WSF 2025 Final Report # 10020

PROJECT: Lower Loup NRD Buffalo County Area Groundwater Model – WSF Application #10020 (awarded October 19, 2022)	**DATE:** MARCH 31, 2025 (FIRST ANNUAL REPORT DUE ON OR BEFORE APRIL 1, 2025)

See Application 10020, Part 7 For Project Tasks Summary and Timeline

PROJECT PROGRESS UP TO APRIL 2025:

LLNRD hired consultant, LRE Water, to complete the Buffalo County Area Groundwater Model (BC Model). This calibration of the localized water model, development of inflow estimates for the streamflow-routing package (SFR) package, and identification of major stream gages for this calibration. A five-layer model grid was created in Leapfrog Works and incorporated into Groundwater Vistas. Adjustments to the SFR were made based on historical stream gauge readings. A first draft of the "Buffalo County Area Groundwater Model Report" was submitted for review to LLNRD staff on December 24, 2024. In this document, 3 example management scenarios were used to test the groundwater model including: 1) stream diversion into an identified managed aquifer recharge area, 2) a theoretical pumping capacity increase on an area industrial well, and 3) a change in pumping allocations on all irrigation wells within the modeling area. Each of these scenarios gave LRE Water an opportunity to document how the model analyzed the theoretical management changes and examined the results which provided considerations and limitations for LLNRD staff to consider going forward. On January 23, LRE Water presented the model and results of the various scenarios to the staff and Board of Directors. The final report was delivered to LLNRD in January 2025 and all invoices were submitted by March 2025.

ANTICIPATED ACTIVITIES FROM NOW UNTIL NEXT ANNUAL REPORT DUE APRIL 1, 2025:

The project is considered complete for this annual report. A revised final report was submitted to the LLNRD, and a presentation was given to the Lower Loup NRD Board of Directors at their January Board Meeting. All modeling files have been shared with LLNRD staff for their use.

ANTICIPATED CASH FLOW FOR REMAINDER OF THE PROJECT:

The LLNRD paid $275,000 to LRE Water (Inc) for WSF Grant Assistance Services including modeling figures from AGF AEM data.

The first reimbursement request was submitted in March 2024 for the 1st half of the project. The reimbursement total was for $109,562.68 and includes both 40% sponsor share ($43,825.07) and 60% WSF share ($65,737.61).

The second reimbursement request is submitted in March 2025 for the 2nd half of the project. Reimbursement total was for $165,437.32 and includes both 40% sponsor share ($66,174.93) and 60% WSF share ($99,262.39).

$0 – The LLNRD and WSF have paid all remaining funding obligations towards this project under grant #10020.

LIKELIHOOD THAT BENEFITS PROJECTED IN APPLICATION 10020 WILL BE REALIZED:
The project tasks have been completed as scheduled. Based on previous experience with working through the WSF, the project achieved all benefits described in the original application.

Staff at the LLNRD and LRE Water are available to discuss this project further, should the need arise.

BUFFALO COUNTY AREA GROUNDWATER MODEL REPORT

Buffalo County, NE

Prepared for:

Lower Loup Natural Resources District

January 2025

6002LLNRD02

The technical material in this report was prepared by or under the supervision and direction of the undersigned:

Thomas Glose, PhD, PG

Jacob Bauer, PG

David S. Hume, NE PG G-0186

The following members of the LRE Water staff contributed to the preparation of this report.

Groundwater Modelers: Tom Glose, PhD, PG, and Jacob Bauer, PG
Senior Project Manager and Environmental Scientist: Jonathan Mohr
Hydrogeologist: Roscoe Sopiwnik, PG, GISP and Mike Plante, PG, GISP
Senior Review: Dave Hume, PG

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SECTION 1: INTRODUCTION

This report describes the development and findings of a groundwater model focused on areas of significant groundwater decline within Buffalo County, NE developed by LRE Water (LRE) and The Flatwater Group (TFG), in partnership with the Lower Loup Natural Resources District (LLNRD). Construction of the Buffalo County Area Groundwater Model (BC Model) began in Spring 2023, and this report documents the final project deliverables.

The primary purpose of the BC Model is to simulate groundwater flow in areas experiencing significant groundwater declines within Buffalo County, located in the south-central portion of the LLNRD. This area, hereafter referred to as the Focus Area, and other significant areas within the BC Model are shown in Figure 1**.** The boundary of the Focus Area follows the boundary of the portion of Buffalo County that is within the LLNRD. This boundary encapsulates all of Water Quantity Area 18 and portions of Areas 13 and 16 as shown in Figure 2. Land use in the Focus Area is primarily agricultural with the main source of water during the growing season coming from precipitation that is supplemented with groundwater-based center pivot irrigation and diversions from surface water bodies.

The BC Model simulates historical groundwater conditions and changes in water levels brought on by changes in precipitation, pumping, streamflow, and other factors. These conditions have affected groundwater flow, and the BC Model's goal is to better understand factors that have led to the observed significant groundwater declines that have occurred in this area, particularly since approximately the year 2000. The BC Model utilizes geologic data provided by the University of Nebraska-Lincoln Conservation and Survey Division (UNL CSD) test holes, Nebraska Department of Natural Resources (NeDNR) geologic logs, and LLNRD's Buffalo County Airborne Electromagnetic (AEM) survey block-flight data that lies within the Focus Area. These data were combined using the 3D geological modeling software Leapfrog Works (Seequent, 2024) to create a geologic framework that was used as the base of the BC Model. From this geologic framework an initial set of hydrogeologic parameters for model input was established.

The BC Model was calibrated to thousands of water level data points, and the final calibrated parameters are within expected ranges. The model reasonably reproduces regional scale variations in water levels that have been observed historically.

Three potential use cases were developed to demonstrate the utility of the BC Model. These cases are: 1) simulating potential benefits from future artificial recharge projects, 2) changes in groundwater levels due to increases in future pumping at a specific location, and 3) the effects on groundwater levels from a simple reduction of groundwater pumping across the Focus Area. These cases highlight the BC Model's capacity to provide input to decision-making related to sustainable groundwater management.

SECTION 2: 3-D HYDROGEOLOGIC FRAMEWORK AND CONCEPTUAL MODEL

2.1 CLIMATE AND TOPOGRAPHY

The BC Model Area falls within the Köppen climate classification and is characterized by a humid continental climate with hot summers and year-round precipitation. Temperatures range from an average high of 87°F in July to an average low of 13°F in January. Precipitation is highest in May, with an average of 4.2 inches of rain, and annual precipitation is approximately 25 inches per year. The region experiences distinct seasonal variations characterized by warm, humid summers and cold, windy winters.

The BC Model region follows the general topographic trend of Nebraska, sloping from west to east following major surface water features. There are two basic topographic regimes within the BC Model Area: 1) dissected plains, which is an area of flat and rolling terrain dissected by stream and creek drainages, and 2) flatter alluvial valleys. Elevations range from approximately 2,500 feet (ft) to 2,700 ft above mean seal level (AMSL) in the northwest portion of the BC Model Area to 1,800 ft to 1,900 ft in the Platte River valley near the southeast boundary.

2.2 SURFACE WATER

Within the BC Model region, major perennial surface water features include the Platte, South Loup, and Middle Loup Rivers, and Mud Creek. These features are the predominant sources of surface water entering the BC Model region. There are several prominent ephemeral or intermittent surface water features, such as the Wood River, that only flow due to runoff events or during limited periods of interaction with the groundwater system.

Staff from the LLNRD conducted a field survey in the Fall of 2023 to evaluate flows in the numerous tributaries that feed into the major surface water features identified above. Of the 28 identified tributaries to the major surface water features discussed above, 13 tributaries within the LLNRD were surveyed along multiple reaches to identify the presence or absence of flow. Twelve of the 13 tributaries were identified to have no flow present along any reach surveyed and were classified as ephemeral. The remaining surveyed tributary had some reaches with flow present and others without and was classified as intermittent (Figure 3). The LLNRD-led survey was instrumental in developing a locally informed classification system that was used by LRE to classify the remaining 15 tributaries following virtual site assessments using Google Earth Pro.

Following surface water feature classification, 14 stream gage stations along the five major features identified above were analyzed to determine frequency and duration of flow events to determine a first order estimate of flow magnitude. This assessment confirmed that inflows would need to be applied to the BC Model for the Platte, South Loup, and Middle Loup Rivers as well as Mud Creek. To quantify the time series of inflows for each site, two gage stations on either side of the upgradient model boundary were identified. Baseflow separation, which is the process of distinguishing between surface and groundwater flows in the stream hydrograph was performed on the discharge data from these gages. The data was then correlated to each drainage area and the monthly average precipitation data to create a numerical relationship. This relationship was applied to the location of the model inflow to generate a time series of discharge for the duration of the numerical simulation.

2.3 PRINCIPAL AQUIFER AND GEOLOGIC MODEL

The geologic units in the BC Model Area consist of younger unconsolidated Quaternary-age fluvial (deposited by rivers and streams) clays, silts, sands, and gravels, Tertiary-age fluvial sediments of the Ogallala Formation, and lacustrine (deposited within a lake) sediment types. The range of depositional environments yields a highly heterogeneous aquifer composed of interbedded sands, gravels, silts, and clays of varying thickness. Collectively these units are referred to as the Principal Aquifer underlying the BC Model Area. Coarser Quaternary-age fluvial sands and gravels are found within the channels of the major rivers (i.e. the South Loup, Middle Loup, and Platte Rivers). These younger deposits are likely to be more transmissive than the older underlying fluvial deposits. Figure 4 shows the surficial geologic map of the BC Model Area (reproduced from Swinehart et al., 1994).

The following sections describe how the geologic data provided by boreholes, geologic maps, and Airborne Electromagnetic Survey Data (AEM) was used to create a geologic model of the BC Model Area.

