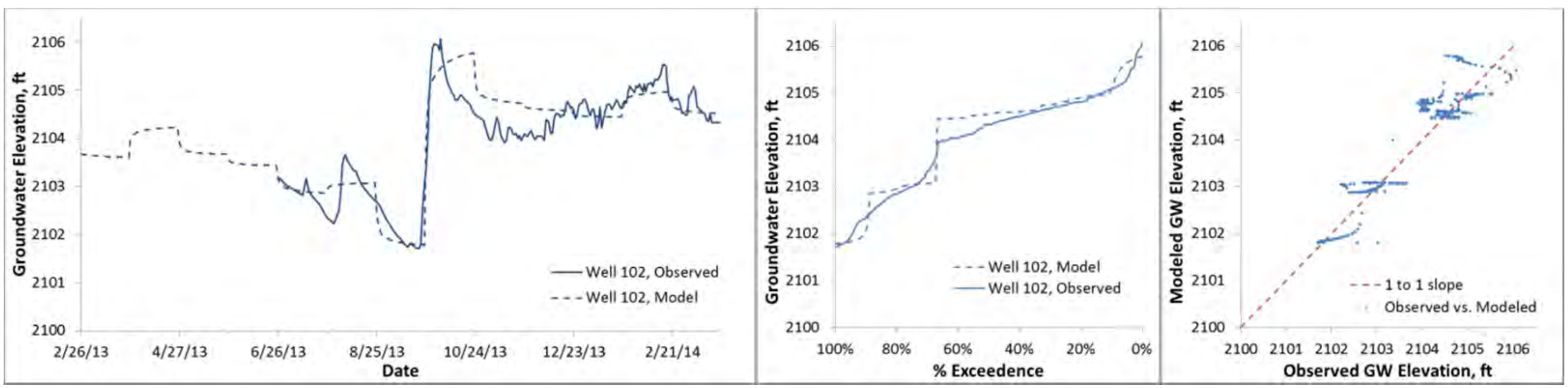


Figure B2. Modeled and observed heads 2013-2014, Fox well 102 (ground surface elevation 2109.6 ft)

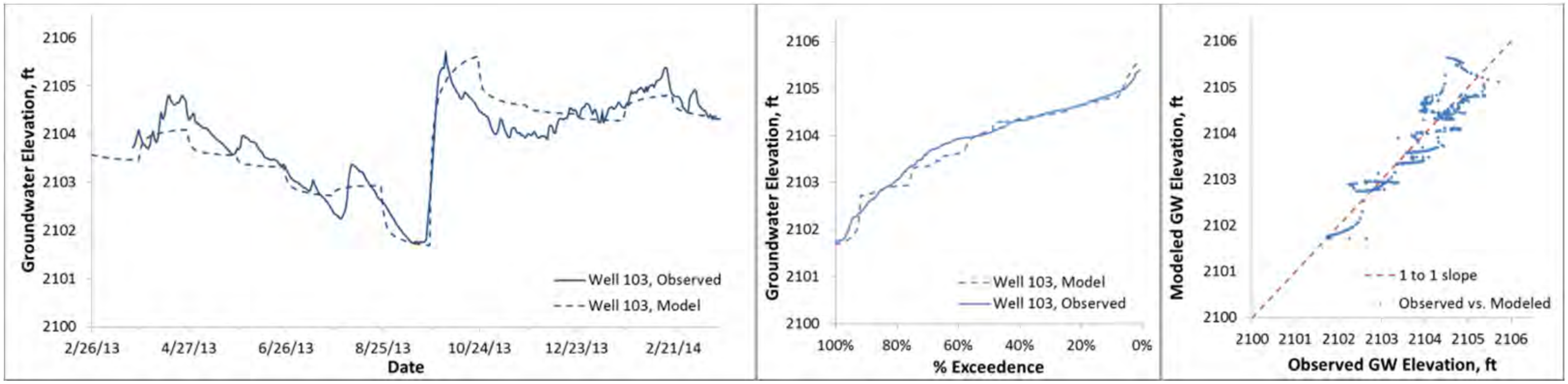


Figure B3. Modeled and observed heads 2013-2014, Fox well 103 (ground surface elevation 2110.3 ft)

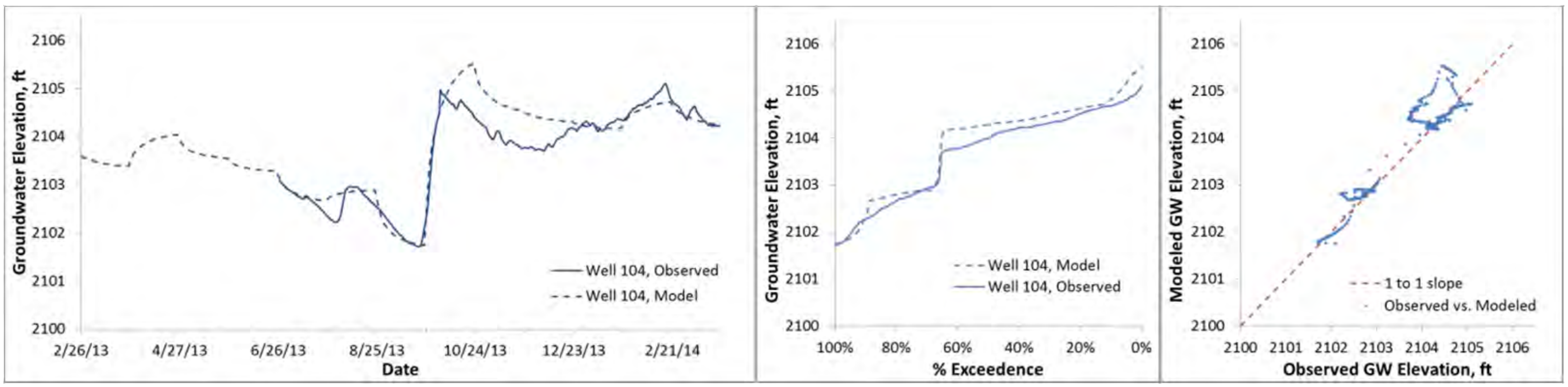


Figure B4. Modeled and observed heads 2013-2014, Fox well 104 (ground surface elevation 2107.1 ft)

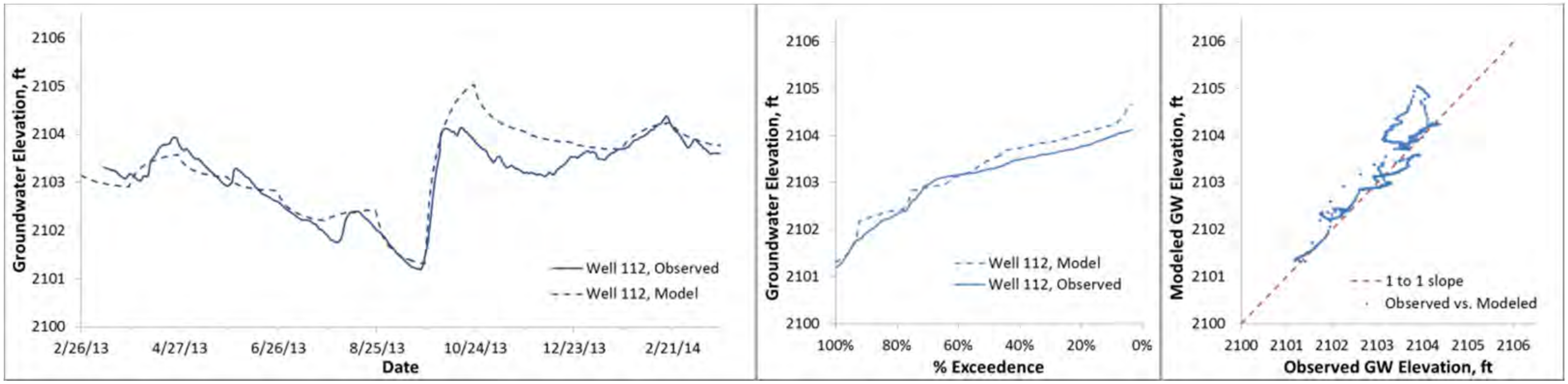


Figure B5. Modeled and observed heads 2013-2014, Fox well 112 (ground surface elevation 2107.4 ft)

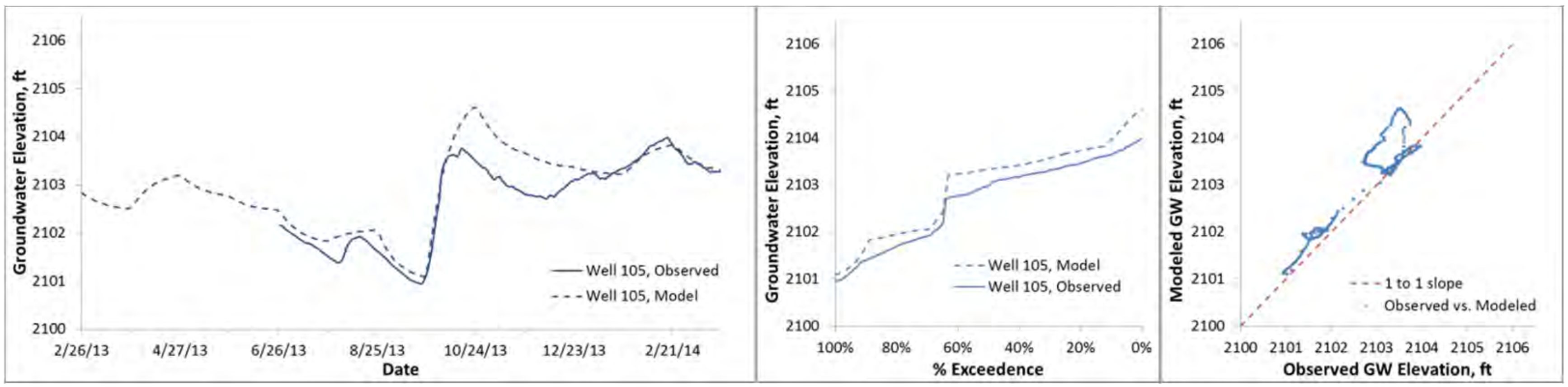


Figure B6. Modeled and observed heads 2013-2014, Fox well 105 (ground surface elevation 2107.7 ft)

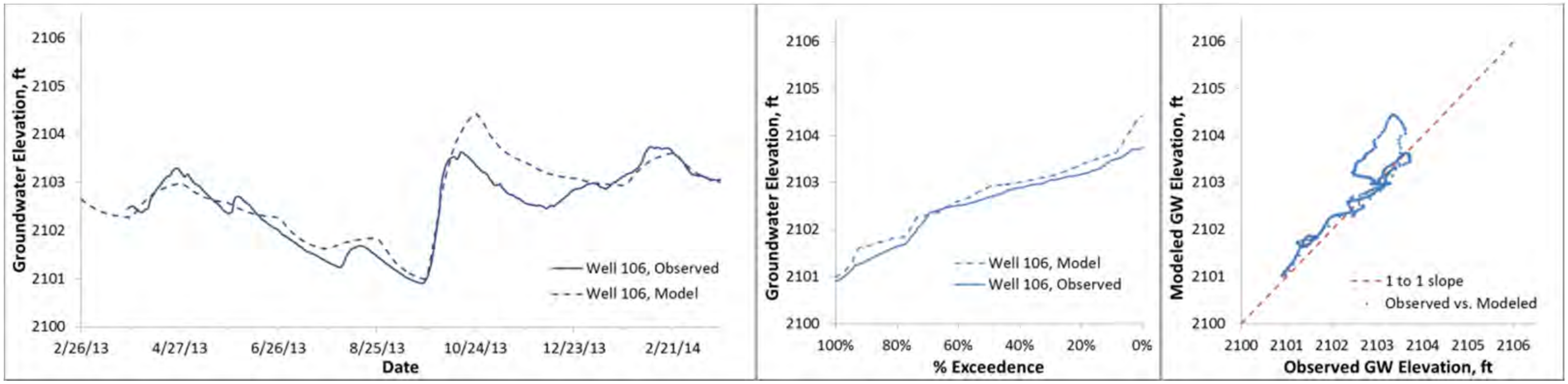


Figure B7. Modeled and observed heads 2013-2014, Fox well 106 (ground surface elevation 2107.7 ft)

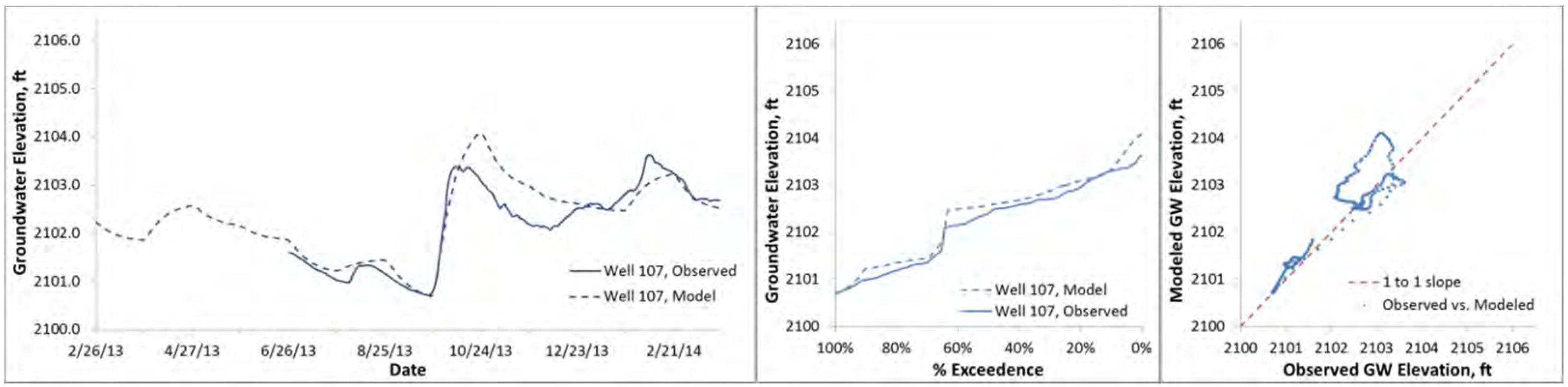


Figure B8. Modeled and observed heads 2013-2014, Fox well 107 (ground surface elevation 2107.7 ft)

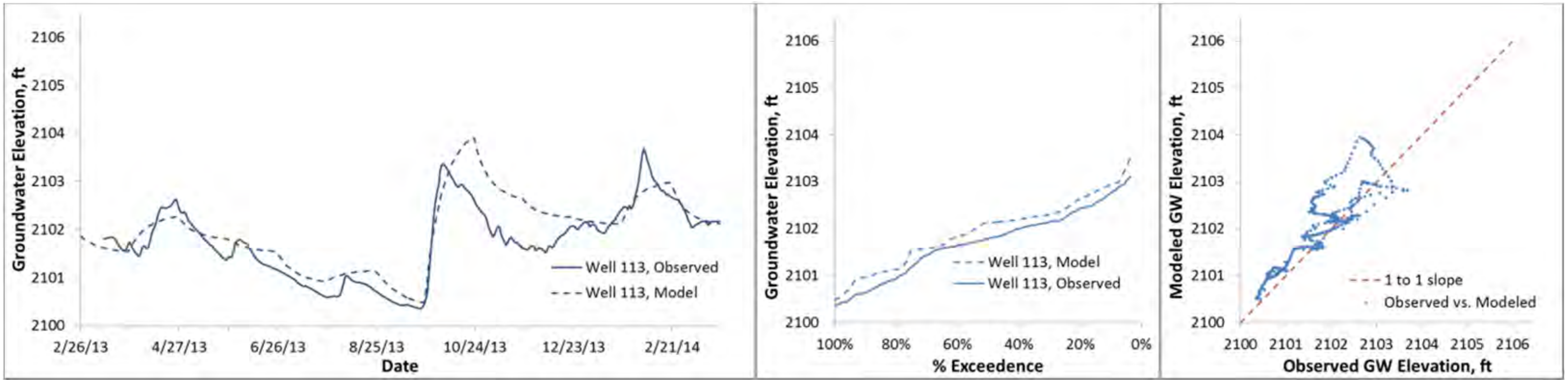


Figure B9. Modeled and observed heads 2013-2014, Fox well 113 (ground surface elevation 2107.6 ft)

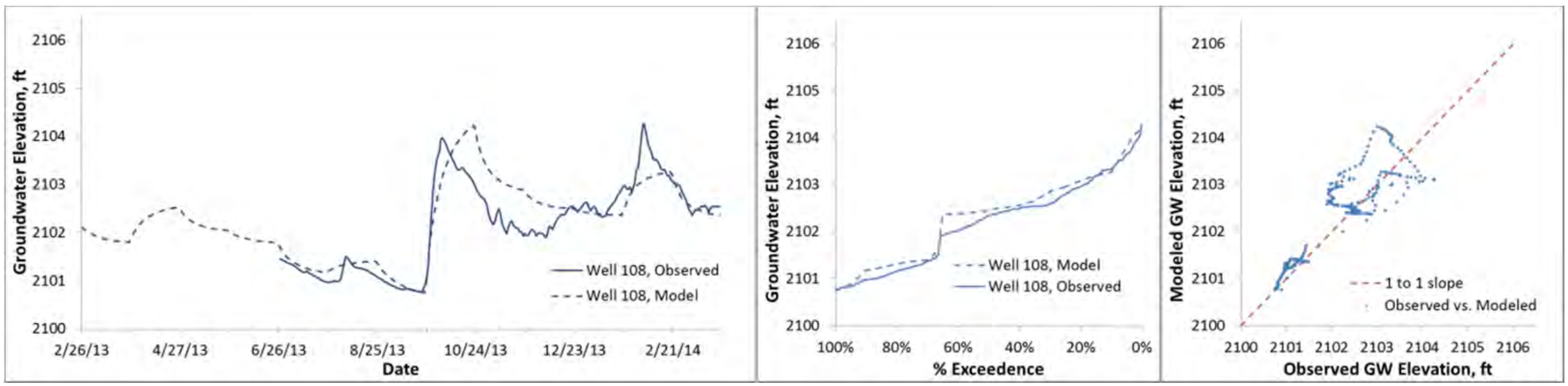


Figure B10. Modeled and observed heads 2013-2014, Fox well 108 (ground surface elevation 2110.5 ft)

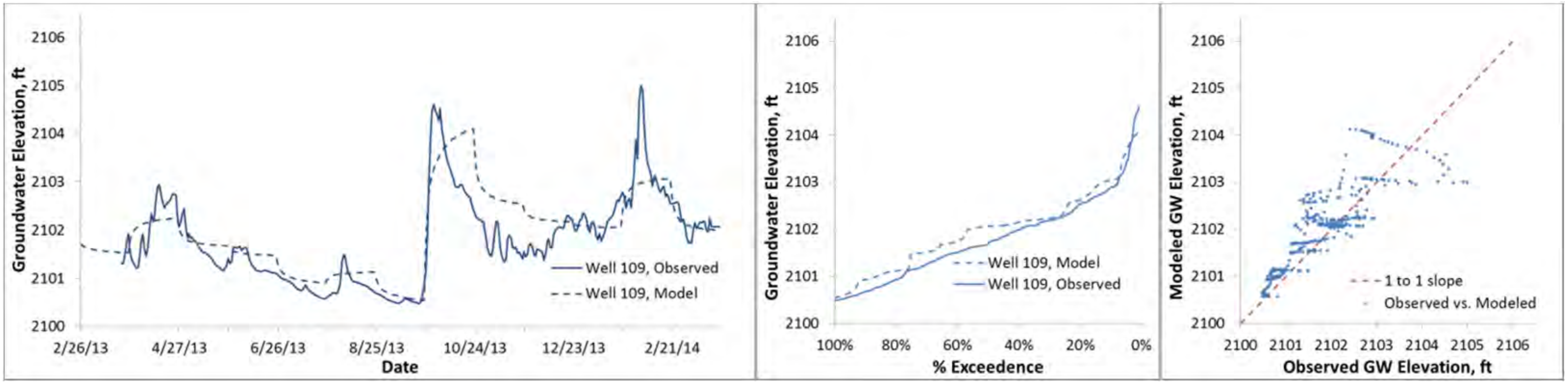


Figure B11. Modeled and observed heads 2013-2014, Fox well 109 (ground surface elevation 2108.1 ft)

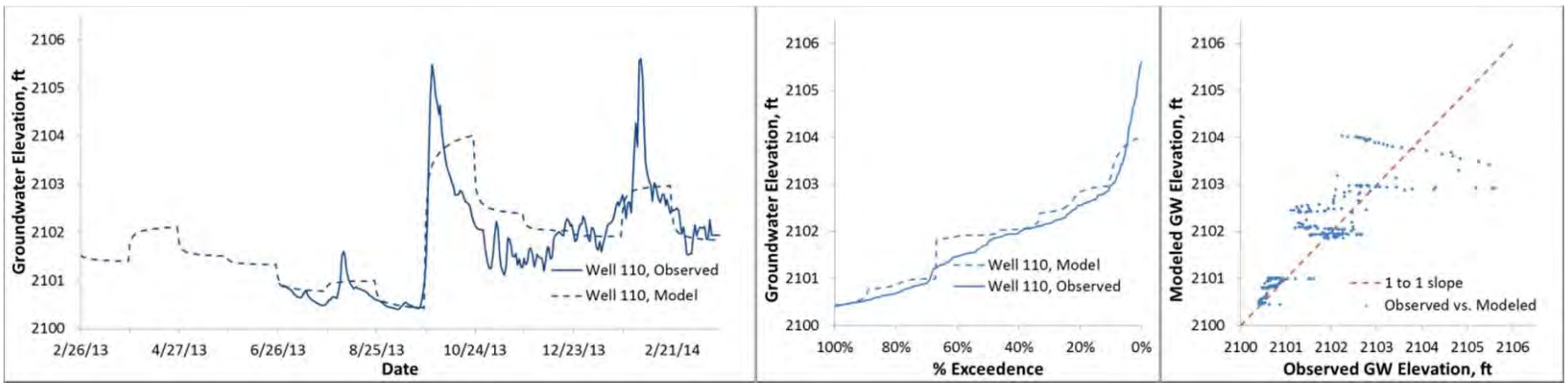


Figure B12. Modeled and observed heads 2013-2014, Fox well 110 (ground surface elevation 2108.9 ft)

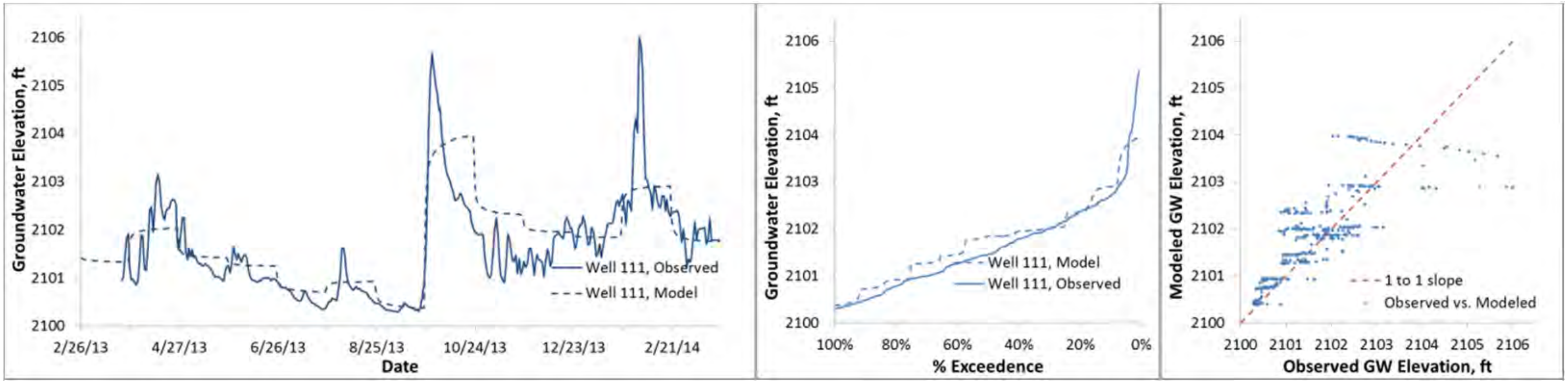


Figure B13. Modeled and observed heads 2013-2014, Fox well 111 (ground surface elevation 2107.9 ft)

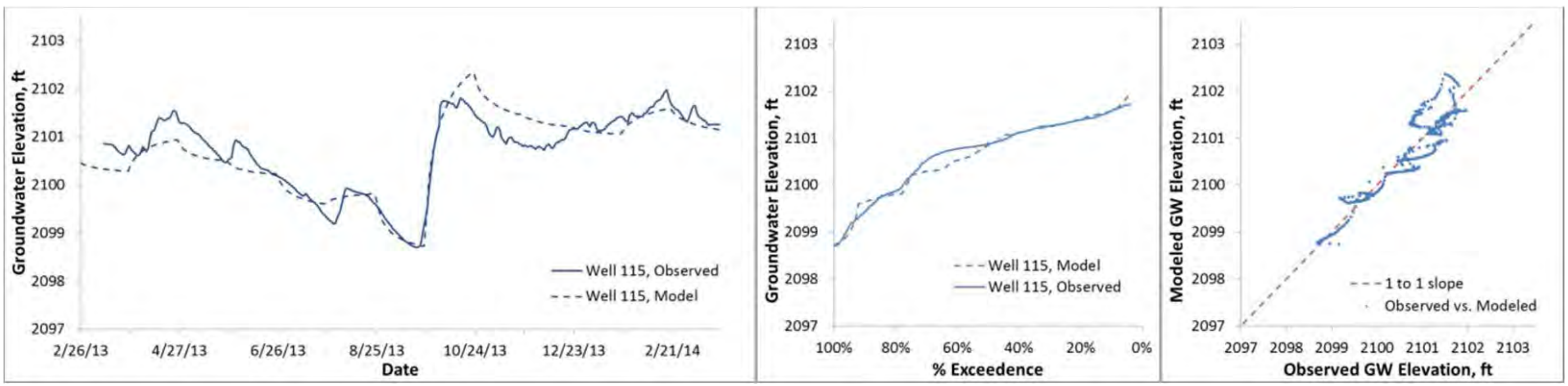


Figure B14. Modeled and observed heads 2013-2014, Fox well 115 (ground surface elevation 2105.9 ft)

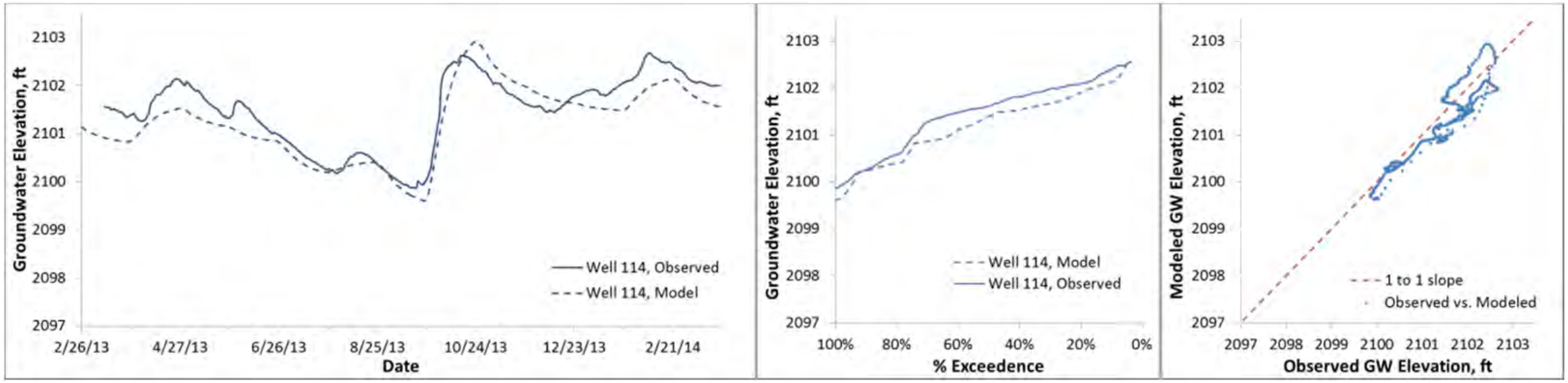


Figure B15. Modeled and observed heads 2013-2014, Fox well 114 (ground surface elevation 2105.6 ft)

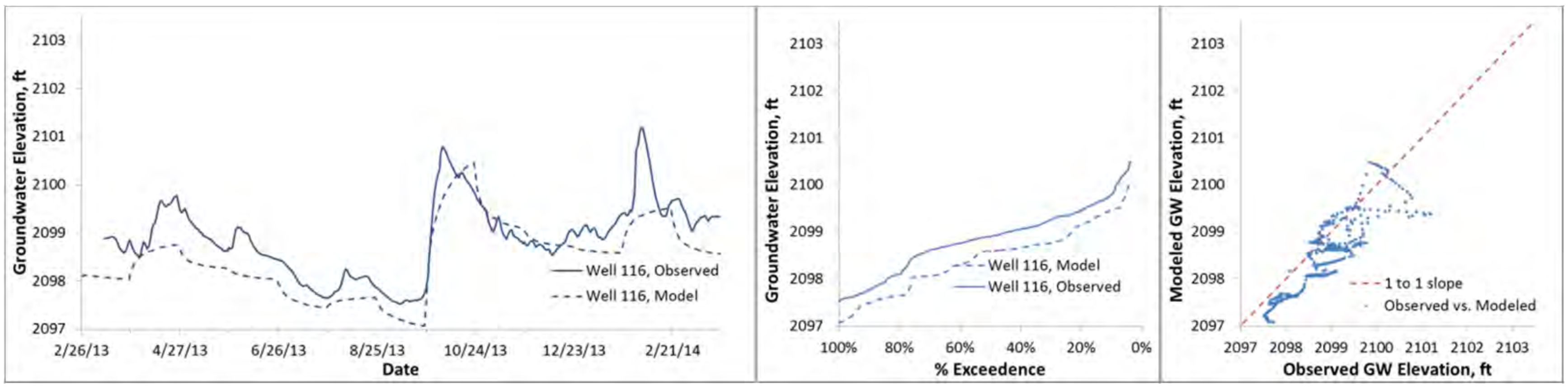


Figure B16. Modeled and observed heads 2013-2014, Fox well 116 (ground surface elevation 2105.0 ft)

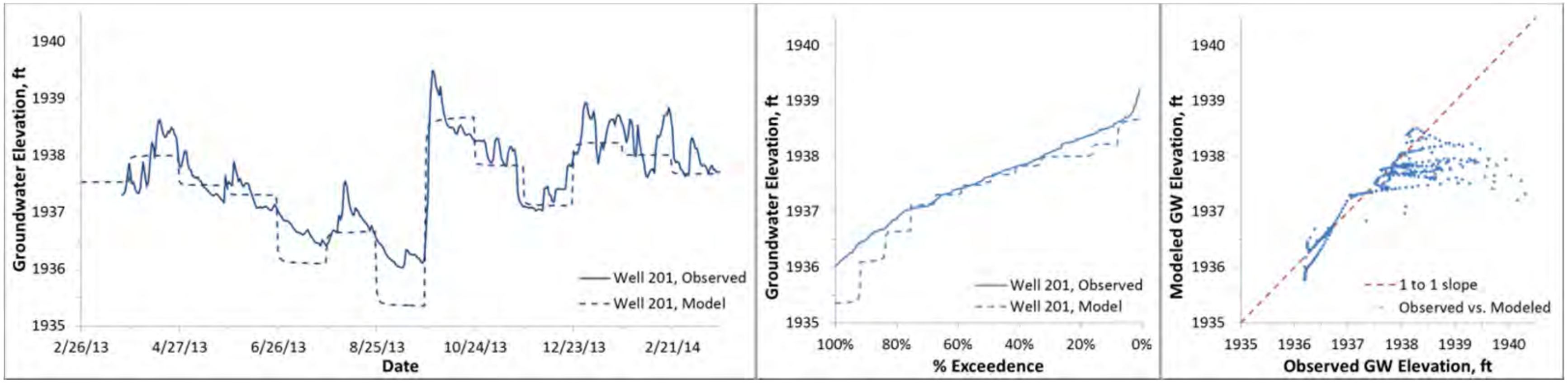


Figure B17. Modeled and observed heads 2013-2014, Binfield well 201 (ground surface elevation 1939.2 ft)

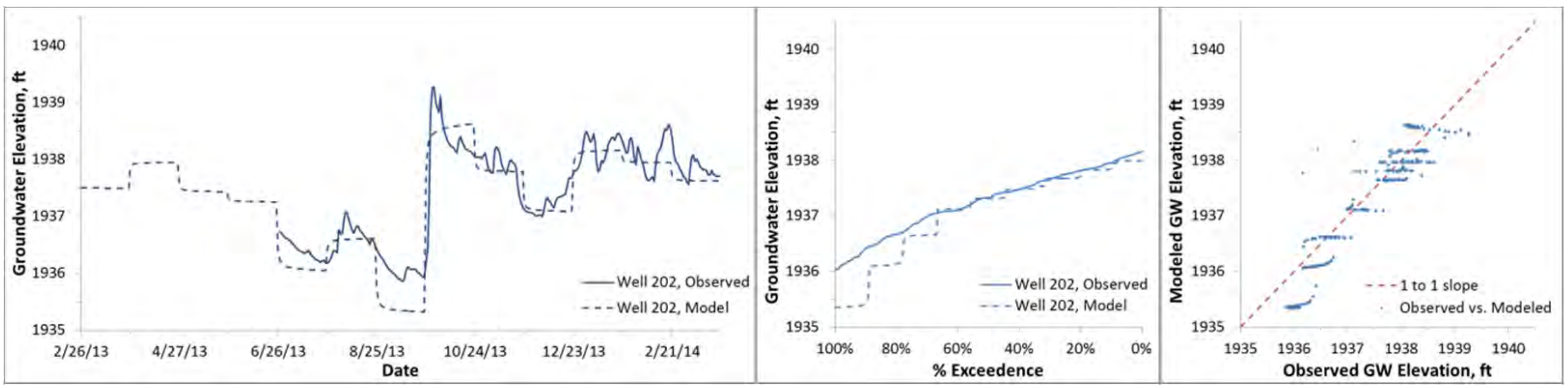


Figure B18. Modeled and observed heads 2013-2014, Binfield well 202 (ground surface elevation 1940.2 ft)

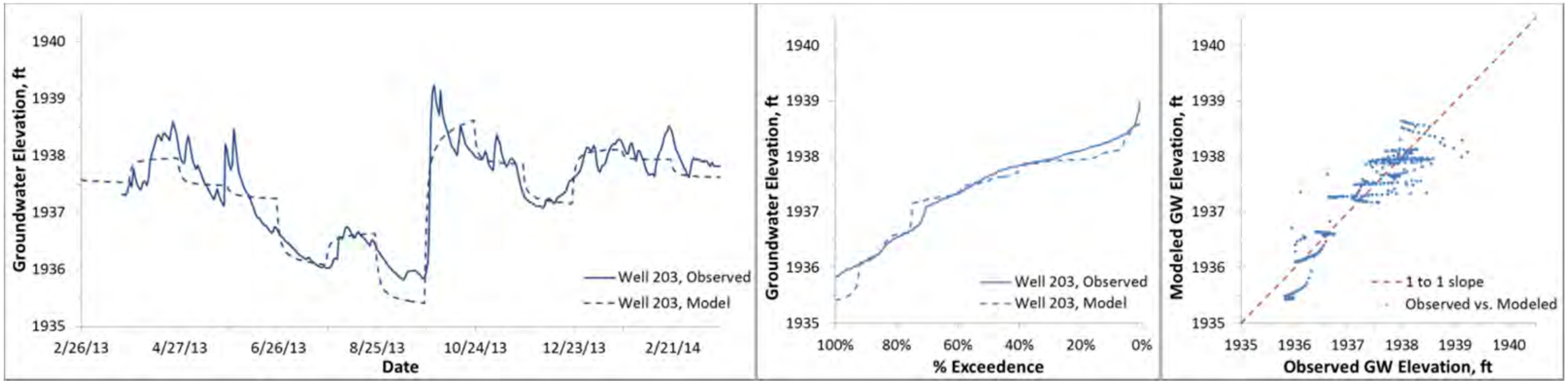


Figure B19. Modeled and observed heads 2013-2014, Binfield well 203 (ground surface elevation 1939.4 ft)

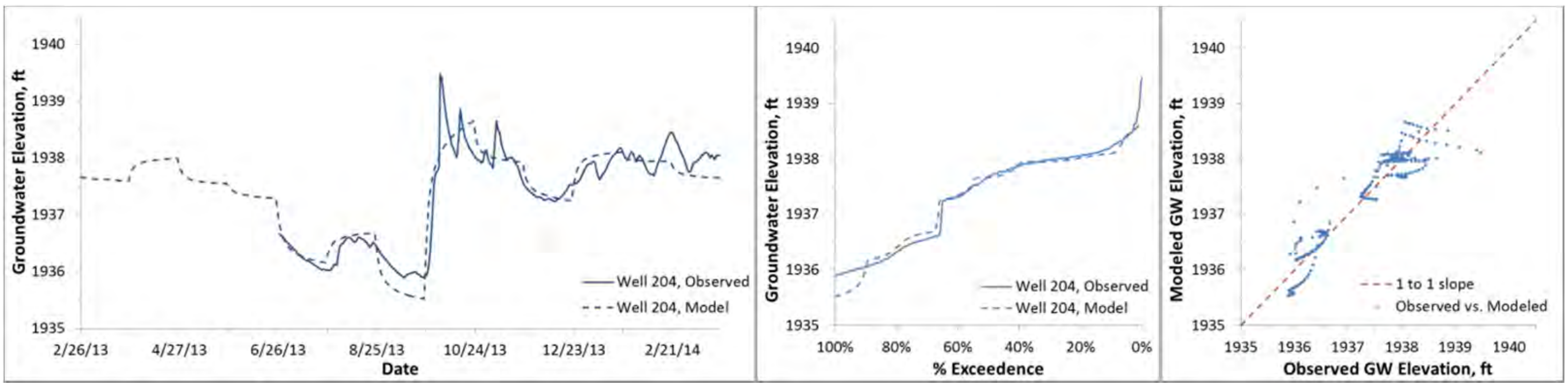


Figure B20. Modeled and observed heads 2013-2014, Binfield well 204 (ground surface elevation 1941.4 ft)

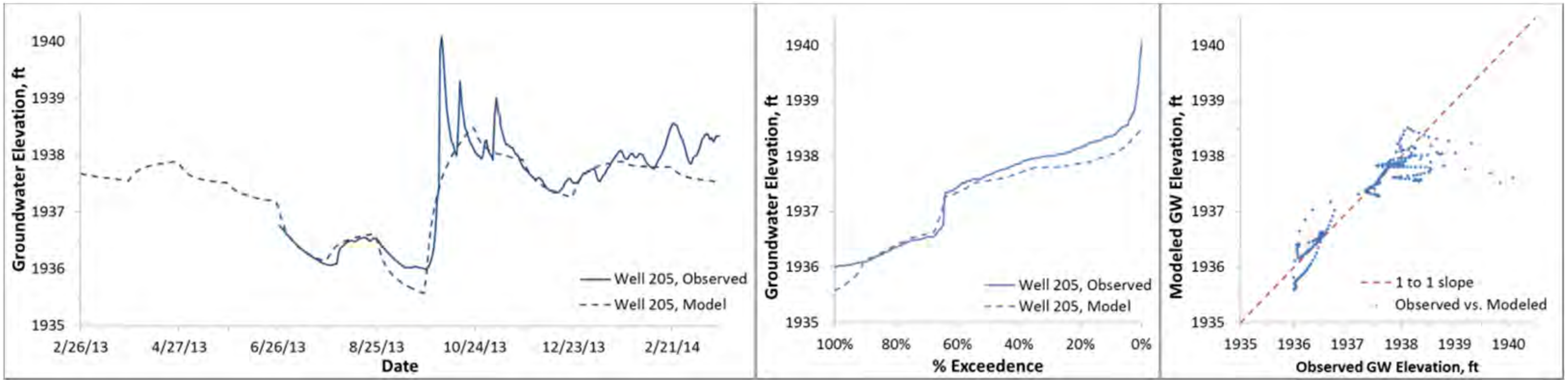


Figure B21. Modeled and observed heads 2013-2014, Binfield well 205 (ground surface elevation 1940.5 ft)

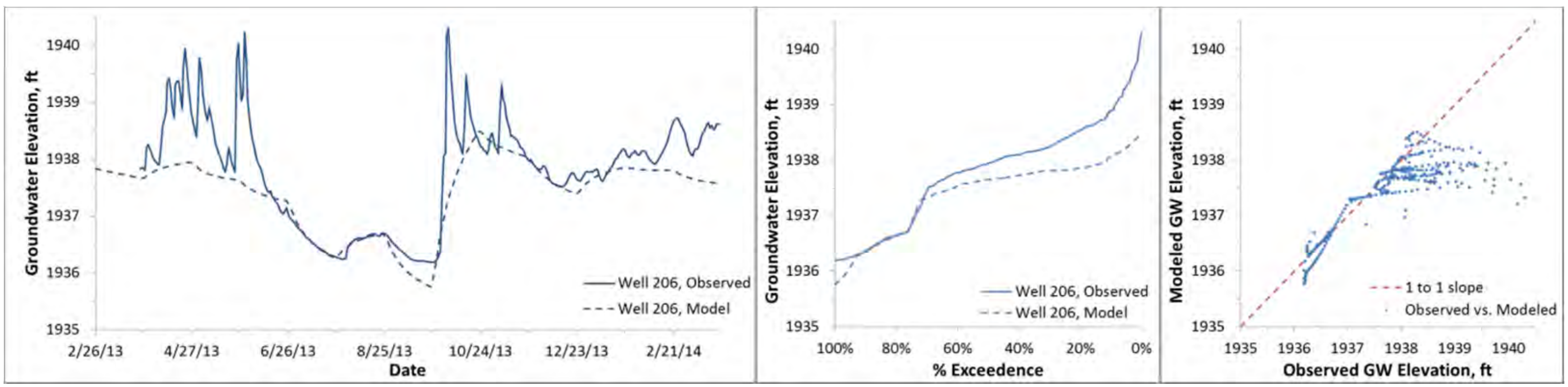


Figure B22. Modeled and observed heads 2013-2014, Binfield well 206 (ground surface elevation 1940.8 ft)

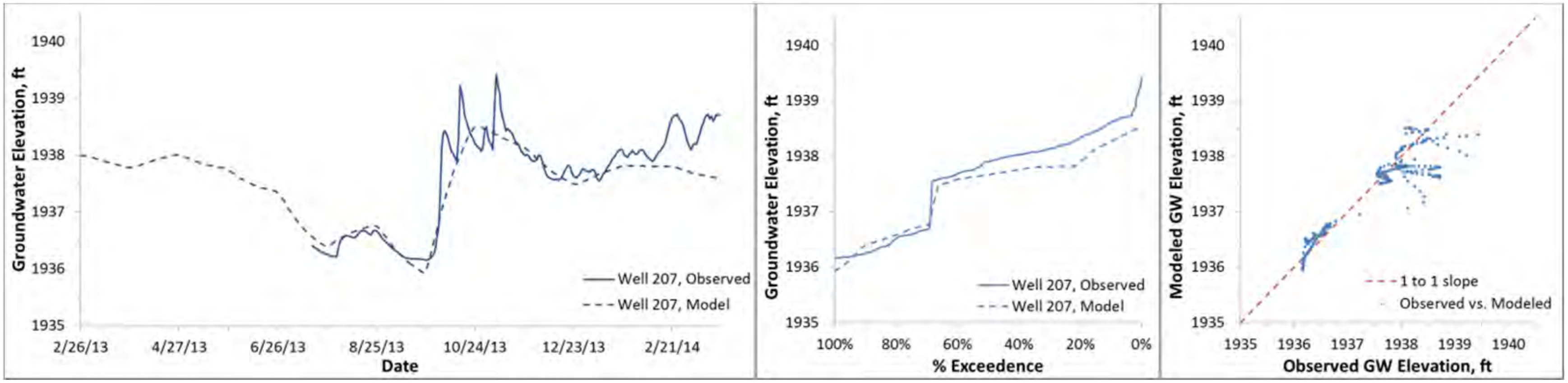


Figure B23. Modeled and observed heads 2013-2014, Binfield well 207 (ground surface elevation 1941.8 ft)

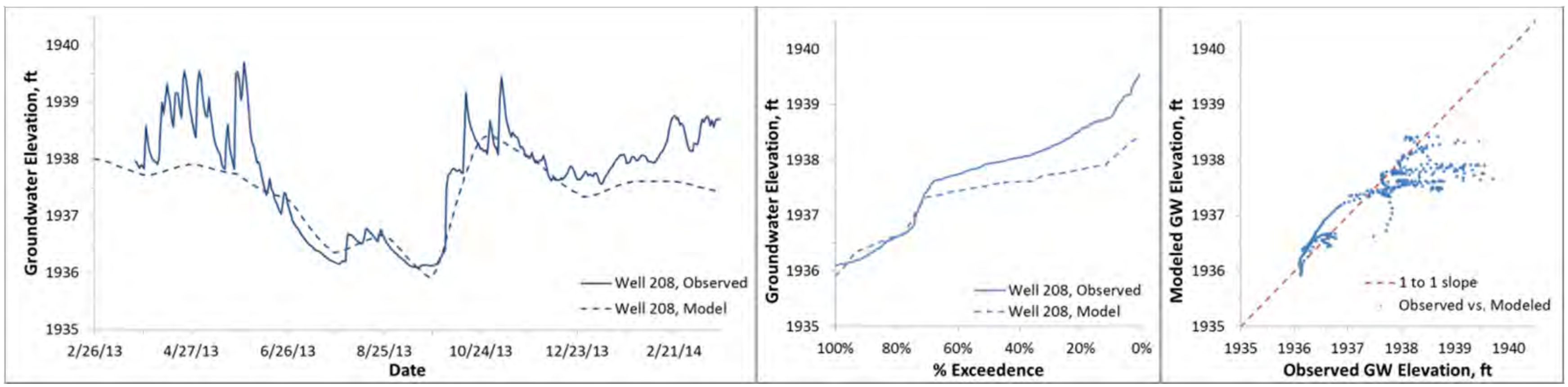


Figure B25. Modeled and observed heads 2013-2014, Binfield well 208 (ground surface elevation 1940.4 ft)