2.3.1 Borehole Data

Geologic borehole data was collected from the UNL CSD and the NeDNR. The UNL CSD is responsible for collecting test hole data, which are drilled with the intent of obtaining geologic data regarding the substrate, groundwater, and other natural resources throughout Nebraska. From this database, 255 test holes were found to be within the BC Model domain. The NeDNR dataset provided an additional 19,300 well logs of varying quality that were also incorporated into the geologic model. The UNL CSD test hole data is considered more reliable and accurate than the NeDNR well logs because the UNL CSD test holes are drilled with the intention of collecting geologic data and logged accordingly by a geologist. As source and quality of the borehole and test hole data varied, lithologies were simplified and classified into two groups representing aquifer material (e.g. sand and gravels) and non-aquifer material (e.g. clays and silts).

2.3.2 Airborne Electromagnetic Survey Data

AEM survey data is collected by towing geophysical instruments, often beneath a helicopter, which send electromagnetic signals into the ground and measure the subsurface response (i.e. resistivity) to create images of the underlying geologic structure. A major strength of AEM survey data is that it provides cost-effective, reasonably high-resolution information across large areas that is generally unavailable from conventional sources. The adoption of AEM surveys as a means of mapping groundwater resources has seen a marked increase in areas at risk of significant groundwater depletion, such as Nebraska.

In the Fall of 2019, the LLNRD commissioned Aqua Geo Frameworks (AGF), a geophysical consulting firm that specializes in AEM survey data acquisition and interpretation, to fly a dense block flight AEM survey along the South Loup River around the Ravenna area. The survey ended up collecting nearly 613 line-miles of data covering an area of approximately 140 square miles (mi^2) which was used to create a hydrogeologic framework of the underlying aquifer (AGF, 2022). This spatially dense data set is positioned within the eastern portion of the Focus Area, providing an invaluable data set that was instrumental in helping delineate local aquifer parameter distributions as described in more detail below. An additional AEM data set that was collected in the southern edge of the BC Model area in 2016 as part of a larger, multi-agency study was also used (AGF, 2017). The unconsolidated material range of resistivity values collected during the surveys were divided into four categories: non-aquifer, marginal aquifer, aquifer, and coarse aquifer.

2.3.3 Leapfrog Works - 3D Geologic Model

The geological data described above was evaluated and integrated into Leapfrog Works (Seequent, 2024) to develop a 3-dimensional (3D) model of the BC Model Area. First, surface and bedrock elevations were established to define the top and bottom of the geologic model domain. The surface elevation was derived from LiDAR surveys in the area. Bedrock elevations were found using a combination of bedrock contacts identified from the spatially distributed geologic logs and the more localized, spatially dense bedrock surfaces provided from the AEM survey conducted by AGF (2017, 2022). Next, the borehole and test hole data were assigned proxy resistivity values that correlate to their assigned lithologic values of aquifer and non-aquifer material. This allowed for the spatially distributed borehole and test hole data to be combined with the more localized and denser AEM survey data, providing broad spatial coverage over the entire BC Model while maintaining higher spatial resolution within the Focus Area. Resistivity values were then interpolated to create a continuous, geologically informed, hydrogeologic framework that provides a basis for an initial hydraulic conductivity field distribution.

2.4 AQUIFER WATER LEVELS AND SURFACE/GROUNDWATER INTERACTIONS

Observed groundwater water levels indicate that the water table surface generally follows the Tòthian pattern for regional groundwater flow in which the water table surface is generally a subdued replica of surface topography. Groundwater in the BC Model Area generally flows from west to east with local variation and converging flow paths toward the South Loup and its perennial tributaries (Brown and Caldwell, 2013).

2.5 CONCEPTUAL MODEL SUMMARY

Groundwater in the BC Model Area originates from precipitation infiltration, inflow from the west, irrigation return flows, canal leakage, and streams leakage. Groundwater exits the BC Model Area through discharge into streams and rivers, outflow to the east, evapotranspiration, and pumping. This conceptual model provides the foundation for simulating groundwater flow dynamics and interactions in the BC Model described in the next section.

SECTION 3: GROUNDWATER MODEL

3.1 MODEL OVERVIEW

The BC Model simulates groundwater flow within focused areas of Buffalo County, specifically within Water Quantity Area 18 and portions of Areas 13 and 16. In these areas, groundwater pumping supports agricultural production, municipalities, and residential/domestic uses. The largest groundwater use by quantity is agricultural, resulting in increased rates of groundwater level declines within the Focus Area since the early 2000s, which is the question that the BC Model is trying to address.

LRE developed the BC Model using MODFLOW, an open-source widely used three-dimensional modular finite-difference flow model developed by the U.S Geological Survey (USGS), that is considered the standard for groundwater modeling. The modeling was completed using the latest iteration, MODFLOW 6 (Langevin et al., 2017). LRE developed the model using Groundwater Vistas (ESI, 2020), a graphical user interface, and external Python scripts.

3.2 MODEL CONSTRUCTION

3.2.1 Model Grid, Layering, and Boundary Conditions

The model grid consists of five layers that were horizontally discretized using unstructured quadtree gridding (Figure 5). Quadtree gridding is used to improve model resolution within areas of interest while maintaining a computationally efficient model with reasonable run-times. The base cell size within the active domain is 2,640 ft (0.5 mi) but within the Focus Area the grid was refined to 1,340 ft (0.25 mi). The grid is oriented west to east and is not rotated. The base of the model was defined as the bedrock elevation map that was constructed using the Leapfrog Works geologic framework. The top of the model was defined using surface elevations generated from light detection and ranging (LiDAR) surveys conducted across the BC Model domain. The difference between the surface elevation and top of bedrock was used to determine the thickness of the model across the domain, which varied the distribution of layer thickness.

The model boundary, referred to as the BC Model Area, was chosen with the goal of minimizing the model's extent while also maintaining reliable boundary conditions and a large enough area to encompass the Focus Area. The BC Model Area is much larger than the Focus Area to: 1) ensure boundary conditions do not influence the results of the Focus Area, 2) ensure the broader hydraulic connectivity and interactions between aquifers is accounted for, 3) account for regional influences of recharge and flow patterns, and 4) improve numerical stability and accuracy of the model.

The BC Model Area covers the southern portion of the LLNRD and portions of Buffalo, Hall, and Dawson County south of the LLNRD boundary as shown on Figure 1. Figure 2 shows the model boundary conditions. The external model boundary was comprised of general head boundaries (GHB) and drain (DRN) boundary conditions. A GHB was used for the eastern and western boundaries as there are no natural boundaries in their vicinity. The GHB values were based on the calibrated groundwater elevations output from the Central Nebraska Model (CENEB) and local water levels shown on nearby wells' geologic logs. The southwestern boundary of the model is comprised of DRN cells as there is a topographic high along this boundary that directs groundwater flow towards the Platte River Valley. Like the GHB values, elevations of these cells were assigned to match contours from CENEB.

There are numerous rivers and streams within the model domain ranging from ephemeral to perennial. These surface water features are represented using the Stream Flow Routing (SFR) package. The SFR package was selected due to its ability to simulate temporal changes in surface water-groundwater hydraulic connections. Five major perennial streams were identified to prescribe transient inflow values: the Platte, South Loup, and Middle Loup Rivers, and Mud Creek. To calculate inflows, long term stream gage data was collected and baseflow separation was performed to quantify flow rates contributed solely from baseflow (i.e. groundwater).

3.2.2 Hydraulic Conductivity

The geologic model derived from the borehole and AEM data was used to assign initial properties to individual MODFLOW grid cells. The resistivity zones were initially divided into four categories: non-aquifer, marginal aquifer, aquifer, and coarse aquifer. While these resistivity categories can be correlated to broad initial hydraulic conductivity ranges, the four categories were further divided into nine hydraulic conductivity zones to allow for greater flexibility in model parameterization and calibration. For example, the coarse aquifer resistivity zone was separated into three hydraulic conductivity zones representing medium sands, coarse sands, and gravels. As model development continued, the number of zones was increased to 12 to reflect the quaternary alluvial sediments within the alluvial flood plains in the upper-most layer of the model. The BC Model hydraulic conductivity field was then modified through model calibration as described in Section 3.3.

3.2.3 Groundwater Model Time Period

The BC Model simulates a 62-year period, spanning January 1959 through December 2020. There are a total of 733 stress periods, with the first being a steady state stress period of one year to establish initial conditions followed by 732 transient stress periods lasting a month each. This time frame provides for a robust calibration period, and allows the model to capture long-term groundwater trends, and changes in trends.

3.2.4 Integration of a Regionalized Soil-Water Balance Model

To more accurately reflect water supplies and uses at the surface, LRE contracted TFG to create a Regionalized Soil-Water Balance Model (RWSB), a crucial component of a robust numerical groundwater flow model. In general, the primary role of the RWSD is to account for available water at the surface and its applications within a balanced budget. Components of the water balance include precipitation, applied irrigation water, evapotranspiration, deep percolation, runoff, and changes in soil water content. The RWSB incorporates vast amounts of data that represent multiple processes and distills them down into a format that is compatible with MODFLOW. Specifically, the RWSB generates spatially and temporally distributed recharge and well packages that are process-based. For a complete account of the construction of the RWSB see Appendix A**,** the full TFG Report.

Recharge was applied to the top active model layer in the BC Model and pumping was assigned to each vertical column of cells based on the presence or absence of alluvial sediments shown in the surficial geologic map (Figure 3). Well depths indicate that most wells in areas where alluvial aquifer material is present are completed within the alluvium. In areas where there is no alluvium, wells are typically completed much deeper. Therefore, pumping was assigned to layers one and two in alluvial areas and assigned to layers two through five in the remaining BC Model Area where alluvium was not present.

3.3 MODEL CALIBRATION

3.3.1 Overview

Model calibration aims to achieve a reasonable correlation between simulated model results and observed field data. The calibration process is generally completed iteratively by changing model parameters to achieve an acceptable fit between simulated and observed data. Once a model is adequately calibrated, a sensitivity analysis is performed to ascertain how a change to a model parameter impacts the output of the model. In areas where there is a great deal of uncertainty, such as locations that lack sufficient observation data or in areas where the interpretation of data introduces uncertainty (e.g. inversion of AEM resistivity data), a set of additional models are run to determine the effect systematic changes to parameter values have on the calibrated model. Although no model can produce entirely perfect or "correct" results everywhere in the model domain, model error is minimized through automated model calibration as described in the following sections.