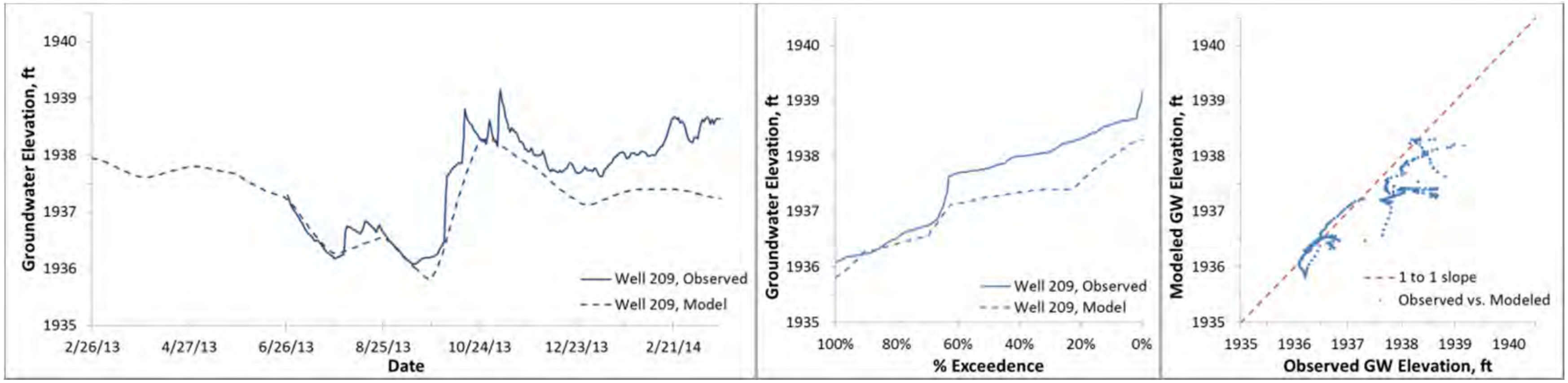


Figure B26. Modeled and observed heads 2013-2014, Binfield well 209 (ground surface elevation 1940.6 ft)

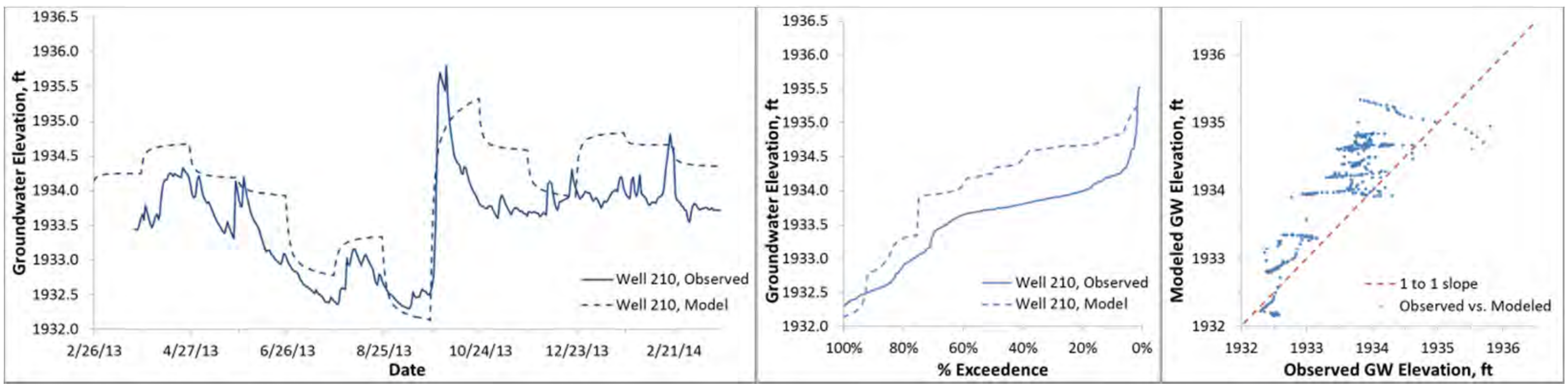


Figure B27. Modeled and observed heads 2013-2014, Binfield well 210 (ground surface elevation 1937.3 ft)

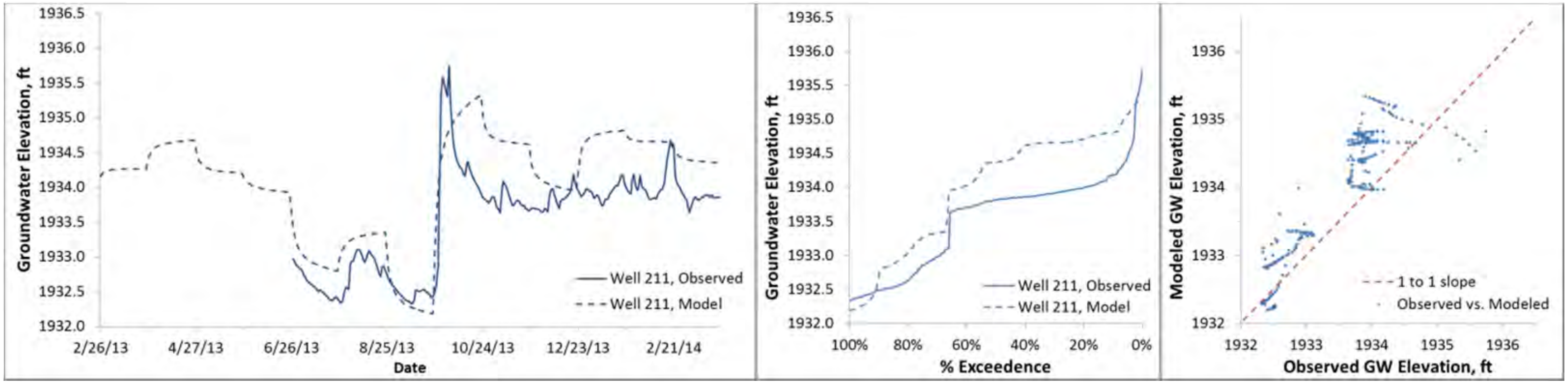


Figure B27. Modeled and observed heads 2013-2014, Binfield well 211 (ground surface elevation 1937.8 ft)

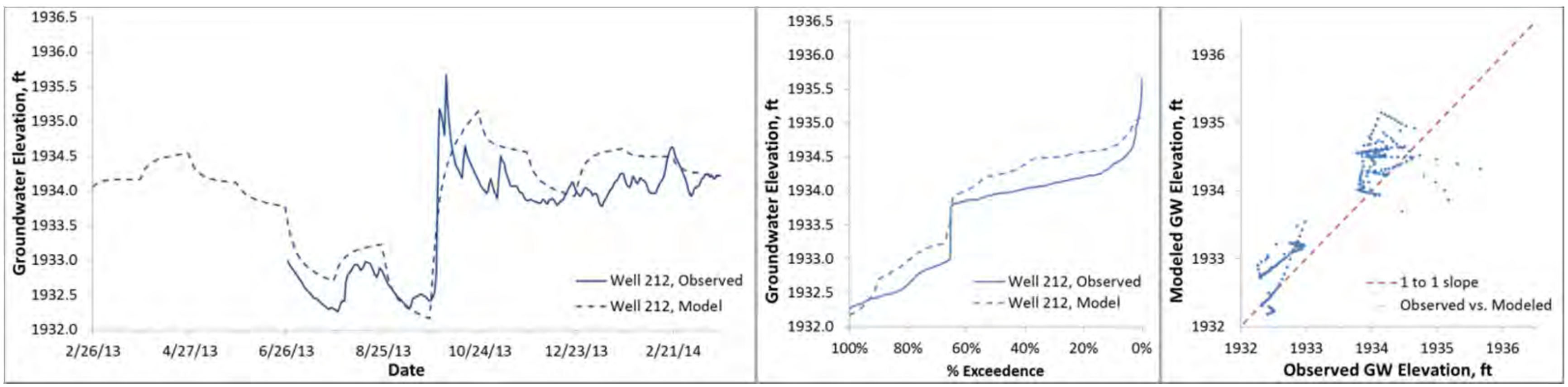


Figure B28. Modeled and observed heads 2013-2014, Binfield well 212 (ground surface elevation 1937.7 ft)

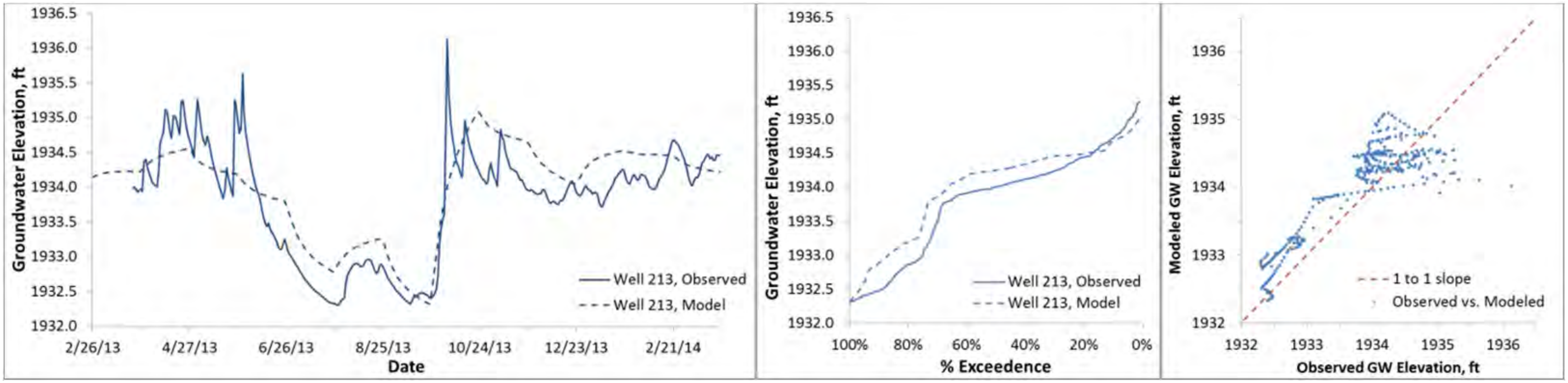


Figure B29. Modeled and observed heads 2013-2014, Binfield well 213 (ground surface elevation 1937.3 ft)

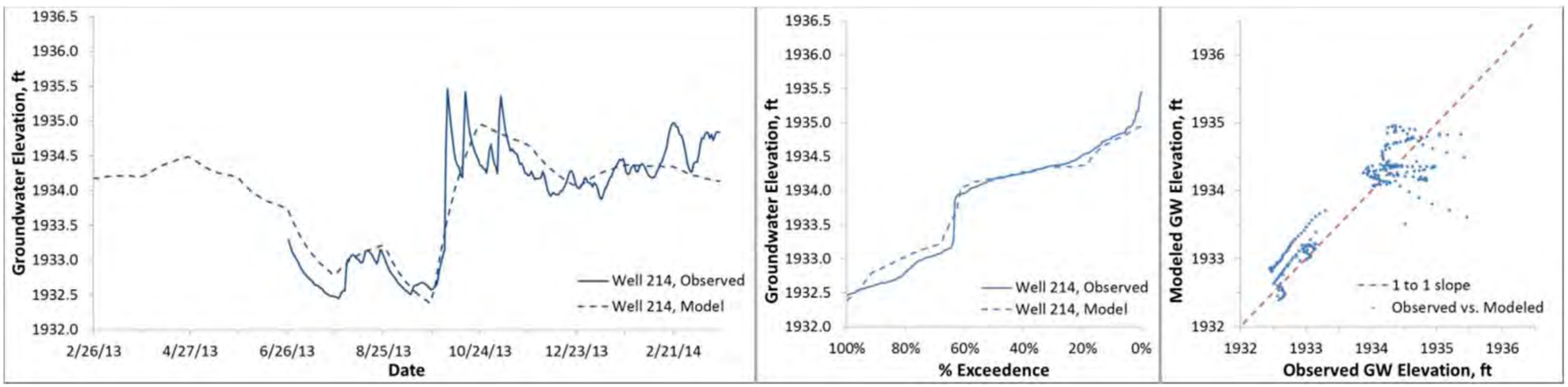


Figure B30. Modeled and observed heads 2013-2014, Binfield well 214 (ground surface elevation 1936.7 ft)

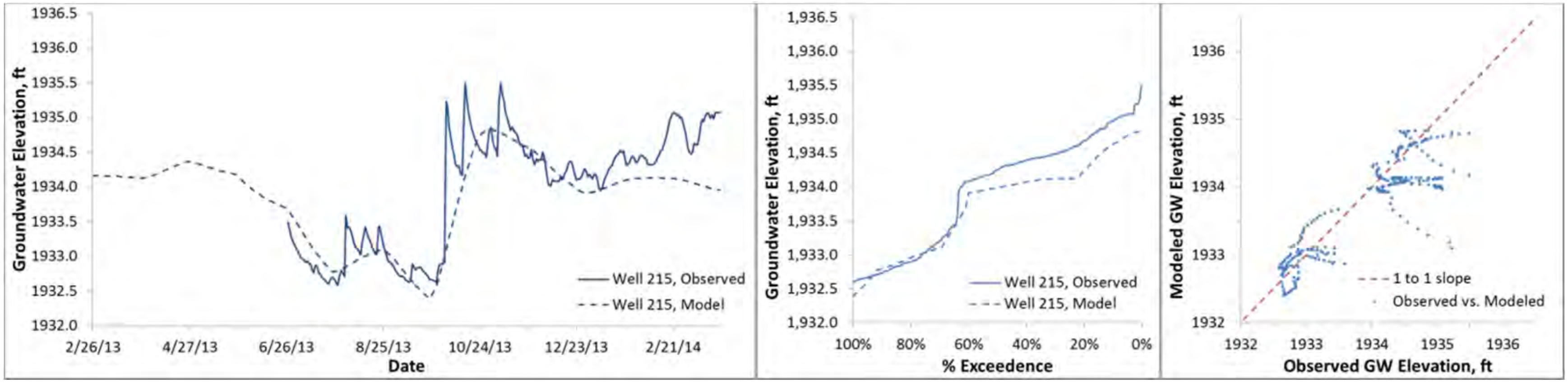


Figure B31. Modeled and observed heads 2013-2014, Binfield well 215 (ground surface elevation 1936.4 ft)

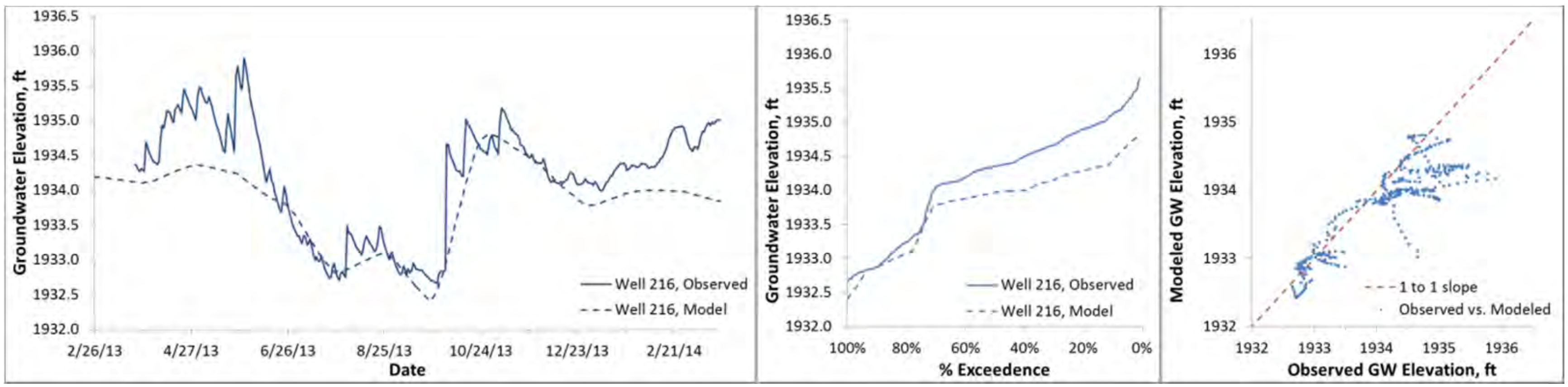


Figure B32. Modeled and observed head 2013-2014s, Binfield well 216 (ground surface elevation 1936.3 ft)

CHAPTER 4APPENDIX C: MODELED & OBSERVED HEADS, SPRING 2013 MODELS

Modeled and observed heads are shown below for the Fox and Binfield sites, refer to **Figures 5** and **6** for well locations. Figures are presented in south to north order and discussed in **SECTION 8** of the report.

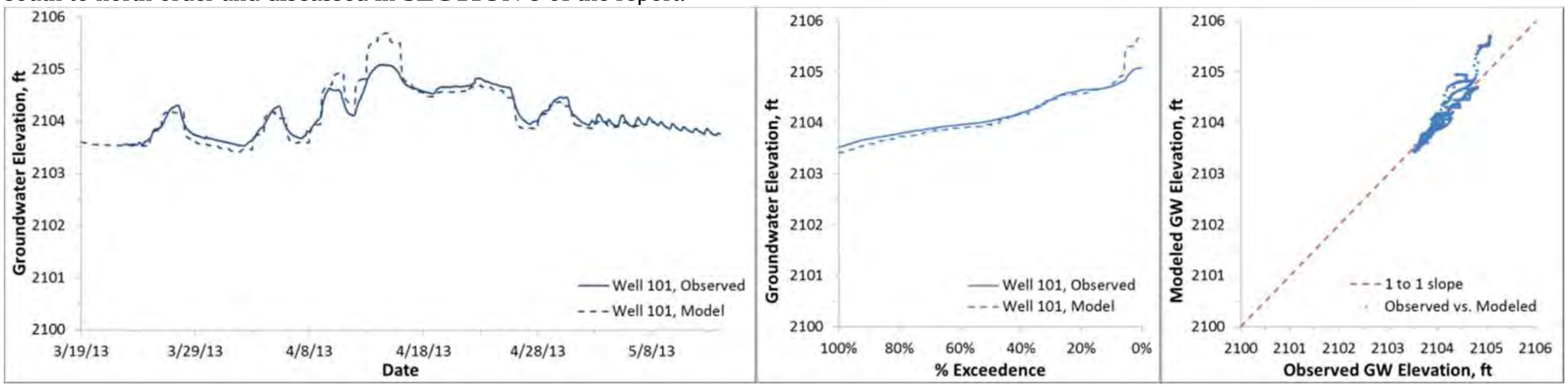


Figure C1. Modeled and observed heads, Fox well 101 (ground surface elevation 2110.075ft)

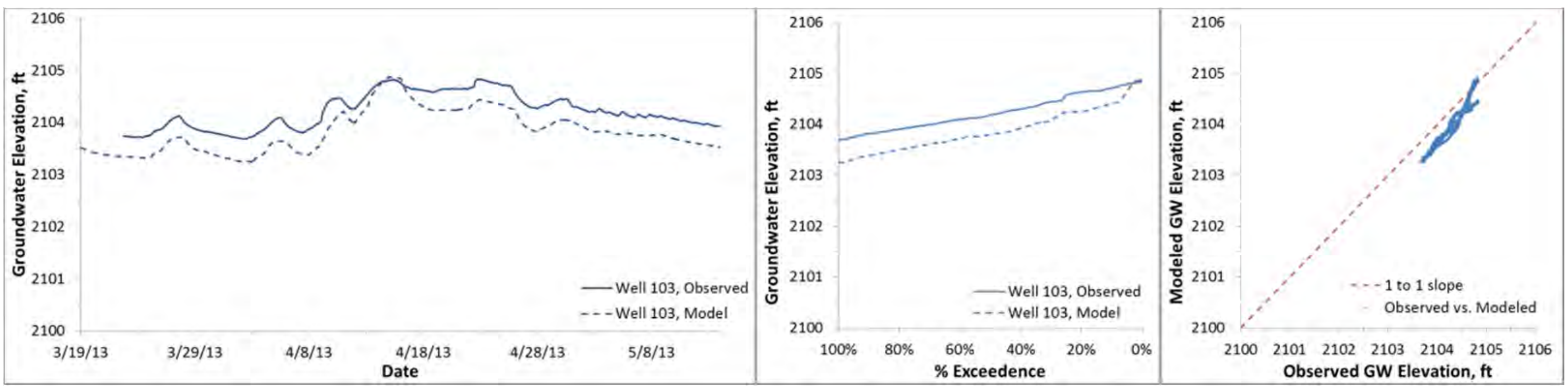


Figure C2. Modeled and observed heads, Fox well 103 (ground surface elevation 2110.3 ft)

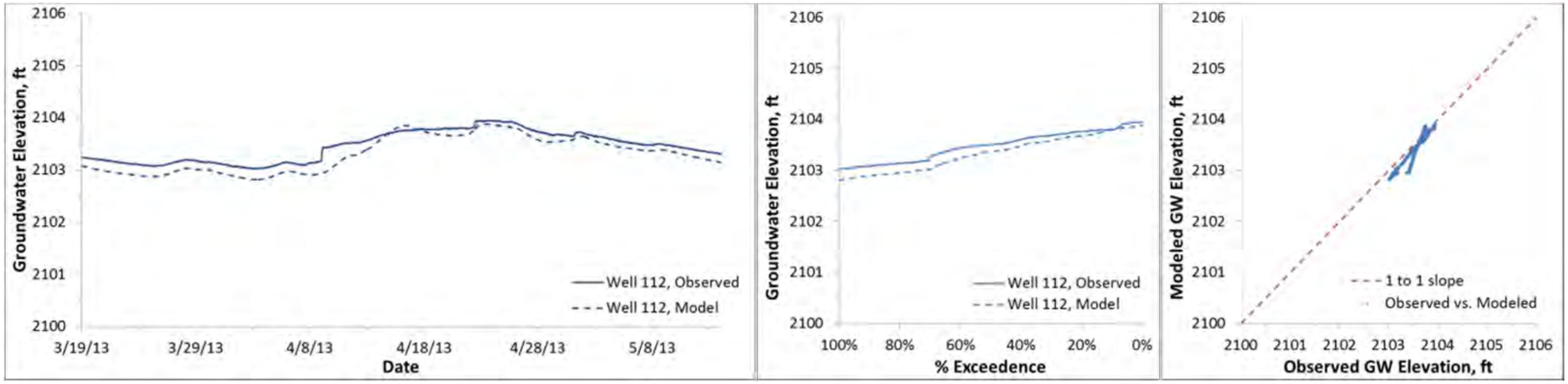


Figure C3. Modeled and observed heads, Fox well 112 (ground surface elevation 2107.4 ft)

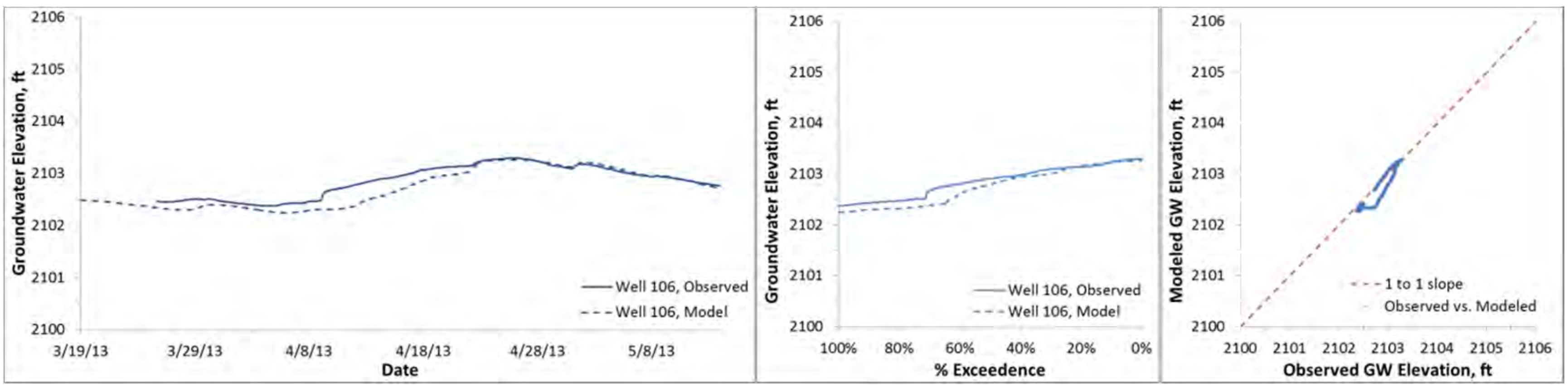


Figure C4. Modeled and observed heads, Fox well 106 (ground surface elevation 2107.7 ft)

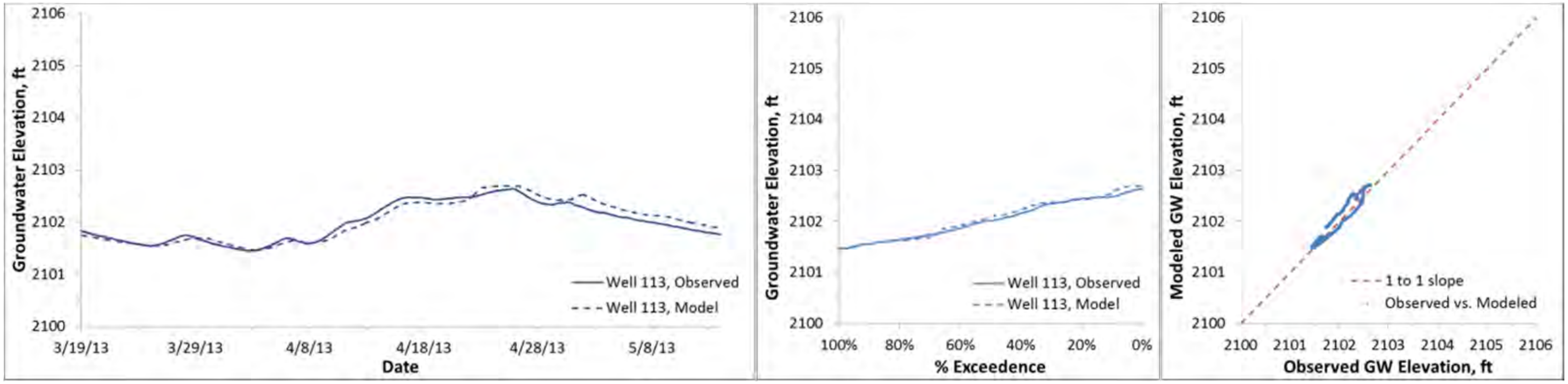


Figure C5. Modeled and observed heads, Fox well 113 (ground surface elevation 2107.6 ft)

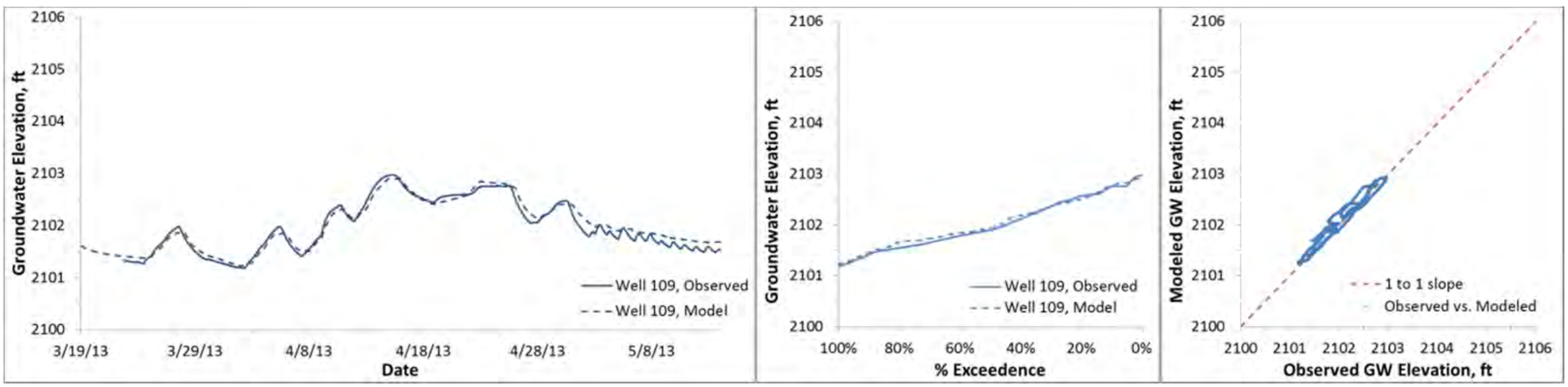


Figure C6. Modeled and observed heads, Fox well 109 (ground surface elevation 2108.1 ft)

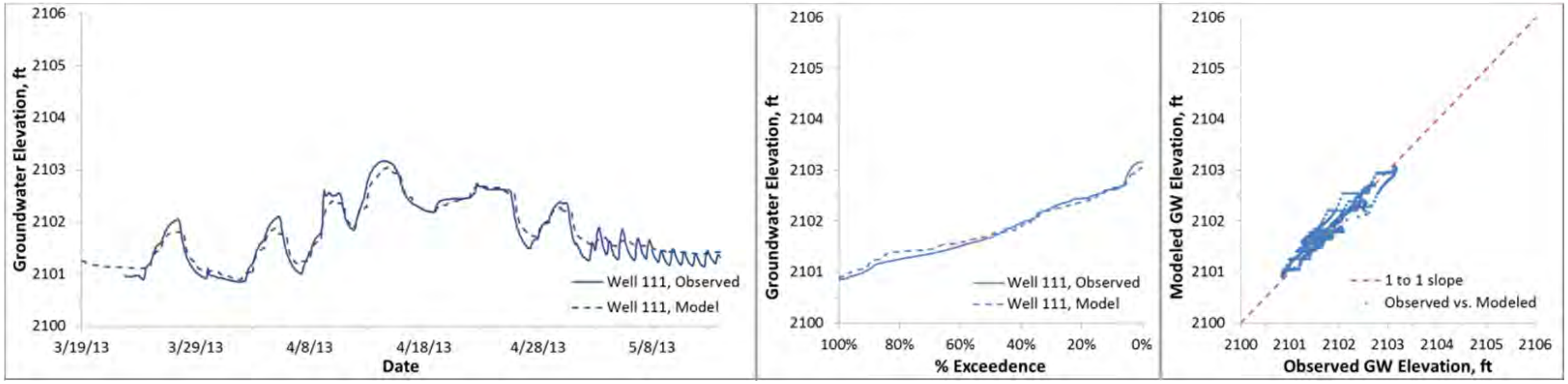


Figure C7. Modeled and observed heads, Fox well 111 (ground surface elevation 2107.9 ft)

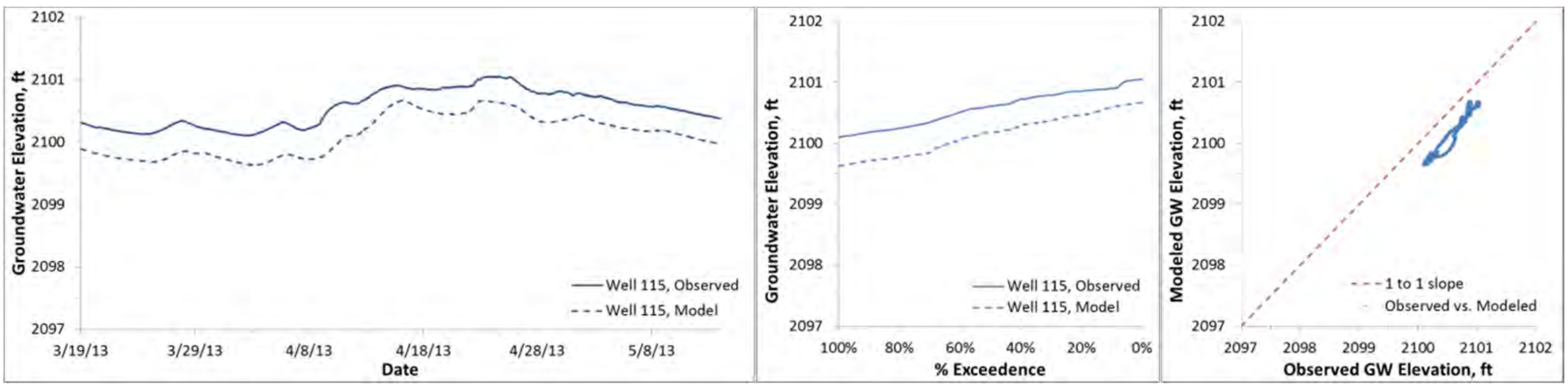


Figure C8. Modeled and observed heads, Fox well 115 (ground surface elevation 2105.9 ft)

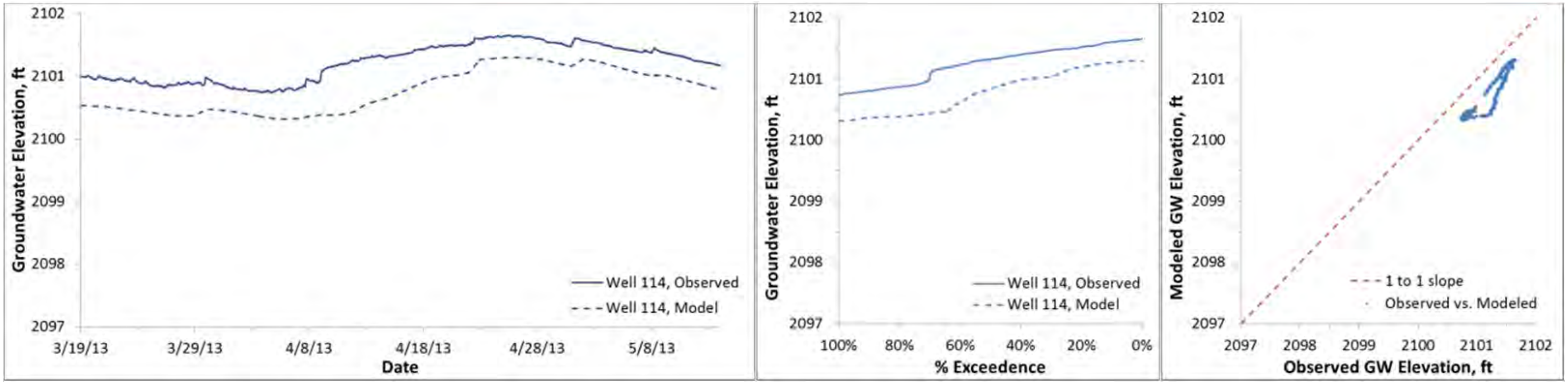


Figure C9. Modeled and observed heads, Fox well 114 (ground surface elevation 2105.6 ft)

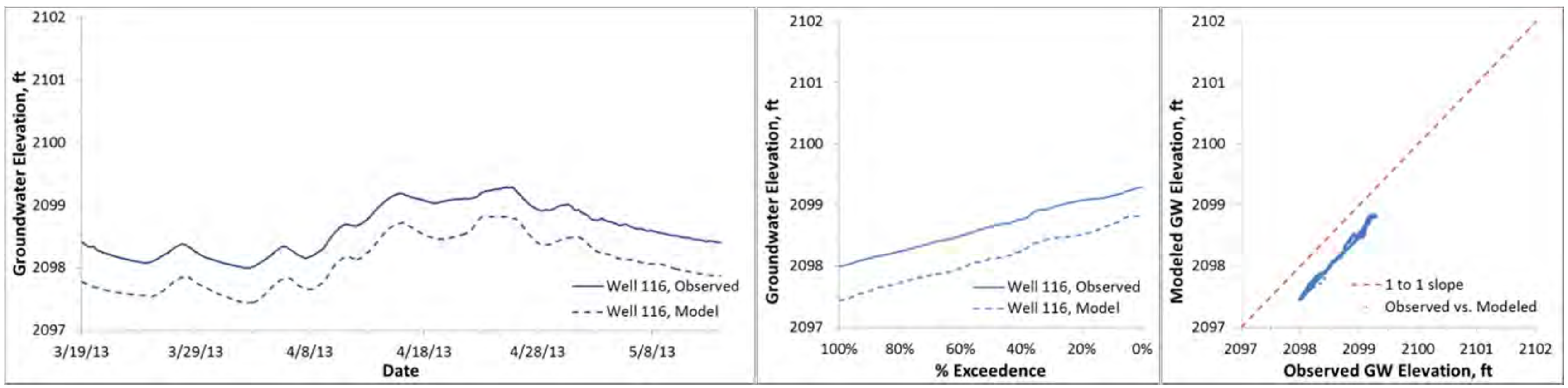


Figure C10. Modeled and observed heads, Fox well 116 (ground surface elevation 2105.0 ft)

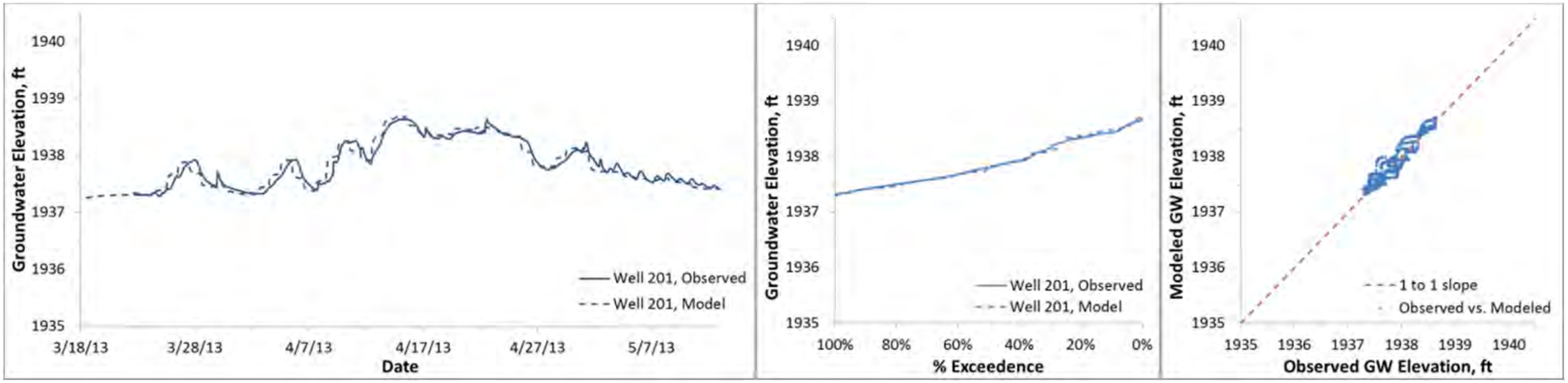


Figure C11. Modeled and observed heads, Binfield well 201 (ground surface elevation 1939.2 ft)

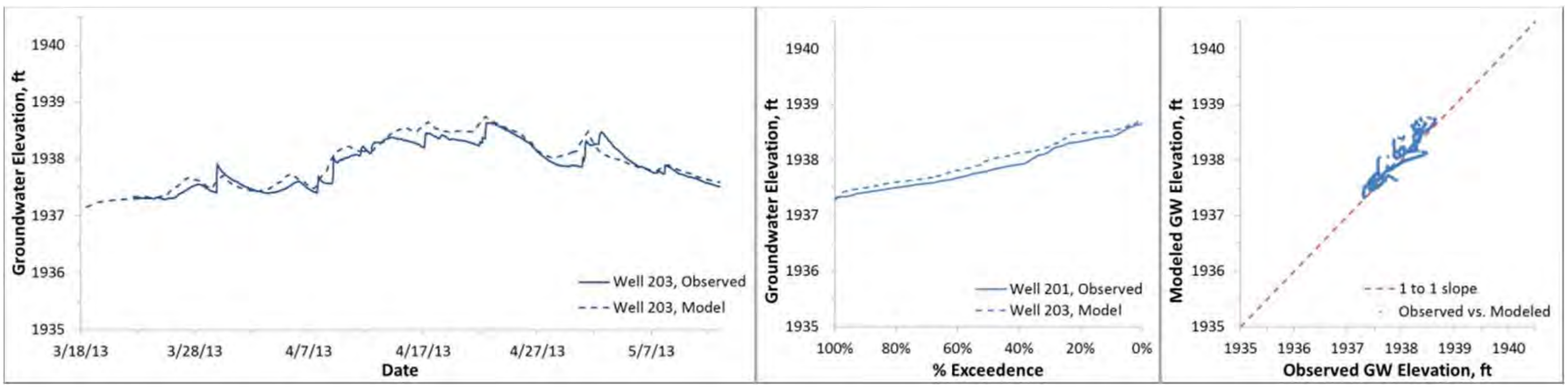


Figure C12. Modeled and observed heads, Binfield well 203 (ground surface elevation 1939.4 ft)

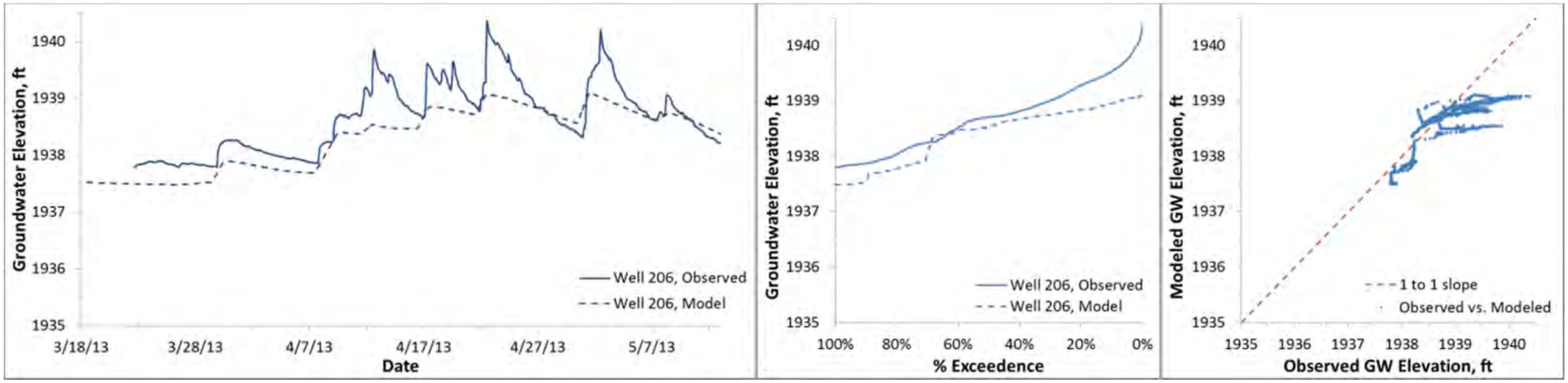


Figure C13. Modeled and observed heads, Binfield well 206 (ground surface elevation 1940.8 ft)

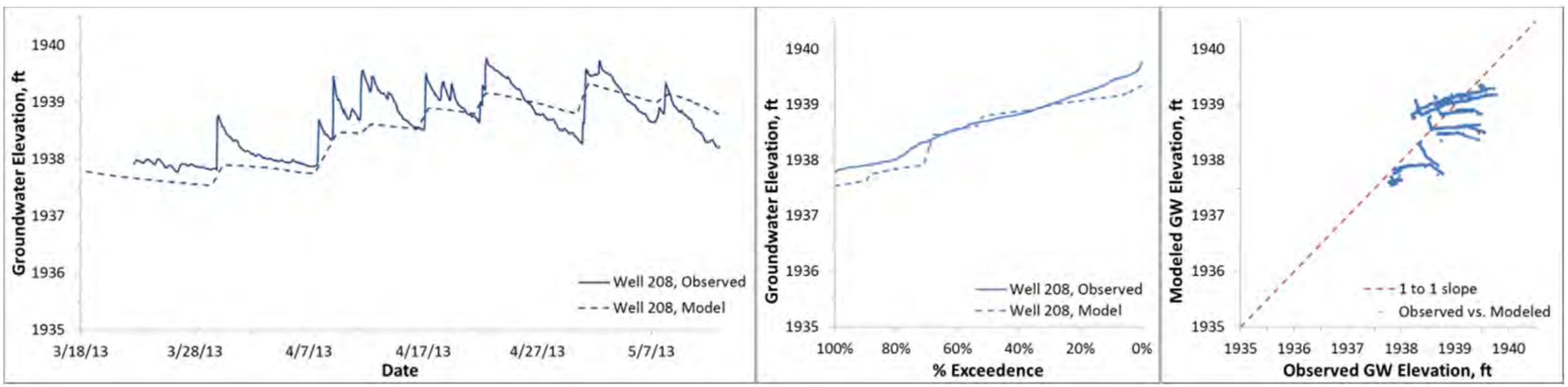


Figure C14. Modeled and observed heads, Binfield well 208 (ground surface elevation 1940.4 ft)

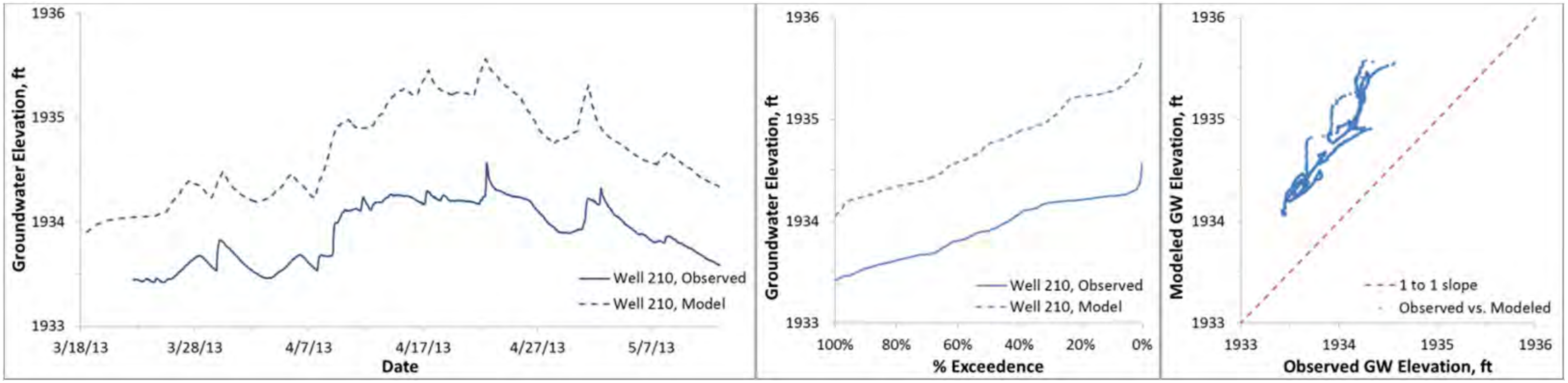


Figure C15. Modeled and observed heads, Binfield well 210 (ground surface elevation 1937.3 ft)

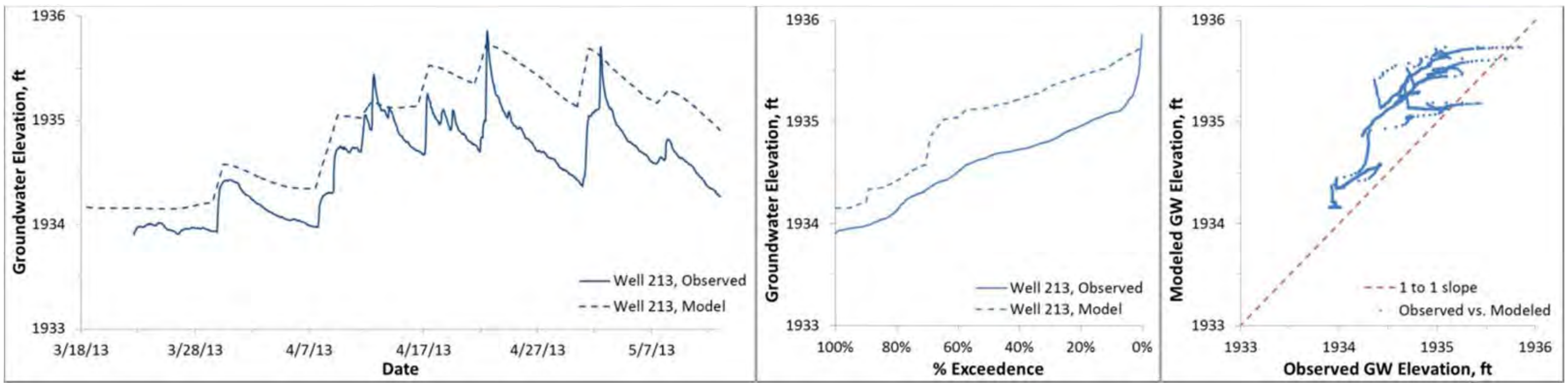


Figure C16. Modeled and observed heads, Binfield well 213 (ground surface elevation 1937.3 ft)

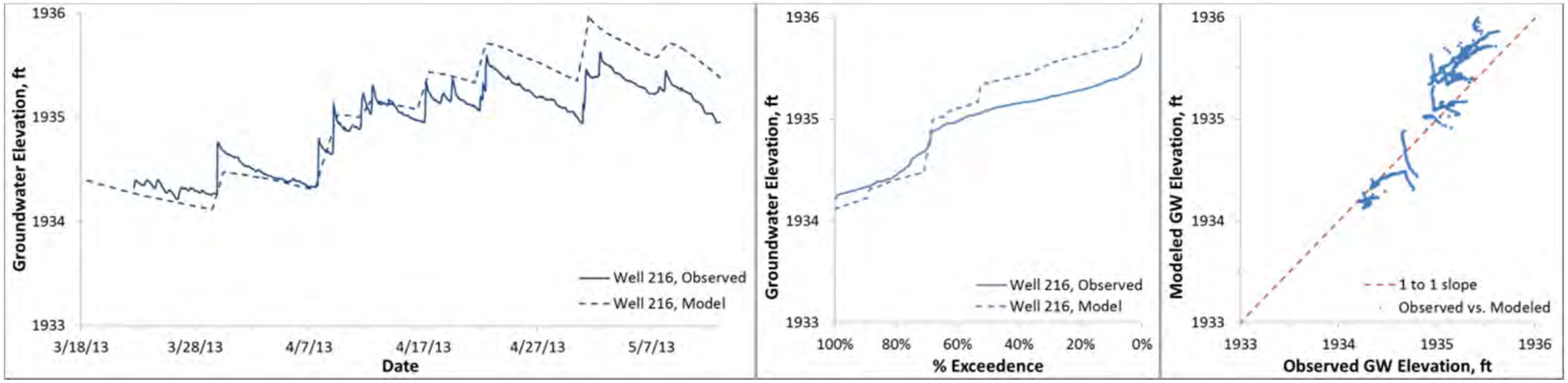


Figure C17. Modeled and observed heads, Binfield well 216 (ground surface elevation 1936.3 ft)

CHAPTER 4 APPENDIX D: MODELED & OBSERVED HEADS, FALL 2013 MODELS

Modeled and observed heads are shown below for the Fox and Binfield sites, refer to **Figures 5** and **6** for well locations. Figures are presented in south to north order and discussed in **SECTION 8** of the report.