3.3.2 Model Calibration Methods and Statistics

The BC Model was calibrated using the PEST-HP version of the automated parameter estimation software suite PEST which is intended for parallelized model calibration (Doherty, 2015). PEST-HP adjusted the twelve hydraulic conductivity zones and storage terms (Ss and Sy) within predefined realistic ranges until the objective function, which measures the discrepancy between simulated and observed values, was minimized. The final value, lower limit, and upper limit of each parameter can be found in Table 1. Transient water level data from 225 wells within the model domain, spanning January 1960 to December 2020, were used as calibration targets. Figure 1 shows the location of the LLNRD, USGS, and CPNRD calibration targets. During model calibration, LLNRD calibration targets were assigned significantly higher weights compared to the USGS and CPNRD calibration targets to emphasize the model fit to observed water levels within the Focus Area.

The calibration plot, showing measured versus observed head values for the model, is illustrated in Figure 5**.** The plot shows that the simulated and observed head values generally compare favorably, falling along the one-to-one line indicating that the model is accurately simulating historical conditions. Figure 6 presents the spatial distribution of model residuals.

The mean difference, or residual mean, between the simulated and observed values is 2.69 ft within the Focus Area. NRMS error measures how well the model's results align with observed data, expressed as a percentage. The NRMS error within the Focus Area is 2.18%. While there is no statistical standard for what constitutes a calibrated model as it is directly related to the modeling objective, the goal of calibration is to minimize errors between what is observed and what is simulated. At the regional scale, the BC Model NRMS based on 23,143 observations is 2.37% and indicates that model error is reasonable and sufficient for the intended use of this model. Complete statistics can be found in Table 2.

3.3.3 Calibrated Parameters

The final calibrated parameters can be found in Table 1. As the geology within the BC Model varies both horizontally and vertically, so do the hydraulic parameters. Figure 7, Figure 8, Figure 9, Figure 10, and Figure 11 show the horizontal and vertical spatial distribution of hydraulic conductivity following model calibration for each model layer detailing the geologic complexity in the area. The estimated values fall within expected ranges for the region's fluvial, lacustrine, and alluvial sediments. Additionally, the hydraulic conductivity and storage values closely match those from the CENEB model, which indicates the parameters derived from calibration within the Focus Area are supported by this additional line of evidence.

3.4 SIMULATED WATER TABLE AND WATER BUDGET

In addition to comparing the simulated and observed head data, the configuration of the regional groundwater flow field based on simulated head contours was considered. The BC Model overlaps with the larger regional CENEB model (Brown and Caldwell, 2013). As the two model domains overlap, groundwater contours by the BC Model and CENEB for the year 1960 were compared in Figure 12. The flow direction and water table elevation are in general agreement, further indicating that the BC Model is calibrated.

Figure 13 presents a comparison of simulated water table contours for 1960 and 2020. In general, there are significant shifts in groundwater elevation contours over this period. This is most prominently displayed in the area south of the South Loup River where the most significant declines have historically occurred.

Figure 15 presents the model water budget through time graphically. The transient model mass balance for the calibrated model, which represents conditions from 1960 to 2020, is included in Table 4. The model inputs and calculated outputs are balanced with a mass balance error of approximately 0.061 cubic feet per day (ft^3/day), which is less than 0.001% of the total model inflows and outflows.

3.5 TRANSIENT WATER LEVELS

Within the Focus Area, observed long-term trends in water levels at eight key LLNRD and USGS gaging stations were selected to represent observed and stimulated trends within the Focus Area. These wells were selected for their spatial distribution across the Focus Area, considering Groundwater Quantity Areas, their locations north and south of the South Loup River, and their periods of record. Water level graphs, also known as "hydrographs", for the eight selected wells are shown in Appendix B. These hydrographs show that observed trends in drawdown are being reasonably simulated by the BC Model. Hydrographs for all wells within the Focus Area can be found in Appendix C.

While hydrographs are effective at showing long-term trends in water level elevation at a specific location, the spatial distribution of water level elevations across an area of interest can more easily identify areas of concern or confidence. The change in groundwater elevation between 1960 to 2020 was quantified to provide an additional comparison to observed measurements (Figure 16). The overall pattern of groundwater elevation declines is like that of what has been observed. An additional two time periods were selected to identify spatial and temporal trends in the Focus Area. The period from 2008 and 2020 was selected as this period corresponds with the initiation of groundwater management initiatives enacted by LLNRD, most notably the closure of the expansion of irrigated acreage, that significantly reduced groundwater declines. To directly compare how these initiatives impacted groundwater declines, the period from 1996 to 2008 was selected as this corresponds to the 13 years prior to substantially increased groundwater management. When comparing the two time periods, the increased groundwater management tactics were impactful, with groundwater elevation declines slowed and, in certain areas, even reversed (Figure 17).

3.6 SENSITIVITY ANALYSIS

A sensitivity analysis is a procedure in which aquifer parameters are varied and the impact on model outputs is quantified and used to analyze the effect of different parameter sets on model outputs. Three key parameters were analyzed: hydraulic conductivity, recharge, and storage (a combination of specific storage and specific yield). Calibrated values for hydraulic conductivity and recharge were adjusted by ± 25%, while storage terms were modified up and down within reasonably defined storage parameter bounds. Table 3 shows the parameter ranges used in the model sensitivity analysis.

Hydrographs generated during the Sensitivity Analysis are provided in Appendix D. These results show that changes to hydraulic conductivity, recharge, and storage create an envelope of groundwater elevations that surround the groundwater elevations found within the calibrated model. Decreasing the hydraulic conductivity and/or increasing recharge shift the groundwater elevation up, but generally the hydrographs maintain similar slopes compared to the base case. Similarly, increasing hydraulic conductivity and/or increasing recharge shifts the water table up while still maintaining a similar slope through time. Increasing storage yields a muted response compared to the base case, while decreasing storage yields steeper declines.

SECTION 4: MODEL PREDICTIONS

4.1 PREDICTIVE TRANSIENT MODEL RUN SETUP

After calibration, additional stress periods were added to extend the model's transient simulation through December 2060. Recharge, pumping, and evapotranspiration for the 2008 through 2020 historical period were repeated to project a base-case future model scenario. This 13-year period was projected into the future because it represents the time period (starting in 2008) that the LLNRD began implementing groundwater management initiatives. This was done so impacts of potential future groundwater management scenarios could be evaluated prior to implementation. Figure 18 presents the predicted drawdown from 2020 through 2060 and is the base-case future scenario to which the next four example model use-cases will be compared. For an in-depth description of individual modeling files setup and execution of the base-case future scenarios and three example management scenarios detailed below see Appendix E.

4.2 EXAMPLE MANAGEMENT SCENARIOS

4.2.1 Stream Diversion to Identified Managed Aquifer Recharge Area

The implementation of stream diversions is a form of managed aquifer recharge (MAR) that is often used to divert stream flows during periods of high flows to other locations or to capture runoff in channel to initiate recharge that increases water levels and storage within the groundwater flow system. To simulate the long-term impact of the potential use of such a groundwater management practice, flows from the South Loup River were diverted to Sand Creek, an ephemeral stream channel, each May from 2021 through 2060. This location was chosen specifically as it is one of the areas that AGF identified as a potential site for MAR. A volumetric rate of 288,750 ft^3/d (1,500 gallons per minute (gpm), 3.3 cubic feet per second (cfs)) was diverted from the South Loup River and discharged into the Sand Creek drainage immediately to the east.

The groundwater elevation was compared to that in the base-case where there was no perturbation to the groundwater system. In the immediate vicinity of where the water was removed from the South Loop River, a small cone of depression forms. In Sand Creek a larger groundwater mound forms. This is shown on Figure 19. Due to the creation of a cone of depression and a groundwater mound, changes in the rate and timing of stream flows were altered. Using the BC Model, an observation point in the model was chosen that represented the location of the St. Michael, NE USGS stream gage on the South Loup River. Changes in stream flow rate and timing at this location were compared and it was found that during the period when stream flow was diverted from the South Loup River to the Sand Creek, flow rates in the stream initially drop (Figure 20). This initial drop is followed by an increase in stream flow later in the year, indicating that short-term MAR is capable of supplementing stream flow during periods of low flow that typically occur later in the year.

Results from this example demonstrate how the BC Model can be used to evaluate the impacts of stream diversions during times of excess flow on local water table elevations. This example scenario can also be easily modified to assess the potential impact of stream diversions to other areas identified as having high MAR potential in the future.

4.2.2 Theoretical Pumping Capacity Increase

There is potential for future industrial development or expansion within the BC Model Area. An example of this kind of development is the KAAPA Ethanol Ravenna plant, which has multiple high-capacity groundwater wells that it utilizes in its manufacturing process. Using existing pumping volume as a guide, a theoretical high capacity well pumping at 13,200 acre-inches per year (~685 gpm) was added to the BC Model in the same location as the KAAPA Plant, effectively doubling the current pumping rate in the area. Pumping commenced at the beginning of model year 2021 and was allowed to continue through 2060 uninterrupted. One-third of the pumped water was consumed in the manufacturing process, one-third was lost to evaporation, and one-third was returned to the South Loup River.

The additional pumping resulted in a water table decline of greater than five feet when compared to the base-case where the status quo was maintained (Figure 21). The cone of depression exhibited by the additional pumping extended outward from the location of the new well to the south to the border of the Focus Area and marginally northward across the South Loup River. This indicates that this additional pumping would have adverse effects on those who have wells within the cone of depression and on South Loup River flows. To quantify this impact, the same observation point described above was used to compare flows through time. It was found that with continual pumping at the KAPPA Ethanol Ravenna Plant, stream flow would decrease by less than 1 cfs by the year 2060 (Figure 22). This scenario demonstrates that the BC Model can be used by the LLNRD to evaluate potential impacts on local stakeholders and water ways from potential future development that would rely on groundwater as a main source of water resources.