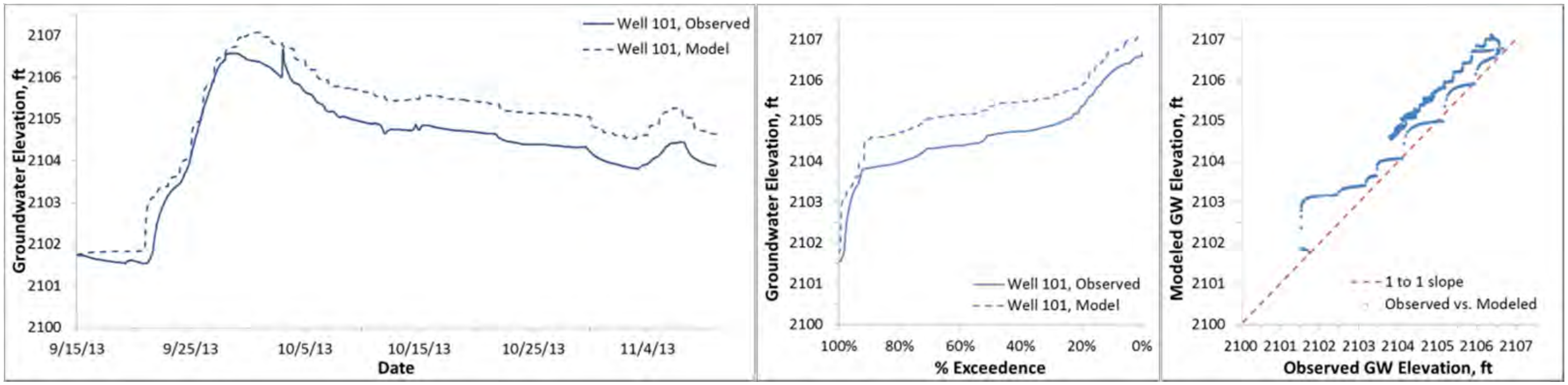


Figure D1. Modeled and observed heads, Fox well 101 (ground surface elevation 2110.1 ft)

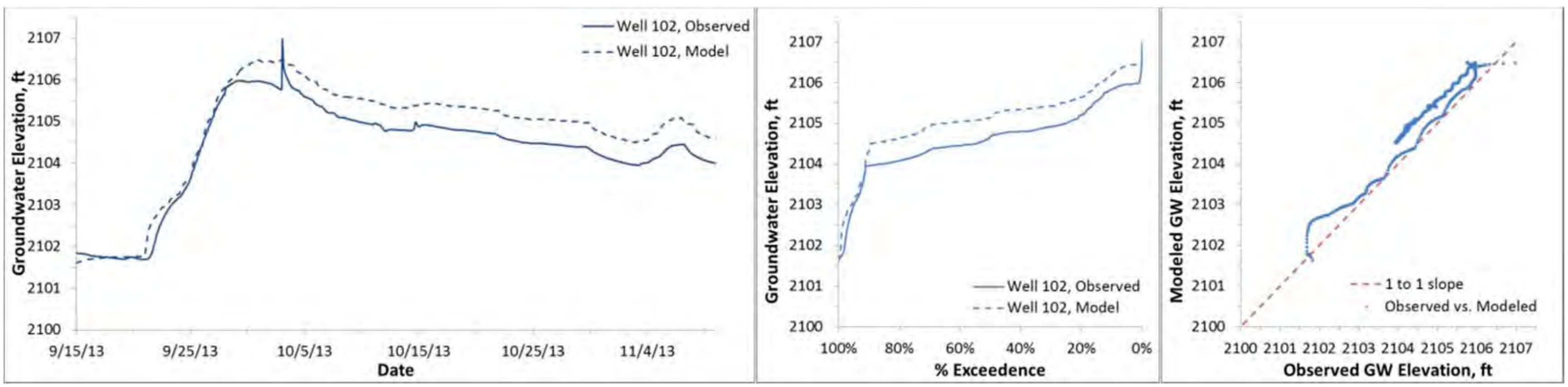


Figure D2. Modeled and observed heads, Fox well 102 (ground surface elevation 2109.6 ft)

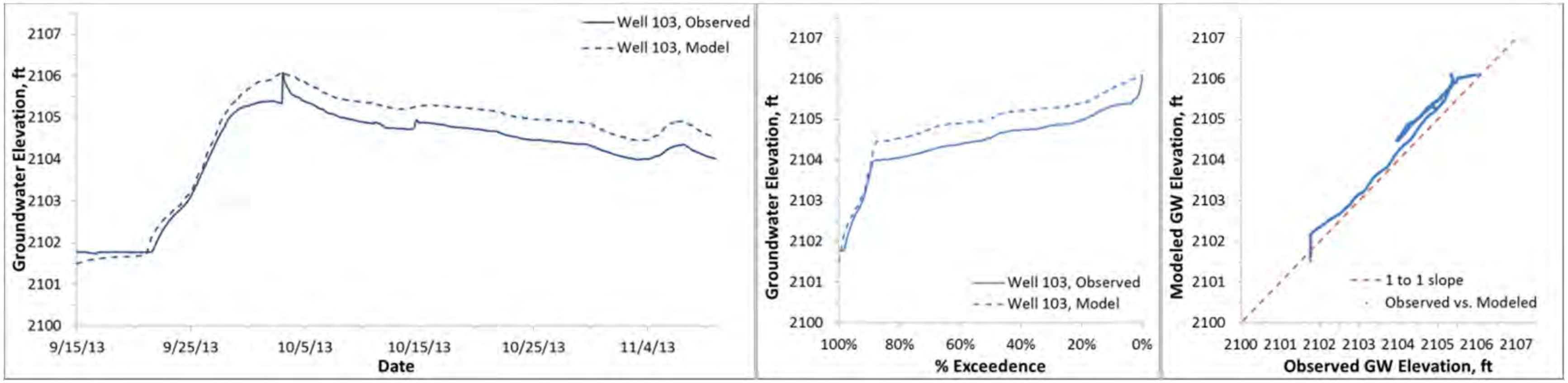


Figure D3. Modeled and observed heads, Fox well 103 (ground surface elevation 2110.3 ft)

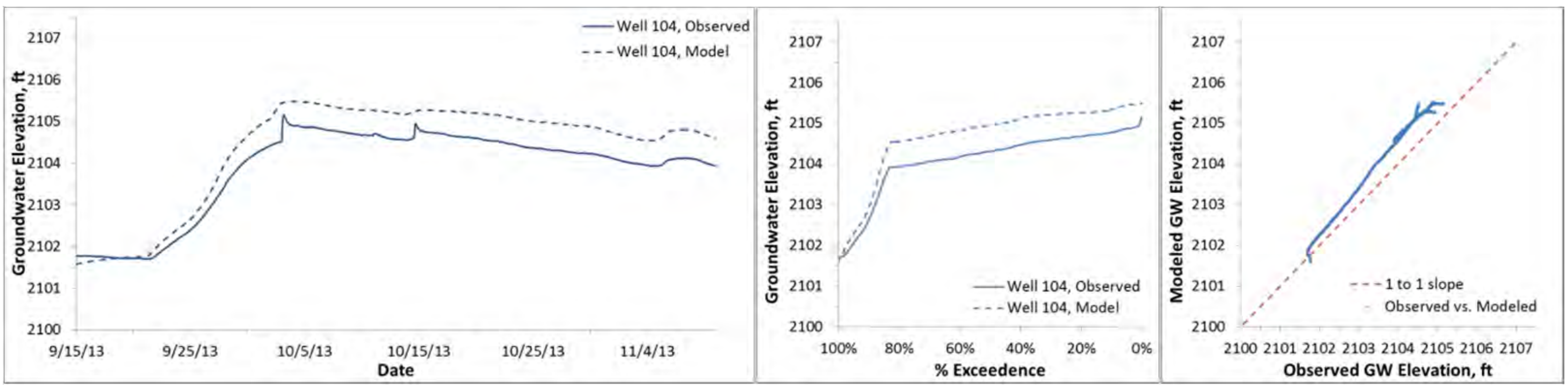


Figure D4. Modeled and observed heads, Fox well 104 (ground surface elevation 2107.1 ft)

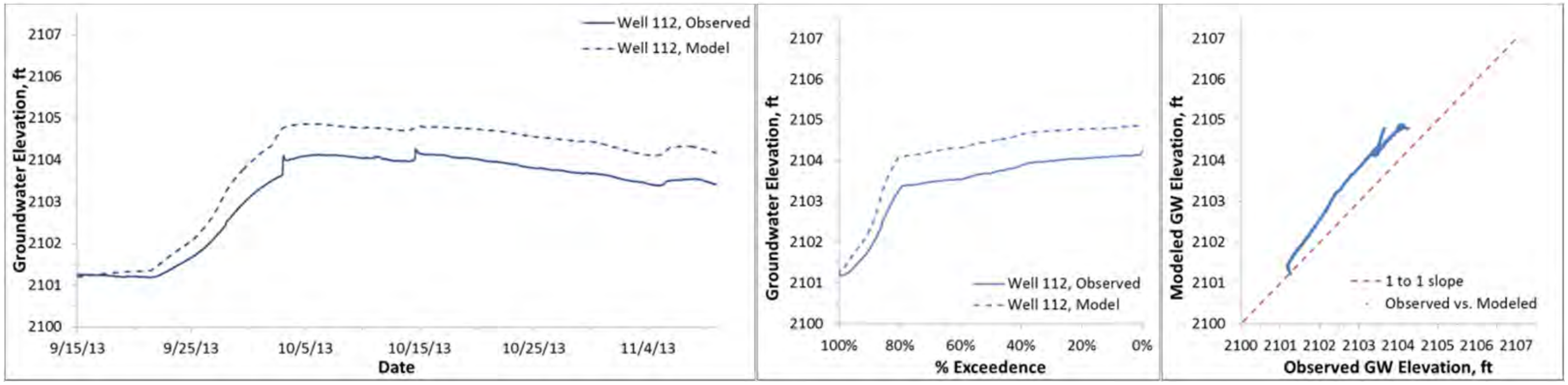


Figure D5. Modeled and observed heads, Fox well 112 (ground surface elevation 2107.4 ft)

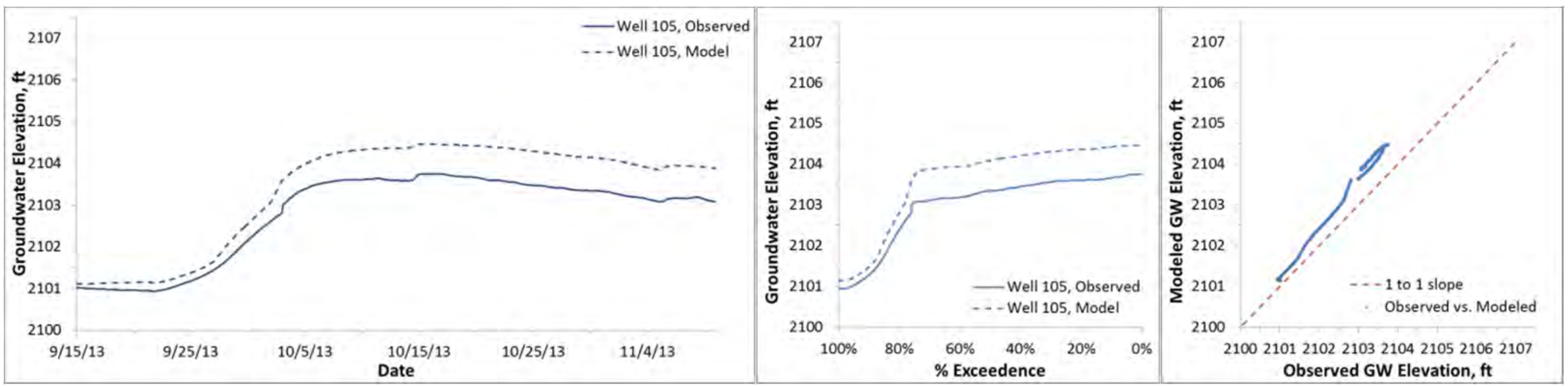


Figure D6. Modeled and observed heads, Fox well 105 (ground surface elevation 2107.7 ft)

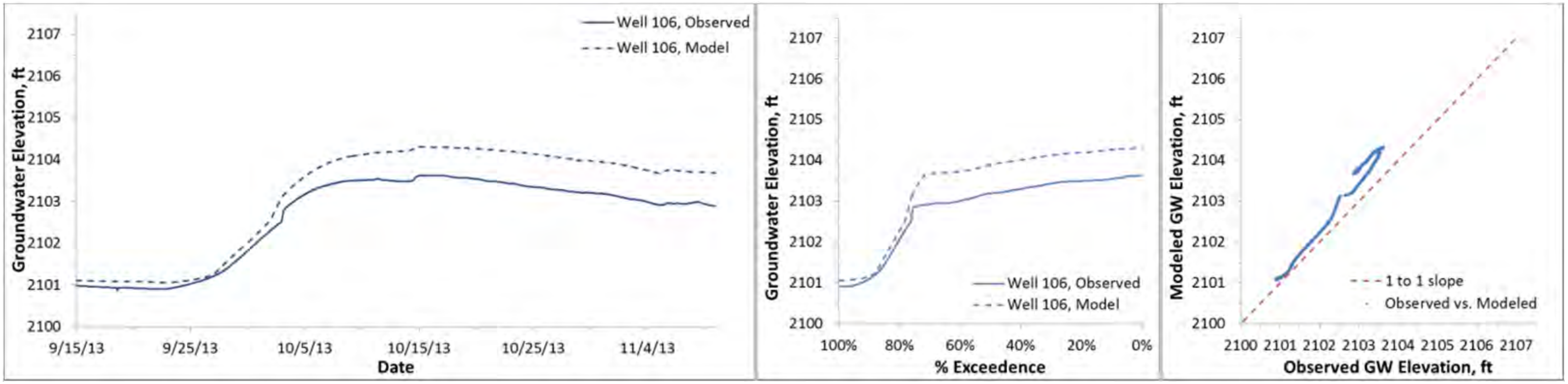


Figure D7. Modeled and observed heads, Fox well 106 (ground surface elevation 2107.7 ft)

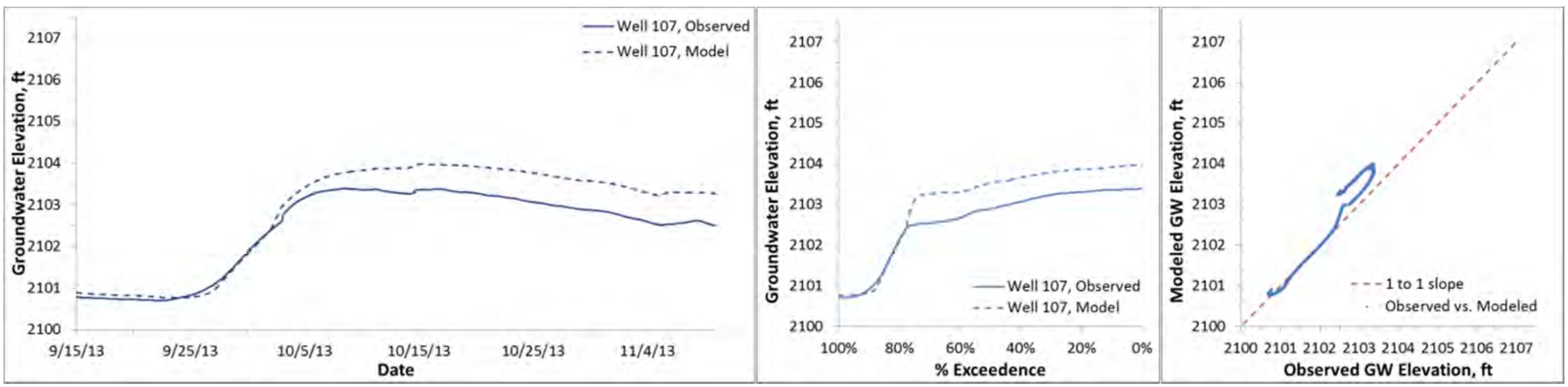


Figure D8. Modeled and observed heads, Fox well 107 (ground surface elevation 2107.7 ft)

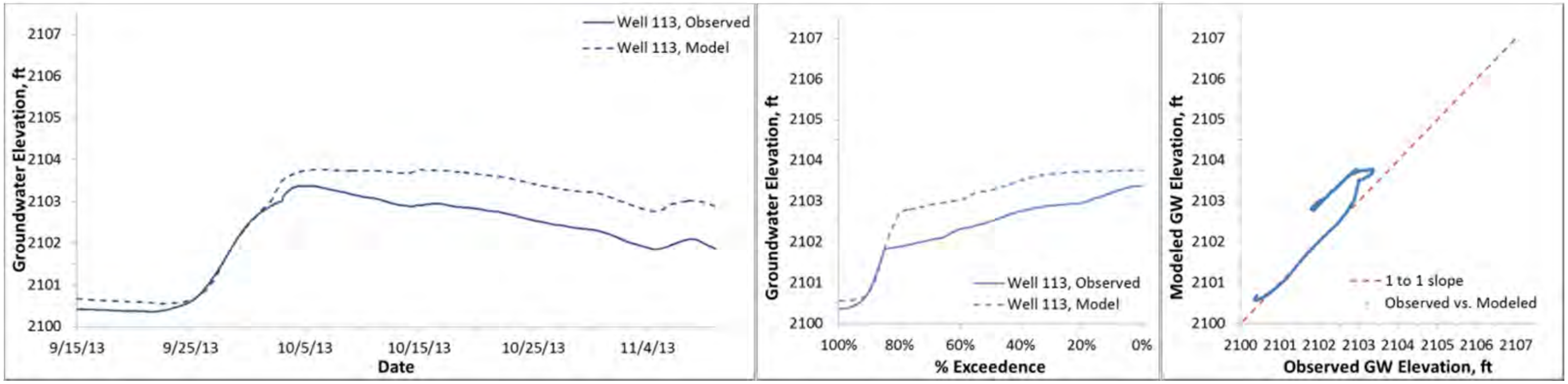


Figure D9. Modeled and observed heads, Fox well 113 (ground surface elevation 2107.6 ft)

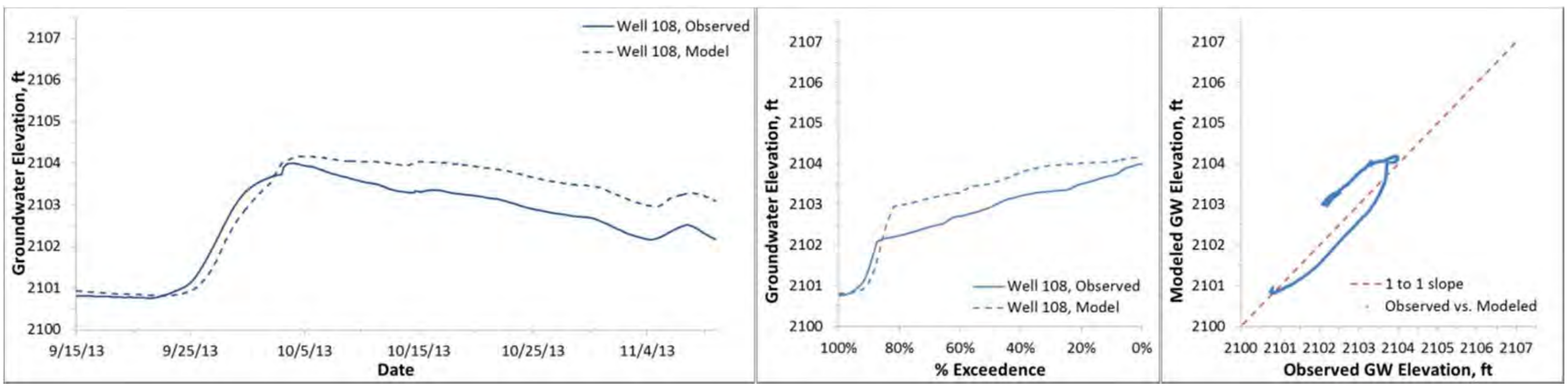


Figure D10. Modeled and observed heads, Fox well 108 (ground surface elevation 2110.5 ft)

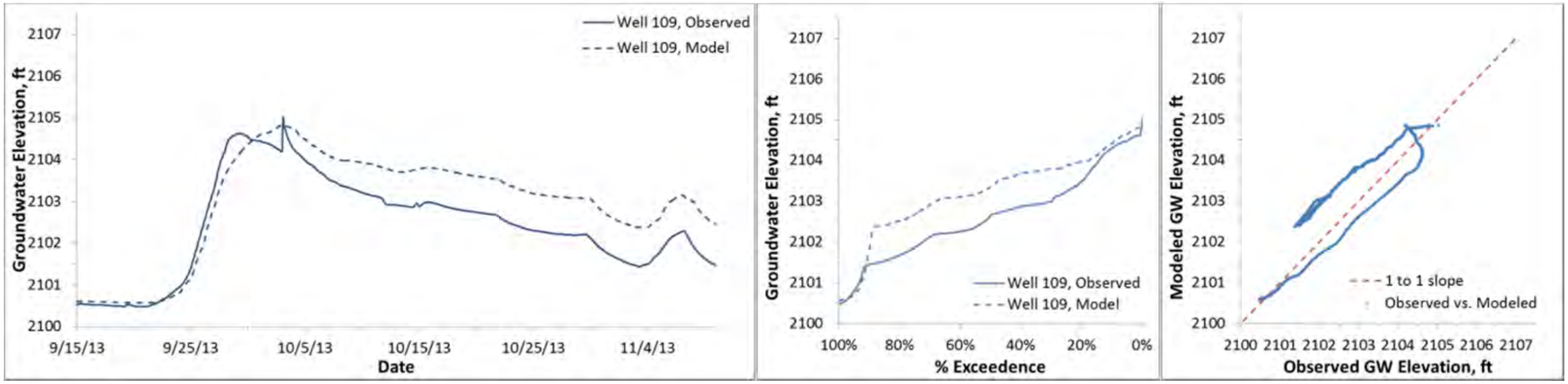


Figure D11. Modeled and observed heads, Fox well 109 (ground surface elevation 2108.1 ft)

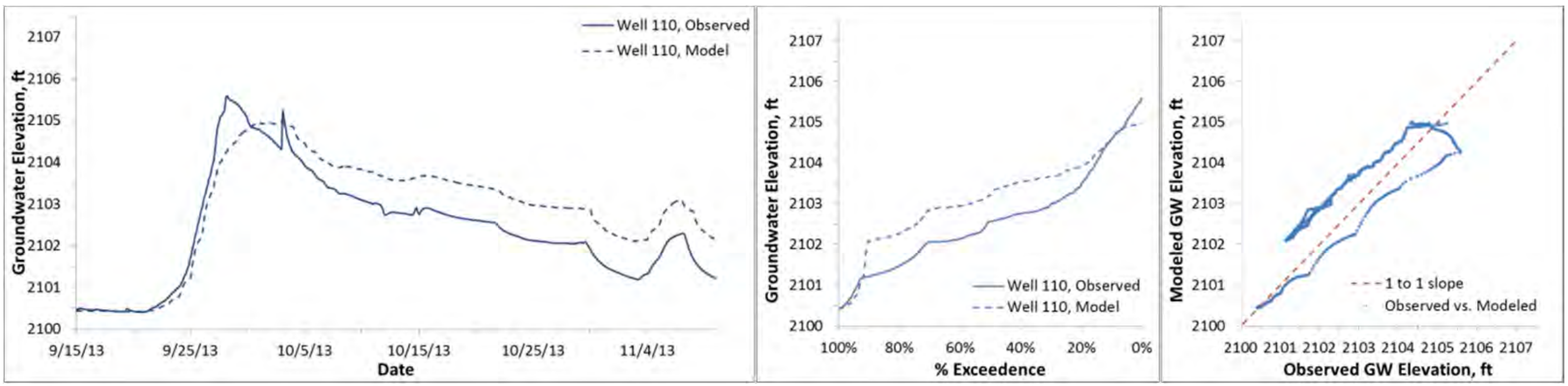


Figure D12. Modeled and observed heads, Fox well 110 (ground surface elevation 2108.9 ft)

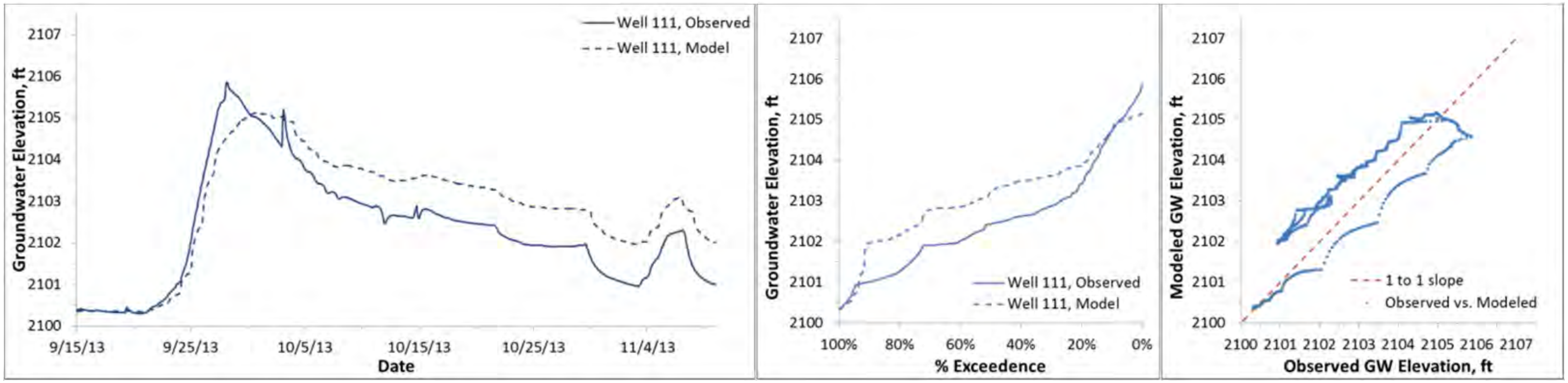


Figure D13. Modeled and observed heads, Fox well 111 (ground surface elevation 2107.9 ft)

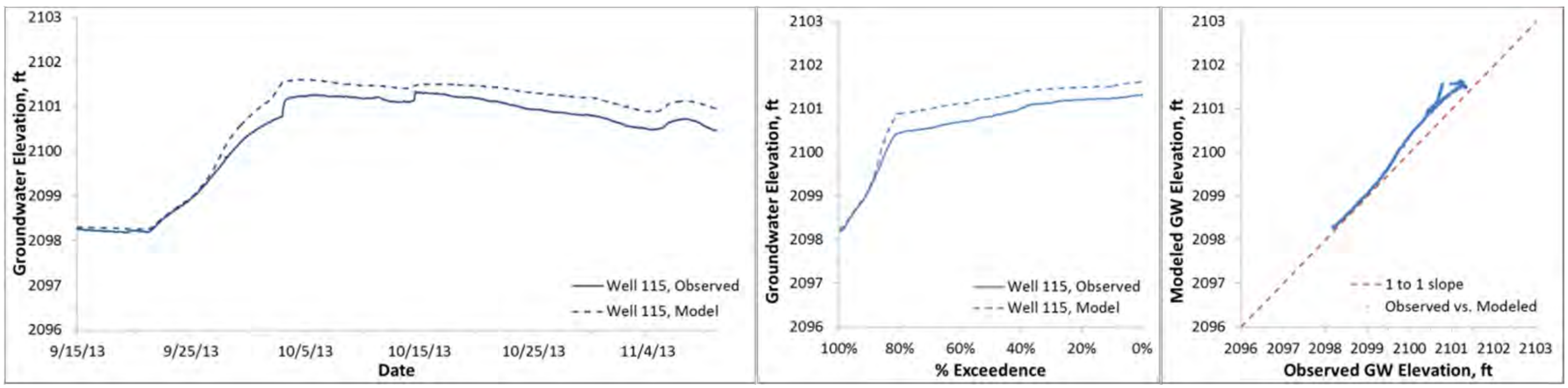


Figure D14. Modeled and observed heads, Fox well 115 (ground surface elevation 2105.9 ft)

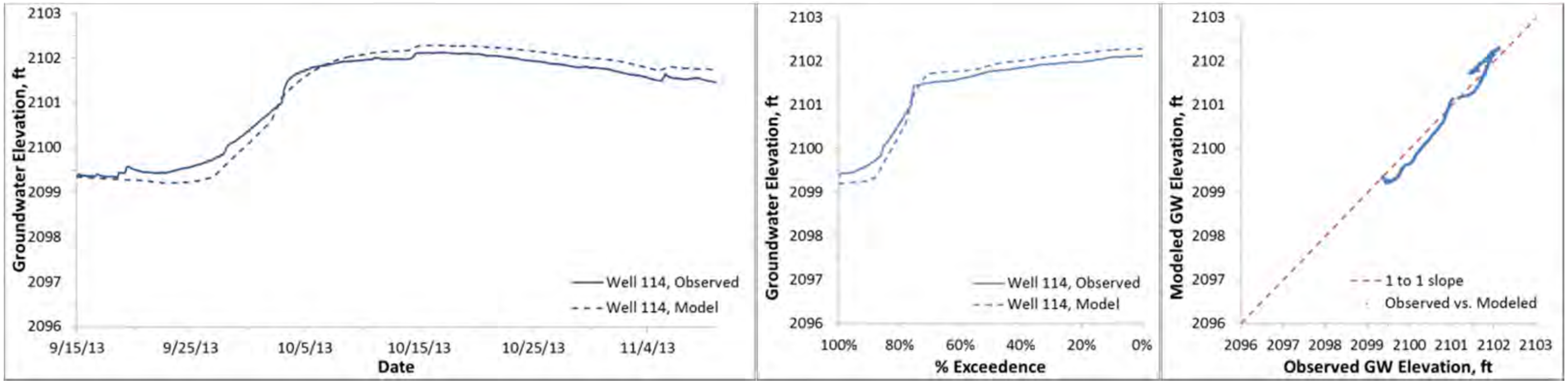


Figure D15. Modeled and observed heads, Fox well 114 (ground surface elevation 2105.6 ft)

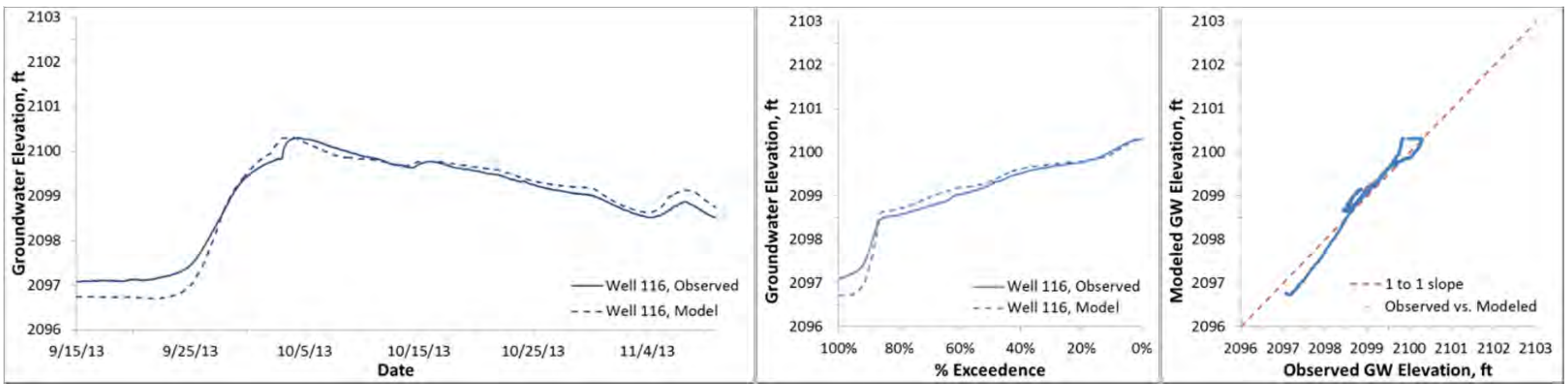


Figure D16. Modeled and observed heads, Fox well 116 (ground surface elevation 2105.0 ft)

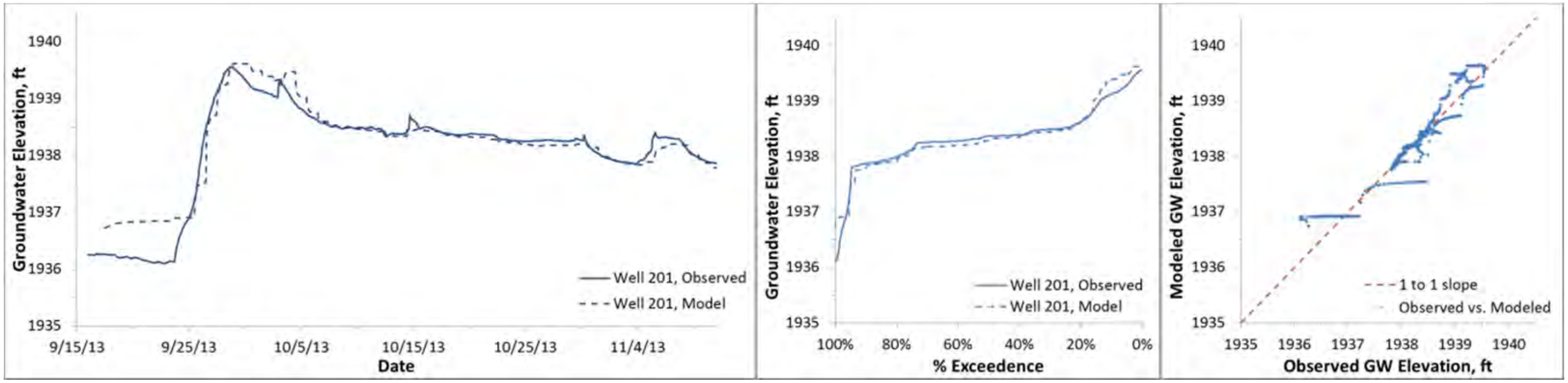


Figure D17. Modeled and observed heads, Binfield well 201 (ground surface elevation 1939.2 ft)

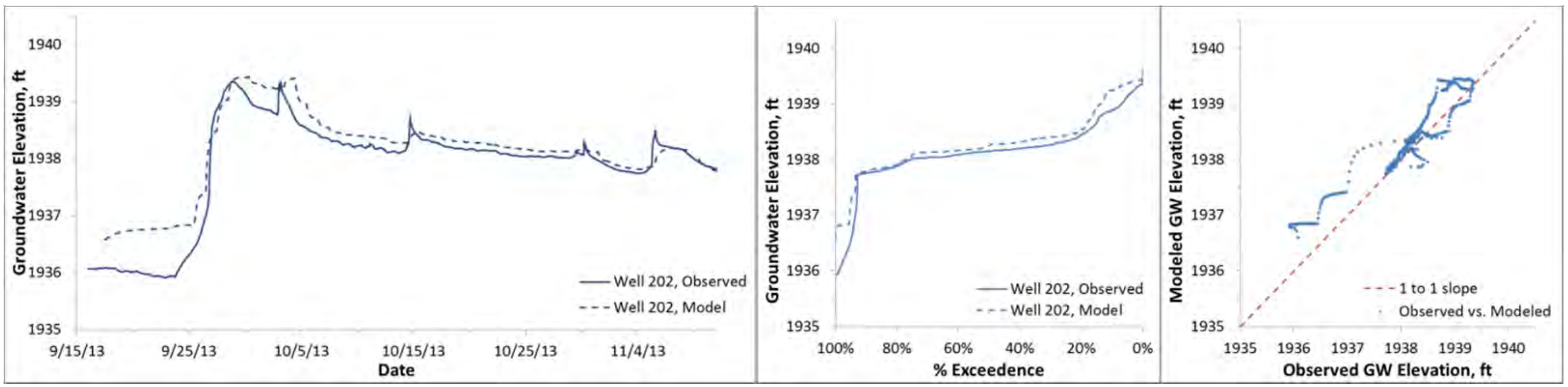


Figure D18. Modeled and observed heads, Binfield well 202 (ground surface elevation 1940.2 ft)

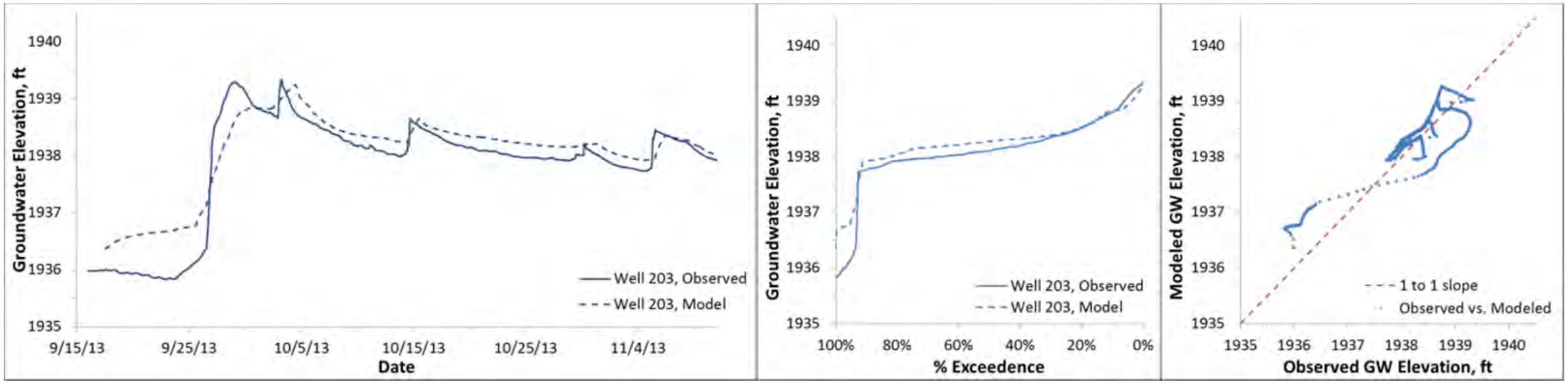


Figure D19. Modeled and observed heads, Binfield well 203 (ground surface elevation 1939.4 ft)