4.2.3 Pumping Allocations

Discussions around the implementation of pumping allocations are difficult and contentious, yet often necessary in areas experiencing expedited groundwater declines. As groundwater managers are stewards of the groundwater resources they oversee, enacting pumping allocations is not a decision that is taken lightly. Tools like the BC Model provide decision makers with the ability to assess the effectiveness of policies through simulations while mitigating the risk associated with traditional trial-and-error approaches. To demonstrate how the evaluation of pumping allocations can be achieved, LRE created four hypothetical pumping allocation scenarios and applied them across the Focus Area to quantify the spatial and temporal impacts on groundwater elevation. Pumping allocations of 12-, 7.5-, 5-, and 2.5-inches were selected to demonstrate that the BC Model is capable of accurately simulating a wide range of scenarios, providing valuable insights for groundwater managers.

In these simulations, pumping is limited to provide a maximum volume of water that corresponds to the specific allocation (i.e. irrigation depth) scenario. To restrict pumping across the Focus Area to the allocation limit, the base-case pumping volume on a model cell by model-cell basis was evaluated. If the applied pumping volume in any given cell within the Focus Area exceeded the allocation scenario limit, it was replaced with the volume of water equivalent to the allocation scenario limit. This resulted in reductions in the overall volume of pumping within the Focus Area of 0.74%, 6.56%, 18.49%, and 44.67% for the 12-, 7.5-, 5-, and 2.5-inch allocations, respectively, when compared to the volume of water pumped during the base-case (no allocation).

From a groundwater management perspective, these scenarios provide a range of possibilities of changes to long-term trends in groundwater elevation declines (Figure 23). For the 12- and 7.5-inch allocations, represented by the blue and orange lines, respectively, groundwater declines will continue with minor changes to the rate of decline. However, the 5-inch allocation scenario (shown in green), resulted in a prominent reduction in the rate of decline while the 2.5-inch allocation scenario (red line), resulted in groundwater elevation gains. These results can also be analyzed from a spatial standpoint which identifies areas that experience the most significant changes and areas that are marginally affected. When compared to the base case (Figure 17), the differing levels of allocations have varying levels of impact. For the 12- and 7.5-inch allocation scenarios, groundwater declines south of the South Loup continue at about the same pace as in the base case (Figure 24). However, for the 5- and 2.5-inch allocation scenarios, there is a more pronounced reduction in the magnitude and area of predicted future declines (Figure 25).

Another aspect of allocations that can be evaluated using the BC Model are the impacts to stream flows. When compared to the base-case, the stricter an allocation, the greater the increase to stream flow through time (Figure 26). These hypothetical scenarios are not intended to provide guidance towards the implementation of allocations for the LLNRD but to serve as an example of the capabilities of the BC Model as an assessment tool.

4.3 LIMITATIONS

The scenarios described above are hypothetical and intended to demonstrate the capabilities of the BC Model as an assessment tool that can be used to evaluate potential management scenarios prior to implementation. The results reported above do not serve as an endorsement for any specific management scenario over another nor are they intended to inform management decisions without further analysis from the LLNRD.

SECTION 5: SUMMARY AND CONCLUSIONS

LRE successfully constructed a groundwater flow model focused on areas of significant groundwater decline within Buffalo County, NE for the LLNRD for the purpose of evaluating and assessing future impacts on their water resources. The flow model combines a conceptual model of the area that identified the various inflows and outflows to the system and a geologic model built from AEM and other geologic data . Major inflows identified were precipitation infiltration, inflow from the west, irrigation return flows, canal leakage, streams leakage with major outflows being discharged into streams and rivers, outflow to the east, evapotranspiration, and pumping.

The foundation of the geologic model was borehole and use of LLNRD's AEM data that was combined in Leapfrog Works to create a cohesive representation of the aquifer system. Hydrogeologic parameters generated from the geologic model were then imported into MODFLOW. This approach successfully merged two differing datasets, well logs and test holes, along with AEM data, to provide a wider range of representation for the BC Model Area. This resulted in a strong and accurate representation of the Focus Area's hydrogeologic characteristics.

Calibration of the MODFLOW model was achieved using spatially and temporally diverse observations of groundwater elevation. The PEST software suite was during model calibration to obtain a reasonable match between historic observations and model simulated values. The BC Model reasonably simulates the generally observed groundwater declines in the Focus Area as compared to observed data provided by LLNRD as shown in the numerous hydrographs in the Focus Area.

To demonstrate the utility of the BC Model, three future scenarios were developed that included a total of six model runs. These scenarios, 1) the implementation of stream diversions for MAR, 2) the theoretical increase in pumping capacity, and 3) changes in pumping allocations, are intended to reflect potential realistic stresses to the groundwater system. The results from these three examples demonstrate that the BC Model can be used to assess potential changes to the groundwater system from proposed initiatives prior to their implementation, providing valuable information to decision makers and stakeholders.

SECTION 6: RECOMMENDATIONS

The following are recommendations for LLNRD staff to consider when utilizing the BC Model as a technical guide for water resources management.

Identify Desired Future Conditions

- To most effectively use the BC Model as a tool to evaluate and assess the performance of groundwater conservation initiatives, the identification of desired, quantifiable future conditions such as groundwater levels or stream flows is advised. This will allow for the development of clearly defined objectives that provide a clear direction and purpose for each devised model scenario. These desired future conditions should be identified through a collaborative effort between the LLNRD staff, the LLNRD Board, and local stakeholders to ensure that all groundwater user needs are considered.

- Having clearly defined desired future conditions will result in the optimization of LLNRD staff resources in terms of model scenario development, and improve the accuracy of the model outcomes as it can be tailored to capture the relevant variable and relationships, and enhance communication between LLNRD staff, the LLNRD Board, and stakeholders as there will be a shared understanding of the project goals.

Maintain High-Frequency Observation Network

- The biannual water level measurements that the LLNRD currently collects provided data that was instrumental in achieving the final model calibration. While these data are adequate for calibration, it is recommended that in areas where groundwater management initiatives are going to be implemented more frequent measurements are collected so their performance can be monitored in real time. This can be achieved through the installation of data loggers or telemetry systems on newly constructed or existing monitoring wells in the area of interest. The information can be shared with the LLNRD Board and public if desired to demonstrate the LLNRD's commitment and aggressive attitude toward groundwater conservation.

Routinely Update the BC Model

- To ensure that the BC Model remains an effective tool for assessing groundwater conservation initiatives the calibration should be revisited periodically. As more information is collected, either through the continued biannual water level measurements, planned aquifer tests, potential future AEM flights, or the drilling of additional test holes, the model performance can be checked, and if needed, enhanced through the ingestion of these data.

Model Use Case Scenarios

- Three examples of possible groundwater management scenarios were described above but the BC Model is capable of being used for a multitude of modified or new scenarios. The foundation of the BC Model, MODFLOW 6, is designed for flexibility and as such current input files can be modified or new ones can be created to quantify changes to components of interest such as the water budget, stream flows, and groundwater elevations. For instance, in the allocation scenarios that were run, a blanket allocation was applied over the entire focus area. These runs could be modified so that allocations are targeted to subareas within the Focus Area that are experiencing the greatest decline in water levels to determine their impact.

SECTION 7: REFERENCES

Aqua Geo Frameworks, LLC. (2017). Framework of Selected Areas in the Twin Platte and Central Platte Natural Resources Districts, Nebraska. https://enwra.org/projects/2016-airborne-electromagnetic-aem-surveys

Aqua Geo Frameworks, LLC. (2020). Airborne Electromagnetic Mapping and Hydrogeologic Framework of Selected Areas along South Loup River Within Lower Loup Natural Resources District.

Brown and Caldwell. (2013). Central Nebraska Groundwater Flow Model. https://dnr.nebraska.gov/sites/default/files/doc/water-planning/20130805_CENEB_ReportFINAL.pdf

Doherty, J., (2015). Calibration and Uncertainty Analysis for Complex Environmental Models. Watermark Numerical Computing, Brisbane, Australia. ISBN: 978-0-9943786-0-6.

Environmental Simulations, Inc. (2020). Groundwater Vistas 8. https://www.groundwatermodels.com/

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. (2017). *Documentation for the MODFLOW 6 groundwater flow model* (No. 6-A55). US Geological Survey.

Seequent, The Bentely Subsurface Company. (2024). Leapfrog Works. https://www.seequent.com/products-solutions/leapfrog-works/

Swinehart, J. B., Dreeszen, V. H., Richmond, G. M., Tipton, M. J., Bretz, R. F., Steece, F. V., Hallberg, G. R., Goebel, J. E., Edited, G. M., & Richmond, I. B. (1994). *Quaternary Geologic Map of the Platte River 4 Degrees x 6 Degrees Quadrangle, United States*. https://pubs.usgs.gov/imap/i-1420/nk-14/

Tables

Table 1: PEST Parameter Limits, Final Values, and Adjusted Final Values

Parameter	Minimum (ft/day)	Maximum (ft/day)	PEST-Derived Final Value (ft/day)	Adjusted Final Value (ft/day)
K_X1	1.00E-02	5	1.00E-02	0.1
K_X2	1.00E-02	5	0.12	0.1
K_X3	1.00E-02	5	5	5
K_X4	5	35	35	35
K_X5	5	35	35	35
K_X6	5	35	9.49	35
K_X7	35	65	35	35
K_X8	35	65	35	35
K_X9	35	65	65	65
K_X10	20	40	40	40
K_X11	40	70	40	65
K_X12	55	250	250	250
Sy	1.00E-06	1.00E-04	1.00E-04	1.00E-04
Ss	5.00E-02	3.50E-01	3.50E-01	3.50E-01

Table 2: Final Calibration Statistics for the BC Model

Statistic	Cumulative	USGS	CPNRD	LLNRD	LLNRD Focus Area
Residual Mean (ft)	-3.70	4.69	-5.58	7.18	2.69
Absolute Residual Mean (ft)	10.20	6.00	10.69	8.39	4.06
Residual Std. Deviation (ft)	12.50	5.99	12.17	10.14	4.69
RMS Error (ft)	13.04	7.60	13.38	12.42	5.41
Min. Residual (ft)	-44.90	-35.86	-44.90	-14.20	-10.68
Max. Residual (ft)	36.67	21.05	34.31	36.67	19.47
Number of Observations	23143	1247	19501	2395	954
Range in Observations (ft)	550.63	375.43	534.24	412.08	248.09
Scaled RMS Error (ft)	2.37%	2.03%	2.51%	3.01%	2.18%

Table 3: Sensitivity Analysis Adjustments to Parameters

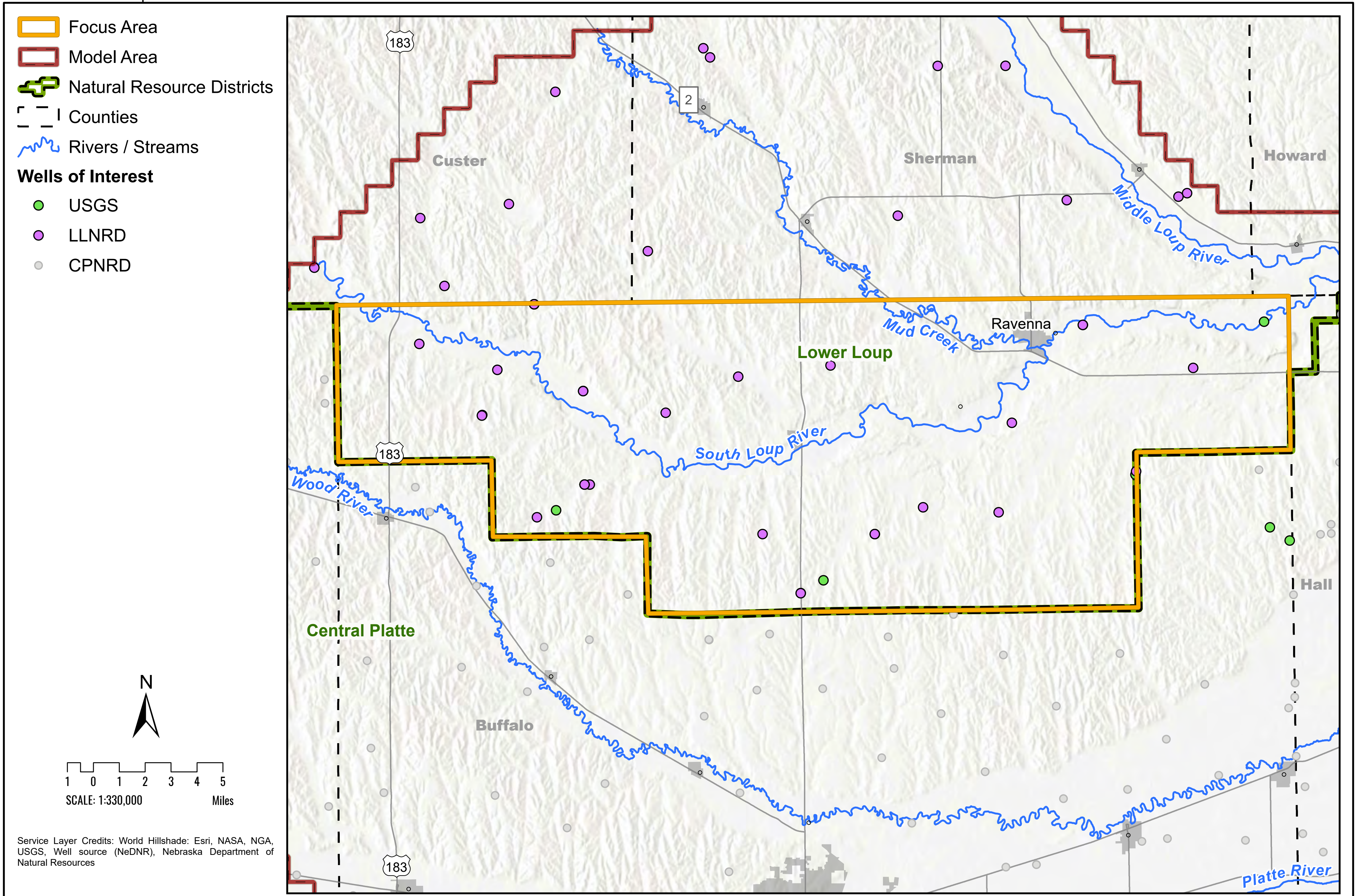
Parameter	Sensitivity Analysis - Higher	Sensitivity Analysis - Lower
K	+25%	-25%
Recharge	+25%	-25%
Ss	1 Order of Magnitude	1 Order of Magnitude
Sy	+0.05	-0.1

Table 4: Annual Water Budget (kAf-yr)

Year	Recharge	GW Inflow	Pumping	Stream Leakage In	GW Outflow	ET	Stream Leakage Out	Δ Storage
1959	8.47	0.41	0.00	0.61	-0.56	-0.37	-4.55	0.00
1960	14.21	0.35	-0.53	0.50	-0.59	-0.47	-5.73	3.27
1961	8.78	0.36	-0.60	0.55	-0.55	-0.46	-5.53	-2.28
1962	8.57	0.35	-0.28	0.55	-0.55	-0.44	-5.39	0.34
1963	4.72	0.37	-0.92	0.66	-0.49	-0.39	-4.94	-7.85
1964	6.06	0.34	-0.64	0.70	-0.51	-0.35	-4.84	-4.02
1965	14.38	0.32	-0.55	0.57	-0.59	-0.37	-5.47	4.55
1966	5.20	0.36	-0.72	0.64	-0.49	-0.37	-5.05	-5.33
1967	17.06	0.34	-1.04	0.61	-0.60	-0.38	-5.78	3.50
1968	8.15	0.34	-1.17	0.67	-0.52	-0.34	-5.29	-4.68
1969	11.32	0.33	-0.80	0.59	-0.63	-0.36	-5.57	0.50
1970	6.86	0.37	-1.67	0.75	-0.50	-0.33	-5.06	-9.07
1971	9.66	0.35	-1.34	0.74	-0.55	-0.30	-5.04	-3.74
1972	7.60	0.36	-1.44	0.87	-0.50	-0.27	-4.78	-5.13
1973	19.10	0.33	-1.55	0.75	-0.60	-0.28	-5.55	4.64
1974	7.58	0.39	-2.80	1.00	-0.50	-0.27	-5.03	-12.08
1975	6.69	0.40	-2.48	1.16	-0.44	-0.22	-4.44	-8.46
1976	6.91	0.42	-2.88	1.36	-0.41	-0.20	-4.23	-10.27
1977	19.52	0.35	-1.86	1.08	-0.52	-0.20	-5.15	6.42
1978	12.53	0.37	-3.00	1.18	-0.52	-0.21	-5.11	-4.80
1979	9.50	0.38	-1.63	1.15	-0.50	-0.20	-4.76	-2.62
1980	7.68	0.42	-3.92	1.26	-0.43	-0.19	-4.49	-10.72
1981	5.50	0.41	-2.76	1.37	-0.40	-0.17	-4.05	-7.33
1982	12.04	0.36	-3.25	1.32	-0.57	-0.18	-4.56	-2.73
1983	14.29	0.37	-3.52	1.32	-0.56	-0.19	-4.72	-3.70
1984	22.64	0.35	-3.45	1.21	-0.67	-0.22	-5.45	3.72
1985	13.45	0.35	-2.28	1.17	-0.57	-0.21	-5.30	0.29
1986	8.59	0.36	-3.63	1.21	-0.52	-0.20	-4.93	-7.08
1987	22.06	0.36	-2.60	0.95	-0.59	-0.23	-5.81	6.57
1988	5.77	0.40	-4.46	1.31	-0.44	-0.19	-4.76	-12.57
1989	6.73	0.42	-2.17	1.24	-0.43	-0.18	-4.39	-3.95

Year	Recharge	GW Inflow	Pumping	Stream Leakage In	GW Outflow	ET	Stream Leakage Out	Δ Storage
1990	8.62	0.39	-4.12	1.24	-0.52	-0.18	-4.36	-7.33
1991	6.99	0.43	-5.65	1.52	-0.45	-0.17	-3.97	-13.82
1992	8.99	0.37	-2.95	1.48	-0.54	-0.17	-4.07	-3.70
1993	25.48	0.34	-0.58	0.96	-0.69	-0.20	-5.37	18.05
1994	5.85	0.39	-3.40	1.08	-0.51	-0.20	-4.61	-8.18
1995	16.71	0.39	-3.86	0.99	-0.57	-0.21	-5.14	-0.66
1996	9.19	0.39	-1.68	0.99	-0.54	-0.20	-4.57	-0.26
1997	8.41	0.39	-3.81	1.07	-0.55	-0.19	-4.41	-6.63
1998	14.17	0.37	-2.10	0.89	-0.64	-0.21	-4.88	3.24
1999	16.82	0.37	-2.46	0.82	-0.68	-0.23	-5.25	4.33
2000	4.69	0.45	-5.50	1.11	-0.46	-0.20	-4.29	-14.44
2001	8.97	0.42	-3.81	1.11	-0.50	-0.19	-4.19	-6.60
2002	5.20	0.47	-5.73	1.32	-0.43	-0.17	-3.72	-13.95
2003	9.51	0.45	-5.60	0.85	-0.45	-0.16	-3.80	-10.51
2004	6.55	0.45	-3.83	0.71	-0.38	-0.14	-3.56	-8.32
2005	14.53	0.41	-4.31	1.16	-0.46	-0.15	-4.04	-0.66
2006	6.75	0.44	-3.87	0.90	-0.37	-0.13	-3.65	-6.38
2007	24.83	0.36	-2.13	1.25	-0.59	-0.17	-4.83	14.33
2008	27.47	0.35	-2.88	0.92	-0.74	-0.20	-5.45	13.38
2009	10.58	0.37	-3.11	1.06	-0.58	-0.20	-4.90	-3.54
2010	22.10	0.34	-1.91	0.88	-0.69	-0.22	-5.41	11.16
2011	10.15	0.35	-2.10	0.92	-0.64	-0.22	-5.02	-0.52
2012	6.21	0.44	-7.75	1.15	-0.46	-0.19	-4.31	-18.19
2013	7.14	0.40	-4.77	1.24	-0.50	-0.17	-3.92	-8.55
2014	8.99	0.38	-1.74	1.18	-0.56	-0.17	-4.02	0.65
2015	12.35	0.40	-4.44	1.09	-0.59	-0.18	-4.18	-3.20
2016	19.19	0.38	-3.35	1.01	-0.67	-0.21	-4.71	4.09
2017	10.83	0.39	-3.10	1.06	-0.61	-0.20	-4.38	-1.72
2018	17.21	0.36	-0.97	0.94	-0.66	-0.20	-4.64	9.27
2019	36.94	0.29	-0.37	0.53	-0.96	-0.29	-6.53	28.21
2020	14.35	0.33	-4.52	0.70	-0.77	-0.30	-5.83	-4.51