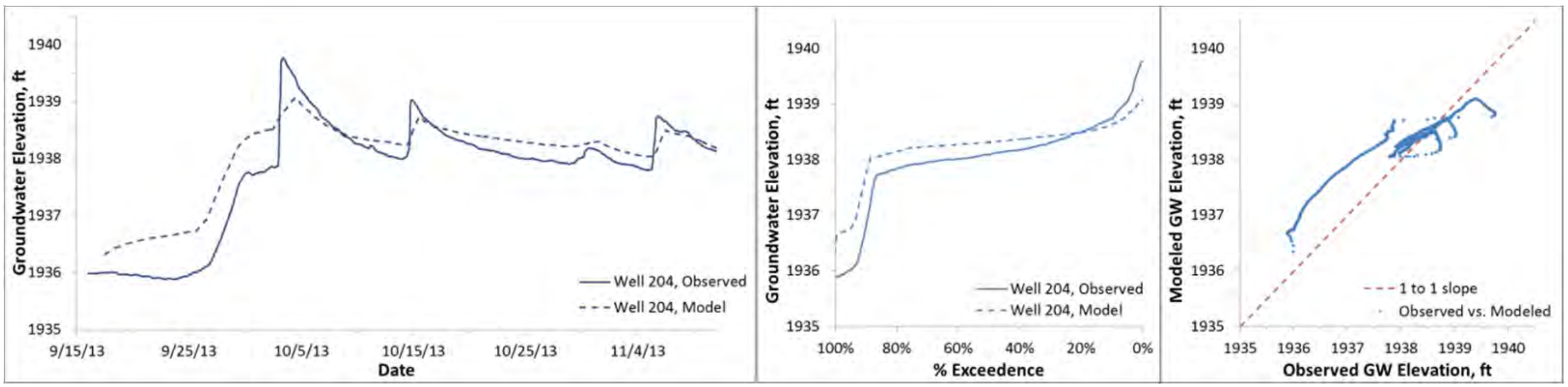


Figure D20. Modeled and observed heads, Binfield well 204 (ground surface elevation 1941.4 ft)

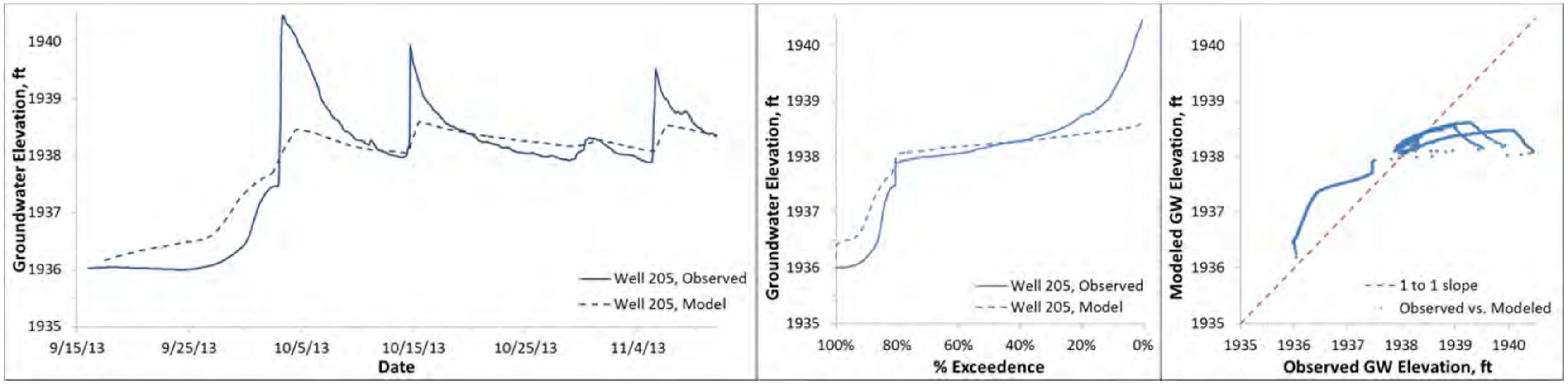


Figure D21. Modeled and observed heads, Binfield well 205 (ground surface elevation 1940.5 ft)

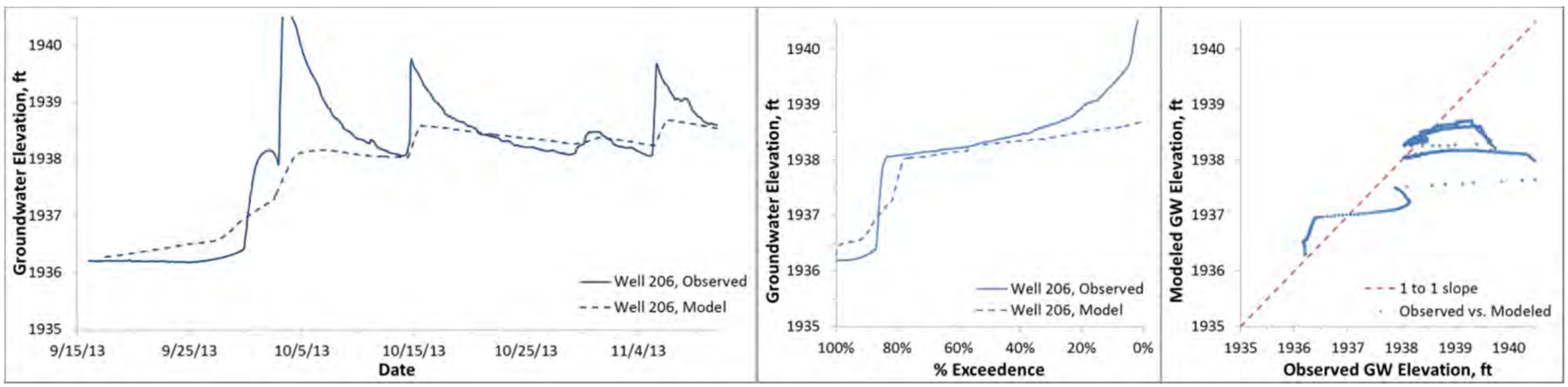


Figure D22. Modeled and observed heads, Binfield well 206 (ground surface elevation 1940.8 ft)

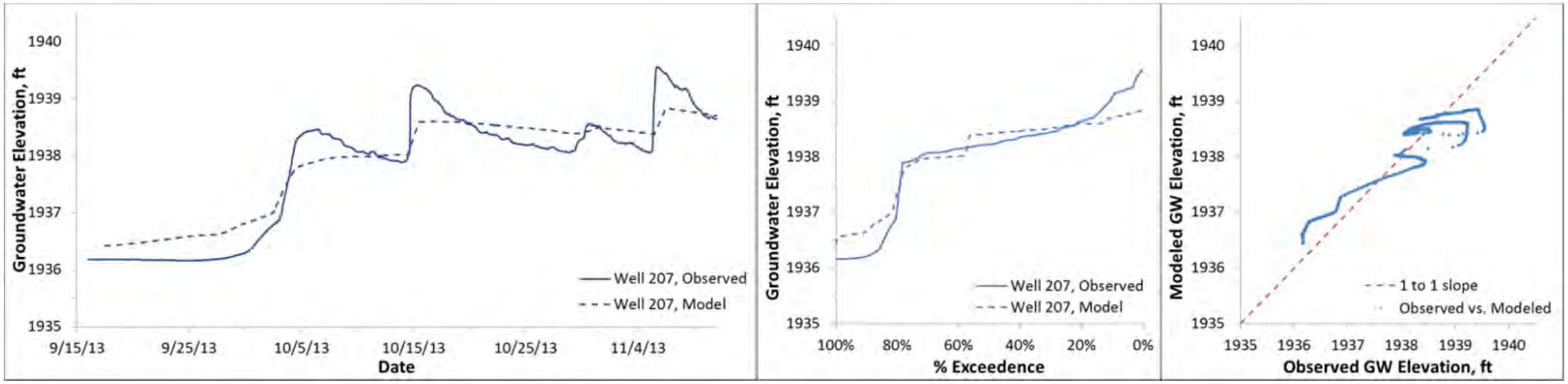


Figure D23. Modeled and observed heads, Binfield well 207 (ground surface elevation 1941.8 ft)

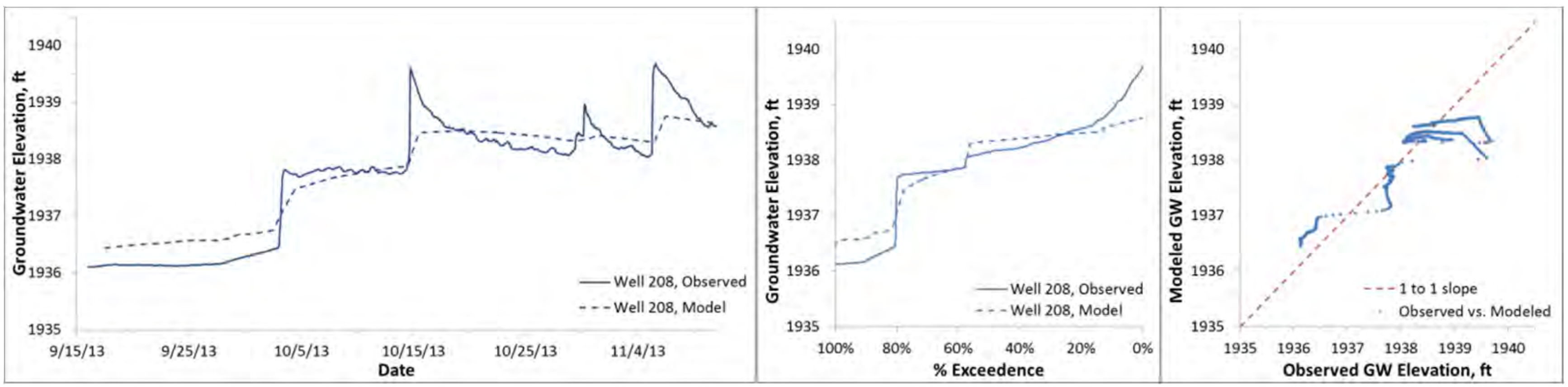


Figure D24. Modeled and observed heads, Binfield well 208 (ground surface elevation 1940.4 ft)

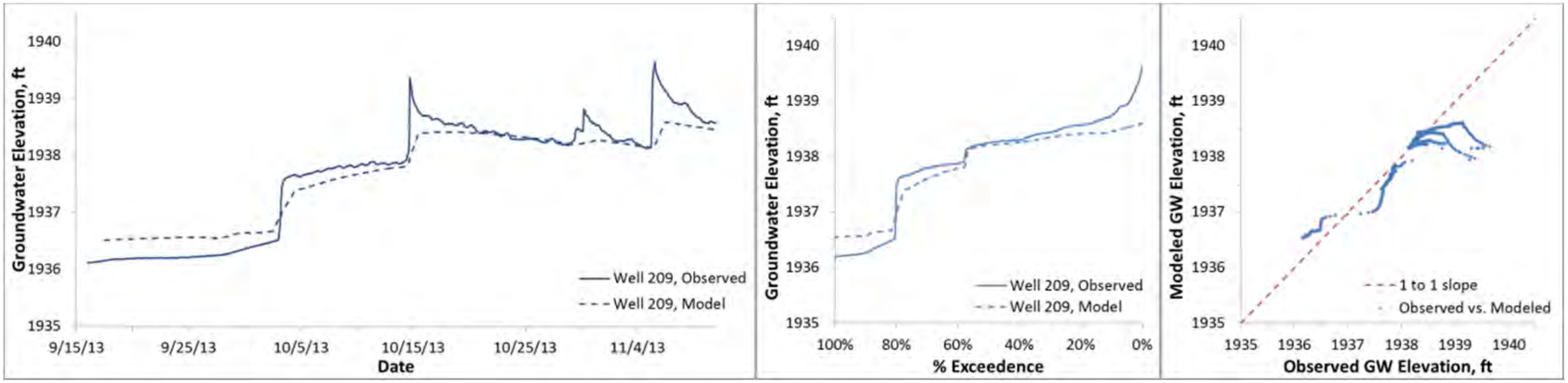


Figure D25. Modeled and observed heads, Binfield well 209 (ground surface elevation 1940.6 ft)

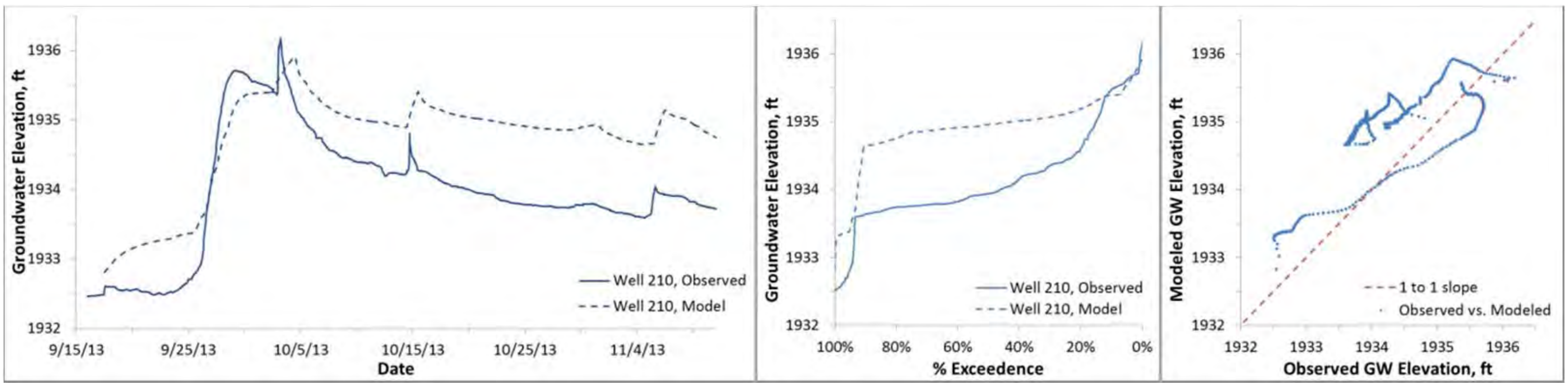


Figure D26. Modeled and observed heads, Binfield well 210 (ground surface elevation 1937.3 ft)

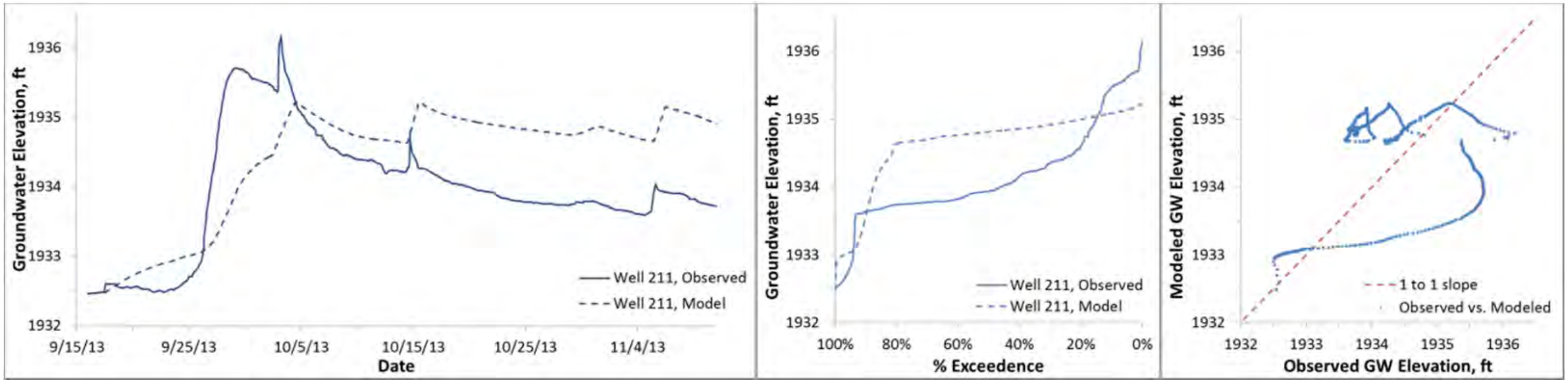


Figure D27. Modeled and observed heads, Binfield well 211 (ground surface elevation 1937.8 ft)

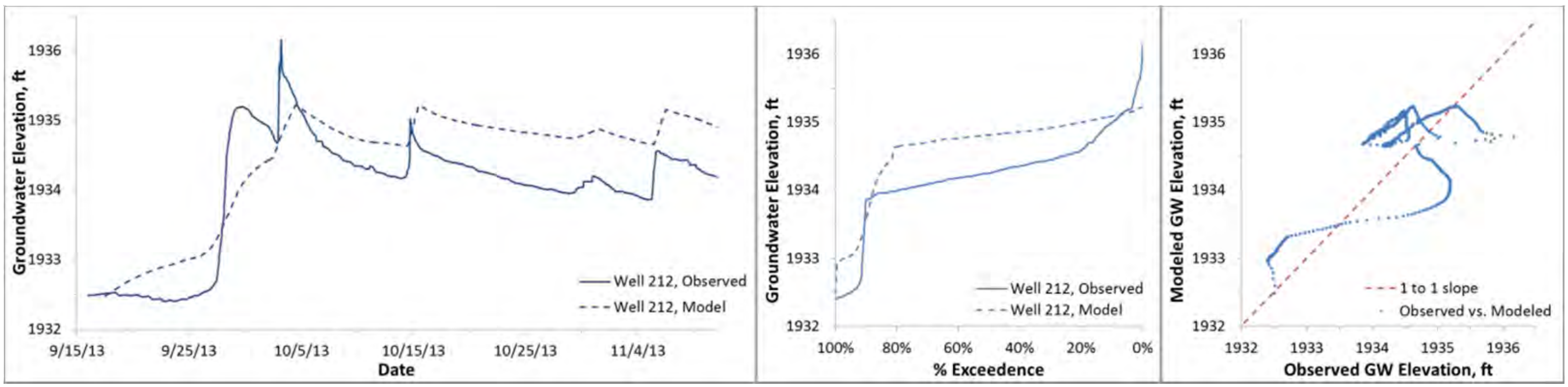


Figure D28. Modeled and observed heads, Binfield well 212 (ground surface elevation 1937.7 ft)

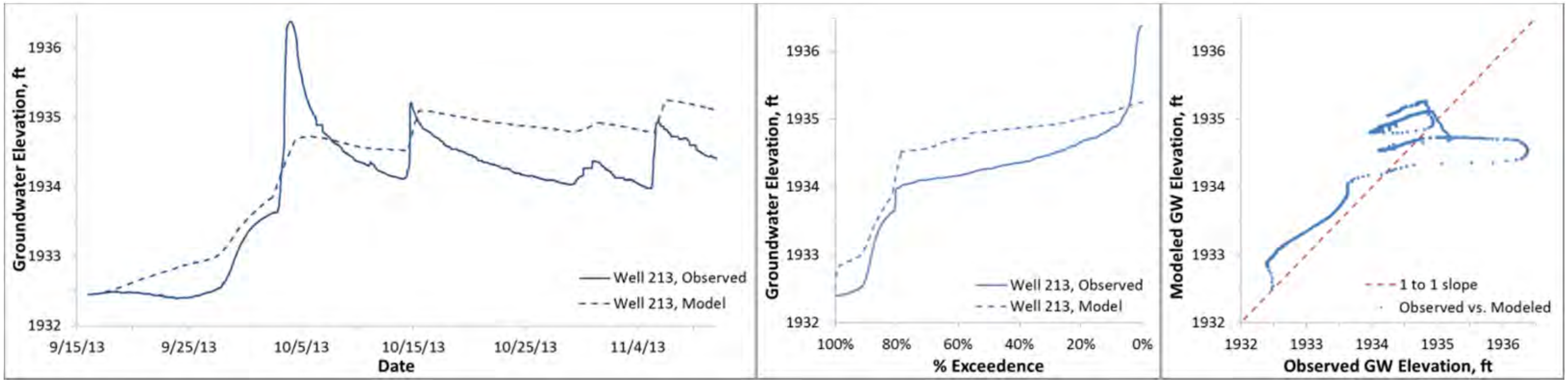


Figure D29. Modeled and observed heads, Binfield well 213 (ground surface elevation 1937.3 ft)

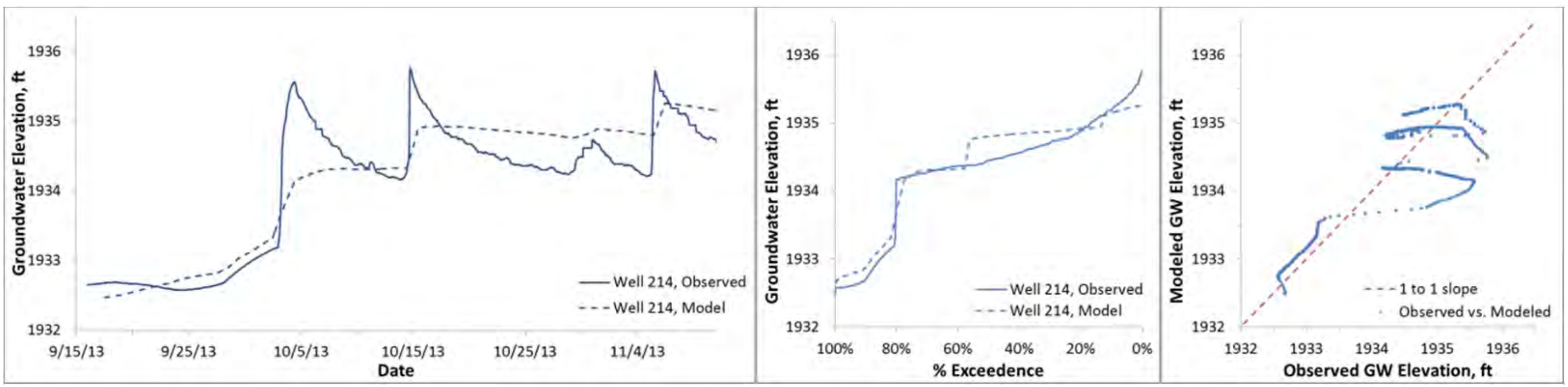


Figure D30. Modeled and observed heads, Binfield well 214 (ground surface elevation 1936.7 ft)

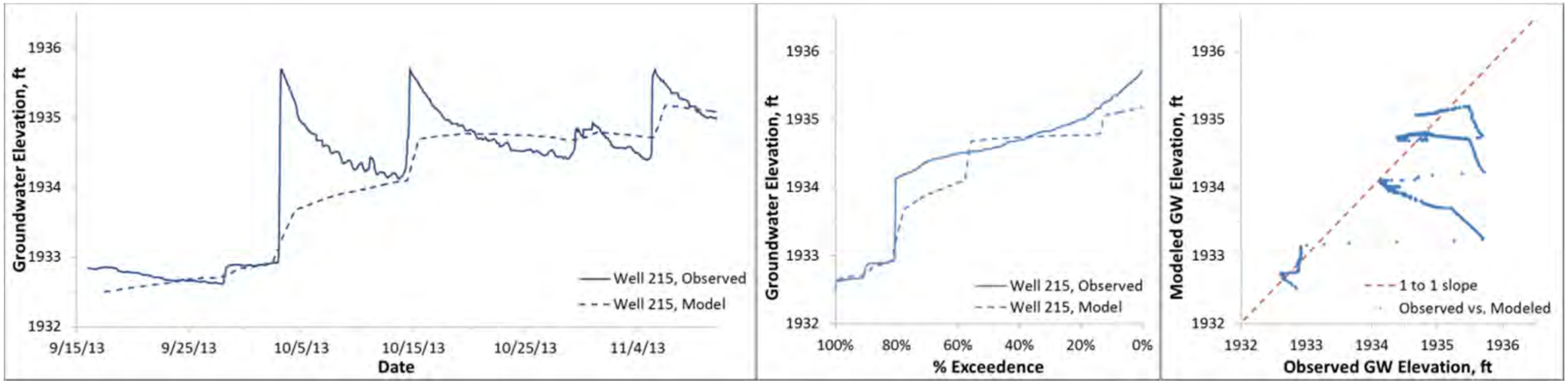


Figure D31. Modeled and observed heads, Binfield well 215 (ground surface elevation 1936.4 ft)

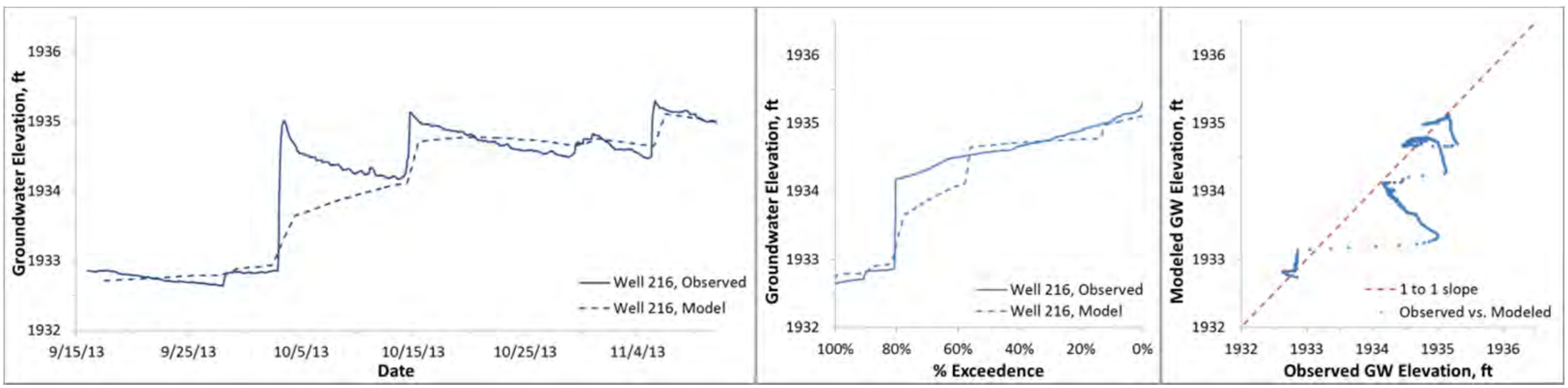


Figure D32. Modeled and observed heads, Binfield well 216 (ground surface elevation 1936.3 ft)

Chapter 4 APPENDIX E: RMSE SPATIAL DISTRIBUTION

The RMSE values for the monitoring wells on the Fox and Binfield sites for the annual and event models are shown below; refer to **Figures 5** and **6** for well locations. Wells 101-111 comprise the western transect and wells 114-116 comprise the eastern transect on the Fox site. Wells 201-209 comprise the western transect and wells 210-216 comprise the eastern transect on the Binfield site.

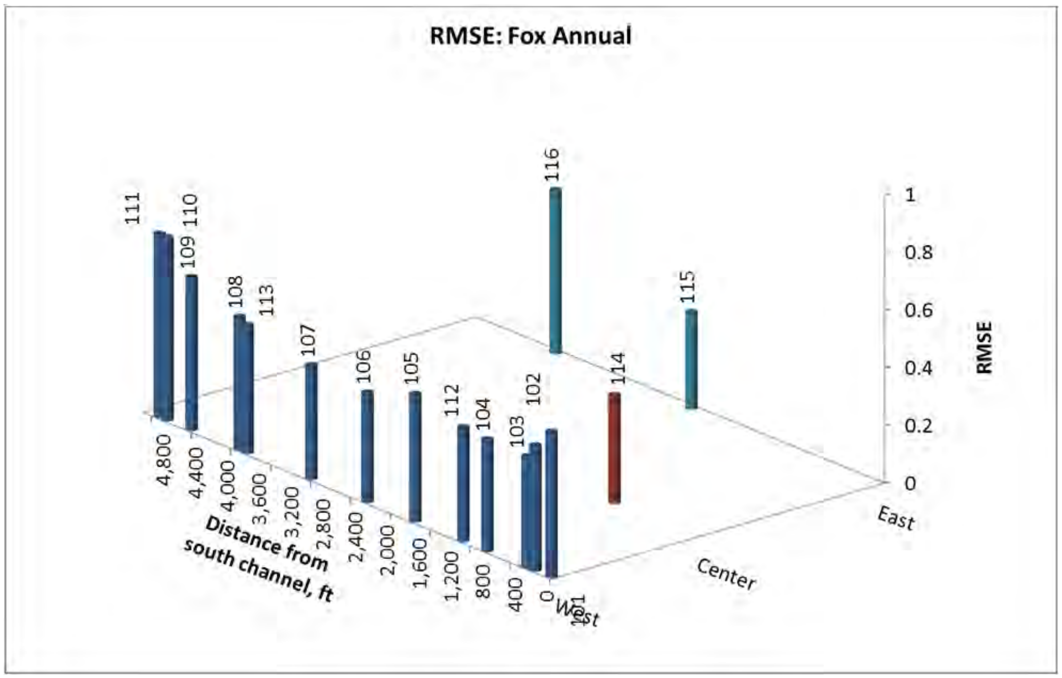


Figure E1. RMSE values for the Fox annual model

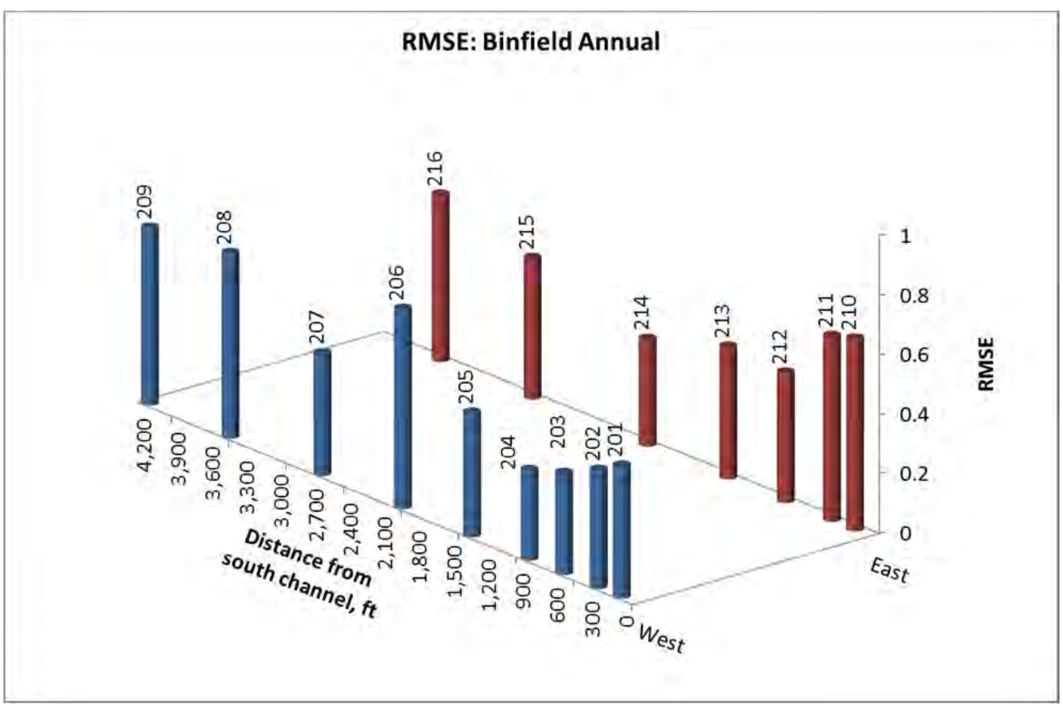


Figure E2. RMSE values for the Binfield annual model

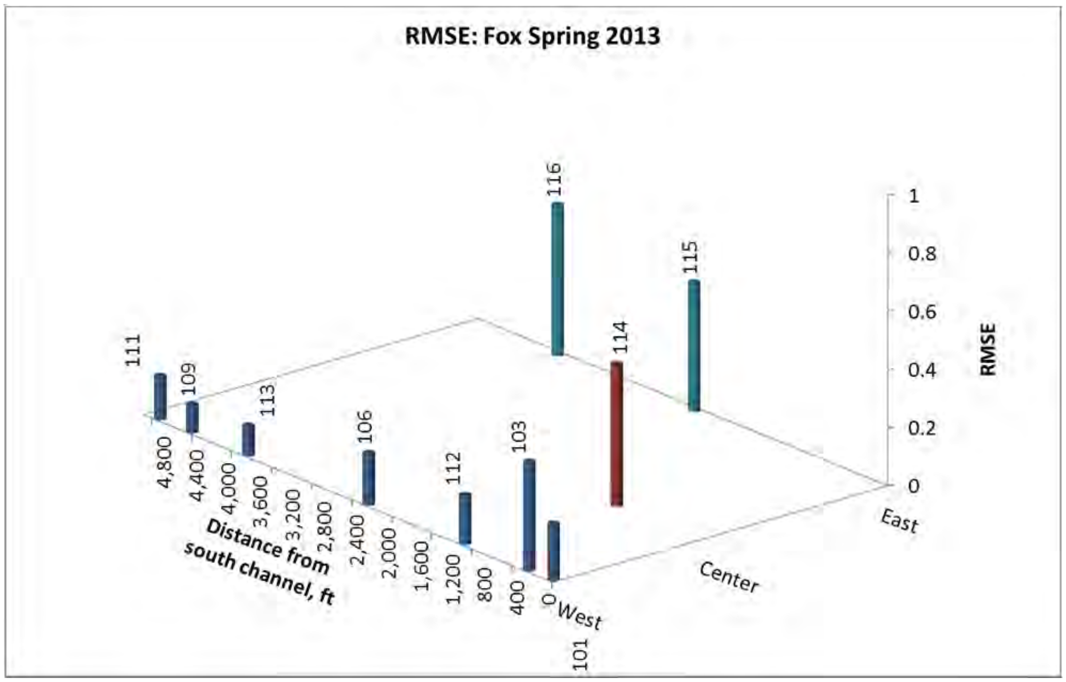


Figure E3. RMSE values for the Fox spring 2013 model

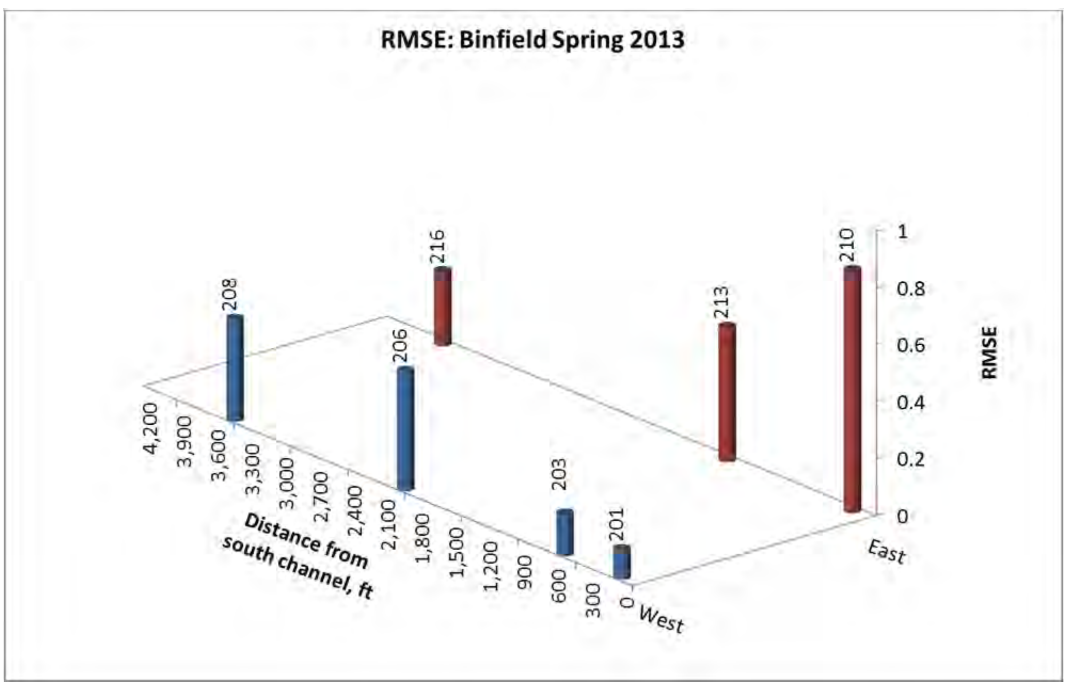


Figure E4. RMSE values for the Binfield spring 2013 model

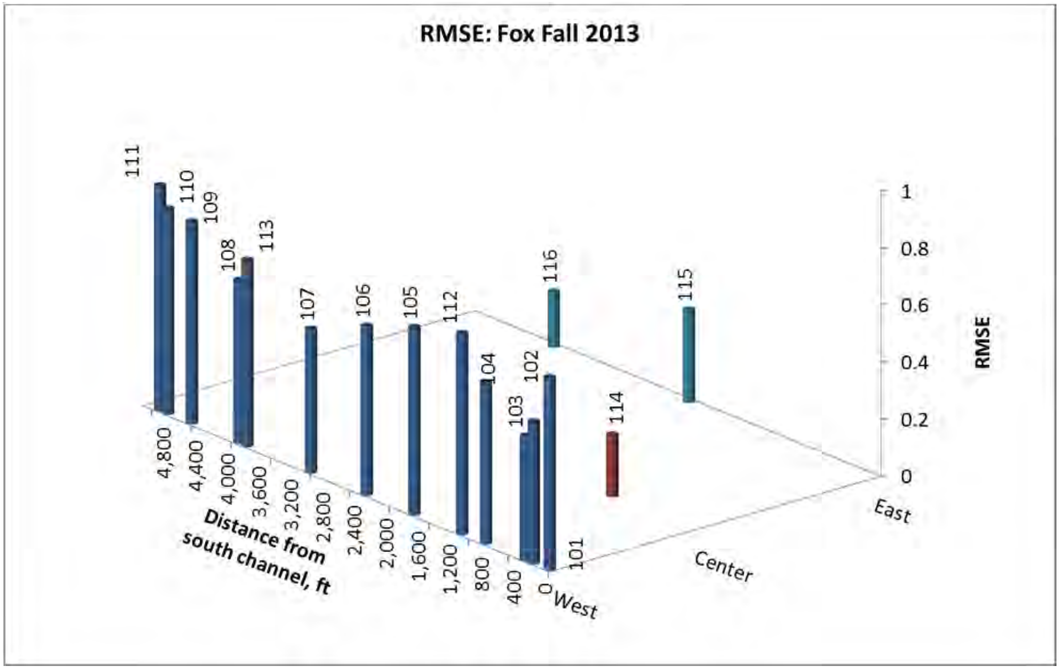


Figure E5. RMSE values for the Fox fall 2013 model

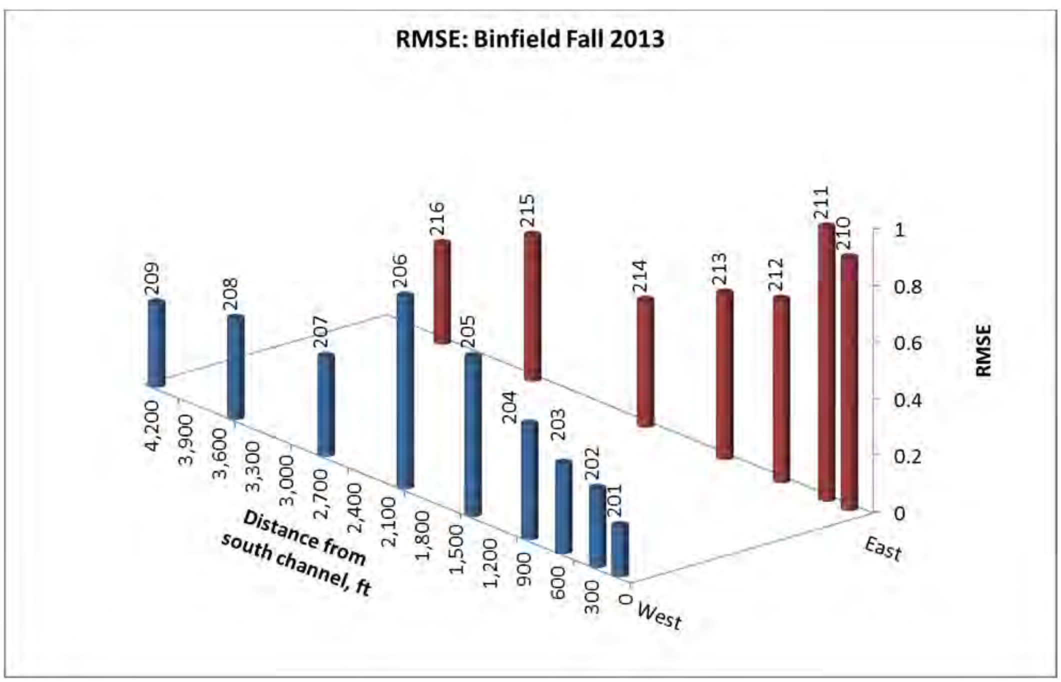


Figure E6. RMSE values for the Binfield fall 2013 model

CHAPTER 4 APPENDIX F: GROUNDWATER ELEVATION MAPS

Contour maps of groundwater elevations and color fill maps of depth to groundwater are presented in Figures **F1** through **F10**. Local areas of higher elevation appear in the color fill maps as areas of greater groundwater depth in red and orange colors. Berms located in the north central portion of the Fox site and in the north eastern corner of the Binfield site appear in the color fill maps. While groundwater elevation is consistent in these areas, depth to groundwater is greater in these areas due to higher ground surface elevations.

Fox Annual Model

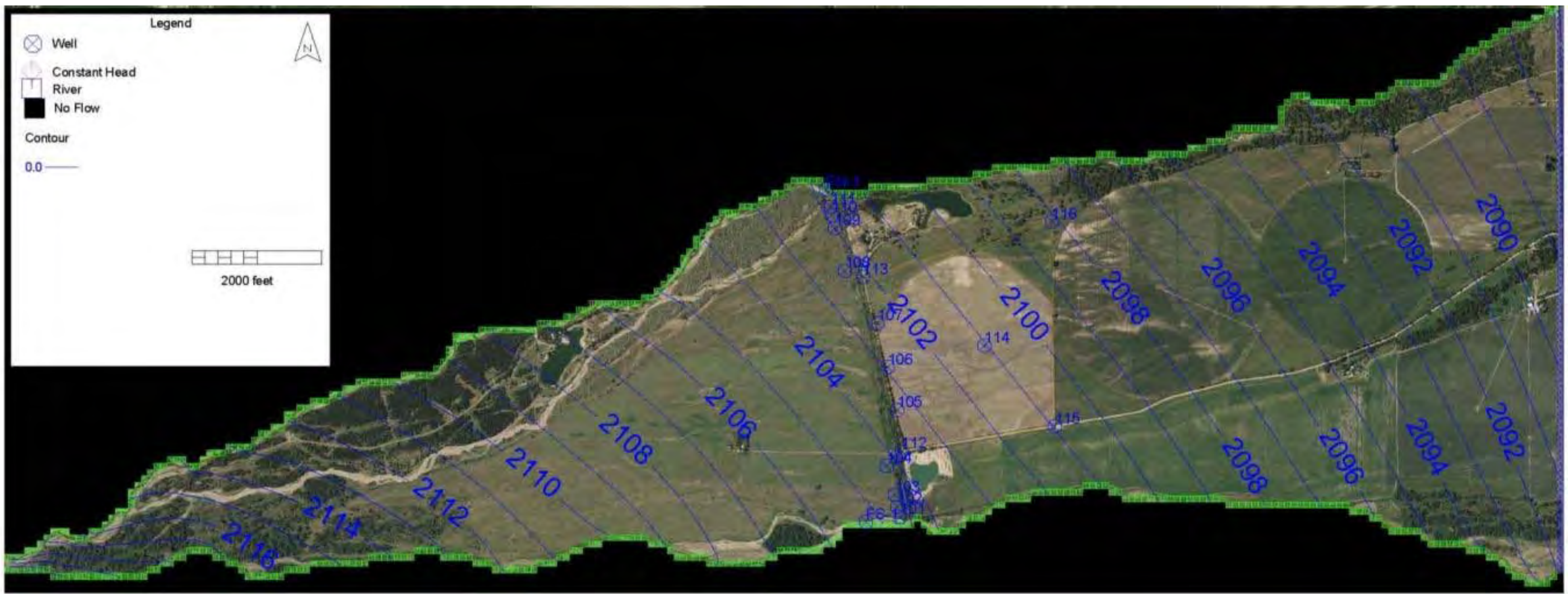


Figure F1. Fox annual model map and groundwater contours at the end of the model run.