Figures



Prepared By:
LRE Water
Nebraska Office
Lincoln
(402) 416-4667

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LOWER LOUP NATURAL RESOURCES DISTRICT
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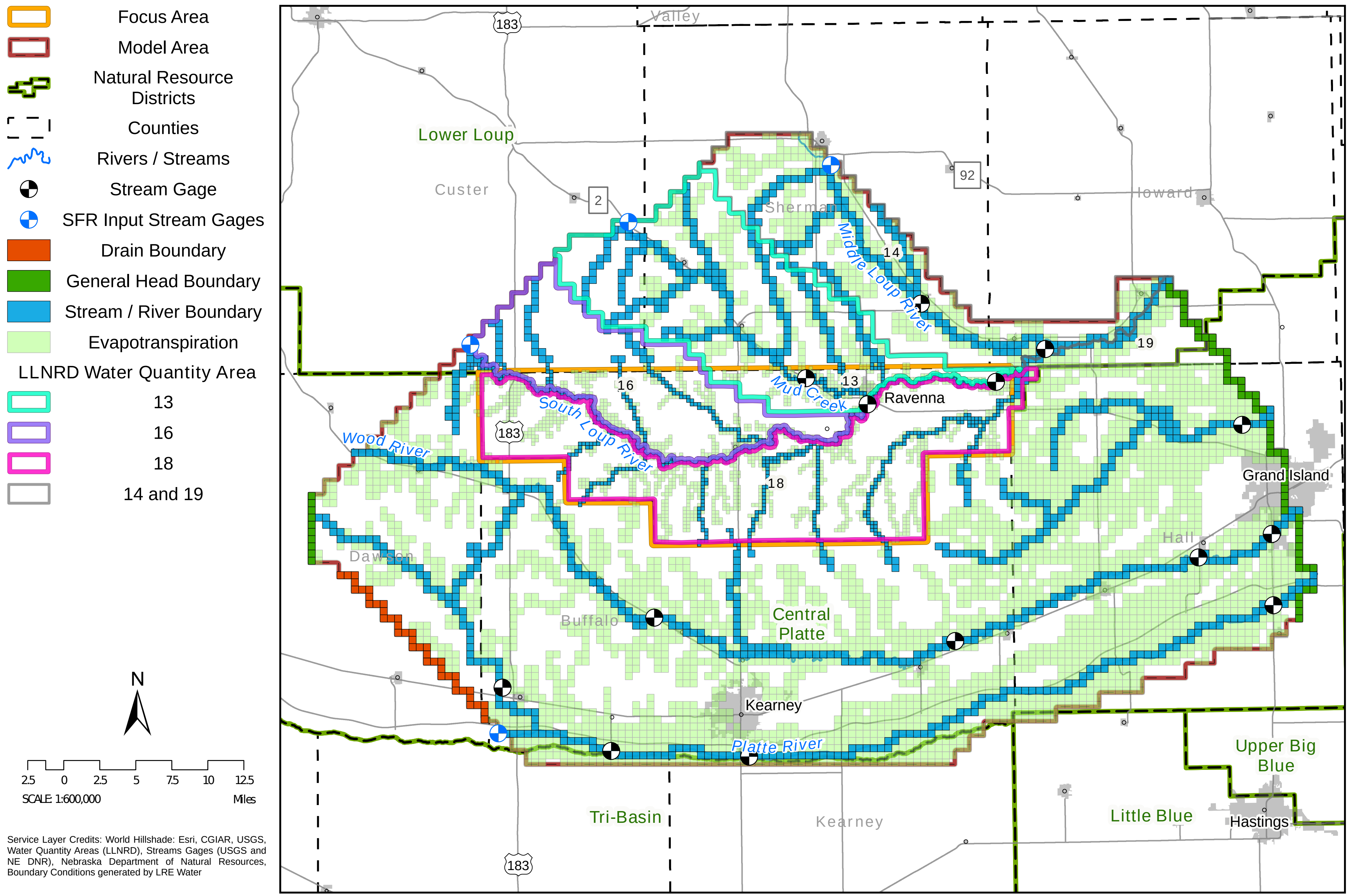
BUFFALO COUNTY, NE

MODEL EXTENT

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/21/2025 | FIGURE: 1



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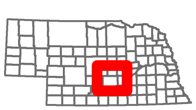

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LRE Water
Nebraska Office
Lincoln
(402) 416-4667

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GAGING STATIONS AND MODEL BOUNDARY CONDITIONS

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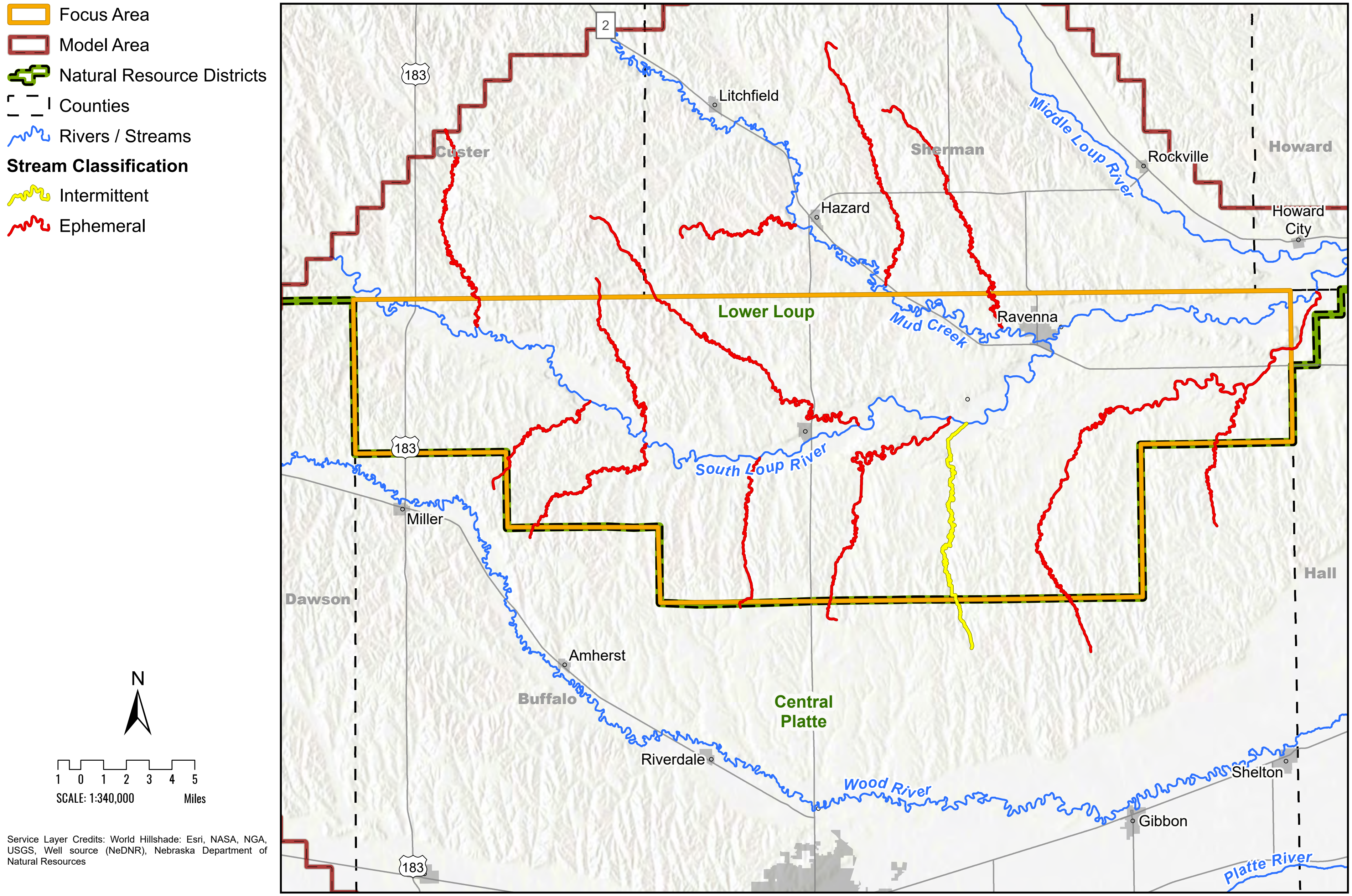

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STREAM TRUTHING SURVEY RESULTS