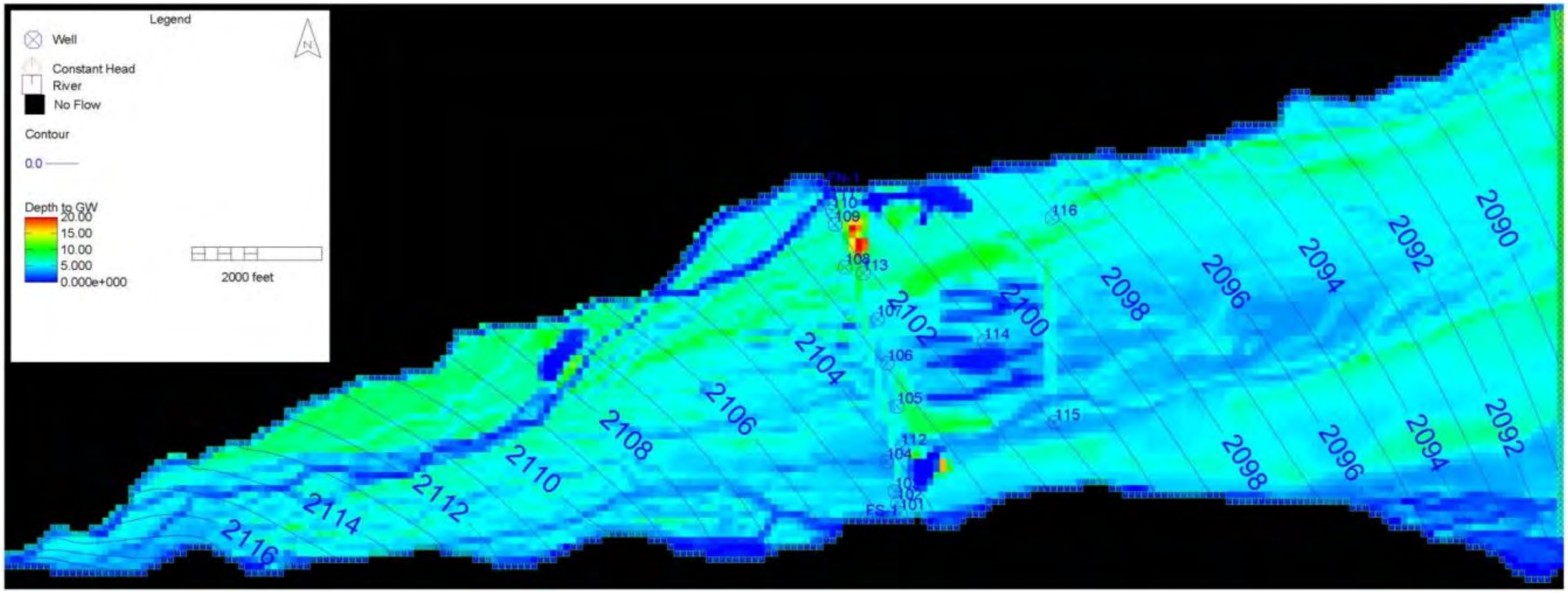
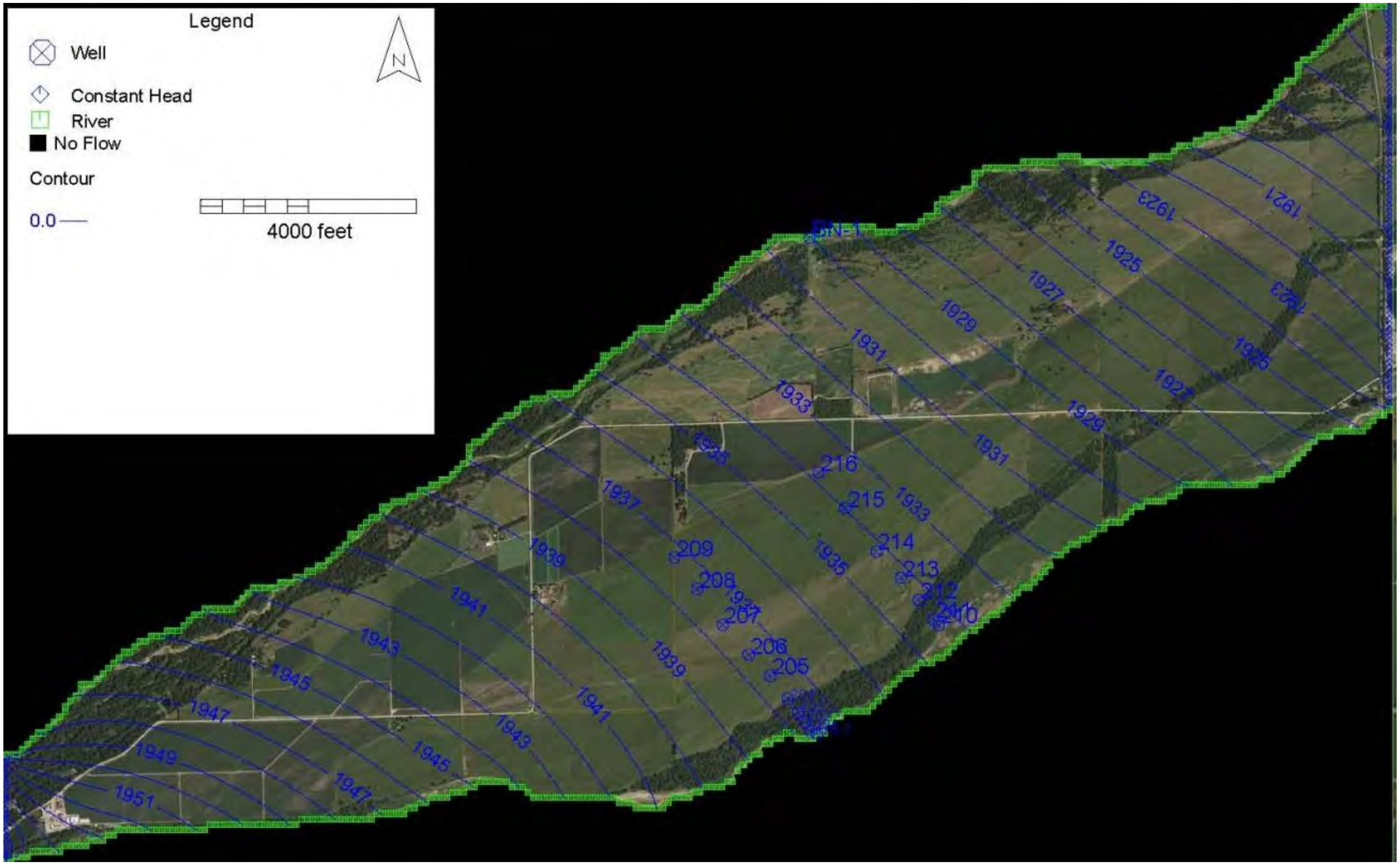


Figure F2. Fox annual model depth to groundwater and groundwater contours at the end of the model run.

994 ***Binfield Annual Model***

995 

996 **Figure F3**. Binfield annual model map and groundwater contours at the end of the model run.

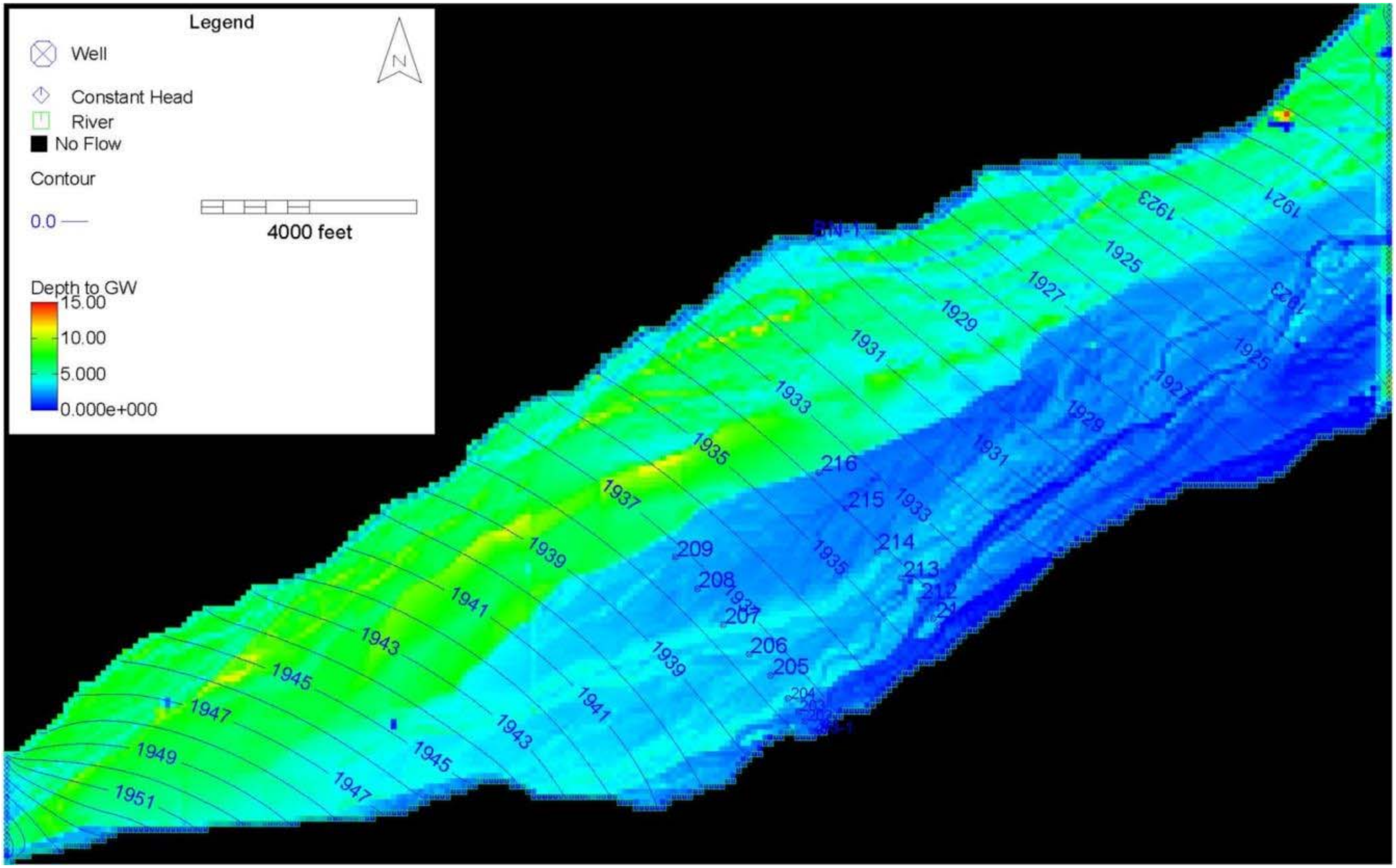


Figure F4. Binfield annual model depth to groundwater and groundwater contours at the end of the model run.

Fox Event Models

Figure F5. Fox spring 2013 model map and groundwater contours at the end of the model run.

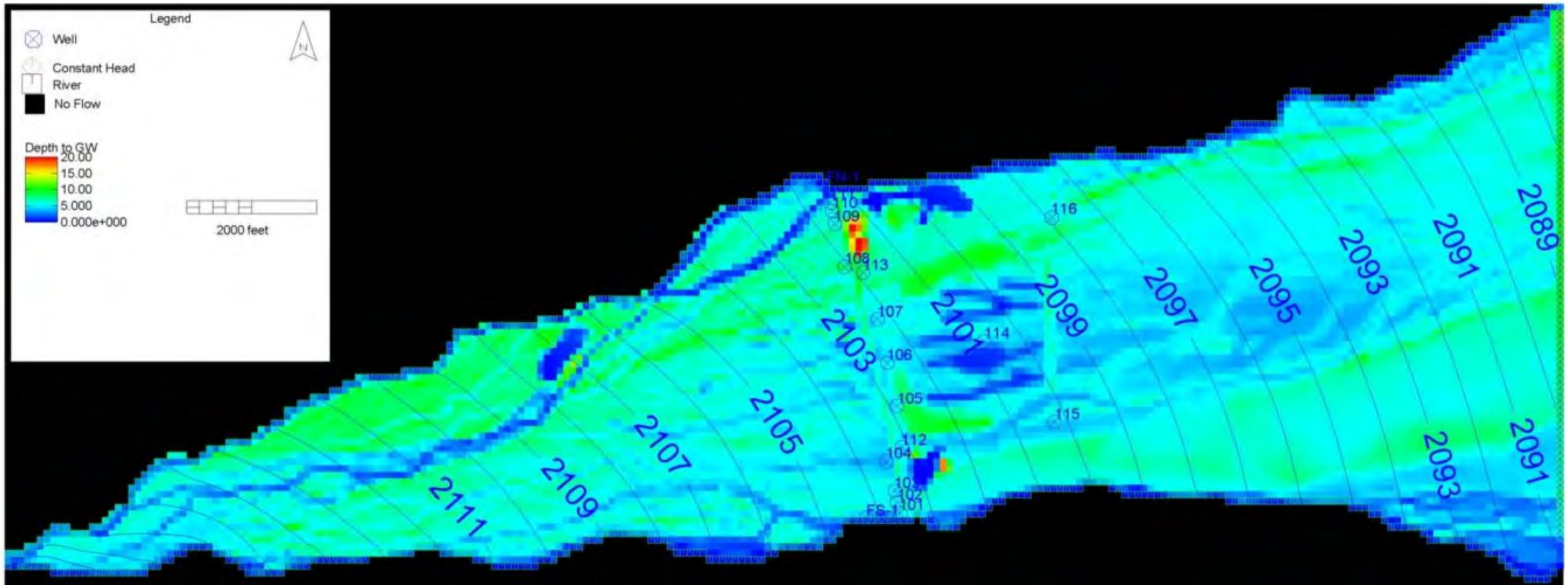
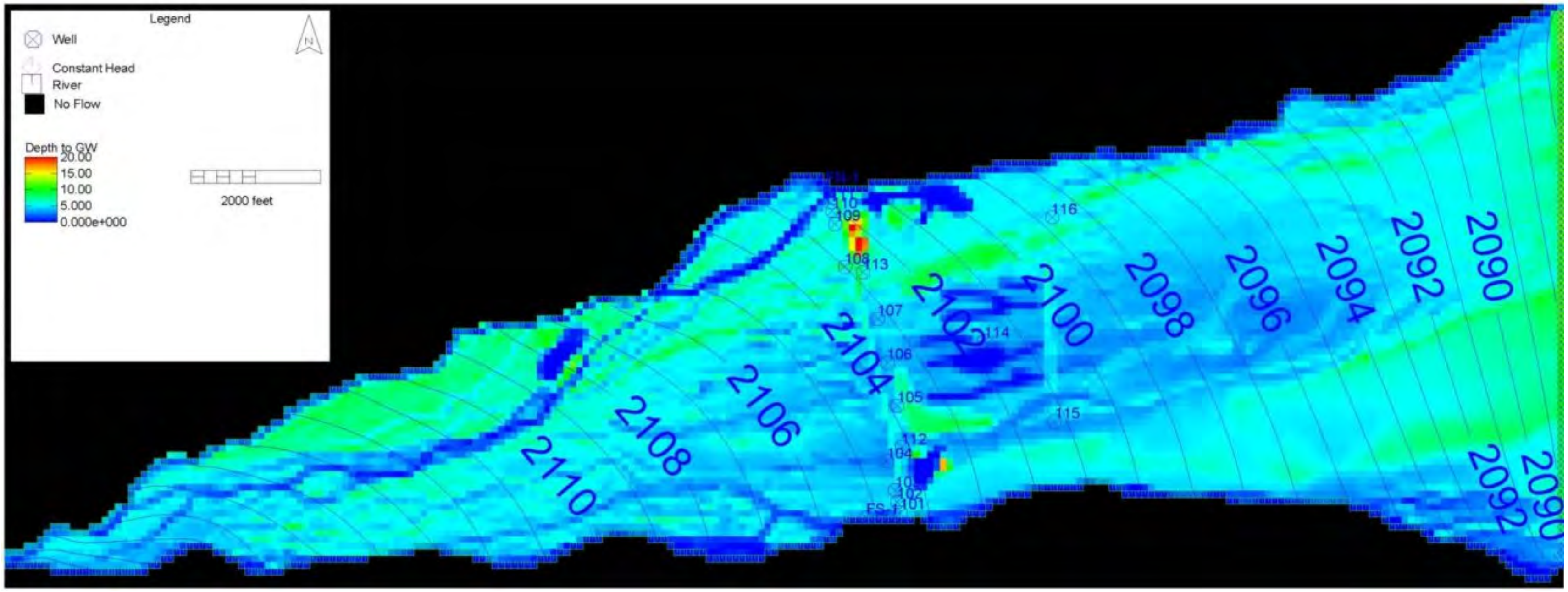


Figure F6. Fox spring 2013 model depth to groundwater and groundwater contours at the end of the model run.

Figure F5. Fox fall 2013 model map and groundwater contours at the end of the model run.



1006
1007 **Figure F6**. Fox fall 2013 model depth to groundwater and groundwater contours at the end of the model run.

Binfield Event Models

Figure F7. Binfield spring 2013 model map and groundwater contours at the end of the model run.

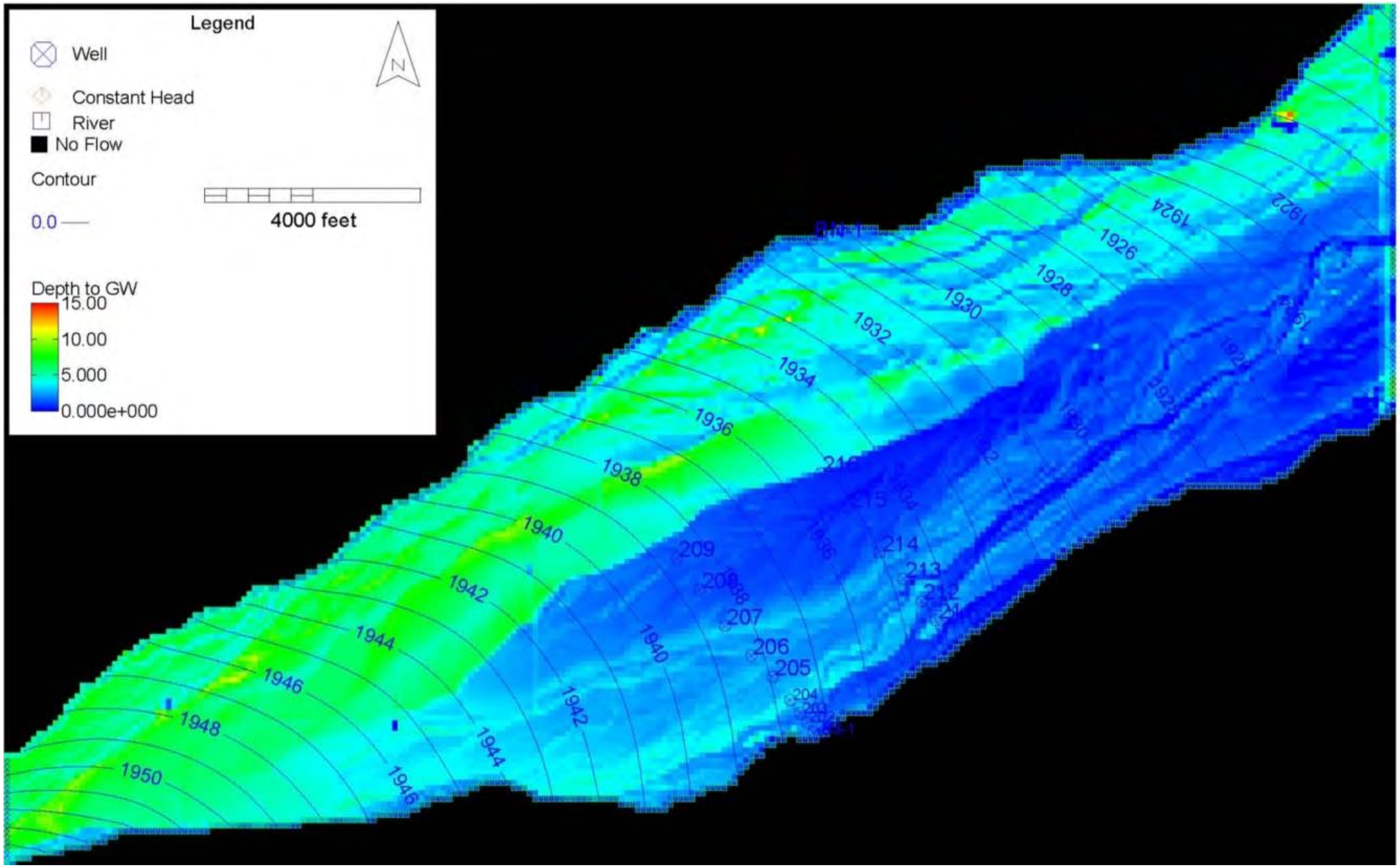


Figure F8. Binfield spring 2013 model depth to groundwater and groundwater contours at the end of the model run.

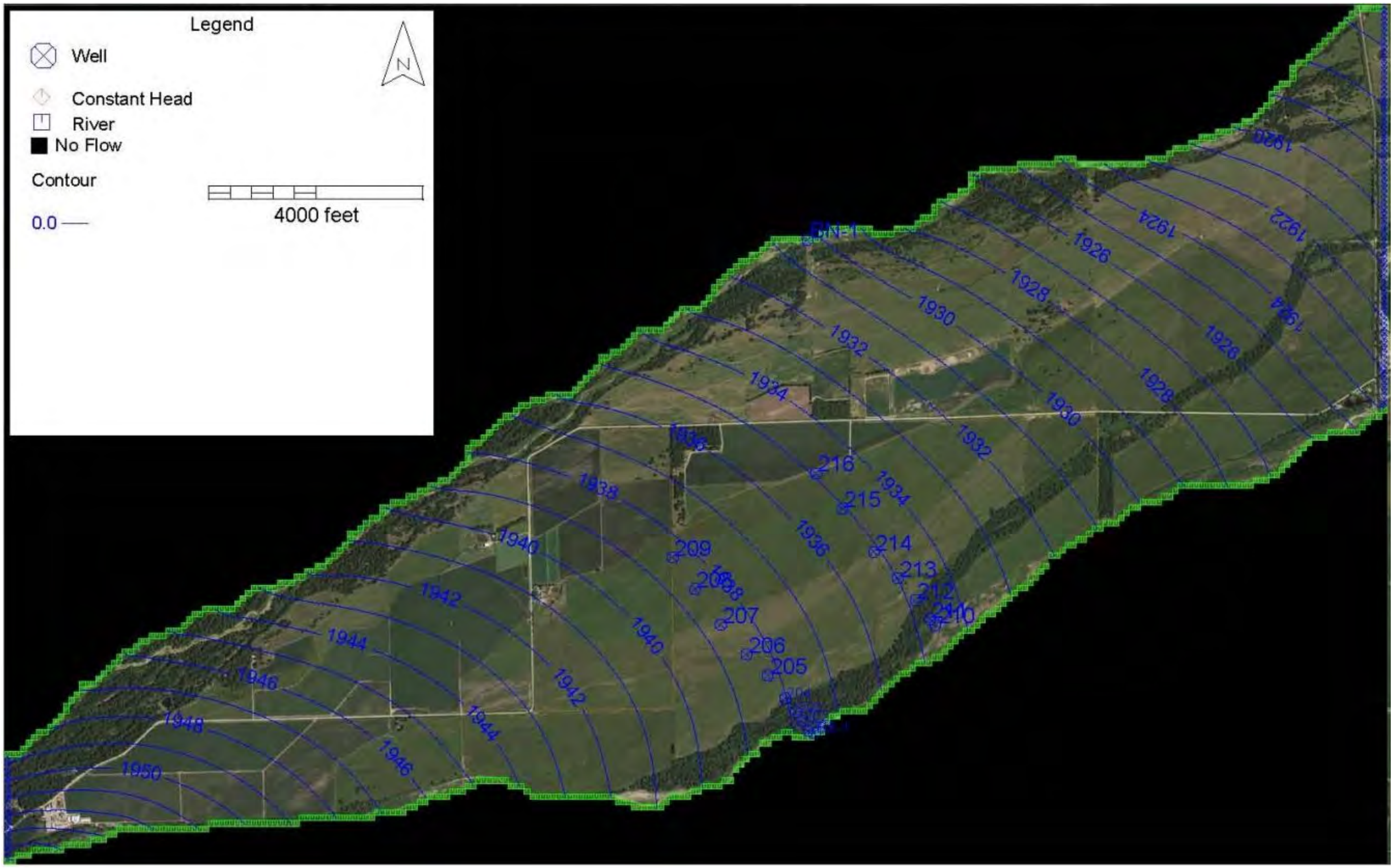
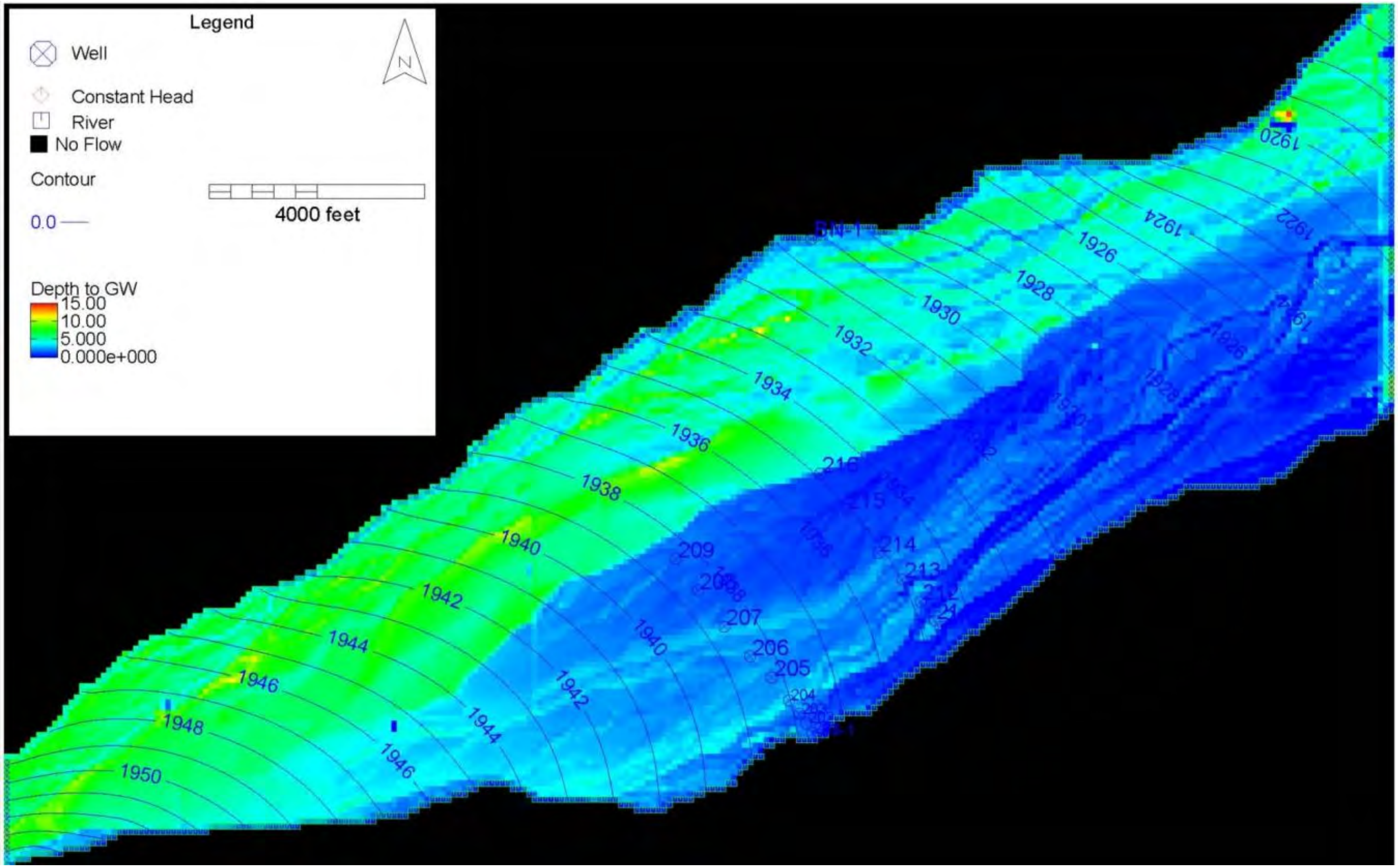


Figure F9. Binfield fall 2013 model map and groundwater contours at the end of the model run.



1015

1016 **Figure F10**. Binfield fall 2013 model depth to groundwater and groundwater contours at the end of the model run.

CHAPTER 4 APPENDIX G: EVAPOTRANSPIRATION RATES

Table G1. Evapotranspiration rates for the annual models

Stress Period	Binfield Annual ET rate (ft/day)	Fox Annual ET rate (ft/day)
1	0.0014	0.0014
2	0.0037	0.0039
3	0.0091	0.0093
4	0.0140	0.0142
5	0.0149	0.0151
6	0.0091	0.0098
7	0.0095	0.0104
8	0.0066	0.0063
9	0.0022	0.0020
10	0.0008	0.0007
11	0.0006	0.0006
12	0.0007	0.0007
13	0.0017	0.0018

Table G2. Evapotranspiration rates for the event models

Stress Period	Binfield Spring 2013 ET rate (ft/day)	Binfield Fall 2013 ET rate (ft/day)	Fox Spring 2013 ET rate (ft/day)	Fox Fall 2013 ET rate (ft/day)
1	0.0013	0.0072	0.0013	0.0052
2	0.0010	0.0074	0.0013	0.0072
3	0.0018	0.0058	0.0010	0.0096
4	0.0019	0.0086	0.0018	0.0133
5	0.0025	0.0141	0.0019	0.0081
6	0.0030	0.0135	0.0025	0.0058
7	0.0018	0.0080	0.0029	0.0097
8	0.0027	0.0118	0.0020	0.0149
9	0.0033	0.0103	0.0030	0.0112
10	0.0044	0.0074	0.0037	0.0080
11	0.0043	0.0057	0.0044	0.0079
12	0.0046	0.0025	0.0048	0.0090
13	0.0078	0.0071	0.0047	0.0065
14	0.0070	0.0037	0.0077	0.0049
15	0.0032	0.0077	0.0075	0.0021
16	0.0028	0.0074	0.0033	0.0067
17	0.0011	0.0105	0.0030	0.0036
18	0.0008	0.0084	0.0014	0.0060

Table G2 (Continued). Evapotranspiration rates for the event models

Stress Period	Binfield Spring 2013 ET rate (ft/day)	Binfield Fall 2013 ET rate (ft/day)	Fox Spring 2013 ET rate (ft/day)	Fox Fall 2013 ET rate (ft/day)
19	0.0019	0.0075	0.0007	0.0071
20	0.0031	0.0065	0.0017	0.0108
21	0.0047	0.0050	0.0028	0.0091
22	0.0043	0.0070	0.0049	0.0083
23	0.0033	0.0022	0.0048	0.0062
24	0.0032	0.0034	0.0037	0.0047
25	0.0007	0.0041	0.0034	0.0074
26	0.0019	0.0033	0.0007	0.0026
27	0.0044	0.0028	0.0018	0.0037
28	0.0045	0.0049	0.0042	0.0036
29	0.0060	0.0051	0.0046	0.0033
30	0.0005	0.0038	0.0060	0.0024
31	0.0029	0.0041	0.0005	0.0048
32	0.0052	0.0045	0.0034	0.0046
33	0.0088	0.0020	0.0054	0.0039
34	0.0069	0.0051	0.0088	0.0039
35	0.0066	0.0044	0.0077	0.0046
36	0.0102	0.0073	0.0064	0.0018
37	0.0086	0.0032	0.0108	0.0049
38	0.0080	0.0001	0.0084	0.0037
39	0.0016	0.0008	0.0079	0.0061
40	0.0083	0.0041	0.0018	0.0029
41	0.0092	0.0025	0.0091	0.0001
42	0.0059	0.0022	0.0099	0.0011
43	0.0069	0.0030	0.0065	0.0027
44	0.0086	0.0017	0.0079	0.0022
45	0.0027	0.0004	0.0087	0.0024
46	0.0047	0.0008	0.0043	0.0024
47	0.0021	0.0014	0.0057	0.0028
48	0.0090	0.0018	0.0031	0.0016
49	0.0131	0.0015	0.0098	0.0003
50	0.0127	0.0010	0.0134	0.0009
51	0.0172	0.0015	0.0120	0.0013
52	0.0150	0.0012	0.0167	0.0015

APPENDIX A – Independent Peer Review Report

Peer Review of *Platte River Recovery Implementation Program Wet Meadows Hydrologic Monitoring Approach*

Draft Summary Report

November 2015

Louis Berger

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Background

The Executive Director's Office (EDO) of the Platte River Recovery Implementation Program (Program) prepared a series of four documents (hereafter referred to as "chapters") describing the Program's approach to monitoring the hydrologic processes at four Program wet meadow sites. The Program began a hydrologic monitoring effort in 2013 focusing on the dominant hydrologic processes occurring at wet meadow sites. The objective of the monitoring effort is to inform the use of Program land, water, and fiscal resources to create, maintain, and/or enhance wet meadows environments along the Associated Habitat Reach (AHR) of the Central Platte River (the Associated Habitat Reach consists of a 90-mile reach of the Platte River in central Nebraska from Lexington to Chapman). The monitoring effort will continue through the end of the Program's first increment in 2019. Data collected as part of the effort will be analyzed to better quantify the relationship between the dominant hydrologic processes. A suite of groundwater models will aid in this analysis. The findings from the monitoring effort will be compiled and undergo peer review toward the end of the Program's first increment.

The Platte River Recovery Implementation Program (Program) is intended to address issues related to endangered species and the loss of critical seasonal habitat in the Platte River in central Nebraska by managing land and water resources using the principles of adaptive management (AM). The application of AM to the Platte River will provide benefits for four protected species (i.e., Whooping Crane, Interior Least Tern, Piping Plover, and Pallid Sturgeon). A critical issue for the Program is understanding the distribution and movement of groundwater at Platte River wet meadow sites.

The Program conducted a peer review of four chapters describing the Program's approach to monitoring the hydrologic processes at four wet meadow sites, as well as the groundwater model developed to assist in hydrologic analysis. The chapters are intended to ensure the monitoring approach is adequate to achieve the monitoring effort's objectives.

1.2 Purpose and Scope of Peer Review

The purpose of this review is to provide a formal, independent, external scientific peer review of the information presented in the four monitoring approach documents. Reviewers were charged with reviewing the monitoring approach, as described in all four chapters, from their particular area of expertise and assessing its sufficiency in addressing the monitoring project's objectives. Factors to be addressed include the scientific merit of the monitoring approach and providing suggestions for its improvement. The peer reviewers were tasked with ensuring any scientific uncertainties are clearly identified and characterized, and the potential implications of the uncertainties for the technical conclusions drawn are clear.

Specifically, the PRRIP requested that reviewers consider and respond to the questions listed below, at a minimum, in their reviews.

General Questions

1. Are the objectives of the monitoring effort clear and obtainable?

2. Will the monitoring approach provide sound and comprehensive data to achieve the Monitoring Plan's objectives?

3. Please identify any additional monitoring equipment or procedures that would allow this study to better achieve its objectives.

4. Are potential biases, errors, or uncertainties appropriately considered within these chapters?

Chapter-Specific Questions

CHAPTER 1

5. Does the conceptual model presented capture all the relevant hydrologic processes? Does it ignore any critical processes?

6. To what degree is the assumption that precipitation can act as a surrogate for overland application of water appropriate?

7. The monitoring approach assumes the understanding of wet meadow hydrologic processes gained through the higher level of monitoring at the Fox and Binfield site can be applied to the Johns and Morse site which receive less extensive monitoring. Is this a reasonable assumption?

8. Given the information currently available, is the well placement and density appropriate to capture site-wide groundwater behavior at each of the four sites?

9. Is the assumption of minimal off-site runoff reasonable?

10. Is the assumption that near surface groundwater behavior is not driven by the behavior of the deeper alluvial aquifer on a daily time scale reasonable?

11. Is the assumption that percolation into the underlying aquifer has a negligible impact on near surface groundwater behavior reasonable?

12. Are single river stage gages used in conjunction with surface water models sufficient to capture surface water behavior at a wet meadow site?

13. Is the approach to relating river stage and discharge reasonable?

14. Is the assumption that precipitation falls fairly uniformly across a wet meadow site reasonable?
15. Does the monitoring approach adequately measure the timing and magnitude of snowmelt and soil freeze/thaw behavior to account for the impact of these processes on groundwater behavior?

CHAPTER 2

16. Does the review of methods of determining ET omit any commonly used method?

17. Are the conclusions drawn from the comparison of methods reasonable and scientifically sound?

18. Is the use of the crop coefficients developed by the USGS for riparian grassland reasonable? Are there other crop coefficients that would provide better results?

CHAPTER 3

19. Does the conceptual soil moisture water balance accurately approximate expected soil moisture behavior at wet meadow sites?

20. Does the soil moisture monitoring approach provide and appropriate level of detail in light of the project's objectives?

CHAPTER 4

21. Is the model domain appropriate to capture groundwater behavior at the wet meadow sites?

22. Is the assumption of a homogeneous aquifer clearly supported and appropriate?

23. Are the model boundary conditions appropriate?

24. Is the use of the MODFLOW evapotranspiration (EVT) package appropriate? Would combining the precipitation and evapotranspiration values into the recharge (RCH) package better represent the physical system?

25. Is the assumption that standing surface water storage is negligible and no surface storage term in the groundwater models reasonable?

26. Can the model adequately simulate the effects ice flows and river stage increases caused by ice dams?

27. Overall, do the models capture the groundwater behavior at the two sites to address the monitoring effort's objectives?

2.0 PEER REVIEW PROCESS

Louis Berger was retained by the PRRIP to facilitate the peer review process. Louis Berger' responsibilities in the peer review process included 11 steps:

1. Develop a clear understanding of the required expertise of each position;
2. Conduct a search for potential candidates;
3. Contact prospective candidates to screen for criteria and conflict of interest;
4. Obtain CVs/resumes, biographical sketch forms, and signed "no-conflict-of-interest" statements from all candidates;
5. Compile a summary report describing recruitment process and candidate qualifications;
6. Communicate with reviewers regarding the selection process;
7. Discuss the scope and charge with the EDO;
8. Participate in an organizational conference call with the reviewers;
9. Distribute materials and commence review;
10. Compile all peer review comments into a spreadsheet and summarize in a summary report; and
11. Submit spreadsheet and summary report to the EDO and facilitate communication between the EDO and reviewers.

2.1 Selection of Reviewers

The Program requested peer review panel member candidates that comprised the following areas of expertise: hydrologic monitoring, evapotranspiration (ET or EVT)/soil moisture, and groundwater modeling. Given the wide range of potential candidates with expertise in those broad areas, Louis Berger focused its recruitment efforts on individuals with experience in wet meadows and/or riparian wetlands, and, to the extent possible, experience in the Great Plains.

In February 2015, Louis Berger submitted a report to the Program that summarized the qualifications of eight candidate reviewers. In March 2015, the Program's Governance Committee selected three reviewers from that list. The panel comprised the following individuals (see Appendix B for biographical sketches):

Dr. Xun-Hong Chen, groundwater modeling
Dr. David Cooper, hydrologic monitoring
Dr. Venkataramana Sridhar, evapotranspiration/soil moisture

2.2 Document Review and Report Development

Following final approval of the three reviewers, Louis Berger initiated the review by distributing the files to the reviewers, including: the wet meadows monitoring approach chapters to be reviewed; the scope of work and schedule for the peer review; files of all references cited in the chapters; and the Program's Adaptive Management Plan. Files were distributed via Louis Berger's FTP site. Louis Berger staff held a kickoff call with three reviewers on April 14, 2015 to discuss the scope of work, deliverables, and schedule, and answer any questions.

Reviewers conducted their independent desktop reviewers between April 14 and May 22, 2015. Louis Berger contacted the reviewers individually to obtain clarification on their comments until June 13, 2015. Reviewers submitted the following deliverables:

1. Responses to the general and chapter-specific questions listed in Section 1.2;
2. Ratings of the set of chapters in five different categories, as well as an overall recommendation; and
3. Specific comments on the text of chapters, by line number (optional).

Upon receipt of the deliverables, Louis Berger compiled the specific comments into a spreadsheet, organized by chapter and line numbers, which was submitted to the PRRIP as a separate deliverable. Louis Berger summarized reviewer responses to the general and chapter-specific questions in this summary report, which also includes their ratings and recommendations. Individual reviewer comments are included as Appendix A. As described in the PRRIP Peer Review Guidelines, reviewers can choose whether they would like their review comments to be anonymous or attributed. Because one reviewer preferred anonymity it was applied to the entire review, thus reviewers were each assigned a number (i.e., Reviewer 1, 2, or 3), in no particular order. The reviewers had the opportunity to review the draft summary report to ensure their comments were captured accurately prior to its submittal to the Program.

3.0 RESULTS

3.1 Responses to General Questions

Below are brief summaries of the individual reviewers' responses to the four general questions posed by the PRRIP. This section is not intended to be a comprehensive summary or to be redundant with the individual comments in Appendix A, but rather attempts to capture some of the primary comments in each reviewer's response to the individual questions, as well as any themes that emerged or comments that were raised by more than one reviewer independently. For the reviewers' full comments see Appendix A and the comments spreadsheet.

Question 1: Are the objectives of the monitoring effort clear and obtainable?

All three reviewers found the monitoring objectives to be clear and obtainable, particularly if certain comments are addressed. Reviewer 1 noted that all four objectives are obtainable and can be achieved with the right scientific methods. Reviewer 2 noted that the objectives are mostly clear and obtainable, but the monitoring approach could be improved by addressing specific comments on ET, soil moisture, and groundwater. Reviewer 3 found the overall objective to quantify groundwater responses to other hydrological processes to be "very clear" and affirmed that the methods are likely to produce data that will make the objectives obtainable, particularly if additional suggestions are incorporated (e.g., see Question 3).

Question 2: Will the monitoring approach provide sound and comprehensive data to achieve the Monitoring Plan's objectives?

All reviewers responded positively to this question. Reviewer 1 stated that the approach is "generally good"; however, could be improved in many places by incorporating his suggestions. Reviewer 2 agreed that the approach will provide a "comprehensive and physically meaningful dataset" to address the project's objectives. Reviewer 3 concluded that the chapters provide an excellent description of the monitoring approaches, and which will provide useful data for analyzing hydrological processes.

Question 3: Please identify any additional monitoring equipment or procedures that would allow this study to better achieve its objectives.

All three reviewers offered recommendations for additional equipment and procedures to improve the likelihood of achieving study objectives. Reviewer 1 recommended that ET be quantified, not estimated, and that specific vegetation ET rates be used to more accurately estimate ET at study sites. He also recommended that more than one staff gauge be installed on the Platte River. Similarly, Reviewer 2 recommended that the Program measure ET more realistically (e.g., using scintillometers to derive area-averaged ET, four-component radiometers to measure long and shortwave radiation, etc.) to augment the proposed data collection effort. Reviewer 3 offered several suggestions, including: adding wells to measure groundwater usage by riparian forests in order to supplement the ET monitoring system; ensuring that there are wells co-located with each of the weather stations to provide data for the precipitation-soil moisture-groundwater recharge monitoring system; investigating and/or providing existing information on the hydraulic properties of the soil, alluvial aquifer, and streambeds.

Question 4: Are potential biases, errors, or uncertainties appropriately considered within these chapters?

Reviewer 1 noted that, in general, the uncertainties are well understood. Reviewer 2 pointed out the need for the crop coefficient approach to be local, otherwise there will be uncertainties in ET estimates and other components. Reviewer 3 noted several areas of potential bias and uncertainty, specifically the fact that ET estimation focuses on grassy areas, not riparian trees, and the areas of uncertainty in the groundwater models; he further describes these uncertainties in response to the Chapter 4 questions.

3.2 Responses to Chapter-Specific Questions

Below are brief summaries of the individual reviewers' responses to the 23 chapter-specific questions posed by the PRRIP. As noted above, these summaries are not intended to be comprehensive or redundant, but attempt to capture an overview of some of the reviewers' primary comments and identify any common themes. While there were a few common themes, in most cases reviewer comments differed significantly from one another, and reflecting their varied backgrounds and areas of expertise. Not only did they differ, but in several cases comments were contrary to one another. For the reviewers' full comments see Appendix A and the comments spreadsheet.

CHAPTER 1

Question 5: Does the conceptual model presented capture all the relevant hydrologic processes? Does it ignore any critical processes?

In response to this question, each reviewer pointed out areas of deficiency in the conceptual model. Reviewer 1 raised questions about the right model boundary and the degree of potential interaction between adjacent lands, their groundwater, and the wet meadow in Figure 2. Reviewer 2 noted that the model includes the major components, but does not account for percolation from the shallow aquifer to the deeper groundwater system. He raised several questions related to the interaction between shallow and deep groundwater systems for consideration. Reviewer 3 stated that the model captures all the important process that may interact with the groundwater system; however, it does not include groundwater ET from the riparian forests, which is an important flux component.

Question 6: To what degree is the assumption that precipitation can act as a surrogate for overland application of water appropriate?

All reviewers raised questions about the appropriateness of this assumption. Reviewer 1 noted the variable effects of precipitation on soil water content, and stated that precipitation alone cannot provide sufficient and sustained soil saturation and groundwater recharge to support and sustain wet meadows. Reviewer 2 stated that this is a reasonable assumption if hydrologic connectivity is limited and precipitation is the only input to subsurface systems; however, this has not been completely ascertained. Reviewer 3 commented that while both precipitation and overland flow cause vertical infiltration and recharge the groundwater system, repeated overland applications may eventually clog the top soil, reduce permeability, and decrease recharge rates.

Question 7: The monitoring approach assumes the understanding of wet meadow hydrologic processes gained through the higher level of monitoring at the Fox and Binfield site can be applied to the Johns and Morse site which receives less extensive monitoring. Is this a reasonable assumption?

Reviewers 1 and 3 found this assumption to be reasonable; however, Reviewer 2 disagreed. Reviewer 1 stated that if the hydrologic and soil conditions are similar and can support wet meadows vegetation, the assumption is reasonable. Reviewer 2 noted that the information provided to compare the sites is insufficient and raised several questions to elucidate whether this assumption is reasonable. Similar to Reviewer 1, Reviewer 3 saw no reason to reject this assumption given that conditions at the sites seem to be similar.

Question 8: Given the information currently available, is the well placement and density appropriate to capture site-wide groundwater behavior at each of the four sites?

Reviewer 1 commented that it appears reasonable for measuring surface water-groundwater interactions, but a more widely distributed set of wells could be helpful for developing water table maps and estimating site ET. Reviewer 2 responded that the placement and density is not appropriate to capture groundwater behavior at the sites. Reviewer 3 noted that the transect wells are well-designed to capture groundwater responses to stream stages and reflect stream infiltration during release events and floods.

Question 9: Is the assumption of minimal off-site runoff reasonable?

Reviewer 1 stated that the assumption is probably reasonable, unless there is considerable snow on the site during a period of high river discharge. Reviewer 2 commented that the assumption of no off-site runoff is not reasonable and noted that high intensity storm events can produce sheet flow that is not available for recharging the shallow aquifer or stream gains. Reviewer 3 responded that, given the flatness of the land surface and permeability of the top soils, he can accept this assumption.

Question 10: Is the assumption that near surface groundwater behavior is not driven by the behavior of the deeper alluvial aquifer on a daily time scale reasonable?

Reviewer 1 affirmed that the wet meadows water tables are highly influenced by the Platte River and suggested some methods for demonstrating this relationship. Reviewer 2 referred to his response to Question 5 regarding the need to prove there is no link (either two-way flux or one-way deep drainage) between the shallow and deep aquifers. Reviewer 3 accepted this assumption, but noted that the groundwater flow model results indicate the Platte River gains a large amount of baseflow around Binfield that may be part of regional groundwater flow and is often related to the deep aquifer.

Question 11: Is the assumption that percolation into the underlying aquifer has a negligible impact on near surface groundwater behavior reasonable?

Reviewer 1 cited evidence that the river is a losing stream through the study reaches (i.e., its elevation is higher than the groundwater, the water table declines with distance from the river), and noted that piezometers could be installed to quantify the vertical head. Reviewer 2 commented that this is not a reasonable assumption, particularly if the soil texture is coarse, in which case percolation could be expected to be lost to the deep groundwater systems. In support of this assumption, Reviewer 3 mentioned the small hydraulic head difference between the alluvial aquifer and Ogallala group, and their separation by a low-permeability aquitard; however, he also noted that if groundwater pumping occurs within wet meadows in the future, a cone of depression could form and cause downward leakage.

Question 12: Are single river stage gages used in conjunction with surface water models sufficient to capture surface water behavior at a wet meadow site?

Reviewer 1 recommended a minimum of two staff gages for making maps of surface water and groundwater recharge. Reviewer 2 stated that this approach was sufficient. Reviewer 3 acknowledged the difficulty in adding more stage gages to a braided river channel with unstable sediments and suggested that a survey be conducted to confirm whether or not the differences in stream stage among the channels are small.

Question 13: Is the approach to relating river stage and discharge reasonable?

Reviewers 1 and 3 found this approach to be straightforward. Reviewer 2 stated that the reasonableness of this approach should be verified by examining satellite or LiDAR imagery to determine if channel cross sections are relatively stationary over the last few years.

Question 14: Is the assumption that precipitation falls fairly uniformly across a wet meadow site reasonable?

Reviewers 1 and 2 disagreed with this assumption. Reviewer 1 stated that this is known to be false, thus having more than one rain gauge is desirable. He added that simple gauges, such as milk jugs with funnels, can be used in combination with the tipping bucket type. Similarly, Reviewer 2 commented that more than one gage is needed to cross-validate gage measurements, especially given that precipitation is the major source of water in these systems. Reviewer 3 noted that monthly and annual precipitation rates can be considered uniformly across a wet meadow.

Question 15: Does the monitoring approach adequately measure the timing and magnitude of snowmelt and soil freeze/thaw behavior to account for the impact of these processes on groundwater behavior?

Reviewer 1 pointed out the heterogeneous distribution of snow due to wind transport, and recommended that if significant snow falls, depths should be quantified at several sites and cores analyzed for density and water content. Reviewer 2 noted that the depth of soil temperature measurement is not specified and recommended that the approach include snow energy balance-incorporated runoff to better understand the influence of snowmelt, freeze/thaw cycles, and rain-on-snow events on runoff and recharge. Reviewer

3 found the approach to be appropriate, but noted that the effects of soil freeze/thaw behavior on infiltration was not described.

CHAPTER 2

Question 16: Does the review of methods of determining ET omit any commonly used method?

All three reviewers found the review to be generally complete. Reviewer 1 noted that the review covers a wide range of techniques and methods, and mentioned one satellite technique not completely covered (i.e., Groeneveld et al. 2007) that is discussed in his specific line comments (see Appendix A and comments spreadsheet). Similarly, Reviewer 2 stated that most commonly used methods are included in the review, with the exception of the use of a scintillometer to measure areal average sensible heat flux. Reviewer 3 agreed that the review was very complete; however, he reiterated the need to estimate groundwater ET for the riparian forest in wet meadows where cottonwood and willow are prevalent (i.e., response to Question 3).

Question 17: Are the conclusions drawn from the comparison of methods reasonable and scientifically sound?

All reviewers agreed that the conclusions are reasonable and scientifically sound. Reviewer 1 found the conclusions to be appropriate and noted that the Bowen Ratio technique to measure ET is the right approach. He mentioned that this technique should be coupled with other methods, such as a continuously recorded monitoring well and soil water content equipment, among others. Reviewer 2 responded affirmatively. Reviewer 3 concluded that this chapter is “an excellent analysis” of the methods described.

Question 18: Is the use of the crop coefficients developed by the USGS for riparian grassland reasonable? Are there other crop coefficients that would provide better results?

All three reviewers raised questions about the reasonableness of this approach. Reviewer 1 initiated his response by pointing out the inaccuracies in the PRRIP’s definition of “wet meadow” and recommending an alternative description (e.g., Batzer and Baldwin 2012); he also discussed this issue in his “Overall Comments on the Four Reports Reviewed” on page A-3. He went on to comment that crop coefficients are not accurate enough for research and should not be used to create a water budget, and instead suggested alternative methods to quantify ET. Reviewer 2 suggested that crop coefficients be developed for each site as opposed to using those developed by USGS, or at a minimum validate the USGS coefficients at one site and extend to the others, if appropriate. Reviewer 3 commented that while this approach may be reasonable for grasslands, it may not be suitable for riparian forests.

CHAPTER 3

Question 19: Does the conceptual soil moisture water balance accurately approximate expected soil moisture behavior at wet meadow sites?

Reviewer 1 noted that the equation is relatively simple; the real question is how to reliably measure the components at shore and long timescales. Reviewer 2 commented that it mostly captures soil moisture movement; however, there are additional pathways that should be considered, such as upward flux and lateral flow between the layers. Reviewer 3 summarized the four components of the equation and noted the importance of and difficulty in estimating groundwater recharge (i.e., percolation). He suggested using groundwater level monitoring data to estimate recharge from precipitation events.

Question 20: Does the soil moisture monitoring approach provide an appropriate level of detail in light of the project's objectives?

Reviewer 1 did not think the approach provided an adequate level of detail and referred to his overall comments for additional topics he thinks should be addressed in order to improve this chapter (see Appendix A). Reviewer 2 commented that the approach may be sufficient; however, the assumption that moisture below 1.85 meters goes into the shallow aquifer or discharges into the stream should be verified. Reviewer 3 summarized the methods and noted that this is a good approach, but additional discussion is needed on how the data will be used to determine soil moisture changes.

CHAPTER 4

Question 21: Is the model domain appropriate to capture groundwater behavior at the wet meadow sites?

Reviewers 1 and 2 found the model domain to be appropriate. Reviewer 3 commented that the size and orientation of the model domain are appropriate, but the arrangement of inactive cells limits flexibility in imposing some boundary conditions, as discussed in Question 23.

Question 22: Is the assumption of a homogeneous aquifer clearly supported and appropriate?

This question was outside of Reviewer 1's expertise. Reviewer 2 noted that this assumption should be evaluated using empirical data or monitoring missions. Reviewer 3 commented that while the aquifer hydraulic properties are not homogenous, it is appropriate to assume homogeneity for the first-step model calibration. However, he did not agree with the assumption of isotropic hydraulic conductivity in the horizontal vs. vertical direction and suggested a smaller K_z value be used in the model, as well as additional support for the assumed thickness of the alluvial aquifer.

Question 23: Are the model boundary conditions appropriate?

Reviewers 1 and 2 found the boundary conditions to be appropriate; however, Reviewer 3 had extensive comments discussing why the spatial arrangement of constant head boundary conditions may not be appropriate and may be the cause of large uncertainty in the outputs (see Appendix A).

Question 24: Is the use of the MODFLOW evapotranspiration (EVT) package appropriate? Would combining the precipitation and evapotranspiration values into the recharge (RCH) package better represent the physical system?

Reviewer 1 did not evaluate this question, but noted an alternative approach he used on a similar project. Reviewer 2 stated that the EVT package is not appropriate and combining precipitation and EVT values into recharge may be part of the solution, but not entirely. He recommended simulating soil moisture dynamics in the vadose zone separately and linking the fluxes with MODFLOW. Conversely, Reviewer 3 found that the EVT package was used appropriately and that the linear option was acceptable given no data to indicate otherwise. He did not recommend combining the hydrological processes into the recharge package.

Question 25: Is the assumption that standing surface water storage is negligible and no surface storage term in the groundwater models reasonable?

All reviewers identified conditions under which this assumption may not be reasonable. Reviewer 1 commented that this assumption may be fine for most years, but would not be reasonable during years when considerable overbank flows occur. Reviewer 2 noted that if storage fluctuates daily or weekly, this assumption is true; however, in some sites the shallow aquifer feeds ponds for more than a month and the ET that occurs needs to be accounted for. Reviewer 3 stated that when groundwater levels are low, there may be limited surface water storage and the occurrence of sloughs may affect groundwater levels.

Question 26: Can the model adequately simulate the effects of ice flows and river stage increases caused by ice dams?

Reviewer 1 did not evaluate this question. Reviewer 2 commented that this is not possible in the existing model framework, unless it can integrate modified river stages dynamically as a result of ice dams. He noted that increased residence time in the stream caused by the impoundment can add recharge to the aquifers. Similarly, Reviewer 3 stated that the model is not able to simulate ice flows and noted that if ice dams elevate the river stage, the increased elevation can be integrated into the river package and groundwater response can be simulated.

Question 27: Overall, do the models capture the groundwater behavior at the two sites to address the monitoring effort's objectives?

Reviewer 1 referenced his specific comments on this chapter that address this topic (see Appendix A and comments spreadsheet). Reviewer 2 stated that the model's performance is reasonable, but there are opportunities to improve predictions and reduce uncertainties (e.g., clarify how measured ET is incorporated into groundwater modeling). Reviewer 3 noted that on the whole the authors did a good job; however, the model would be improved by revising boundary conditions, as suggested in Question 23.

3.3 Ratings and Recommendations

Reviewers rated the set of chapters using a rating system provided by the Program where 1 = Excellent; 2 = Very Good; 3 = Good; 4 = Fair; 5 = Poor. Below is a table summarizing each reviewer's ratings:

Table 3-1. Reviewer comprehensive ratings of combined set of chapters, by category.

Category	Reviewer 1	Reviewer 2	Reviewer 3
Scientific soundness	2	2	1.5
Degree to which conclusions are supported by the data	1	2	2
Organization and clarity	2	1	1
Conciseness	1	1	1.5
Important to objectives of the Program	1	1	1

Reviewers were then asked to provide their recommendation to either accept the chapters, accept them with revisions, or deem them unacceptable. All three reviewers recommended that the chapters be accepted with revisions. Reviewer 1 described three issues that could be improved upon to allow "a recommendation of accept" (see page A-3). Reviewer 2 simply listed the 13 question responses where his expected revisions are described (see page A-19). Similarly, Reviewer 3 listed two question responses that describe his expected revisions (see page A-38).

3.4 Other Specific Comments

The reviewers submitted 92 other specific comments, which Louis Berger compiled into a spreadsheet, organized by chapter and line number, along with reviewer name; this spreadsheet will be used by the PRRIP in preparing responses to the comments. In some cases the reviewers referred to these specific comments in their responses to the questions above and in their full individual comments (Appendix A).

4.0 REFERENCES

The following references were cited in Section 3.0 above. The citations for other references recommended by the reviewers are included in their individual comments in Appendix A.

Batzer, D. and S. Baldwin. 2012. Wetland habitats of North America. Ecology and conservation concerns. University of California Press. 408p.

Groeneveld, D. P, W. Baugh, J. Sanderson, D. J. Cooper. 2007. Annual groundwater evapotranspiration mapped from single satellite scenes. Journal of Hydrology 344:146-156.

5.0 APPENDICES

Appendix A: Individual Reviewer Comments

Appendix B: Reviewer Biographical Sketches

APPENDIX A: INDIVIDUAL REVIEWER COMMENTS

Peer Review submitted by Reviewer 1

Review of:

Platte River Recovery Implementation Program Wet Meadows Hydrologic Monitoring Approach

May 2015

Overall Comments on the Four Reports Reviewed

The PRRIP is an innovative program working to characterize wet meadows along the Platte River in central Nebraska. The four reports were well written; their scientific goals and approaches were generally suitable and should provide excellent data for understanding and managing the sites.

I understand that these reports are aimed at hydrologic monitoring and analysis. But the goals of the hydrologic monitoring, analysis and future management will be used for the preservation, creation and management of habitat for whooping cranes and other species. Therefore, information on the habitat needs of these organisms from a hydrological and ecological perspective would be important to present. For example, why are wet meadows critical to these organisms, and what aspects of the hydrologic regime are particularly key to the species of plants that create the vegetation that the birds key in on.

Little information is present on what exactly the PRRIP considers wet meadows. Therefore, I read the document by Ramirez and Weir (2010) to learn more. This report has an extensive review of wet meadows, including definitions (page 4). Based on this literature review of wet meadows based on Nebraska studies I understand why the definition from Mitch and Gosselink (1993) is used. Since not all wet meadows are dominated by species of grasses, but also include sedges, rushes, reeds, etc. this definition may be too narrow. For example, Table 3 in Ramirez and Weir (2010) distinguishes several types of vegetation that occur in wet meadow complexes, including sedge meadows, which are not "grasslands". Hence the presentation of wet meadows as grasslands can be misleading from an ecological and hydrologic perspective since the hydrologic regime required to support meadows dominated by mesic prairie species such as Andropogon gerardii, is much more broad and less specific than the hydrologic regime required to support Carex emoryi, Carex pellita, and Symphyotrichum lanceolatum that dominate sedge meadow communities.

It would be worthwhile to identify wet meadows as complexes of several communities including dry ridges (not necessarily grasslands), mesic prairie (grasslands), sedge meadows (not grasslands) and emergent wetlands (not grasslands). All of these community types provide habitat for key plant and animal species, and most likely the cranes and other focus species utilize communities that are not dominated by grasses. Of these community types reviewed in the Crane Trust report, the sedge meadows are the wet meadow type that best fits the description of Mitch and Gosselink (1993). The mesic prairie and dry ridges are not necessarily even wetlands therefore they would not have saturated soils for long duration (at least two consecutive weeks) during the growing season.

With a recognition that multiple communities, each with distinctive hydrologic regimes including frequency, depth and duration of flooding and/or shallow water tables within the root zone, it is clear that each community will have distinctive rates of evapotranspiration (ET) seasonally and annually. Thus, ET research should focus on quantifying ET rates and processes from each community in the study areas. This would provide a much more accurate and realistic approach for quantifying overall ET from the study areas. A community vegetation map could be used then to determine the area that each ET rate would be applied to in each study area and make it possible to quantify total

ET for the study sites. These ET rates would be built into the ground water modeling effort to provide the most robust view of hydrologic processes on site.
My four report reviews follow, and the comments for each provide some suggestions for revision that could improve and clarify the research reports. It should be noted that my expertise is in Ecohydrology. I am not a ground water modeler. Therefore my review of chapters 1, 2 and 3 is complete, while my review of chapter 4 is somewhat general.

Literature Cited

Mitch, W. and J. Gosselink. 1993. Wetlands. Van Nostrand and Reinhold. New York.

Ramirez, F-C, and E. Weir. 2010. Wet meadow literature and information review. Crane Trust. 10 November 2010. 42 pages.

Peer Review Rating & Recommendation

RATING

Please score each aspect of this set of chapters using the following rating system: 1 = Excellent; 2 = Very Good; 3 = Good; 4 = Fair; 5 = Poor

Category Rating Scientific soundness __2
Degree to which the monitoring approach addresses the project’s objectives __1 Organization and clarity __2

Conciseness __1
Important to objectives of the Program 1

RECOMMENDATION (Check One) Accept ______
Accept with revisions __x____ Unacceptable ______

Suggested Revisions to be able to change recommendation to "Accept"

A few aspects of the report could be improved to allow "a recommendation of accept".

1. Add information on the characteristics of meadows that are being addressed in this report. Clearly many meadow types are present and they are lumped into a single category. Each type will have distinct vegetation, hydrologic regime, and ET rates. Provide a means of using the meadow type data in calculating ET rates for the sites.
2. It should be acknowledged that the crop coefficients used (my comment 18) may not be suitable as they are for only one of the meadow types. In addition, the use of atmometers may not be suitable for research purposes (my comment on line 392 of the ET chapter).
3. Please add information to the soil moisture chapter on how the moisture probes are installed and whether they were calibrated for your soil types.

(For use by internal review panel only)
RECOMMENDATION (check one)
Accept
Accept after revision
Unacceptable

General Questions

1. *Are the objectives of the monitoring effort clear and obtainable?*
All four objectives are obtainable. With the right scientific methods all can be achieved.

2. *Will the monitoring approach provide sound and comprehensive data to achieve the Monitoring Plan's objectives?*
The monitoring plan approach is generally good. There are many places where it can be improved. I have outlined my suggestions in the following review of each chapter.

3. *Please identify any additional monitoring equipment or procedures that would allow this study to better achieve its objectives.*
ET should be quantified on the study sites, not estimated. More than one staff gauge

should be installed in the Platte River. Each meadow supports multiple vegetation types, each of which will likely support distinctive ET rates. The vegetation could be a guide to more a accurate ET estimation for study sites.

4. Are potential biases, errors, or uncertainties appropriately considered within these chapters?
In general the uncertainties are well understood.

Review of Chapter 1: Wet Meadow Hydrologic Monitoring.

Chapter Specific Questions:

5. Does the conceptual model presented capture all the relevant hydrologic processes? Does it ignore any critical processes?
I assume that the conceptual model is presented in Figure 2, which identifies the water inputs and outputs from a typical wet meadow cross section. This diagram assumes that there is no input from deeper ground water sources, while probably is correct. I'm a bit unclear about the right model boundary and how much interaction there might be with adjacent lands and their ground water, and the meadow identified here.

6. To what degree is the assumption that precipitation can act as a surrogate for overland application of water appropriate?
Precipitation is highly variable in its effects on soil water content. The water table depth or the presence of surface water can strongly influence infiltration or runoff following any precipitation event. Precipitation cannot provide sufficient soil saturation or duration of saturation to support and sustain wet meadows. If it could wet meadows would occur in areas far from rivers and on sites lacking ground water discharge. Precipitation can provide important soil water for plant growth, but it is unlikely to be a significant ground water recharge component and alone could not support wet meadows.

7. The monitoring approach assumes the understanding of wet meadow hydrologic processes gained through the higher level of monitoring at the Fox and Binfield site can be applied to the Johns and Morse site which receive less extensive monitoring. Is this a reasonable assumption?
If Johns and Morse have similar hydrologic regimes and soil types, and can support similar wet meadow vegetation, then yes this is a reasonable assumption.

8. Given the information currently available, is the well placement and density appropriate to capture site-wide groundwater behavior at each of the four sites?

It looks fine for capturing processes of surface water-ground water connections and interactions. For building water table maps of the study areas, for use in estimating entire site ET, having a more widely distributed set of wells could be helpful. For example at Binfield there are two transects of wells and large areas of the site have no wells. Adding a few more wells would provide the needed coverage. Wells of the depth installed here can be drilled by hand with a soil bucket auger.

9. Is the assumption of minimal off-site runoff reasonable?

Probably … unless there is considerable snow on site during a period of high river discharge when considerable runoff may occur.

10. Is the assumption that near surface groundwater behavior is not driven by the behavior of the deeper alluvial aquifer on a daily time scale reasonable?

Its pretty clear from the analyses presented that the wet meadow water tables are highly influenced and likely supported by the Platte River. It would be nice to demonstrate this with river stage/water table elevation maps, stable ion ratios, and stable isotope ratios as tracers.

11. Is the assumption that percolation into the underlying aquifer has a negligible impact on near surface groundwater behavior reasonable?

One report demonstrated that the Platte River stage is higher in elevation than the ground water, and Figure 2 also displays a water table declining in elevation with distance from the Platte River. Thus the river is losing through the study reaches. The installation of piezometers to quantify vertical head would resolve this issue.

12. Are single river stage gages used in conjunction with surface water models sufficient to capture surface water behavior at a wet meadow site?

For making maps of surface water and ground water recharge I would install a minimum of two staff gages, one gage at the up-gradient end of the study site and another at the downstream end. That way the elevation of the river surface at any stage can be used to compare with the ground water elevation under the meadows. It will facilitate the construction of water surface maps to clarify flow directions and depth to water table relationships for the entire site.

13. Is the approach to relating river stage and discharge reasonable?

Yes, this is straightforward.

14. Is the assumption that precipitation falls fairly uniformly across a wet meadow site reasonable?

We know that this is not true. One precipitation gauge located 100 or 1000 m from another could record quite different amounts of precipitation from any event. Therefore, having more than one rain gage is desirable. Not all gages need to be the tipping bucket type. Some can be simple gallon milk bottles, with funnels and vegetable oil in the jug to limit evaporation, to determine total precipitation during various periods of the summer. These more simple gages can be measured and emptied weekly or monthly to determine total precipitation variance compared with a tipping bucket gage.

15. Does the monitoring approach adequately measure the timing and magnitude of snowmelt and soil freeze/thaw behavior to account for the impact of these processes on groundwater behavior?

Snow is a solid and therefore can be transported by wind once it falls. In many areas of the Great Plains snow drifts and its distribution is highly heterogeneous. I would worry that one site to photograph snow depth could misrepresent total snow on site and its water content. Therefore, along with the one or two photo stations, it might be worthwhile if significant snow occurs to have several more sites where snow depth is quantified. At these sites snow cores should be analyzed for density and water content to compare with the one winter precipitation gage that appears to occur on site.

Specific Comments by Line Number

Line 81: Since a lot of discussion revolves around "wet meadows" it would be nice to have a definition of this ecosystem complex up front.

L89: I would not use hydrology in this way. Hydrology is a science, its not what is measured.

L 96: Here it would be nice to be more specific. What "hydrologic regime" is suggested to be the right one? This report provides essentially no information about the vegetation of these wet meadows. For scientists who know plants, information on the dominant species can help us understand the overall hydrologic processes and water table depths that occur on site.

L 105. Understood that there is not clear direction in literature about the water levels that support wet meadows in this area. Can a broader search be conducted to understand wet meadows in general? For example wet meadows have been a subject of research in the Rocky Mountains, Great Basin, and Sierra Nevada for many decades and plentiful data is available to characterize the hydrologic regime of those meadow types.

L110. I think a more important question might be: Which wet meadows are connected to the Platte River stage, and which are not. And on what time scale are meadows connected? We've measured ground water flow over many km and it took up to a year for water from a stream to reach the study wetlands (Wurster, Cooper, Sanford 2005).

L157: This is overly simplistic. Not all rises in river stage will produce a rise or lowering of ground water elevation. Or the time frame for these changes could vary from site to site and with distance from the river.

L 212: It's interesting that there is no arrow or flow component from right to left, meaning ground water flow from the uplands toward the river. Has this been proven?

L235: I would not suggest using the term pristine, as it assumes a level of integrity that is not possible along the Platte River where settlers have been modifying the vegetation and hydrologic regime for more than 100 years. Clearly the pre settlement hydrologic regime of seasonal river flooding is altered, and looking closely at the site on Google Earth, fence lines, flowing wells and other features are apparent, indicating heavy use of domestic livestock.

L346: Is there an adjacent staff gauge that is continuously monitored?

L423. It might be desirable to have a staff gauge at the upstream and downstream end of each study area.

L433. This is not necessary. If the loggers are well below the water table there is no chance of them freezing. If the water table drops below the level of the logger then yes the gauges should be removed.

L 573 **–** The proposed method is quite generic … using the Penman equation and data from local weather stations. The weather stations are not located in the wet meadows. So the data are quite generic for central Nebraska. The crop coefficient approach also is commonly used, but you cannot approximate the error in this approach, because nowhere have you actually measured ET in the meadows.

L 594 **–** The issue of using atmometers is quite complex. Plants have stomata and regulate water flux from leaves to the atmosphere. Ceramic plates do not have stomata. Ceramic plates used in atmometers could "transpire" at much higher rates than plants. The research on these devices by Colorado State University was for upland agricultural crops to schedule irrigation events. I know of no literature that tests these in wet meadows or other wetlands. I discuss this in more detail in my review of Chapter 2.

L 633. There is no information presented on how the sensors were installed. This is very important to communicate with readers. Were there pits dug and the sensors installed horizontally into the intact soil, or exactly how were they installed?

L645. There is insufficient methodology presented on how these CRNP sites are instrumented. Are access tubes installed? How were they installed? How are measurements made?

L679. These cork sensors do not always work. If there is considerable mineral sediment transported with the flowing water this can foul the gages and make it impossible for the cork to adhere to the gage wall.

Chapter 2 – Wet Meadow ET White Paper

16. Does the review of methods of determining ET omit any commonly used method? This review does a good job of addressing a wide range of techniques and methods and fairly assesses their strengths and weaknesses for the study area. One satellite technique not completely covered is by Groeneveld et al. 2007. I have comments on this chapter in my specific line comments below.

17. Are the conclusions drawn from the comparison of methods reasonable and scientifically sound?

In the end, the conclusions seem appropriate. Accurate data are needed and therefore a costly and intensive field campaign to measure ET using Bowen Ratio techniques is required. Having done similar work for 20 years, I can say that this is the right conclusion. A modeling effort using Penman or Priestly-Taylor can be used to fill gaps in the data when technical issues result in failure of any instruments. Using data from the BR system will allow the construction of robust models that can be used to estimate daily, monthly or annual ET. The BR system should be coupled with a continuously recorded monitoring well, soil water content equipment, net radiation, and measures of vegetation composition, leaf area and production.

18. Is the use of the crop coefficients developed by the USGS for riparian grassland reasonable? Are there other crop coefficients that would provide better results?

The crop coefficients developed by Hall and Rus (2013) are for a Poa pratensis dominated grassland, which is typically not a wet meadow. The definition of wet meadow in PPRIP 2012 (page 2), and taken from Mitch and Gosselink (1993) is not suitable. Wet meadows are NOT grasslands with waterlogged soil near the surface but without standing water most of the year. I know both Mitch and Gosselink and they have never worked in wet meadows as occur in Nebraska. Herbaceous plants dominate wet meadows for the most part, but they certainly do not have to be grasslands. Wet meadows must have mineral, not organic soils. Wet meadows correctly have seasonally saturated soils. We present a more suitable concept of wet meadow in our chapter (Cooper et al. 2012) in the more current book “Wetland Habitats of North America” (Batzer and Baldwin 2012).

The concepts of crop coefficients are fine for scheduling irrigation, or other management activities. They are not accurate enough for research, and they should not be used to create a water budget or water balance for the study area. The only accurate way to develop an accurate water budget is to measure ET with a Bowen Ratio system or Eddy Correlation. Other features of the water budget such as water table depth, flow through the site, etc. should also be measured. Once many years of on site ET have been measured and the relationship of ET to water table depth, soil moisture, air temperature, and net radiation have been modeled then perhaps a crop coefficient for this site could be developed. But it would be more useful to develop a calibrated Penman-Montieth and/or Priestly Taylor model that can be used to quantify ET long term using the variables described above.

Specific Comments by Line Number

L 139. A wet meadow crop coefficient could be inaccurate due to a range of issues. First, wet meadows with shallow water tables are not subject to the same transpiration limitations as upland crops. Second, since there are so few actual measures of wet meadow ET, creating and using a crop coefficient for wet meadows, could produce very approximate ET rates with unknown error. How would this error be evaluated?

L 142. This is a good reason to make original measures of ET, and not rely on crop coefficients that will absolutely introduce unknown error into your models. We've measured wet meadow ET (Sanderson and Cooper 2008, Cooper et al. 2006) and its not that hard to get this right. The methods you propose at the end of this document are suitable for accurate measures of ET.

L156. Wet meadow plants also have varying root depths and root density with depth, and these are key variables in modeling. Because the position of the water table and available energy and time in the year will drive ET, an understanding of root distribution can really help predict ET functions for different species, communities and water table depths.

L183. Lysimeters provide the most unrealistic "ecosystem" for estimating ET. Landscapes with intact soil structure and long-lived plants form over very long periods of time, hundreds to thousands of years. Lysimeter construction, for the most part, destroys soil structure and deals with plants and vegetation that do not reflex the ecosystems that people really want to measure. Even "monolithic" lysimeters provide unrealistic ecosystems because they cut off the roots of plants that may take decades or longer to form.

L 221. The ground water simulating lysimeters are also highly artificial, considering ground water to be a "pool".

L 266. This paragraph should include a few sentences about vegetation. Refilling lysimeters is more than sediment, it's also vegetation. How long does it take for planted or transplanted species to attain similar above ground/below ground relationships similar to natural vegetation in their functioning for water acquisition and transpiration?

L313. This is not true. Lysimeters provide estimates of ET for the soil and vegetation within the lysimeter. I have never seen a lysimeter where the vegetation truly was representative of the surroundings, other than for sites with annual crops, or turf grass. For long-lived meadow plants attaining natural root distribution and density within the lysimeter is difficult to achieve.

L317. Again, the assumption must be strengthened - this assumes ground water is a pool sitting at the base of the lysimeter. For the Platte River this may not be a suitable assumption because ground water flows through the soil laterally as well as vertically. In addition, periodic flooding and the lateral movement are critical for salt distribution regulation.

L 324. It is key to recognize that the type of vegetation will determine how long it takes for a lysimeter to reflect the local vegetation. For annual plants it's a short period of time. For shrubs or some clonal sedge species it may be unattainable.

L. 392. One of my colleagues at CSU, Dr. Troy Bauder, is the author of the 1999 CSU report (CSU 1999). I communicated with him and he said that auto-logging atmometers compare reasonably well to ASCE ETr using alfalfa as a reference cover. They should be used mainly for irrigation scheduling. For research purposes they would have to be calibrated using actual wet meadow ET. Since wet meadow ET from the study area does not appear to exist, I feel that this method may be too inaccurate for use in this program.

I also suggest you consider adding the following reference: Gleason, D.J., A.A. Andales, T.A. Bauder, J.L. Chavez. 2013. Performance of atmometers in estimating reference evapotranspiration in a semi-arid environment. Agricultural Water Management 130: 27-35.

L 452. Plants that are adapted to western environments have more than "some resistance to evaporation" but can have nearly complete control of transpiration rates through their stomata. Pans are suitable for providing an estimate of evaporation from small lakes, and could be useful for times when there is surface water in the study areas. Without surface water in the study area, the pan rates are not particularly informative.

L642. The biggest problem we have had with Bowen ratio equipment was lightning strikes, directly onto or near the stations. This can destroy much of the equipment, particularly the data loggers.

L904. We have used Priestley-Taylor ET models for wet meadows because they provide a reasonable approximation of ET under well-watered conditions (Sanderson and Cooper 2008). Of course we were able to calibrate these models with detailed multi year data sets from Bowen ratio stations are multiple sites.

L 994 and 1007. It seems that you are making the assumption that the work done by Hall and Rus (2013) provide a suitable crop coefficient for use with the Penman equations. I am unsure if this is a valid assumption. Having read this report provided in your appendix, their work does not include what I would call wet meadow sites. The “grassland” site is dominated by Poa pratensis, which is not a wet meadow plant in most regions of the U.S. and is not typically a phreatophyte. The water table depth measured at well GW2 is shallow enough that some evaporation from the water table directly to the atmosphere surely occurs. Whether any of the plant species present are using ground water is not established. The crop coefficient developed for this grassland may not be suitable for wet meadows in this same area. It would depend on whether the plants in wet meadows are phreatophytes, and have different water use patterns than the grassland species at this reference site. The crop coefficients developed by Irmak et al. (2013) are for two woody plant species and one tall marsh plant. Therefore, these are useful, but not suitable for wet meadows.

L 1086. Without testing the accuracy of Penman-Monteith methods compared to measured ET rates on the same site, I’m not sure the statement on this line can be made.

L 1093. You should also consider the methods of Groeneveld et al. (2007) for mapping ET from satellite scenes.

L 1269. We came to this same conclusion two decades ago in perfecting water balance models for the San Luis Valley in south-central Colorado. These models now form the basis of a decision support system used by the State of Colorado for water rights.
http://cdss.state.co.us/basins/Pages/RioGrande.aspx
ET from native vegetation had historically been estimated using lysimeters and other methods, but it was unknown how accurate these estimates were. Since the amount of water used by native vegetation in this huge region that has shallow water tables was in the range of several hundred thousand acre feet/year, it was a vital issue to develop an accurate water balance for the entire valley. By using Bowen Ratio instruments over several years we were able to show that the previous estimates were not even close to actual ET and by plugging these data into the developing decision support system, much greater accuracy and predictability could be obtained. I feel that the proposal provided by Irmak (2012) could provide the needed data set for wet meadow ET.

Literature Cited

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Groeneveld, D. P, W. Baugh, J. Sanderson, D. J. Cooper. 2007. Annual groundwater evapotranspiration mapped from single satellite scenes. Journal of Hydrology 344:146-156.

Hall, BM and DL Rus. 2013. Comparison of water consumption in two riparian vegetation communities along the central Platte River, Nebraska, 2008-09 and 2011. USGS Scientific Investigations Report 2013-5203.

Irmak, S. 2012. Continuous measurement of wet meadow evapotranspiration other surface energy balance variables and soil water status. Proposal submitted to PRRIP.

Irmak, S. and others. 2013. Evapotransipiration crop coefficients for mixed riparian plant community and transpiration crop coefficients for common reed, cottonwood and peach-leaf willow in the Platte River basin, Nebraska-USA. J. Hydrology 481: 177- 190.

Mitsch, W. and J. Gosselink. 1993. Wetlands. Van Nostrand and Reinhold. NY.

Sanderson, J. and D. J. Cooper. 2008. Ground water discharge by evapotranspiration in wetlands of an arid intermountain basin. Journal of Hydrology 351:344-359.

Chapter 3 – Soil Moisture Monitoring Plan Memo

Chapter 3 Questions:

19. Does the conceptual soil moisture water balance accurately approximate expected soil moisture behavior at wet meadow sites?

This is a relatively simple equation. The question is how to measure the components reliably and on short and long time scales.

20. Does the soil moisture monitoring approach provide and appropriate level of detail in light of the project's objectives?

Not really. I have comments below that could add to the information provided for a more adequate review, analysis and comment of the methods.

Overall Comments

This chapter addresses two methods for quantifying soil moisture dynamics. There are a few topics that I feel should be added this chapter. First, how are the Theta soil moisture probes installed? Installation is a key aspect of obtaining useful data. Are the probes installed into intact soils, or excavated soils? Is the vegetation intact so that ET rates for the sites reflect the natural range of variation for the site? Second, how and when are the Theta soil moisture probes calibrated? Without calibration the probes provide data of unknown quality (Kaleita et al. 2005). The calibration is needed to determine soil moisture across a range of soil water contents and soil types. The calibration is done using volumetric soil samples collected and analyzed to determine actual water content in relation to the output from the Theta probes. An error analysis is also accomplished to determine the number of probes needed to obtain adequate accuracy.

The neutron technique is interesting, but I have no direct experience with it. As I mention below, I wonder how this technique works in wet meadows with a range of water table depths, or where the capillary fringe reaches the soil surface. In the journal articles I read I could find no testing of this method in sites with very high soil water content. Figure 1 in Zreda et al. (2008) indicates that the "slowing-down" power of the medium is highly related to volumetric moisture content. At soil moisture content above 0.1 (10%) there appears to be little difference in the contribution of hydrogen. Therefore, I am wondering whether this method is useful for sites that have substantially higher soil moisture content duration at least part of the year. And of course the early summer when soil water content and water table are highest, is the time of the year that could have the highest ET rates.

Specific Comments

L. 39. It seems that water can also enter as flood water from the Platte River, or overland flow from adjacent upland or meadow sites. The water table can also rise in response to Platte River rise, recharging soil water content.

L 50. Plants, even "phreatophytes", acquire soil water so the quantification of soil water content on a daily time step is critical for understanding ET and potential ET. This point is made in the following paragraphs of the report.

L 57. Some citations would be good here to support these rooting depths.

L 61. It could be useful to add soil texture and structure as a key variable for potential soil moisture holding capacity, and the volume of water held at field capacity, which varies horizontally, especially in complex fluvial terrain as these wet meadows occupy.

L 81. I would think that this is subject to debate. I would argue that Precipitation and ET determine, relative to soil water storage, what water, if any, is available for percolation to the water table. In addition, the counteracting capillary rise certainly influences percolation rates and processes.

L 91. Capillary rise for this soil type should be quantified, not assumed to be negligible. Until it is proven that capillary rise is zero, this equation could be considered: $(I + CR) – ET – PERC = \Delta S$

L 105. Here the capillary rise is not stated to be negligible, but limited by the sandy soil.

L 153 and Figures 6 and 7. Unfortunately when the soil moisture sensors, and likely other instruments, were installed the site was highly disturbed removing the vegetation. Therefore, this site cannot be used to calculate the equation for PERC as it has an unrepresentative ET rate. The soil moisture data from these sites would be unreliable for representing the soil moisture dynamics of meadow areas shown in the background that are fully vegetated and could have much higher ET rates and very different infiltration rates due to differences in litter, root density and penetration. I would suggest that different approaches be used to install soil moisture sensors other than digging up the site.

L 156. I have never used the CRNP system, but reading through a set of journal articles, some of which are footnoted on this page, makes it seem like a useful and reliable approach. Franz et al. (2013) suggest that the method can explain 79% of the variability in data sets. Is that sufficient for the purpose of this work on the Platte River? It might be. I also wonder how this method would work in sites with a very high water table, say May and June when a water table is within 50 cm of the soil surface.

L 178. Would driving with a pickup be possible during high water table periods?

Literature Cited

Franz, T.E., M. Zreda, R. Rosolem, TPA Ferre. 2013. A universal calibration function for determining of soil moisture with cosmic---ray neturons. Hydrol. Earth Syst. Sci 17: 453---460.

Kaleita, A.L., J. Heitman, S Lgosdon. 2005. Field calibration of the Theta Probe for Des Moines lobe soils. Applied Engineering in Agriculture 21: 865---870.

Zreda, M., D. Desilerts, T. Ferre, R Scott. 2008. Measuring soil moisture content non---invasively at intermediate spatial scale using cosmic---ray neutrons. Geophysical Research Letters 35, L21402, doi: 10.1029/2008GL035655

Chapter 4 – Wet Meadow Groundwater Model Report

Overall Comments:
Depth to water table in each grid cell should be estimated.
Vegetation composition and ET maps should be created.

Questions:
21. Is the model domain appropriate to capture groundwater behavior at the wet meadow sites?
It seems appropriate.

22. Is the assumption of a homogeneous aquifer clearly supported and appropriate?
I cannot tell.

23. Are the model boundary conditions appropriate?
They seem appropriate.

24. Is the use of the MODFLOW evapotranspiration (EVT) package appropriate? Would combining the precipitation and evapotranspiration values into the recharge (RCH) package better represent the physical system?
I cannot evaluate this. Our work with the State of Colorado on the Rio Grande Decision Support System did not use this package. We created ET functions based on depth to the water table and vegetation type. These functions were then assigned to each grid cell in the model based on analysis of the vegetation in each grid cell, and the depth to water table determined by a network of monitoring wells and the model calculations.

25. Is the assumption that standing surface water storage is negligible and no surface storage term in the groundwater models reasonable?
For most years I would think this is fine. But on large Platte River flow years, when considerable overbank flows occur, this would likely not be reasonable.

26. Can the model adequately simulate the effects ice flows and river stage increases caused by ice dams?
I cannot evaluate this.

27. Overall, do the models capture the groundwater behavior at the two sites to address the monitoring effort's objectives?
I have comments below that address this topic.

Specific Comments:

L 121. This is not very clear, "quantify the volume of flow passing between the river and the groundwater". It makes it seem that some volume is moving in a layer beside the river, but not into the ground water system.

L 139. Here is the same phrase, I think the author is trying to say that the goal is to quantify the amount of water that moves from the river into the ground water system.

L 267. Why wasn't specific yield measured for these soils?

L 358. I assume that the steady state version of the ground water models are based on water table measurements from the installed monitoring wells?

L 371. Where is the data on rooting depth(s) of plant species on these sites? We worked on the concept of extinction depth for vegetation at sites in Colorado's San Luis valley for 20 years and have found that most ET functions based on water table depth are guesses that are unlikely to be correct and may not be close to reality. The only way to really determine this is to measure ET, with a Bowen Ratio system or Eddy covariance system, at the full range of water table depths that occur, and build the functions from real data. Of course these functions will vary with vegetation type, leaf area, plant density, transpiration rates etc. And the rooting depth is not really that good an indicator for a number of reasons. First it's really hard to determine the "rooting depth" of any plant species. Second, most roots are in the upper 50 cm of soil, and the fact that there are a few roots deeper than 100 cm is not necessarily very instructive. Not all roots are identical in their water uptake.

L 440, Figure 7. Why was well 208 observed and modeled? As stated on L 432, these models do a poor job of replicating daily and weekly water table dynamics.

L 472. The issue with this approach is that a water table rise of 1---2 feet, which is not captured by the model would result in a huge recharge event into the soil. So would it be possible to improve the model or analysis of data using soil moisture sensors?

L 543. Here it's stated that extinction depth had little effect on the model. But the depths analyzed were 4---7 feet during the modeled period. A site with a water table 4---7 feet below the ground is certainly not a wet meadow. So why is such a site being analyzed?

L 763. I guess I would like to hear from ground water modeling experts, but from my view as an ecologist the model misses the rise in water table driven by high stream stage and precipitation events that last less than a month. These hydrologic events seem critical to driving soil water recharge and ET processes at certain times of the year.

For Appendix B, it would be nice for each of the hydrographs presented to tell us the elevation of the ground surface. While the elevation of water table observed and modeled is interesting, it would be just as interesting to see how well the model did with shallow vs. deeper water table sites.

Peer Review submitted by Reviewer 2

Peer Review Rating & Recommendation

RATING

Please score each aspect of this set of chapters using the following rating system: 1 = Excellent; 2 = Very Good; 3 = Good; 4 = Fair; 5 = Poor

Category	Rating
Scientific soundness	2
Degree to which the monitoring approach addresses the project's objectives	2
Organization and clarity	1
Conciseness	1
Important to objectives of the Program	1

RECOMMENDATION (Check One)

Accept
Accept with revisions X_
Unacceptable

Revisions are expected in the following areas:

A) See Question 5 Response
B) See Question 6 Response
C) See Question 7 Response
D) See Question 9 Response
E) See Question 10 Response
F) See Question 14 Response
G) See Question 15 Response
H) See Question 18 Response
I) See Question 19 Response
J) See Question 22 Response
K) See Question 24 Response
L) See Question 26 Response
M) See Question 27 Response

1. Are the objectives of the monitoring effort clear and obtainable?

The objectives are clear and obtainable for the most part. However, there are comments embedded in some specific chapters: ET, soil moisture and groundwater on the monitoring and modeling effort to help improve the wet meadow surface hydrology and ground water hydrology.

2. Will the monitoring approach provide sound and comprehensive data to achieve the Monitoring Plan's objectives?

Yes, certainly it provides a comprehensive and physically meaningful dataset to achieve the monitoring plan's objectives.

3. Please identify any additional monitoring equipment or procedures that would allow this study to better achieve its objectives.

Clearly, they need to measure ET more realistically. Scintillometer to derive area-averaged ET (actually sensible heat flux) along with four-component radiometers (longwave, shortwave for both incoming long and shortwave radiation) and ground heat flux for vadose zone (in the drier part of the study area) could augment the stated suite of data being collected. Infiltration to partition precipitation (in the precipitation reduction factor) would help advance recharge calculations.

4. Are potential biases, errors, or uncertainties appropriately considered within these chapters?

Crop coefficient approach need to be local, otherwise, converting reference ET to actual ET can lead to uncertainties in ET which can then propagate uncertainties in other water budget components and recharge as well. Precipitation reduction factor to partition recharge can be derived with site-specific infiltrometer tests. Also, soil moisture below 1.85 m is currently designated as recharge and that need to be ascertained.

Chapter-Specific Questions

CHAPTER 1

5. Does the conceptual model presented capture all the relevant hydrologic processes? Does it ignore any critical processes?

The conceptual model covers P, RGW, ET, Delta S1 and Delta S2 within the domain boundary. However, it does not account for the part of deeper percolation to deep groundwater systems. On page 12, para 1, they emphasize the delinked nature of deeper and shallow ground water system in the functioning of wet meadows. It is possible that shallow aquifer systems as depicted in the Figure 2, and the conceptual model components capture most of the hydrologic budget. However, it is better to include the loss of part of percolation to deep groundwater systems so that the water budget closure can be reasonable. What if the future precipitation increases the deeper groundwater levels to be higher so that it connects with shallow system at some point? In other words, will there be any upward flux from deep to shallow systems? Ogallala Aquifer discharge seemingly experience depleting the water table elevation and it might have some effects on shallow system as well. In that case, will some of the shallow systems drain into deeper aquifers due to gradient and gravity?

6. To what degree is the assumption that precipitation can act as a surrogate for overland application of water appropriate?

If the hydrologic connectivity is limited to an extent that all the inputs to subsurface systems is solely from precipitation, it is a reasonable assumption. The hydrologic connectivity can't be completely ascertained until there is some effort dedicated to investigate if the wet meadows are not receiving inputs through subsurface lateral flow outside of the domain. So, the lateral flow into the domain needs to be quantified to treat the wet meadow system as a closed system entirely driven by precipitation inputs only. Line 207- 308 assumption on this needs to be paid attention as the systems can be changing.