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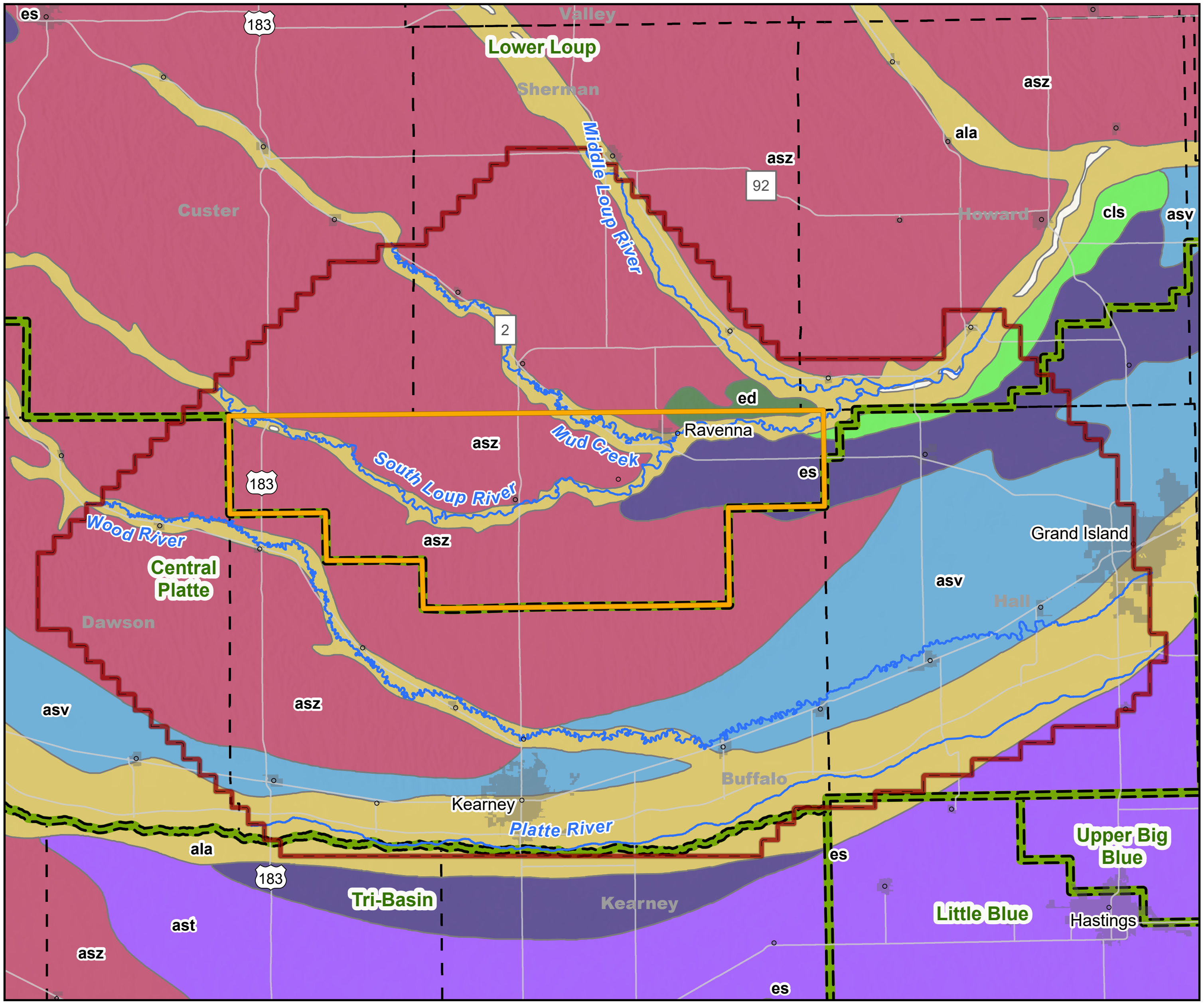
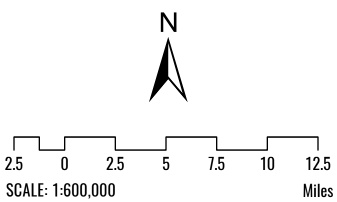
Focus Area
Model Area
Natural Resource Districts
Counties
Rivers / Streams

Surface Geology

ala - Alluvial silt, clay, sand, and gravel
ast - Alluvial gravelly sand and locally underlying lacustrine sand
asv - Gravelley sand of platte, north platte, and south platte river terraces
asz - Alluvial sand, pebble gravel, and lacustrine sand and silt
cls - Chert-clast clayey silt to silty clay loam colluvium
ed - Dune sand
es - Eolian sheet sand





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Nebraska Office
Lincoln
(402) 416-4667

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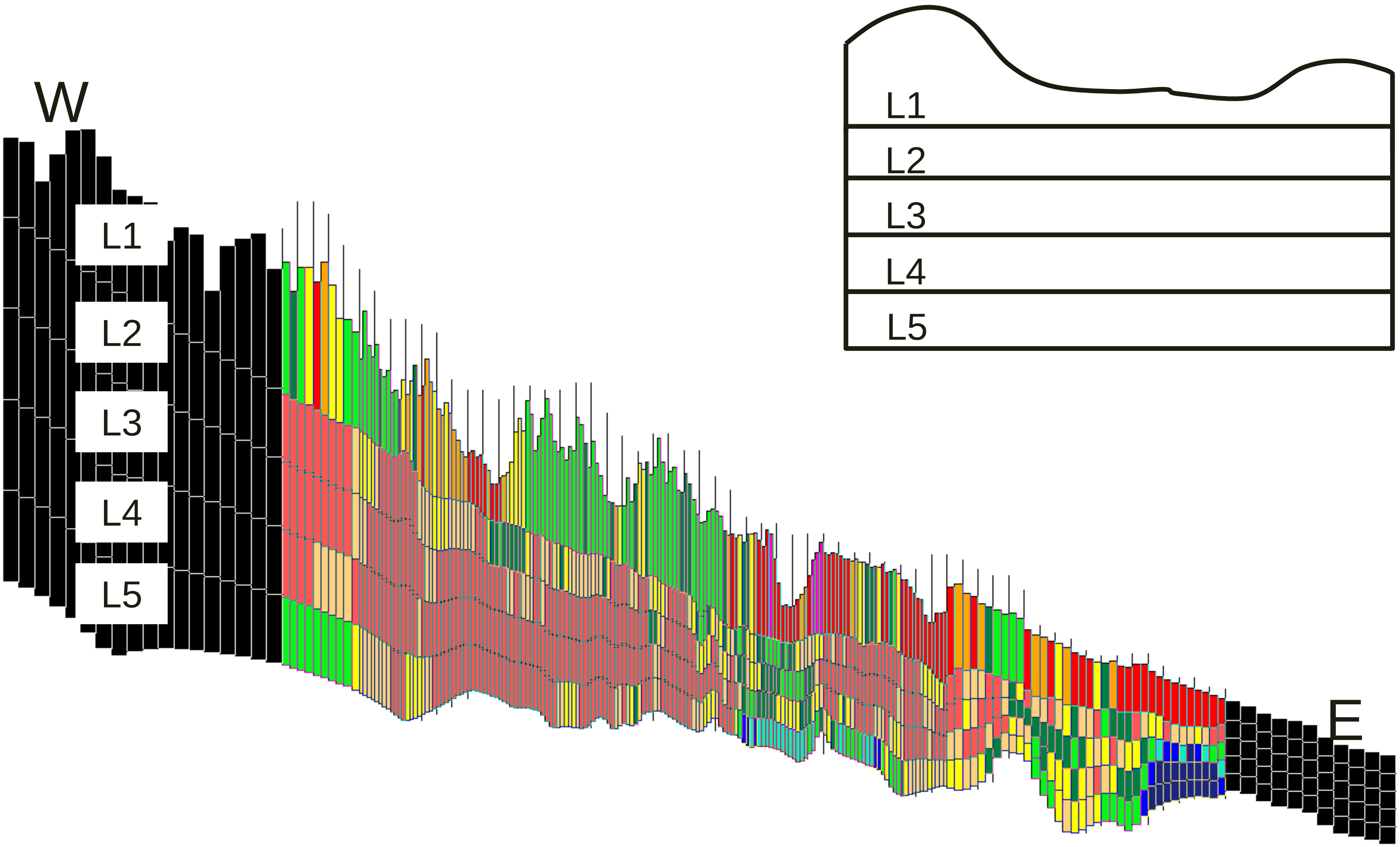
SURFICIAL GEOLOGY