7. The monitoring approach assumes the understanding of wet meadow hydrologic processes gained through the higher level of monitoring at the Fox and Binfield site can be applied to the Johns and Morse site which receive less extensive monitoring. Is this a reasonable assumption?

Higher level monitoring at Binfield is evident (9 West and 7 East). However, the information provided to compare across the sites is insufficient. Why is the difference between east and west side number of wells? It is possible that the drawdown or exchanges may not be symmetrical on both sides, but a schematic on assumed water table elevation map on either side would help understand better. The depth is uniform for this site at 10 ft and will that be sufficient to capture the lowering water table elevation away from the channel with this uniform depth is not clear. In other words, can they go deeper away from the channel like they do at Fox (and Johns and Morse)?

8. Given the information currently available, is the well placement and density appropriate to capture site-wide groundwater behavior at each of the four sites?

No.

9. Is the assumption of minimal off-site runoff reasonable?

The assumption of no off-site runoff or on-site runoff is not reasonable. The study proposes to use crest A type gage measurements to measure in two sites. It might be a good start and based on the flow information they can decide whether they should have in the other two sites, (Johns and Morse). The reason to measure, as obvious, is that high intensity storm events can produce sheet flow and that is not available for recharging shallow aquifer or stream gains. If the water budget closure is a problem, this assumption of no off-site runoff can be contributing to that error. Also, if there are some best management practices that can be implemented to harvest and augment shallow groundwater systems or directly into the wet meadows that will be adding value as rainwater harvesting techniques are proven to mitigate erosion and increase recharge potential.

10. Is the assumption that near surface groundwater behavior is not driven by the behavior of the deeper alluvial aquifer on a daily time scale reasonable?

As mentioned in the earlier response, this delinked shallow and deep aquifer system need to be proven to make sure that it is a right assumption. Because even if there is no explicit two way linking (downward and upward flux exchanges between shallow and deeper systems), certainly many systems, including sandy soils, one way deep drainage to recharge deeper aquifer system can be possible. If that amount of water is not accounted for, the gain or baseflow assumptions in the hydrological framework can be slightly higher and it can lead to errors in wet meadows storage.

11. Is the assumption that percolation into the underlying aquifer has a negligible impact on near surface groundwater behavior reasonable?

It is not reasonable to assume that, particularly if the soil texture is coarse. Even though it may be recharging at a higher rate as in the Sandhills region, the geology and stratigraphy of this area should be evaluated to make sure that the loose sandy soils do not exist. If that texture supports high permeability, percolation or some amount of precipitation is expected to be lost to deep groundwater systems which needs to be accounted for.

12. Are single river stage gages used in conjunction with surface water models sufficient to capture surface water behavior at a wet meadow site?

Yes. It is sufficient.

13. Is the approach to relating river stage and discharge reasonable?

They are relating the discharge with river stage with both USGS flow measurements and HEC-RAS modeling. Flow percentages of each channel at a given stage are only an approximation of the real channel flow. Depending on how good the channel cross sections, the flow estimations can vary. If there is a way to check and make sure that channel cross sections are relatively stationary in the past few years, using satellite or LIDAR (if available) imageries, it might to justifiable to state this approach is reasonable and it is recognized that they are referring to it in Line 688-694.

14. Is the assumption that precipitation falls fairly uniformly across a wet meadow site reasonable?

One gage is not sufficient. A second precipitation gage is necessary, given that precipitation is the major source of water input in these complex systems. This is primarily to cross-validate the gage measurements, or at best as a back up to first one if it fails. While they can get the HPRCC data for validation, it is important that they have more than one. Because of active convective precipitation systems that can contribute to highly localized precipitation events, measuring precipitation at all of the wet meadow sites deserves great attention. Further validation is also highly desirable during the recharge period (typically during late winter) and Spring (when Gulf of Mexico moisture arrives at this region) by using NWS-based radar estimates of precipitation.

15. Does the monitoring approach adequately measure the timing and magnitude of snowmelt and soil freeze/thaw behavior to account for the impact of these processes on groundwater behavior?

AWDN HPRCC stations measure soil temperature and this project is proposing to use that. However, the depth of measurement is not specified. Soil freeze/thaw behavior plays an important role in facilitating through-flow (through voids) when the temperature excursions above 32 °F occur. Also, the rain on snow event can be contributing to winter time surface runoff and that precipitation is not available for recharge on-site. So, snow energy balance-incorporated runoff in the winter (especially when the future is expected to see warmer winters), would help improve the understanding if snowmelt or freeze/thaw cycle or rain-on-snow events play a role in runoff or recharge behavior.

CHAPTER 2

16. Does the review of methods of determining ET omit any commonly used method?

They have done fairly well in reviewing various ET methods. Most of the commonly used methods are shown. They clearly spelled out the equations, variables, and coefficients. However, one new method of measuring ET is not mentioned and that is using Scintillometer. It is a wonderful piece of equipment, with a receiver and a transmitter, to measure areal average sensible heat flux which is used to calculate latent heat flux (with additional measurements for net radiation and ground heat flux) for a swath of 1-2 km or more if there is homogeneity in grass cover. The transect can be set after a careful site investigation but it should certainly add value to getting ET measurements beyond one point, which would in turn help get multiple pixel values (100 m) of recharge from the same transect to use it in the MODFLOW simulations mentioned later.

17. Are the conclusions drawn from the comparison of methods reasonable and scientifically sound?

Yes, they are reasonable and scientifically sound.

18. Is the use of the crop coefficients developed by the USGS for riparian grassland reasonable? Are there other crop coefficients that would provide better results?

This reviewer think that crop coefficients can be developed for each site, instead of adopting USGS- developed coefficients. If cost is an issue, at best, they could try validating USGS coefficients for at least one site, and determine if the difference exceeds 5% in difference, then they could extend developing new coefficients for other sites.

CHAPTER 3

19. Does the conceptual soil moisture water balance accurately approximate expected soil moisture behavior at wet meadow sites?

The conceptual soil moisture water balance captures soil moisture movement mostly. However, this reviewer considers more additional pathways for the moisture to move in the domain. And they are: the upward flux (exfiltration) from the two layers shown in figure. That is, the opposite of infiltration and percolation shown. The ponding shown in Figure 1 of Chapter 2 is because of that effect. While the water table rises or the reach gains are at high rates, this process can occur. The second aspect is the lateral flow from the layers. It is mentioned in some form but not explicitly. Obviously, if the soil is sandy or coarse-grained, it limits the lateral flow. Otherwise, a good portion of downward moving moisture can move laterally and end up in the stream.

20. Does the soil moisture monitoring approach provide and appropriate level of detail in light of the project's objectives?

It is proposed to use AWDN soil moisture Theta probes for four depths. The total observation depth thus goes to 1.85 meters. It is possible that capturing the soil moisture movement within these depths would be sufficient mostly. However, it can be interpreted that any moisture below 1.85 m is assumed to go into shallow aquifer or discharge into the stream. This assumption need to be verified at some point because as mentioned earlier, if the soil is deeper or if there is an upward flux this assumption may not hold good. Grammar mistake in line 147. Revise 'may not extrapolated' to 'may not be extrapolated'

CHAPTER 4

21. Is the model domain appropriate to capture groundwater behavior at the wet meadow sites?

Yes, the domain is appropriate. Given that the simulation is at 100 m resolution, it is fine.

22. Is the assumption of a homogeneous aquifer clearly supported and appropriate?

The homogeneous assumption should be evaluated. Isotropic conditions (Kx=Ky=Kz) and shallow alluvial aquifer treated as a separate unit from Ogallala aquifer should be proven with empirical data or monitoring missions.

23. Are the model boundary conditions appropriate?

Yes, specific head; river; no-flow cells are appropriate.

24. Is the use of the MODFLOW evapotranspiration (EVT) package appropriate? Would combining the precipitation and evapotranspiration values into the recharge (RCH) package better represent the physical system?

No, the use of the MODFLOW EVT package is posing some issues with results. Combining precipitation and EVT values into the recharge (RCH) can be part of the solution partly but not entirely. MODFLOW treating ET as a linearly varying variable with depth to water is really simplistic. Vadose zone processes, when the soil is partly unsaturated, determine the partitioning between ET and recharge and the linear relationship assumption can lead to errors in water table elevations. The best approach is to simulate the soil moisture dynamics in the vadose zone separately and link the fluxes (including recharge component) with MODFLOW. That way, it is not only refining your ET input but also the recharge component.

25. Is the assumption that standing surface water storage is negligible and no surface storage term in the groundwater models reasonable?

If the storage is fluctuating on a daily or weekly scales, this assumption is true. However, in some study sites and in the area, shallow aquifer systems feed the ponds for more than a month and there can be some significant amount of ET from these surface storage being lost and that needs to be accounted for. This will also help improve the predictions of water table and baseflow to the stream.

26. Can the model adequately simulate the effects ice flows and river stage increases caused by ice dams?

It is not possible in the existing modeling framework, unless the model can get the inputs on modified river stage dynamically due to ice dams. The impoundment is certainly adding residence time in the stream which in turn can add recharge to aquifers. Additionally any bank full discharge leading to the inundation of ponds on either side of the channel/Platte River can change the surface water- groundwater exchanges. A brief review of historic ice dam build up in the area and how to integrate in the modeling framework is very helpful.

27. Overall, do the models capture the groundwater behavior at the two sites to address the monitoring effort’s objectives?

The performance of the model in predicting the groundwater dynamics is reasonable. But there is room to improve predictions or reduce uncertainties. For example, 0.5 ft RMSE in water table elevations on average can be less (Table 7 at Binfield), as they rightly claim, due to cell size. However, for shallow aquifer system if that depth is not correctly simulated, it can impact ET, runoff or recharge estimates. Line 391-398. Reduction factor for precipitation (0.3-0.6) is purely empirical and needs to be physically explainable. Can they perform site-specific infiltration measurements (e.g. ring infiltrometer) to ascertain this? How measured ET is incorporated in groundwater modeling is not clear.

Peer Review submitted by Reviewer 3

General Questions

1. Are the objectives of the monitoring effort clear and obtainable?

Comments: The document (Chapter 1) clearly stated four objectives. Each of the first three objectives is related to an individual question regarding the response of the water table (groundwater table) in the wet meadows to river stage fluctuations, precipitation events, and evapotranspiration, respectively. The fourth objective is to investigate groundwater responses to combined water management actions such as upstream water release, overland flooding in wet meadows, and pooling of water in the depressed parts of wet meadows. It is very clear that the focus of these objectives is to quantify groundwater responses to other hydrological processes occurring by nature or by management.

The Program installed and plans to install field hydrological monitoring systems to monitor groundwater responses to the three major hydrologic processes: changes in river stage, precipitation-infiltration-percolation process, and evapotranspiration. After reviewing this document, I believe that "percolation" actually means to "recharge to groundwater". "Recharge" is more widely used by groundwater hydrologists to describe the amount of water that arrives at the water table and is added to the groundwater system. I suggest that "percolation" is replaced by "recharge". Installation of groundwater monitoring well networks and stream gages was to meet the first objective. Installation of weather stations, soil moisture monitoring, instrumentation for ET measurements and conducting soil moisture survey were to meet the second and third objectives. MODFLOW-based groundwater flow models for the site-scales were developed and calibrated for simulating groundwater responses to the management scenarios; the modeling activities meet the fourth objective.

Overall, the field hydrological monitoring systems and the numerical model will be able to produce useful data that will make the study objective obtainable. However, I have a few suggestions that will likely make the monitoring system produce a more complete data set for the study objectives.

2. Will the monitoring approach provide sound and comprehensive data to achieve the Monitoring Plan's objectives?

Comments: The documents provide an excellent description of the monitoring approaches. The Program installed their own groundwater wells and stream gages and also used some existing wells and stream gages (USGS and NDNR). The weather stations, soil probes, ET instrumentation and soil moisture survey will provide useful data to analyze the hydrological processes in the vadose zone and the root zone.

3. Please identify any additional monitoring equipment or procedures that would allow this study to better achieve its objectives.

Comments: While the hydrological monitoring system is pretty comprehensive, adding some monitoring devices will provide a more complete method for detecting the interactions of the groundwater systems in the wet meadows to other hydrological processes. The suggestions is as follows:

I suggest that the consumption of groundwater by the riparian forests in the wet meadows to be monitored. Here, "the riparian forests" refers to cottonwood, willows, etc. After reviewing the study area maps, a good portion of the wet meadows is covered by riparian forests, which can consume a large amount of groundwater during the growing season. The monitoring system for evapotranspiration seems to be appropriate to crop-type vegetation but does not address the groundwater consumption by the riparian trees. A previous monitoring activity in the Platte River valley near Alda and Kearney detected diurnal fluctuations of the water table that indicated the consumption of groundwater by the riparian.

The use of groundwater by riparian trees can be measured by monitoring the diurnal fluctuations of the water tables from wells installed in the tree areas. The amount of groundwater consumption can be estimated, with a low cost, from the water level data, for example, using the White method (White, 1932; Loheide et al., 2005). Some wells have already been installed in the riparian tree areas and groundwater level data have been collected. New wells can be added to other riparian tree areas. This monitoring activity will provide supplementary data to the ET monitoring system.

One of the objectives is to quantify the response of the groundwater to precipitation or overland water application. At the study sites, weather stations were installed to monitor precipitation and soil moisture at the Binfield and Fox sites. If a groundwater well is added and co-located with each of the weather stations, it will produce very complete sets of hydrological data: from the atmosphere (precipitation) to the soil (soil moisture) and then to the groundwater system. The direct response from the water table to precipitation events will be very useful to estimate groundwater recharge. Healy and Cook (2002) provided an excellent description on how to estimate groundwater recharges from the water table fluctuations. At the Binfield site, Well 206 seems to be co-located with the weather station. My guess is that the installation of Well 206 was to monitor the response of changes to the groundwater system to the stream stage. However, Well 206 can also be considered as instrumentation in the precipitation-soil moisture-groundwater recharge monitoring system. At the Fox site, Well 114 is far away from the weather station, so I suggest adding a new well that is co-located with the weather station. For the Johns and Morse site, similar considerations should be taken if a weather station is to be installed.

While the groundwater system is a central part of the monitoring and modeling efforts, the information on the hydraulic properties of the alluvial aquifer as well as the streambeds should be expanded. The Program may have conducted field investigations about the hydraulic properties of the alluvial aquifer, but the groundwater flow modeling activities have not demonstrated the richness of the data. In addition, stream-aquifer interaction is a major component of the monitoring program; the knowledge of the streambed hydraulic conductivity is needed. Some data may have been published in reports and journal articles. I understand that the current focus of the hydrologic monitoring is on the water flux. However, the hydraulic properties of the soil, aquifer and streambeds through which the water moves through are important information.

4. Are potential biases, errors, or uncertainties appropriately considered within these chapters?

Comments: Groundwater level monitoring for quantification of the response of the groundwater system in the wet meadow areas to the changes in river stage is well designed. ET monitoring methods can produce a good estimate of the ET values at the land surface; they will unlikely produce the ET rate of groundwater. I think that the ET estimation proposal has mainly focused on the grassy areas; the ET estimation for the riparian trees was not mentioned. "Percolation" (groundwater recharge) values determined through soil moisture monitoring programs should be cross-checked by other methods that estimate groundwater recharge. All groundwater flow models have uncertainties in the hydraulic parameter estimation.

The boundary conditions in the groundwater flow models pose a large uncertainty in the model outputs. The river leakage modeling results indicated that the river segment in the Fox wet meadow area is a losing stream (a typo in line 860 of Chapter 4, change "gaining" to "losing"). In contrast the river segment in the Binfield wet meadow area becomes a gaining stream (again, a typo in line 872, change "losing" to "gaining"). Attention should be paid to changes from losing to gaining conditions between the two study sites. This change might be partially caused by the numerical model design, not representing the real stream-aquifer hydrological conditions. I will further explain this uncertainty for the questions for Chapter 4.

Chapter-Specific Questions

CHAPTER 1

5. Does the conceptual model presented capture all the relevant hydrologic processes? Does it ignore any critical processes?

The monitoring systems capture all the important hydrologic processes that have the potential to interact with the groundwater system. However, the use of groundwater directly by the riparian forests (or woods) is an important flux component, which is not estimated. I call this process as groundwater ET. Publications indicate that the riparian trees and other vegetation can use a large amount of groundwater.

6. To what degree is the assumption that precipitation can act as a surrogate for overland application of water appropriate?

Precipitation leads to groundwater recharge. Both precipitation and overland flow will lead to vertical infiltration and produce recharge to the groundwater system. However, precipitation events usually do not clog the top soils. Overland flow application may disturb the top soils. Repetition of overland flow applications (or artificial recharge) may eventually clog the top soil, reduce the permeability, and eventually decrease the recharge rates.

7. The monitoring approach assumes the understanding of wet meadow hydrologic processes gained through the higher level of monitoring at the Fox and Binfield site can be applied to the Johns and Morse site which receive less extensive monitoring. Is this a reasonable assumption?
Comments: I don't see any reasons that can reject this assumption. The hydrological, geological, ecological and climatic conditions seem to be similar among these sites.

8. Given the information currently available, is the well placement and density appropriate to capture site-wide groundwater behavior at each of the four sites?

The transect wells are good designs for capturing the responses of the groundwater system at varied distances to the changes in stream stages. The water levels from these wells can very well reflect the stream infiltration processes during water releases upstream and during flood events.

At each weather station, I suggest installing a groundwater well to monitor groundwater responses to recharges from precipitation events. Monitoring wells should also be installed to monitor the consumption of groundwater in the riparian forests. I noted that several wells have been already installed in the riparian forests. The water level data from these wells can be used to estimate groundwater ET for these trees. However, I believe that additional wells need to be installed in the riparian trees to capture the spatial pattern of groundwater ET in the riparian zone.

I suggest that monitoring wells to be installed near the stream gages in the north channel at the Binfield site. I understand that the north channel is much narrower than the south (main) channel at the Binfield site. For a better understanding of the groundwater response to the river stages of both channels, it is desirable to put two to three wells near the gage of the north channel. These are shallow wells, so the cost for well installation will not be high.

9. Is the assumption of minimal off-site runoff reasonable?

Comments: Given that the land surface is relatively flat and that the top soils are permeable, I can accept this assumption.

10. Is the assumption that near surface groundwater behavior is not driven by the behavior of the deeper alluvial aquifer on a daily time scale reasonable?

Comments: I can accept this assumption for the wet meadows on a daily time scale. However, the groundwater flow model results indicated that the Platte River in the Binfield area gains a large amount of baseflow. That baseflow might be the component of the regional groundwater flow and is usually related to the deep layer of the aquifer.

11. Is the assumption that percolation into the underlying aquifer has a negligible impact on near surface groundwater behavior reasonable?

Comments: I guess that “the underlying aquifer” here refers to the Ogallala Group beneath the alluvial aquifer. Based on some of my own data from monitoring groundwater levels in the alluvial aquifer and in the Ogallala Group in this area, the hydraulic head difference between the two layers is very small during non-irrigation seasons. Furthermore, the alluvial aquifer and the Ogallala Group are separated by a low-permeability aquitard. That means that the water exchanges under natural conditions are minimal. However, if water supply wells or irrigations wells operate in the wet meadows or in the adjacent areas, pumping in the Ogallala Group (confined aquifer) can lead to a large cone of depression. Under these circumstances, the water from the alluvial aquifer can leak into the Ogallala aquifer even though an aquitard separates the two aquifers. The content in Chapter 4 indicates that such wells do not exist. However, in the future, if such pumping wells are installed, their impact on the alluvial aquifer needs to be assessed using a multiple-layer groundwater flow model.

12. Are single river stage gages used in conjunction with surface water models sufficient to capture surface water behavior at a wet meadow site?

Comments: I understand the difficulties for putting more stage gages because of the braided characteristics of the river channel and instability of the channel sediments. The channel elevation survey data (for example, the channel surface elevation maps and channel gradient) may be useful in assisting the estimation/interpolation of river stages in the study area. When stream stage is high and the sandbars are under water, the stream stage across the main channel may be the same. When the stream stage is low and the sandbars are emerged above the water, stream stages in the braided channels may differ. It may be desirable to conduct a survey to find out whether the difference of stream stage in these channels is small.

13. Is the approach to relating river stage and discharge reasonable?

Comments: I can agree with the approach.

14. Is the assumption that precipitation falls fairly uniformly across a wet meadow site reasonable?

Comments: I think the monthly and annual rates can be considered uniformly across a wet meadow.

15. Does the monitoring approach adequately measure the timing and magnitude of snowmelt and soil freeze/thaw behavior to account for the impact of these processes on groundwater behavior?

Comments: Use of winter precipitation gages and cameras, as described in Section of Winter Precipitation, seems to be appropriate for measuring the timing and magnitude of snow accumulation and snowmelt. The effect of soil freeze/thaw behavior to hydrological processes such as infiltration was not described.

CHAPTER 2

16. Does the review of methods of determining ET omit any commonly used method?

Comments: This is a very complete review of methods for ET estimation from the land surface. Most of the described methods are for estimating ET where the vegetation mainly uses soil water (except for the groundwater lysimeter method). However, as I suggested in previous sections, estimation of groundwater ET for the riparian forest needs to be considered for the wet meadows where cottonwood and willow cover a large portion of the area. A large number of publications have been available for estimation of groundwater ET in riparian areas.

17. Are the conclusions drawn from the comparison of methods reasonable and scientifically sound?

Comments: This chapter provides an excellent analysis of the advantages, disadvantages, applicability, cost, etc. for the described methods.

18. Is the use of the crop coefficients developed by the USGS for riparian grassland reasonable? Are there other crop coefficients that would provide better results?

Comments: The use of the crop coefficients is probably acceptable for the grass lands. But it needs an analysis whether it is suitable for the riparian forests.

CHAPTER 3

19. Does the conceptual soil moisture water balance accurately approximate expected soil moisture behavior at wet meadow sites?

Comments: Figure 4 in this chapter is a schematic representing the water components related to the unsaturated zone. This schematic approximates the soil moisture behaviors for the wet meadows. Equation 1 (line 96, I – ET – PERC = S) lists the four important water components. The report assumes that infiltration (water entering the land surface) is equal to precipitation for the wet meadows area. Three of the four water components (I, ET, and S) will be collected or derived from hydrological monitoring systems. Thus, percolation (PERC) can be estimated which is actually the groundwater recharge. Groundwater recharge is a very important flow component and one of the monitoring objectives is to quantify the groundwater recharge from precipitation. Conducting a good estimate of groundwater recharge is a challenging task. I suggest that the estimated groundwater recharge is checked by using other methods.

Groundwater recharge can also be estimated by other methods. One of simple and cost-effective methods is to use groundwater level monitoring data. The water-table fluctuation method is described in detail by Healy and Cook (2002). Water levels from some wells in the existing well network may be good enough to estimate groundwater recharge from precipitation events. These wells need to be located far from the river channels so that river stage fluctuations have minimal impact on the water levels at these wells.

20. Does the soil moisture monitoring approach provide and appropriate level of detail in light of the project's objectives?

Comments: The soil moisture probes at the weather stations are installed at four depths (10, 25, 50, and 100 cm below the land surface) and provide point measurements (the report did not specify data collecting time intervals for these probes). The cosmic-ray neutron probes will collect area-averaged soil moisture for about 70-acre areas with monitoring depth of 15 to 40 cm and time intervals of 1 hour. Vehicle-mounted cosmic-ray neutron probes (rover survey) are used to collect soil moisture for the whole area of the wet meadows at 1-minute interval.

These are good approaches for collecting soil moisture data. These methods cover different depths and have different time intervals. It needs to provide discussion on how these soil moisture data will be used to determine soil moisture changes (S) in equation 1.

CHAPTER 4

21. Is the model domain appropriate to capture groundwater behavior at the wet meadow sites?

Comments: This is a very good report documenting the model development and calibration processes. The size and orientation of the model domain are appropriate. However, the arrangement of the inactive cells limited the flexibility for imposing appropriate constant head boundary conditions in up-gradient border for the two models (see my additional comments for question 23).

22. Is the assumption of a homogeneous aquifer clearly supported and appropriate?

Comments: It is clear that the aquifer hydraulic properties (for example the hydraulic conductivity and specific yield) are not homogeneous. However, for the first-step model calibration, the assumption of homogeneity is acceptable. Clearly, water levels from some wells better match with the modeled water levels than the water levels from other wells. This may be an indication of heterogeneous aquifer properties.

I cannot agree with the assumption of isotropic hydraulic conductivity in the horizontal vs. vertical direction (Kx = Kz) although isotropic assumption for Kx = Ky in the horizontal plane is acceptable. Aquifer pumping tests and streambed tests in this area indicate that the vertical hydraulic conductivity Kz is smaller than the horizontal hydraulic conductivity; the ratio of Kx to Kz can be 10 to 50 for the alluvial aquifer and 3 to 10 for the streambeds. Although the assumption of isotropic hydraulic conductivity in the vertical direction will unlikely affect the model results (due to the fact of the one-layer aquifer model), I still suggest that a smaller Kz value be used for the model.

The assumption of a uniform thickness of 80 feet for the alluvial aquifer (from the land surface to the base) is probably close to the real thickness values of the alluvial aquifer. I would still like to see that test-hole data logs or references are cited to support this assumption. I saw some publications that indicate the thickness of the alluvial sediments in the area is around 60 feet.

The specific yield value seems to be reasonable.

23. Are the model boundary conditions appropriate?

Comments: I believe that the spatial arrangement of constant head boundary conditions did not fully reflect the real groundwater flow systems that flow in and out of the study sites. This might be a key factor that causes a large uncertainty in the model outputs.

Because the model imposes a large number of inactive cells, the constant head condition in the up-gradient boundary (or the west domain border) was not appropriately given. For the Fox site, constant head boundary was given only in the east boundary (the down-gradient border); no constant head boundary conditions were given on the west border. This is due to the arrangement of the inactive cells that leads to a pinch-out aquifer between the river channels in the west. As a result, the modeled aquifer system showed that a large volume of groundwater flows out of the alluvial aquifer (4,117 AF as shown in Figure A2). This flow-out water volume must come from the river leakage and into the aquifer system (3,324 AF as shown in Figure A2). In reality, groundwater moves into the alluvial aquifer from the western border. The water budget numbers (Figure A2) implied that the river segment lost a large volume of water to the aquifer during the modeled period; this is probably not real. To remedy this, a nearly-equal aquifer width in the up-gradient border (compared to the down-gradient border) needs to be arranged so that constant head boundary conditions are imposed and the regional groundwater flow will move into the modeled aquifer. This can be done in two ways: 1) convert some of the inactive cells north of the north channel to active cells, 2) move the west border of the model domain toward to east by 1~1.5 miles.

For the Binfield model, constant head boundary conditions were imposed on both the up- and down-gradient borders. However, the width of the active cells in the up-gradient border is only about ¼ of the width of the down-gradient border. Yet, according to Figure A3, the flow-in groundwater along the up-gradient border is 2,985 AF more than the flow-out groundwater along the down-gradient. Some of the extra flow-in water must flow out of the aquifer through the river channel as baseflow. I suggest that the water budget numbers be carefully evaluated for all of the model scenarios shown in Appendix A. Furthermore, I suggest that inflows from the river, outflows from the river, inflows from the constant boundary and outflows from the constant head boundary are explicitly plotted in the figures of A2 through A7.

I think that the model can be designed in such a way that the flow-in water from the up-gradient border is approximately equal to the flow-out water along the down-gradient border. Under this circumstance, the stream-aquifer interaction can be better modeled.

The north channel and south channel are the model boundaries of the active-cell areas. The authors used River package to represent the two river channels. This is acceptable to me because river-aquifer interaction is a key component for understanding the interactions of the groundwater system and the surface hydrological processes. Model uncertainty can come from two aspects: 1) streambed leakace and 2) the river channel geometry. River leakace is equal to krb/b; here krb is the vertical hydraulic conductivity of the top layer of the channel sediments and b is the thickness. The report used krb = 10 ft/day and b = 0.1 m. These values need to be supported by data. For the river channel geometry, the south channel is pretty wide (up to 720~839 feet) when it is fully covered by water. The report used only one cell (100 ft by 100 ft) to represent the south channel. I understand that the channel width across the north and south bank was factored into the riverbed conductance. My question is whether the actual channel width is represented in the model by multiple cells for example 5 to 8 cells for the south channel?

24. Is the use of the MODFLOW evapotranspiration (EVT) package appropriate? Would combining the precipitation and evapotranspiration values into the recharge (RCH) package better represent the physical system?

Comments: EVT package is appropriately used in the model. Some studies indicated nonlinear decreases of the ET value from the land surface to the extinct depth. There are currently no data sets to verify this for the two study sites. Thus, the linear option is acceptable.

I would not recommend combining the hydrological processes into recharge package. I would suggest conducting additional investigation of groundwater ET in the study sites.

25. Is the assumption that standing surface water storage is negligible and no surface storage term in the groundwater models reasonable?

Comments: When the groundwater level is low, the wet meadows may have limited surface water storage. The documents indicated the existence of sloughs that drains groundwater at some sites. Occurrence of sloughs may thus affect groundwater levels and they can be modeled when the model is updated.

26. Can the model adequately simulate the effects ice flows and river stage increases caused by ice dams?

Comments: The model is not able to simulate ice flows. The river package used in the model needs only the river stage information (as well as riverbed conductance). If ice dams elevate the river stage, which can be recorded at the river gages, the river stage elevation can be inputted into the river package, and groundwater response can be simulated to the elevated stream stage. Streambed hydraulic conductivity can be slightly lower under cold water, compared to summers.

27. Overall, do the models capture the groundwater behavior at the two sites to address the monitoring effort's objectives?

Comments: Overall, the authors did a good job in the model development although some revisions on boundary conditions can be done to improve the model quality. A model update is recommended when new hydrological and geological data become available.

Editorial suggestions:

Chapter 1
Lines 21, 22, 26, 27, 34, 35, and 36, use upper case for the first letter of each word, to be consistent with other sub-titles.
Line 113, "management its water resources", do you mean "management for its water resources"?
Line 129, "determine" to "determining".
Line 153 Figure 1, I suggest adding root system to the tree on the right-hand side and let the root system touch the water table. The riparian trees in the study area can directly consume groundwater during the growing season. Do the same for Figure 2.
Line 167, in this section, I would like to add a statement indicating that the grass root (at least some) and riparian trees can directly consume groundwater from the water table.
Line 176, "of the site" to "the site".
Line 236, "that not been" to "that has not been".

Line 253-254, “The sites comprise vary in size…”. This sentence needs re-wording.
Line 352, “in monitored with” to “is monitored with”.
Line 402, the last word “is”, change it to “are”.
Line 567, The sentence starting with “The energy balance approach…” needs a verb after “approach”.
Line 570, “at wet meadow sites” to “at the wet meadow sites”.
Line 621, “groundwater behavior” to “the groundwater table”.
Line 642, “to for”, delete “to”.
Line 673, “will monitored” to “will be monitored”.
References, I suggest using consistent format for the authors’ names.

Chapter 2
Line 102, “assume” to “assumed”.
Line 147, “may not extrapolated” to “may not be extrapolated”.
Line 219, “in to” to “into”.
References: please spell all authors’ names in “et al.”

Chapter 3
Line 379, “Equation 2”? Do you mean “Equation 3”?
Line 509, “Equation 4”? Do you mean “Equation 5”?
Line 1338, I suggest changing “BIBLIOGRAPHY” to “REFERENCES”, to be consistent with other chapters.
The title of a journal article in some references uses upper case for the first letter of each word; in other references, only the first letter of the first word of a title uses upper case. I suggest using a consistent citation format for all the references.

Chapter 4
Line 11, change “hydrology” to “hydrological data”.
Line 11, change “though” to “through”.
Line 86, change “Baseline Parameter Values” to “Baseline parameter values”, to be consistent with other table captions.
Line 184, change “extends” to “extend”.
Line 213 (Table 2), change “57 days” to “58 days” for the Fox event and the Binfield event.
Line 219-221, in this area, the shallow alluvial aquifer is separated from the Ogallala aquifer by an aquitard.
Line 237, for the Fox site area, the thickness of the alluvial sediments may be around 60 feet.
Line 378, please give the values of the ET rates for each stress.
Line 404-407, I am glad to see that the report documented that nearby irrigation pumping did not affect the groundwater flow in the wet meadow areas.
Line 420, these three equations are equation 2 to equation 4. Equation 1 appears in page 15.
Line 553, change “equation 1” to “equation2”.
Line 860, “losing reach”? I think this is a typo. It is “gaining” stream based on your water budget of the model outputs.
Line 872, “gaining reach”? According to the water budget of the model outputs, it is a “losing reach”.

References:

Healy, R. W., and P.G. Cook, 2002. Using groundwater levels to estimate recharge. Hydrogeology Journal 10: 91–109.

Loheide, S. P., II, J. J. Butler Jr., and S. M. Gorelick, 2005. Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment, Water Resour. Res., 41, W07030, doi:10.1029/2005WR003942.

White, W. N., 1932. A method of estimating groundwater supplies based on discharge by plants and evaporation from soil – results of investigation in Escalante Valley, Utah, U. S. Geol. Surv. Water Supply Pap., 659, 105 pp.

4. Statistical design and analyses: Are they appropriate and correct? Can the reader readily discern which measurements or observations are independent of which other measurements or observations? Are replicates correctly identified? Are significance statements justified?

5. Conclusions: Has the author(s) drawn conclusions from insufficient evidence? Are the interpretations of the data logical, reasonable, and based on the application of relevant and generally accepted scientific principles? Has the author(s) overlooked alternative hypotheses?

6. Errors: Point out any errors in technique, fact, calculation, interpretation, or style.

7. Citations: Are all (and only) pertinent references cited? Are they provided for all assertions of fact not supported by the data in the manuscript?

D. FAIRNESS AND OBJECTIVITY

If the research reported in this paper is flawed, criticize the science, not the scientist. Harsh words in a review will cause the reader to doubt your objectivity; as a result, your criticisms will be rejected, even if they are correct!

Comments should show that:
1. You have read the entire manuscript carefully,
2. Your criticisms are objective and correct, and are not merely differences of opinion, and are intended to assist the author in improving the manuscript, and
3. You are qualified to provide an expert opinion about the research reported in this manuscript.

E. ANONYMITY

You may sign your review if you wish. If you choose to remain anonymous, avoid comments to the authors that may serve as clues to your identity, and do not use paper that bears the watermark of your institution.

RATING:
Please score each aspect of this manuscript using the following rating system: 1=excellent, 2=very good, 3=good, 4=fair, 5=poor.

	Rating
Scientific soundness	1.5
Degree to which conclusions are supported by the data	2
Organization and clarity	1
Cohesiveness of conclusions	1.5
Conciseness	1.5
Importance to objectives of the Program (For use by internal review panel only)	1

RECOMMENDATION	(check one)
Accept	
Accept after revision (See my comments for questions 3 and 23)	✓
Unacceptable	

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APPENDIX B: REVIEWER BIOGRAPHICAL SKETCHES

Proposed Peer Review Panel Member for Platte River Recovery Implementation Program

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Education	Ph.D.

Unique Qualifications

1 Investigated stream-aquifer hydrologic connectedness between the Platte River and the High Plains Aquifer betwee Lexington and Ashland; **2** developed river-aquifer numerical models in the Kearney-Duncan area to analyze stream-aquifer interactions; **3** performed 7 aquifer tests in the High Plains Aquifer of the Platte River Valley to determine hydrualic properties; **4** Conducted transmission loss analysis of the Platte River between Kearney and Grand Island; **5** monitored groundwater responses to stream fluctuation, precipitation and evapotraspiration in the Kearney-Alda area, Nebraska.

Short Biography of Proposed Peer Review Panelist

Education

1994 Ph.D., Hydrogeology, Department of Geology and Geophysics, University of Wyoming. Advisor: Dr. Leon Borgman (member of the National Academy of Engineering).
1988 M.S., Geology, Department of Geosciences, California State University, Northridge
1982 B.S., Geology, Department of Geology, Zhejiang University, Hangzhou, China

Working Experience

Professor, 7/2005-present, School of Natural Resources, University of Nebraska-Lincoln
Associate Professor, 7/98 to 6/2005, School of Natural Resources, University of Nebraska-Lincoln
Assistant Professor, 10/94 to 6/98, Conservation and Survey Division, University of Nebraska-Lincoln
Consulting Hydrogeologist, 05/1991 to 8/1994, TriHydro Corporation, Laramie, Wyoming
Instructor, 01/82 to 08/85, Zhejiang University, China.

Research Areas

Groundwater flow model develoment for agricultural watershes, hydrogeology of the High Plains Aquifer and streambeds, hydroloigcal connectedness of surface water and groundwater, groundwater level monitoring, groundwater ET measurements, and streamflow depltion analysis.

Services and Affiliations

Associate editor, Journal of hydrology (2008-present); Fellow, Geological Society of America (2011-present); Fellow Center For Great Plains Studies.

Publications, Presentations, Grants and Course taught

108 peer-reviewed publications, 23 research and contract reports, 11 proceesdings papers, 74 conference presentations, 59 invited presentations, and 35 grants. I taught two courses: Applied Groudnwater Modeling and Geostatistics.

Proposed Peer Review Panel Member for
Platte River Recovery Implementation Program

Name	David J. Cooper
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Education	Ph.D.

Unique Qualifications

I have worked in meadow and wetland ecosystems for more than 30 years, have published more than 100 peer review books, and journals, and have worked in most region and meadow types in North America. I do sponsored research in support of federal and state agencies, and currently have research projects on 4 continents. My research integrates hydrology, ecology, geomorphology and land/water management.

Short Biography of Proposed Peer Review Panelist

David COoper is a senior research scientist and professor at Colorado State University in Fort Collins, Colorado. He has worked on wetland issues in the western US for more than 30 years. His work analyzes hydrologic processes supporting wetlands and wetland plant species, restoration, long term monitoring study design and protocols, and impact assessments. Much of his work is in support of federal agencies, such as the National Park Service, and Forest Service, but he also works for every federal, state and local government level, as well as non profit, for profit and conservation groups interested in research to support land management and restoration. He has trained more than 40 MS and PhD students and has an active research and consulting program on 4 continents. He has served as peer reviewer for many federal programs for agencies such as EPA, Corps of Engineers, and Bureau of Reclamation. He also serves as associate editor of the journal Wetlands.

APPENDIX B – Executive Director's Office Responses to Independent Peer Review Comments

PLATTE RIVER RECOVERY IMPLEMENTATION PROGRAM
EDO Response to Peer Review Comments – General Questions
Wet Meadow Hydrologic Monitoring Approach Chapters

The format of these EDO responses are as follows:

- **Original question to peer reviewers in bold text**
- Louis Berger summarized responses from peer reviewers in standard text
- *EDO response in italicized red text*

Question 1: Are the objectives of the monitoring effort clear and obtainable?

All three reviewers found the monitoring objectives to be clear and obtainable, particularly if certain comments are addressed. Reviewer 1 noted that all four objectives are obtainable and can be achieved with the right scientific methods. Reviewer 2 noted that the objectives are mostly clear and obtainable, but the monitoring approach could be improved by addressing specific comments on ET, soil moisture, and groundwater. Reviewer 3 found the overall objective to quantify groundwater responses to other hydrological processes to be “very clear” and affirmed that the methods are likely to produce data that will make the objectives obtainable, particularly if additional suggestions are incorporated (e.g., see Question 3).

ED Office responses to other questions and specific reviewer comments address the general issues raised by the reviewers.

Question 2: Will the monitoring approach provide sound and comprehensive data to achieve the Monitoring Plan’s objectives?

All reviewers responded positively to this question. Reviewer 1 stated that the approach is “generally good”; however, could be improved in many places by incorporating his suggestions. Reviewer 2 agreed that the approach will provide a “comprehensive and physically meaningful dataset” to address the project’s objectives. Reviewer 3 concluded that the chapters provide an excellent description of the monitoring approaches, and which will provide useful data for analyzing hydrological processes.

The ED Office appreciates the positive comments.

Question 3: Please identify any additional monitoring equipment or procedures that would allow this study to better achieve its objectives.

All three reviewers offered recommendations for additional equipment and procedures to improve the likelihood of achieving study objectives. Reviewer 1 recommended that ET be quantified, not estimated, and that specific vegetation ET rates be used to more accurately estimate ET at study sites. He also recommended that more than one staff gauge be installed on the Platte River. Similarly, Reviewer 2 recommended that the Program measure ET more realistically (e.g., using scintillometers to derive area-averaged ET, four-component radiometers to measure long and shortwave radiation, etc.) to augment the proposed data collection effort. Reviewer 3 offered several suggestions, including: adding wells to measure groundwater usage by riparian forests in order to supplement the ET monitoring system; ensuring that there are wells co-located with each of the weather stations to provide data for the precipitation-soil moisture-groundwater recharge monitoring system; investigating and/or providing existing information on the hydraulic properties of the soil, alluvial aquifer, and streambeds.

The ED Office addresses all of these concerns in the chapter specific questions and the comment spreadsheet.

Question 4: Are potential biases, errors, or uncertainties appropriately considered within these chapters?

Reviewer 1 noted that, in general, the uncertainties are well understood. Reviewer 2 pointed out the need for the crop coefficient approach to be local, otherwise there will be uncertainties in ET estimates and other components. Reviewer 3 noted several areas of potential bias and uncertainty, specifically the fact that ET estimation focuses on grassy areas, not riparian trees, and the areas of uncertainty in the groundwater models; he further describes these uncertainties in response to the Chapter 4 questions.

The ED Office addresses all of these concerns in the chapter specific questions and the comment spreadsheet.

Responses to Chapter-Specific Questions

CHAPTER 1

Question 5: Does the conceptual model presented capture all the relevant hydrologic processes? Does it ignore any critical processes?

In response to this question, each reviewer pointed out areas of deficiency in the conceptual model. Reviewer 1 raised questions about the right model boundary and the degree of potential interaction between adjacent lands, their groundwater, and the wet meadow in Figure 2. Reviewer 2 noted that the model includes the major components, but does not account for percolation from the shallow aquifer to the deeper groundwater system. He raised several questions related to the interaction between shallow and deep groundwater systems for consideration. Reviewer 3 stated that the model captures all the important process that may interact with the groundwater system; however, it does not include groundwater ET from the riparian forests, which is an important flux component.

Comments from Reviewer 1 were addressed by amending Chapter 1 to include further clarification regarding the interaction between groundwater at wet meadow sites and adjacent lands. Comments from Reviewer 2 were addressed by adding specific language to Chapter 1 regarding the less permeable layer separating the alluvial and Ogallala aquifers and providing supporting documentation. Comments from Reviewer 3 were addressed by removing trees in Figures 1 and 2 of Chapter 1 to clarify that the focus of this effort is on wet meadows, not riparian forests.

Question 6: To what degree is the assumption that precipitation can act as a surrogate for overland application of water appropriate?

All reviewers raised questions about the appropriateness of this assumption. Reviewer 1 noted the variable effects of precipitation on soil water content, and stated that precipitation alone cannot provide sufficient and sustained soil saturation and groundwater recharge to support and sustain wet meadows. Reviewer 2 stated that this is a reasonable assumption if hydrologic connectivity is limited and precipitation is the only input to subsurface systems; however, this has not been completely ascertained. Reviewer 3 commented that while both precipitation and overland flow cause vertical infiltration and recharge the groundwater system, repeated overland applications may eventually clog the top soil, reduce permeability, and decrease recharge rates.

The reviewers' concerns were addressed by amending Chapter 1 to explain how this assumption will be tested at the Fox site by comparing groundwater response to precipitation with groundwater response to water pumped onto the site.

Question 7: The monitoring approach assumes the understanding of wet meadow hydrologic processes gained through the higher level of monitoring at the Fox and Binfield site can be applied to the Johns and Morse site which receives less extensive monitoring. Is this a reasonable assumption?

Reviewers 1 and 3 found this assumption to be reasonable; however, Reviewer 2 disagreed. Reviewer 1 stated that if the hydrologic and soil conditions are similar and can support wet meadows vegetation, the assumption is reasonable. Reviewer 2 noted that the information provided to compare the sites is insufficient and raised several questions to elucidate whether this assumption is reasonable. Similar to Reviewer 1, Reviewer 3 saw no reason to reject this assumption given that conditions at the sites seem to be similar.

Reviewer 2's comments suggest a misreading of the question. The comments focus on the different number of wells in the western and eastern well transects on the Binfield site. The reviewer does not address the different level of monitoring between the Fox and Binfield sites and the Johns and Morse sites.

Question 8: Given the information currently available, is the well placement and density appropriate to capture site-wide groundwater behavior at each of the four sites?

Reviewer 1 commented that it appears reasonable for measuring surface water-groundwater interactions, but a more widely distributed set of wells could be helpful for developing water table maps and estimating site ET. Reviewer 2 responded that the placement and density is not appropriate to capture groundwater behavior at the sites. Reviewer 3 noted that the transect wells are well-designed to capture groundwater responses to stream stages and reflect stream infiltration during release events and floods.

Reviewer 1's suggestion that additional wells would be helpful for estimating site-wide ET were noted. The site-wide soil moisture data collected by the CRNP rover may be used in a similar fashion. Reviewer 2 does not provide any reasons or alternative suggestions for why the current placement and density is not able to capture groundwater behavior. The EDO notes Reviewer 2's concern; however, in light of the positive responses from the other two reviewers the EDO will assume the current level of monitoring is adequate.

Question 9: Is the assumption of minimal off-site runoff reasonable?

Reviewer 1 stated that the assumption is probably reasonable, unless there is considerable snow on the site during a period of high river discharge. Reviewer 2 commented that the assumption of no off-site runoff is not reasonable and noted that high intensity storm events can produce sheet flow that is not available for recharging the shallow aquifer or stream gains. Reviewer 3 responded that, given the flatness of the land surface and permeability of the top soils, he can accept this assumption.

The comments from Reviewer 2 were addressed by amending Chapter 1 to include explain that even during high intensity rain events, runoff is assumed to accumulate in low lying areas onsite rather than flowing off site.

Question 10: Is the assumption that near surface groundwater behavior is not driven by the behavior of the deeper alluvial aquifer on a daily time scale reasonable?

Reviewer 1 affirmed that the wet meadows water tables are highly influenced by the Platte River and suggested some methods for demonstrating this relationship. Reviewer 2 referred to his response to Question 5 regarding the need to prove there is no link (either two-way flux or one-way deep drainage) between the shallow and deep aquifers. Reviewer 3 accepted this assumption, but noted that the groundwater flow model results indicate the Platte River gains a large amount of baseflow around Binfield that may be part of regional groundwater flow and is often related to the deep aquifer.

While the stable ion/isotope ratio methods suggested by Reviewer 1 are outside of the scope of this monitoring effort, the river stage and water table maps recommended by Reviewer 1 will be developed from the data collected. Concerns from Reviewers 2 focused on recharge to a deeper aquifer system, not interaction between deeper and shallower portions of a single aquifer. EDO responses to Reviewer's comments on Question 5 address the lack of connection between the alluvial aquifer and the deeper Ogallala aquifer. Reviewer 3's comments regarding the relationship between baseflow and deeper aquifer is noted. The EDO will evaluate groundwater data to confirm this connection is not driving groundwater flow on a daily timescale.

Question 11: Is the assumption that percolation into the underlying aquifer has a negligible impact on near surface groundwater behavior reasonable?

Reviewer 1 cited evidence that the river is a losing stream through the study reaches (i.e., its elevation is higher than the groundwater, the water table declines with distance from the river), and noted that piezometers could be installed to quantify the vertical head. Reviewer 2 commented that this is not a reasonable assumption, particularly if the soil texture is coarse, in which case percolation could be expected to be lost to the deep groundwater systems. In support of this assumption, Reviewer 3 mentioned the small hydraulic head difference between the alluvial aquifer and Ogallala group, and their separation by a low-permeability aquitard; however, he also noted that if groundwater pumping occurs within wet meadows in the future, a cone of depression could form and cause downward leakage.

Reviewer 1's responses address the connection between the river and the groundwater and will be investigated with the river stage and groundwater monitoring planned for the wet meadow sites. The comment does not address percolation from the alluvial aquifer into the underlying Ogallala aquifer. Reviewer 2's concern about percolation into the deeper aquifer was addressed by the discussion of the layer of lower permeability between the alluvial and Ogallala aquifer and the inclusion of reference material. Reviewer 3's suggestion that groundwater pumping may cause a cone of depression is noted and will guide data analysis if pumping occurs.

Question 12: Are single river stage gages used in conjunction with surface water models sufficient to capture surface water behavior at a wet meadow site?

Reviewer 1 recommended a minimum of two staff gages for making maps of surface water and groundwater recharge. Reviewer 2 stated that this approach was sufficient. Reviewer 3 acknowledged the difficulty in adding more stage gages to a braided river channel with unstable sediments and suggested that a survey be conducted to confirm whether or not the differences in stream stage among the channels are small.

Reviewer 1's suggestion of a higher level of monitoring for river stage was addressed by amending Chapter 1 with further description of the data that will be collected to measure the upstream to downstream water surface elevation gradient.

Question 13: Is the approach to relating river stage and discharge reasonable?

Reviewers 1 and 3 found this approach to be straightforward. Reviewer 2 stated that the reasonableness of this approach should be verified by examining satellite or LiDAR imagery to determine if channel cross sections are relatively stationary over the last few years.

Reviewer 2's concerns regarding stationarity of channel cross sections will be addressed through ongoing field measurements of river discharge at river stage gage locations as described in Chapter 1.

Question 14: Is the assumption that precipitation falls fairly uniformly across a wet meadow site reasonable?

Reviewers 1 and 2 disagreed with this assumption. Reviewer 1 stated that this is known to be false, thus having more than one rain gauge is desirable. He added that simple gauges, such as milk jugs with funnels, can be used in combination with the tipping bucket type. Similarly, Reviewer 2 commented that more than one gage is needed to cross-validate gage measurements, especially given that precipitation is the major source of water in these systems. Reviewer 3 noted that monthly and annual precipitation rates can be considered uniformly across a wet meadow.

The concerns raised by the reviewers will be addressed by installing a second rain gage on the Binfield site and comparing the readings from the two gages to test this assumption.

Question 15: Does the monitoring approach adequately measure the timing and magnitude of snowmelt and soil freeze/thaw behavior to account for the impact of these processes on groundwater behavior?

Reviewer 1 pointed out the heterogeneous distribution of snow due to wind transport, and recommended that if significant snow falls, depths should be quantified at several sites and cores analyzed for density and water content. Reviewer 2 noted that the depth of soil temperature measurement is not specified and recommended that the approach include snow energy balance-incorporated runoff to better understand the influence of snowmelt, freeze/thaw cycles, and rain-on-snow events on runoff and recharge. Reviewer 3 found the approach to be appropriate, but noted that the effects of soil freeze/thaw behavior on infiltration was not described.

The concerns of Reviewer 1 regarding the heterogeneous distribution of large snowfall is noted; however, taking snow core samples and analyzing them for water content falls outside of the scope of this monitoring effort. Similarly, the snow energy balance suggested by Reviewer 2 is also beyond the scope of this monitoring effort. Chapter 1 was amended to include the depth of soil temperature measurements and further explanation of winter precipitation and the freeze-thaw cycle's impact on infiltration.

CHAPTER 2

Question 16: Does the review of methods of determining ET omit any commonly used method?

All three reviewers found the review to be generally complete. Reviewer 1 noted that the review covers a wide range of techniques and methods, and mentioned one satellite technique not completely covered (i.e., Groeneveld et al. 2007) that is discussed in his specific line comments (see Appendix A and comments spreadsheet). Similarly, Reviewer 2 stated that most commonly used methods are included in the review, with the exception of the use of a scintillometer to measure areal average sensible heat flux. Reviewer 3 agreed that the review was very complete; however, he reiterated the need to estimate groundwater ET for the riparian forest in wet meadows where cottonwood and willow are prevalent (i.e., response to Question 3).

The EDO disagrees that remote sensing method described in the Groeneveld et al. 2007 paper can be considered a "commonly used method." While many variations of analyzing remote sensing data to provide ET information are being developed, the METRIC and SEBAL methods described in Chapter 2 represent two of the most commonly used approaches. The use of scintillometer's to measure sensible heat flux and estimate ET as suggested by Reviewer 2 certainly shows promise as an evolving method; however, it appears the method requires further development before it could be considered a "commonly used method." Reviewer 3's comments regarding riparian forests were addressed in the EDO response to Question 5.

Question 17: Are the conclusions drawn from the comparison of methods reasonable and scientifically sound?

All reviewers agreed that the conclusions are reasonable and scientifically sound. Reviewer 1 found the conclusions to be appropriate and noted that the Bowen Ratio technique to measure ET is the right approach. He mentioned that this technique should be coupled with other methods, such as a continuously recorded monitoring well and soil water content equipment, among others. Reviewer 2 responded affirmatively. Reviewer 3 concluded that this chapter is "an excellent analysis" of the methods described.

The EDO thanks the reviewers for their positive comments.

Question 18: Is the use of the crop coefficients developed by the USGS for riparian grassland reasonable? Are there other crop coefficients that would provide better results?

All three reviewers raised questions about the reasonableness of this approach. Reviewer 1 initiated his response by pointing out the inaccuracies in the PRRIP's definition of "wet meadow" and recommending an alternative description (e.g., Batzer and Baldwin 2012); he also discussed this issue in his "Overall Comments on the Four Reports Reviewed" on page A-3. He went on to comment that crop coefficients are not accurate enough for research and should not be used to create a water budget, and instead suggested alternative methods to quantify ET. Reviewer 2 suggested that crop coefficients be developed for each site as opposed to using those developed by USGS, or at a minimum validate the USGS coefficients at one site and extend to the others, if appropriate. Reviewer 3 commented that while this approach may be reasonable for grasslands, it may not be suitable for riparian forests.

In an effort to confirm the current ET estimates at the Fox and Binfield sites, the Program will analyze satellite data using the METRIC algorithm in conjunction with the detailed soil moisture data collected from the CRNP rover surveys to develop additional ET estimates. These estimates will serve to inform the ability of the USGS crop coefficients to capture site-wide variations in ET at both sites. Chapter 1 was amended to include a description of the combined METRIC and CRNP ET estimates that will be used to compare to the AWDN ET estimates and the USGS crop coefficients.

Reviewer 1 suggests that the very concept of crop coefficients is "fine for scheduling irrigation, or other management activities" but is not appropriate for research. While the approach proposed by Reviewer 1 involves using eddy covariance or Bowen Ratio systems to determine ET. The EDO understands that using crop coefficients introduces uncertainty and error into the water budget calculations. The ultimate aim of this monitoring effort is to guide "management activities," not to publish research papers on the findings. In light of this ultimate aim and the high equipment costs and personnel time requirements associated with the methods proposed by Reviewer 1, the EDO respectfully disagrees. Reviewer 2 does not address the question of if using crop coefficients is reasonable but simply states that crop coefficients can be developed for the sites. The EDO agrees that crop coefficients can be developed but the high equipment and personnel costs are not warranted in light of the reasonably available crop coefficients. Reviewer 3's concerns about the use of riparian grassland crop coefficients not being applicable to riparian forest are valid; however, the focus of this monitoring effort is solely wet meadows and not riparian forest.

CHAPTER 3

Question 19: Does the conceptual soil moisture water balance accurately approximate expected soil moisture behavior at wet meadow sites?

Reviewer 1 noted that the equation is relatively simple; the real question is how to reliably measure the components at short and long timescales. Reviewer 2 commented that it mostly captures soil moisture movement; however, there are additional pathways that should be considered, such as upward flux and lateral flow between the layers. Reviewer 3 summarized the four components of the equation and noted the importance of and difficulty in estimating groundwater recharge (i.e., percolation). He suggested using groundwater level monitoring data to estimate recharge from precipitation events.

Reviewer 2's comment regarding upward flux or exfiltration is not clearly explained in the reviewer's comments. The ponding shown in Figure 1 of Chapter 2 was a result of surface water flow across the site during high flows in the fall of 2013, not from "exfiltration" as suggested by the reviewer. The process the reviewer seems to be describing is one of the groundwater table rising to at or above the ground surface. In these instances, the soil is completely saturated and no vadose zone exists. Chapter 3 was amended to include a description of the assumption of negligible lateral flow at the scale of the monitoring effort. The ED Office intends to use groundwater data to verify recharge from precipitation events as suggested by Reviewer 3. A reference to this is included in Chapter 1.

Question 20: Does the soil moisture monitoring approach provide an appropriate level of detail in light of the project's objectives?

Reviewer 1 did not think the approach provided an adequate level of detail and referred to his overall comments for additional topics he thinks should be addressed in order to improve this chapter (see Appendix A). Reviewer 2 commented that the approach may be sufficient; however, the assumption that moisture below 1.85 meters goes into the shallow aquifer or discharges into the stream should be verified. Reviewer 3 summarized the methods and noted that this is a good approach, but additional discussion is needed on how the data will be used to determine soil moisture changes.

Chapter 3 was amended to address the overall comments and specific concerns raised by Reviewer 1. Refer to the comment response spreadsheet for specific additions. In response to Reviewer 2's comment regarding verifying the fate of soil moisture below the observation depth, the ED Office will evaluate all soil moisture data in conjunction with groundwater monitoring well data and precipitation and ET data. The concern regarding upward flux and lateral movement of soil moisture are addressed in the ED Office's response to the previous question. Chapter 3 was amended to include further explanation of how soil moisture data will be used to determine changes in soil moisture to address the comments of Reviewer 3.

CHAPTER 4

Question 21: Is the model domain appropriate to capture groundwater behavior at the wet meadow sites?

Reviewers 1 and 2 found the model domain to be appropriate. Reviewer 3 commented that the size and orientation of the model domain are appropriate, but the arrangement of inactive cells limits flexibility in imposing some boundary conditions, as discussed in Question 23.

See ED Office responses to Question 23.

Question 22: Is the assumption of a homogeneous aquifer clearly supported and appropriate?

This question was outside of Reviewer 1's expertise. Reviewer 2 noted that this assumption should be evaluated using empirical data or monitoring missions. Reviewer 3 commented that while the aquifer hydraulic properties are not homogenous, it is appropriate to assume homogeneity for the first-step model calibration. However, he did not agree with the assumption of isotropic hydraulic conductivity in the horizontal vs. vertical direction and suggested a smaller K_z value be used in the model, as well as additional support for the assumed thickness of the alluvial aquifer.

The EDO and Bill Hahn, the Program's special consultant for groundwater hydrology, agree that anisotropy in the vertical direction should not have any impact on a model with only one layer. If the model had more than one layer, the vertical hydraulic conductivity would impact groundwater flow in the vertical direction; however, this does not apply to this set of models. The EDO will conduct an informal sensitivity test to confirm this assumption. Additional citation was added to address Reviewer 3's concern regarding the assumed aquifer thickness.

Question 23: Are the model boundary conditions appropriate?

Reviewers 1 and 2 found the boundary conditions to be appropriate; however, Reviewer 3 had extensive comments discussing why the spatial arrangement of constant head boundary conditions may not be appropriate and may be the cause of large uncertainty in the outputs (see Appendix A).

The EDO discussed Reviewer 3's concerns at length and believe that Reviewer 3's suggestions reflect a misunderstanding of the model's functionality. The suggested changes in constant head boundaries assume that regional groundwater levels drive groundwater behavior at the Fox and Binfield sites. Both sites are located on islands and river stage plays a dominant role in groundwater behavior. Adding additional constant head boundaries would not accurately model this relationship. Reviewer 3's suggestions of carefully evaluating the water budget will be taken into consideration to ensure that the model results are properly communicated.

Question 24: Is the use of the MODFLOW evapotranspiration (EVT) package appropriate? Would combining the precipitation and evapotranspiration values into the recharge (RCH) package better represent the physical system?

Reviewer 1 did not evaluate this question, but noted an alternative approach he used on a similar project. Reviewer 2 stated that the EVT package is not appropriate and combining precipitation and EVT values into recharge may be part of the solution, but not entirely. He recommended simulating soil moisture dynamics in the vadose zone separately and linking the fluxes with MODFLOW. Conversely, Reviewer 3 found that the EVT package was used appropriately and that the linear option was acceptable given no data to indicate otherwise. He did not recommend combining the hydrological processes into the recharge package.

The ED Office disagrees with Reviewer 2's conclusions that a separate vadose zone simulation is needed. Reviewer 2's suggestion of a separate vadose zone simulation is outside of the scope of this effort and is not likely to improve substantively on the current approach. Soil moisture data from the CRNP will measure some of the vadose zone dynamics a separate model would attempt to simulate. Reviewer 3's comments support the ED Office views regarding the use of the ET package in MODFLOW.

Question 25: Is the assumption that standing surface water storage is negligible and no surface storage term in the groundwater models reasonable?

All reviewers identified conditions under which this assumption may not be reasonable. Reviewer 1 commented that this assumption may be fine for most years, but would not be reasonable during years when considerable overbank flows occur. Reviewer 2 noted that if storage fluctuates daily or weekly, this assumption is true; however, in some sites the shallow aquifer feeds ponds for more than a month and the ET that occurs needs to be accounted for. Reviewer 3 stated that when groundwater levels are low, there may be limited surface water storage and the occurrence of sloughs may affect groundwater levels.

Reviewer 1's suggestion that this assumption may not hold when considerable overbank flow occurs will be evaluated by observing the model's ability to simulate groundwater conditions during the two events in 2015 that caused significant overbank flows. Reviewer 2 concern regarding ET being accounted for if groundwater-fed ponds persist for more than a month will be addressed by the EVT package in MODFLOW which will remove ET from any cell in the model with standing water at the full ET rate. Reviewer 3's comments were not clear as to how the occurrence of sloughs might impact surface water storage in the system. The ED Office suggests that modeling the sloughs as drains may slightly improve localized model performance but would not significantly impact the overall model results.

Question 26: Can the model adequately simulate the effects of ice flows and river stage increases caused by ice dams?

Reviewer 1 did not evaluate this question. Reviewer 2 commented that this is not possible in the existing model framework, unless it can integrate modified river stages dynamically as a result of ice dams. He noted that increased residence time in the stream caused by the impoundment can add recharge to the aquifers. Similarly, Reviewer 3 stated that the model is not able to simulate ice flows and noted that if ice dams elevate the river stage, the increased elevation can be integrated into the river package and groundwater response can be simulated.

Any increases in river stage due to ice jams will be incorporated into the river package as suggested by Reviewer 3. The ice jam and subsequent flooding at the Binfield site in early 2015 will be used to test the model's ability to simulate groundwater response to ice jams.

Question 27: Overall, do the models capture the groundwater behavior at the two sites to address the monitoring effort's objectives?

Reviewer 1 referenced his specific comments on this chapter that address this topic (see Appendix A and comments spreadsheet). Reviewer 2 stated that the model's performance is reasonable, but there are opportunities to improve predictions and reduce uncertainties (e.g., clarify how measured ET is incorporated into groundwater modeling). Reviewer 3 noted that on the whole the authors did a good job; however, the model would be improved by revising boundary conditions, as suggested in Question 23.

Reviewer 1's specific comments are addressed in the comments spreadsheet and Reviewer 3's boundary condition suggestions are addressed in the response to Question 23.

PRRIP RESPONSES TO INDIVIDUAL PEER REVIEW COMMENTS

Comment ID #	Chapter	Line #	Reviewer	Comment	PRRIP Response
1	throughout		Reviewer 3	I suggest that "percolation" is replaced by "recharge." See response to General Question #1.	Text added: For the purposes of this study, percolation is synonymous to groundwater recharge.
2	overall		Reviewer 1	I understand that these reports are aimed at hydrologic monitoring and analysis. But the goals of the hydrologic monitoring, analysis and future management will be used for the preservation, creation and management of habitat for whooping cranes and other species. Therefore, information on the habitat needs of these organisms from a hydrological and ecological perspective would be important to present. For example, why are wet meadows critical to these organisms, and what aspects of the hydrologic regime are particularly key to the species of plants that create the vegetation that the birds key in on.	Additional text was added in Chapter 1 to further clarify the connection between whooping cranes and wet meadow habitat. Some of the information requested by Reviewer 1 is outside the scope of these documents and the role of wet meadows in the whooping crane life cycle is still a topic of debate within the Technical Advisory Committee of the PRRIP.
3	1	21 - 36	Reviewer 3	Lines 21, 22, 26, 27, 34, 35, and 36, use upper case for the first letter of each word, to be consistent with other sub-titles.	sub-titles changed for consistant capitalization
4	1	81	Reviewer 1	Since a lot of discussion revolves around "wet meadows" it would be nice to have a definition of this ecosystem complex up front. Also see comments on this topic in "Overall Comments on the Four Reports Reviewed" (Appendix A).	Text added: The Program defines wet meadows in the Central Platte River Valley as "grasslands with waterlogged soil near the surface but without sanding water most of the year."
5	1	89	Reviewer 1	I would not use hydrology in this way. Hydrology is a science, its not what is measured.	"hydrology" changed to "hydrologic processes"
6	1	96	Reviewer 1	Here it would be nice to be more specific. What "hydrologic regime" is suggested to be the right one? This report provides essentially no information about the vegetation of these wet meadows. For scientists who know plants, sometime information on the dominant species can help us understand the overall hydrologic processes and water table depths that occur on site.	Tables of vegetation added in Appendix C
7	1	105	Reviewer 1	Understood that there is not clear direction in literature about the water levels that support wet meadows in this area. Can a broader search be conducted to understand wet meadows in general? For example wet meadows have been a subject of research in the Rocky Mts, Great Basin, Sierra Nevada for many decades and plentiful data is available to characterize the hydrologic regime of those meadow types.	Text added to indicate Platte River wet meadow hydrology is specifically being addressed. The sandy river bed and soils separate Platte River wet meadows from most mountainous wet meadow sites with poorly draining soils.
8	1	110	Reviewer 1	I think a more important question might be: Which wet meadows are connected to the Platte River stage, and which are not. And on what time scale are meadows connected? We've measured ground water flow over many km and it took up to a year for water from a stream to reach the study wetlands (Wurster, Cooper, Sanford 2005).	Text added: nor can the degree and timing of a wet meadow's hydrologic connectivity to the Platte River.
9	1	113	Reviewer 3	"management its water resources", do you mean "management for its water resources"?	changed to "management of its water resources"
10	1	129	Reviewer 3	"determine" to "determining".	Changed
11	1	153	Reviewer 3	Figure 1, I suggest adding root system to the tree on the right-hand side and let the root system touch the water table. The riparian trees in the study area can directly consume groundwater during the growing season. Do the same for Figure 2.	Trees were remove from both figures to clarify the focus of this study is only on wet meadow habitat, not riparian forest.
12	1	157	Reviewer 1	This is overly simplistic. Not all rises in river stage will produce a rise or lowering of ground water elevation. Or the time frame for these changes could vary from site to site and with distance from the river.	Text added: The degree of influence river stage changes have on groundwater elevation decreases with increasing distance from the river. Wet meadow sites further from the river may not respond to smaller changes in river stage and may be influenced more by other hydrologic processes.
13	1	167	Reviewer 3	in this section, I would like to add a statement indicating that the grass root (at least some) and riparian trees can directly consume groundwater from the water table.	Text added: Water transpired by vegetation may have originated from soil moisture or directly from the groundwater when groundwater is at or above the vegetation's root zone.
14	1	176	Reviewer 3	"of the site" to "the site".	changed
15	1	212	Reviewer 1	Its interesting that there is no arrow or flow component from right to left, meaning ground water flow from the uplands toward the river. Has this been proven?	Text added: Groundwater flow onto the site from adjacent land (not from the river) is not included in this conceptual model. Two of the wet meadow sites (the Binfield and Fox sites) are situated on islands in the Platte River and adjacent groundwater flow is assumed to have a minimal impact on groundwater below the sites. The Johns site is also situated between two river channels but does not have the same island configuration as the Binfield and Fox sites. Adjacent groundwater is not thought to have a significant influence on the site. The Morse site is located furthest from the river and may be impacted by adjacent groundwater. Several nearby wells will be monitored to determine the degree of influence adjacent groundwater flows have on groundwater behavior at the Morse site.

Comment ID #	Chapter	Line #	Reviewer	Comment	PRRIP Response
16	1	235	Reviewer 1	I would not suggest using the term pristine, as it assumes a level of integrity that is not possible along the Platte River where settlers have been modifying the vegetation and hydrologic regime for more than 100 years. Clearly the pre settlement hydrologic regime of seasonal river flooding is altered, and looking closely at the site on Google Earth, fence lines, flowing wells and other features are apparent, indicating heavy use of domestic livestock.	text changed: … prototypical wet meadow habitat that has not been significantly altered through soil tilling
17	1	236	Reviewer 3	“that not been” to “that has not been”.	changed
18	1	253 - 254	Reviewer 3	“The sites comprise vary in size…”. This sentence needs re-wording.	Text changed: The sites represent a variety of site areas, proximities to the river, management histories, and functionalities as wet meadow habitat.
19	1	346	Reviewer 1	Is there an adjacent staff gauge that is continuously monitored?	No, the pressure transducers are capable of recording water levels above the ground surface as well.
20	1	352	Reviewer 3	“in monitored with” to “is monitored with”.	changed
21	1	402	Reviewer 3	the last word “is”, change it to “are”.	changed
22	1	423	Reviewer 1	It might be desirable to have a staff gauge at the upstream and downstream end of each study area.	Text expanded to include: Gradients are measured on a regular basis using survey-grade GIS equipment at the upstream and downstream ends of the site to test this assumption and results are compared to the Program’s HECRAS surface water models.
23	1	433	Reviewer 1	This is not necessary. If the loggers are well below the water table there is no chance of them from freezing. If the water table drops below the level of the logger then yes the gauges should be removed.	This paragraph is describing river stage gages, not groundwater gauges. River stage may fluctuate widely and ice regularly forms along the river's edge.
24	1	567	Reviewer 3	The sentence starting with “The energy balance approach…” needs a verb after “approach”.	"measures" added.
25	1	570	Reviewer 3	“at wet meadow sites” to “at the wet meadow sites”.	changed
26	1	573	Reviewer 1	The proposed method is quite generic, using the Penman equation and data from local weather stations. The weather stations are not located in the wet meadows. So the data are quite generic for central Nebraska. The crop coefficient approach also is commonly used, but you cannot approximate the error in this approach, because nowhere have you actually measured ET in the meadows.	The HPRCC weather stations are located in the middle of the Fox and Binfield sites. Weather stations are not located at the Johns or Morse sites but data from nearby HPRCC stations will be used.
27	1	594	Reviewer 1	The issue of using atmometers is quite complex. Plants have stomata and regulate water flux from leaves to the atmosphere. Ceramic plants do not have stomata. Ceramic plates used in atmometers could “transpire” at much higher rates than plants. The research on these devices by Colorado State University was for upland agricultural crops to schedule irrigation events. I know of no literature that tests these in wet meadows or other wetlands. I discuss this in more detail in the review of Chapter 2.	Comment noted.
28	1	621	Reviewer 3	“groundwater behavior” to “the groundwater table”.	Changed
29	1	633	Reviewer 1	There is no information presented on how the sensors were installed. This is very important to communicate with readers. Were there pits dug and the sensors installed horizontally into the intact soil, or exactly how were they installed?	Text added: Sensors were installed by digging a pit near the base of the HPRCC weather station and inserting the sensors horizontally into the intact soil.
30	1	642	Reviewer 3	“to for”, delete “to”.	Changed
31	1	645	Reviewer 1	There is insufficient methodology presented on how these CRNP sites are instrumented. Are access tubes installed? How were they installed? How are measurements made?	Text and reference added: The sensors are installed on posts according to the methodology outlined in the CRNP field installation guide.
32	1	673	Reviewer 3	“will monitored” to “will be monitored”.	Changed
33	1	679	Reviewer 1	These cork sensors do not always work. If there is considerable mineral sediment transported with the flowing water this can foul the gages and make it impossible for the cork to adhere to the gage wall.	Text added: While crest stage gages may not function properly when flowing water has a high mineral sediment load, they are assumed to provide reliable information for the quality of water anticipated with precipitation runoff.
34	1	References	Reviewer 3	References, I suggest using consistent format for the authors’ names.	Author's names changed to consistent format
35	3	102	Reviewer 3	“assume” to “assumed”.	Changed
36	2	139	Reviewer 1	A wet meadow crop coefficient could be inaccurate due to a range of issues. First, wet meadows with shallow water tables are not subject to the same transpiration limitations as upland crops. Second, since there are so few actual measures of wet meadow ET, creating and using a crop coefficient for wet meadows, could produce very approximate ET rates with unknown error. How would this error be evaluated?	A discussion of how error associated with using crop coefficients for wet meadows does not seem to fit into this section of the white paper where the reference crop approach is being described.
37	2	142	Reviewer 1	This is a good reason to make original measures of ET, and not rely on crop coefficients that will absolutely introduce unknown error into your models. We’ve measured wet meadow ET (Sanderson and Cooper 2008, Cooper et al. 2006) and its not that hard to get this right. The methods you propose at the end of this document are suitable for accurate measures of ET.	Noted
38	3	147	Reviewer 3	“may not extrapolated” to “may not be extrapolated”.	Changed

Comment ID #	Chapter	Line #	Reviewer	Comment	PRRIP Response
39	2	156	Reviewer 1	Wet meadow plants also have varying root depths and root density with depth, and these are key variables in modeling. Because the position of the water table and available energy and time in the year will drive ET, an understanding of root distribution can really help predict ET functions for different species, communities and water table depths.	Noted
40	2	183	Reviewer 1	Lysimeters provide the most unrealistic “ecosystem” for estimating ET. Landscapes with intact soil structure and long-lived plants form over very long periods of time, hundreds to thousands of years. Lysimeter construction, for the most part, destroys soil structure and deals with plants and vegetation that do not reflex the ecosystems that people really want to measure. Even “monolithic” lysimeters provide unrealistic ecosystems because they cut off the roots of plants that may take decades or longer to form.	Text added to "Assumptions" section: Lysimeters are not able to capture the complexity of native vegetation and soil structure that occur over large spatial and timescales. For example, lysimeters are likely too small for large vegetation with extensive root structure and establishing representative root structure for long lived plants may not be possible.
41	3	219	Reviewer 3	“in to” to “into”.	Changed
42	2	221	Reviewer 1	The ground water simulating lysimeters are also highly artificial, considering ground water to be a “pool”.	See text added to "Disadvantages" section in response to comment on line 317
43	2	266	Reviewer 1	This paragraph should include a few sentences about vegetation. Refilling lysimeters is more than sediment, its also vegetation. How long does it take for planted or transplanted species to attain similar above ground/below ground relationships that become similar to natural vegetation in their functioning for water acquisition and transpiration?	Text added: The refilling method must account for the time it takes for vegetation to establish a similar root structure and achieve a growth stage comparable to the surrounding vegetation.
44	2	313	Reviewer 1	This is not true. Lysimeters provide estimates of ET for the soil and vegetation within the lysimeter. I have never seen a lysimeter where the vegetation truly was representative of the surroundings, other than for sites with annual crops, or turf grass. For long-lived meadow plants attaining natural root distribution and density within the lysimeter is difficult to achieve.	Addressed in other responses.
45	2	317	Reviewer 1	Again, the assumption must be strengthened that this assumes ground water is a pool sitting at the base of the lysimeter. For the Platte River this may not be a suitable assumption because ground water flows through the soil laterally as well as vertically. In addition, periodic flooding and the lateral movement are critical for salt distribution regulation.	Text added to "Disadvantages" section: Weighing lysimeters are not able to capture lateral movement of groundwater and may not capture the effects of seasonal flooding.
46	2	324	Reviewer 1	It is key to recognize that the type of vegetation will determine how long it takes for a lysimeter to reflect natural the natural vegetation. For annual plants it’s a short period of time. For shrubs or some clonal sedges, it may be unattainable.	Text added: Lysimeters may never be able to fully represent the complexity of the natural vegetation found in diverse ecosystems such as wet meadows.
47	2	392	Reviewer 1	One of my colleagues at CSU, Dr. Troy Bauder, is the author of the 1999 CSU report (CSU 1999). I communicated with him and he said that auto-logging atmometers compare reasonably well to ASCE ETr using alfalfa as a reference cover. They should be used mainly for irrigation scheduling. For research purposes they would have to be calibrated using actual wet meadow ET. Since wet meadow ET from the study area does not appear to exist, I feel that this method may be too inaccurate for use in this program. I also suggest you consider adding the following reference: Gleason, D.J., A.A. Andales, T.A. Bauder, J.L. Chavez. 2013. Performance of atmometers in estimating reference evapotranspiration in a semi-arid environment. Agricultural Water Management 130: 27-35.	Text added: Atmometers have been shown to closely agree closely to reference evapotranspiration estimated from weather station data and are well suited irrigation scheduling (Gleason et al., 2013).
48	2	452	Reviewer 1	Plants that are adapted to western environments have more than “some resistance to evaporation” but can have nearly complete control of transpiration rates through their stomata. Pans are suitable for providing an estimate of evaporation from small lakes, and could be useful for times when there is surface water in the study areas. Without surface water in the study area, the pan rates are not particularly informative.	Noted.
49	2	642	Reviewer 1	The biggest problem we had with Bowen ratio equipment was lightning strikes, directly onto or near the stations. This can destroy much of the equipment, particularly the data loggers.	Noted.
50	2	904	Reviewer 1	We have used Priestley-Taylor ET models for wet meadows because they provide a reasonable approximation of ET under well-watered conditions (Sanderson and Cooper 2008). Of course we were able to calibrate these models with detailed multi year data sets from Bowen ratio stations are multiple sites.	Noted.

PRRIP RESPONSES TO INDIVIDUAL PEER REVIEW COMMENTS

Comment ID #	Chapter	Line #	Reviewer	Comment	PRRIP Response
51	2	994, 1007	Reviewer 1	It seems that you are making the assumption that the work done by Hall and Rus (2013) provide a suitable crop coefficient for use with the Penman equations. I am unsure if this is a valid assumption. Having read this report provided in your appendix, their work does not include what I would call wet meadow sites. The "grassland" site is dominated by Poa pratensis, which is not a wet meadow plant in most regions of the U.S. and is not typically a phreatophyte. The water table depth measured at well GW2 is shallow enough that some evaporation from the water table directly to the atmosphere surely occurs. Whether any of the plant species present are using ground water is not established. The crop coefficient developed for this grassland may not be suitable for wet meadows in this same area. It would depend on whether the plants in wet meadows are phreatophytes, and have different water use patterns than the grassland species at this reference site. The crop coefficients developed by Irmak et al. (2013) are for two woody plant species and one tall marsh plant. Therefore, these are useful, but not suitable for wet meadows.	Noted.
52	2	1086	Reviewer 1	Without testing the accuracy of Penman-Monteith methods compared to measured ET rates on the same site, I'm not sure the statement on this line can be made.	Text changed: The Penman-Monteith method is assumed to be able to estimate evapotranspiration data on wet meadow sites and data collected by the AWDN weather stations allows for hourly calculations.
53	2	1093	Reviewer 1	You should also consider the methods of Groeneveld et al. (2007) for mapping ET from satellite scenes.	Based on a review of the paper cited, this method does not appear to fall in the category of "one of the most common algorithms used to calculate evapotranspiration from satellite data."
54	2	1269	Reviewer 1	We came to this same conclusion two decades ago in perfecting water balance models for the San Luis Valley in south-central Colorado. These models now form the basis of a decision support system used by the State of Colorado for water rights. http://cdss.state.co.us/basins/Pages/RioGrande.aspx ET from native vegetation had historically been estimated using lysimeters and other methods, but it was unknown how accurate these estimates were. Since the amount of water used by native vegetation in this huge region that has shallow water tables was in the range of several hundred thousand acre feet/year, it was a vital issue to develop an accurate water balance for the entire valley. By using Bowen Ratio instruments over several years we were able to show that the previous estimates were not even close to actual ET and by plugging these data into the developing decision support system, much greater accuracy and predictability could be obtained. I feel that the proposal provided by Irmak (2012) could provide the needed data set for wet meadow ET.	Noted.
55	3	References	Reviewer 3	please spell all authors' names in "et al."	Changed
56	3	39	Reviewer 1	It seems that water can also enter as flood water from the Platte River, or overland flow from adjacent upland or meadow sites. The water table can also rise in response to Platte River rise, recharging soil water content.	Text added: The unsaturated zone at wet meadow sites may become saturated from above due to occasional surface flooding or from below if groundwater levels rise in response to high river stage.
57	3	50	Reviewer 1	Plants, even "phreatophytes", acquire soil water so the quantification of soil water content on a daily time step is critical for understanding ET and potential ET. This point is made in the following paragraphs of the report.	Noted
58	3	57	Reviewer 1	Some citations would be good here to support these rooting depths	Citation added.
59	3	61	Reviewer 1	It could be useful to add soil texture and structure as a key variable for potential soil moisture holding capacity, and the volume of water held at field capacity, which varies horizontally, especially in complex fluvial terrain as these wet meadows occupy.	Text added: Changes in soil texture and structure lead to variances in soil moisture content both horizontally and vertically.
60	3	81	Reviewer 1	I would think that this is subject to debate. I would argue that Precipitation and ET determine, relative to soil water storage, determine what water, if any, is available for percolation to the water table. In addition, the counteracting capillary rise certainly influences percolation rates and processes.	Text changed: . Percolation is a key process in determining the impact precipitation and evapotranspiration have on groundwater levels
61	3	91	Reviewer 1	Capillary rise for this soil type should be quantified, not assumed to be negligible. Until it is proven that capillary rise is zero, this equation could be considered: (I + CR) – ET – PERC = ΔS	Text added: capillary rise is thought to only impact the lower 10 to 25 cm of this boundary based on the capillary rise associated with the medium to coarse sand present onsite. For the purposes of this investigation, capillary rise is considered negligible
62	3	105	Reviewer 1	Here the capillary rise is not stated to be negligible, but limited by the sandy soil.	Sentence deleted
63	3	147	Reviewer 2	Revise 'may not extrapolated' to 'may not be extrapolated'	Changed

PRRIP RESPONSES TO INDIVIDUAL PEER REVIEW COMMENTS

Comment ID #	Chapter	Line #	Reviewer	Comment	PRRIP Response
64	3	153, Figures 6 and 7	Reviewer 1	Unfortunately when the soil moisture sensors, and likely other instruments, were installed the site was highly disturbed removing the vegetation. Therefore, this site cannot be used to calculate the equation for PERC as it has an unrepresentative ET rate. Therefore, the soil moisture data from these sites would be unreliable for representing the soil moisture dynamics of meadow areas shown in the background that are fully vegetated and would have much higher ET rates and very different infiltration rates due to differences in litter, root density and penetration. I would suggest that different approaches be used to install soil moisture sensors other than digging up the site.	Text added to Section III B to include a description of the installation and calibration of the ThetaProbes. The soil moisture probes were installed by excavating a pit, installing the soil moisture probes in the adjacent undisturbed soil, and filling the pit in. While the excavated pit does not have vegetation or the same root structure, the location of the probes is in undisturbed soil. The disturbance may alter the readings somewhat but the EDO does not consider this to unduely influence the readings.
65	3	156	Reviewer 1	I have never used the CRNP system, but reading through a set of journal articles, some of which are footnoted on this page, makes it seem like a useful and reliable approach. Franz et al. (2013) suggest that the method can explain 79% of the variability in data sets. Is that sufficient for the purpose of this work on the Platte River? It might be. I also wonder how this method would work in sites with a very high water table, say May and June when a water table is within 50 cm of the soil surface.	The 79% variability is considered sufficient for this work. The equipment performed well in 2015 when the Binfield site was flooded twice.
66	3	178	Reviewer 1	Would driving with a pickup be possible during high water table periods?	Text added: or an all-terrain vehicle (ATV)
67	2	379	Reviewer 3	“Equation 2”? Do you mean “Equation 3”?	Changed.
68	2	509	Reviewer 3	“Equation 4”? Do you mean “Equation 5”?	Changed.
69	2	1338	Reviewer 3	I suggest changing “BIBLIOGRAPHY” to “REFERENCES”, to be consistent with other chapters.	Changed.
70	3	References	Reviewer 3	The title of a journal article in some references uses upper case for the first letter of each word; in other references, only the first letter of the first word of a title uses upper case. I suggest using a consistent citation format for all the references.	Titles changed to have consistant capitalization.
71	4	11	Reviewer 3	change “hydrology” to “hydrological data”.	Changed.
72	4	11	Reviewer 3	change “though” to “through”.	Changed.
73	4	86	Reviewer 3	change “Baseline Parameter Values” to “Baseline parameter values”, to be consistent with other table captions.	Changed.
74	4	121	Reviewer 1	This is not very clear, “quantify the volume of flow passing between the river and the groundwater”. It makes it seem that some volume is moving in a layer beside the river, but not into the ground water system.	Text changed: passing from the river into the groundwater and from the groundwater into the river
75	4	139	Reviewer 1	Here is the same phrase, I think the author is trying to say that the goal is to quantify the amount of water that moves from the river into the ground water system.	Text changed: The numerical models track the amount of water that passes from the river into the groundwater and from the groundwater into the river
76	4	184	Reviewer 3	change “extends” to “extend”.	Changed.
77	4	213	Reviewer 3	Table 2: change “57 days” to “58 days” for the Fox event and the Binfield event.	Changed.
78	4	219 - 221	Reviewer 3	in this area, the shallow alluvial aquifer is separated from the Ogallala aquifer by an aquitard.	Text changed: and the underlying aquitard between the Ogallala aquifer and the alluvial aquifer acting as the layer’s bottom elevation
79	4	237	Reviewer 3	for the Fox site area, the thickness of the alluvial sediments may be around 60 feet.	Citations added for aquifer depth. The model is not expected to be impacted by a 20' difference in aquifer thickness, changing the aquifer depth would be compensated by changes in transmissivity calibration.
80	4	267	Reviewer 1	Why wasn’t specific yield measured for the on site soils?	Data from the COHYST modeling effort was used.
81	4	358	Reviewer 1	I assume that the steady state version of the ground water models are based on water table measurements from the installed monitoring wells?	No, they are based on measured river stage. Resulting modeled groundwater elevations were compared to observed groundwater elevations
82	4	371	Reviewer 1	Where is the data on rooting depth(s) of plant species on these sites? We worked on the concept of extinction depth for vegetation at sites in Colorado’s San Luis valley for 20 years and have found that most ET functions based on water table depth are guesses that are unlikely to be correct and may not be close to reality. The only way to really determine this is to measure ET, with a Bowen Ratio system or Eddy covariance system, at the full range of water table depths that occur, and build the functions from real data. Of course these functions will vary with vegetation type, leaf area, plant density, transpiration rates etc. And the rooting depth is not really that good an indicator for a number of reasons. First it’s really hard to determine the “rooting depth” of any plant species. Second, most roots are in the upper 50 cm of soil, and the fact that there are a few roots deeper than 100 cm is not necessarily very instructive. Not all roots are identical in their water uptake.	What reviewer 1 suggests is outside of the capabilities of the MODFLOW ET package. The extenction depth is an approximation. The general suggestion that roots at shallower depths uptake more water than roots at lower depths is captured in the ET package as less ET is removed from the groundwater when levels are near the extinction depth.
83	4	378	Reviewer 3	please give the values of the ET rates for each stress.	ET rates for all stress periods added as Appendix G.
84	4	404 - 407	Reviewer 3	I am glad to see that the report documented that nearby irrigation pumping did not affect the groundwater flow in the wet meadow areas.	Noted.

PRRIP RESPONSES TO INDIVIDUAL PEER REVIEW COMMENTS

Comment ID #	Chapter	Line #	Reviewer	Comment	PRRIP Response
85	4	420	Reviewer 3	these three equations are equation 2 to equation 4. Equation 1 appears in page 15.	Changed.
86	4	440	Reviewer 1	Figure 7: Why was well 208 observed and modeled? As stated on L 432, these models do a poor job of replicating daily and weekly water table dynamics.	Well 208 was observed because it is one of the monitoring wells. It was modeled to see how well the model compares to observed values. While the model does not capture the daily variations largely due to precipitation inputs, it does capture the general water table response. Figure 7 is specifically showing the model's performance over a range of hydraulic conductivity values
87	4	472	Reviewer 1	The issue with this approach is that a water table rise of 1-2 feet, which is not captured by the model would result in a huge recharge event into the soil. So would it be possible to improve the model or analysis of data using soil moisture sensors?	COMMENT 1: Large water table rises from precipitation are captured by the recharge package in MODFLOW. Soil moisture data from the CRNP will be incorporated in future model runs but was not available when these models were developed. Fundamentally, MODFLOW is a groundwater model, not a unsaturated zone model.
	4	543	Reviewer 1	L 543. Here it's stated that extinction depth had little effect on the model. But the depths analyzed were 4-7 feet during the modeled period. A site with a water table 4-7 feet below the ground is certainly not a wet meadow. So why is such a site being analyzed?	COMMENT 2: The extinction depth is the point where ET is considered to equal zero, roughly equal to the rooting depth of the site's vegetation. We tested the sensitivity to different rooting depths. Also, there are many places when groundwater is below 4 feet deep during dry summer months, especially below high ridges characteristic of wet meadows. This does not indicate the site does not behave as a wet meadow during the spring and fall when groundwater is closer to the surface.
88	4	553	Reviewer 3	change "equation 1" to "equation2".	Equation 1 is the correct equation. It describes MODFLOW's calculation of the riverbed conductance term.
89	4	763	Reviewer 1	I guess I would like to hear from ground water modeling experts, but from my view as an ecologist the model misses the rise in water table driven by high stream stage and precipitation events that last less than a month. These hydrologic events seem critical to driving soil water recharge and ET processes at certain times of the year.	The EDO dissagrees with the suggestion that the models "miss" groundwater response to stream stage and precipitation changes that last less than one month. An examinationn of the figures of the event model performance in Appendix C and D shows the models clearly capture groundwater behavior on a daily to weekly time scale. These models were developed to specifically capture groundwater behavior relating to recharge and ET processes in the spring and fall during whooping crane migration season.
90	4	860	Reviewer 3	"losing reach"? I think this is a typo. It is "gaining" stream based on your water budget of the model outputs.	Changed.
91	4	872	Reviewer 3	"gaining reach"? According to the water budget of the model outputs, it is a "losing reach".	Changed.
92	Appendix B		Reviewer 1	For Appendix B, it would be nice for each of the hydrographs presented to tell us the elevation of the ground surface. While the elevation of water table observed and modeled is interesting, it would be just as interesting to see how well the model did with shallow vs. deeper water table sites.	Ground surface elevations added to figure titles

PLATTE RIVER
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for the Governance Committee of the Platte River Recovery Implementation Program