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/21/2025 | FIGURE: 4



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BUFFALO COUNTY AREA GROUNDWATER MODEL
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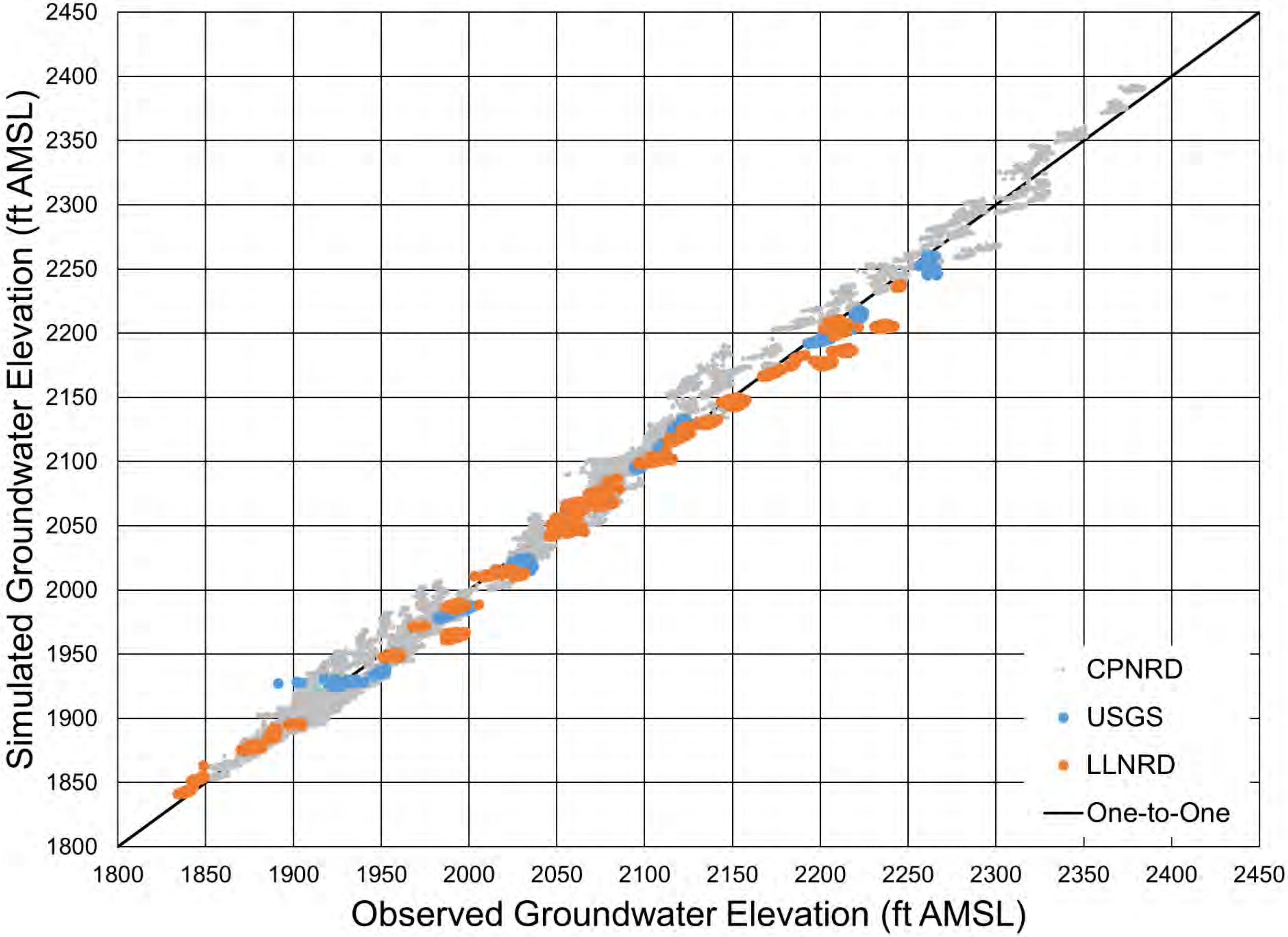
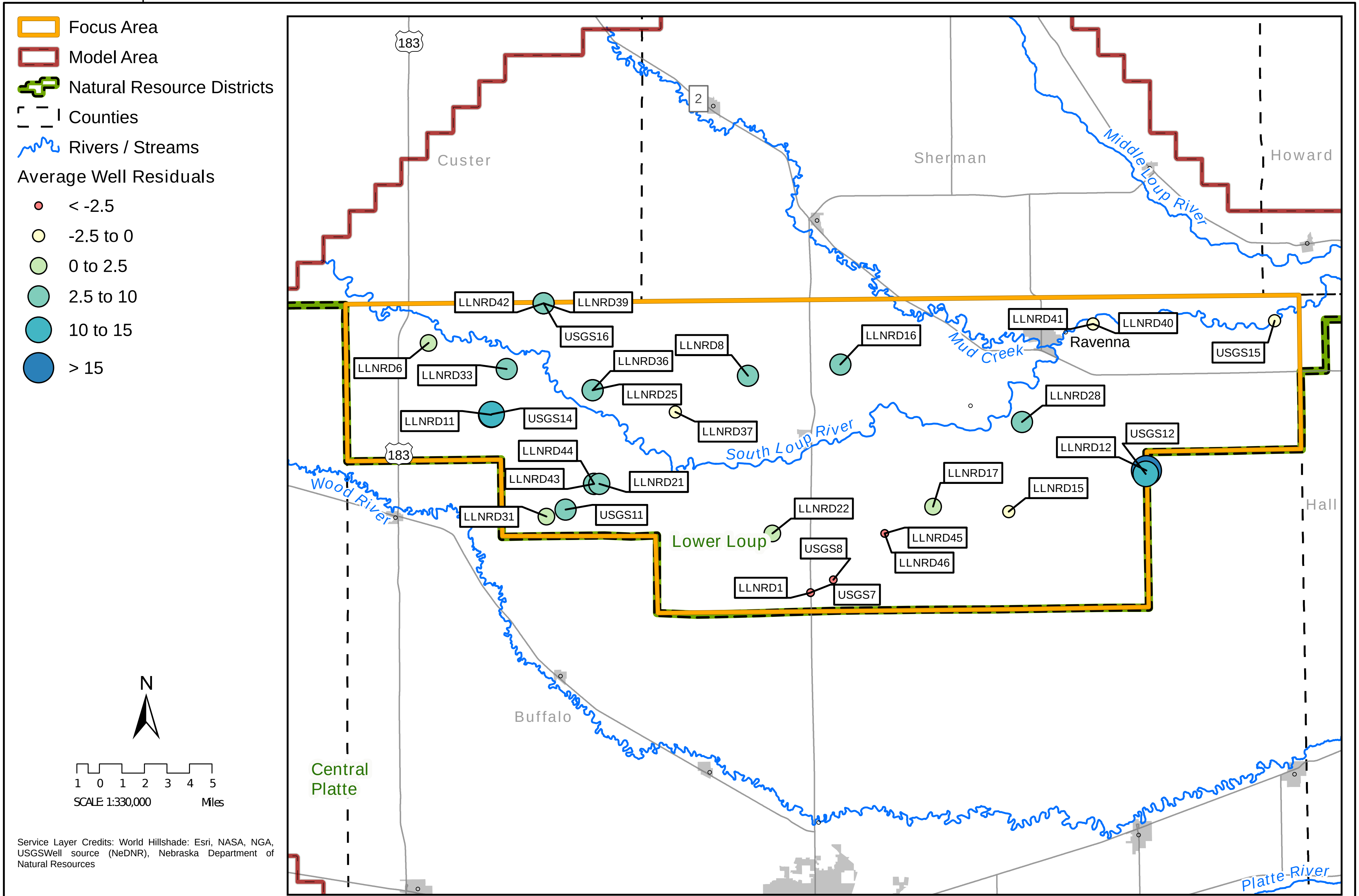
BC MODEL CROSS SECTION

FILE:	DATE: 1/21/2025	FIGURE: 5



CONNECTING WATER TO LIFE	Prepared By: LRE Water Nebraska Office Lincoln (402) 416-4667	LOWER LOUP NATURAL RESOURCES DISTRICT BUFFALO COUNTY AREA GROUNDWATER MODEL BUFFALO COUNTY, NE CALIBRATION SCATTER PLOT FILE: Calibration_Stats_Breakdown.xlsx — DATE: 1/21/2025 — FIGURE: 6



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Nebraska Office
Lincoln
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SPATIAL DISTRIBUTION OF AVERAGE RESIDUALS

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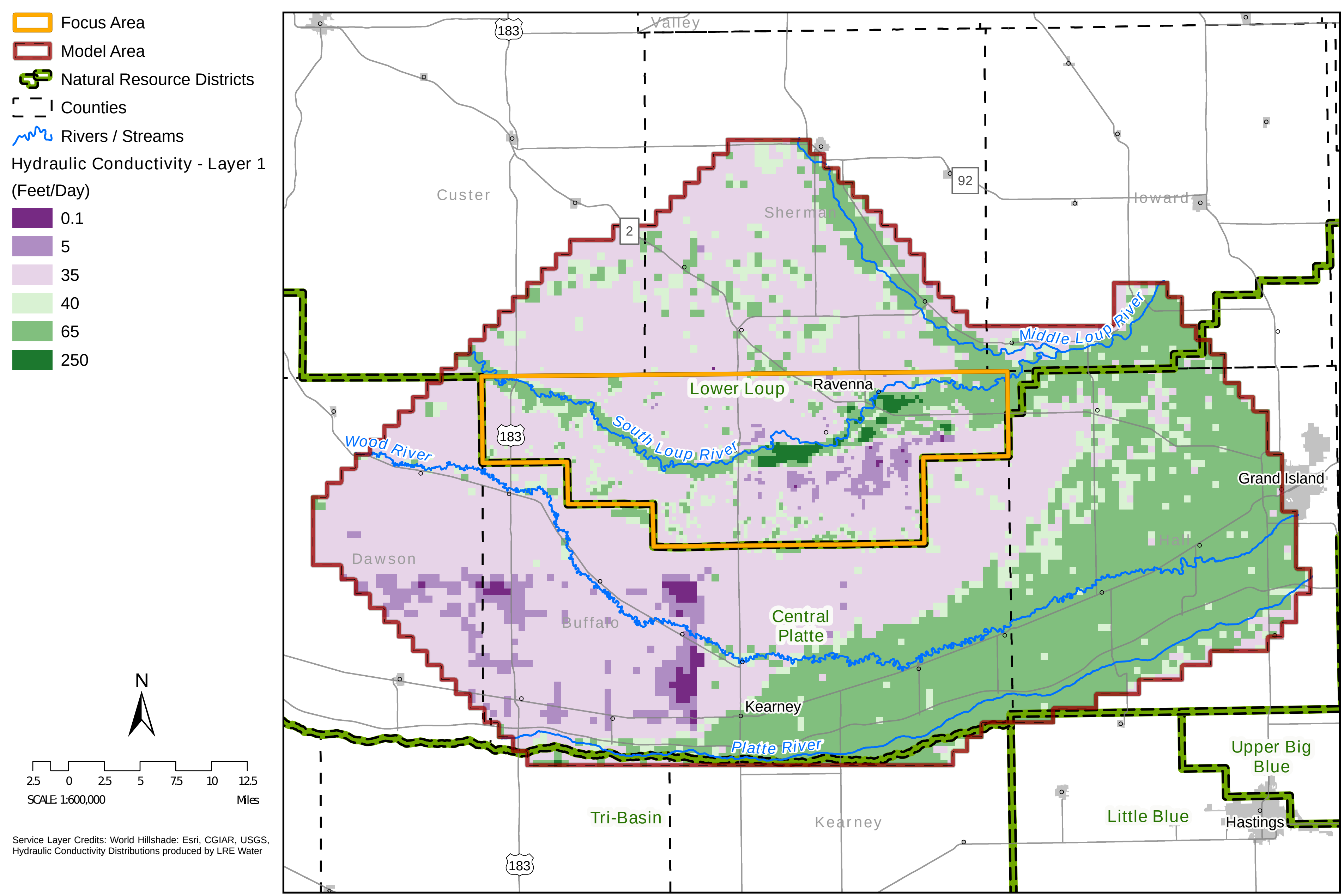

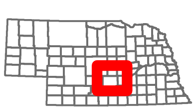

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Nebraska Office
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LAYER 1 K DISTRIBUTION

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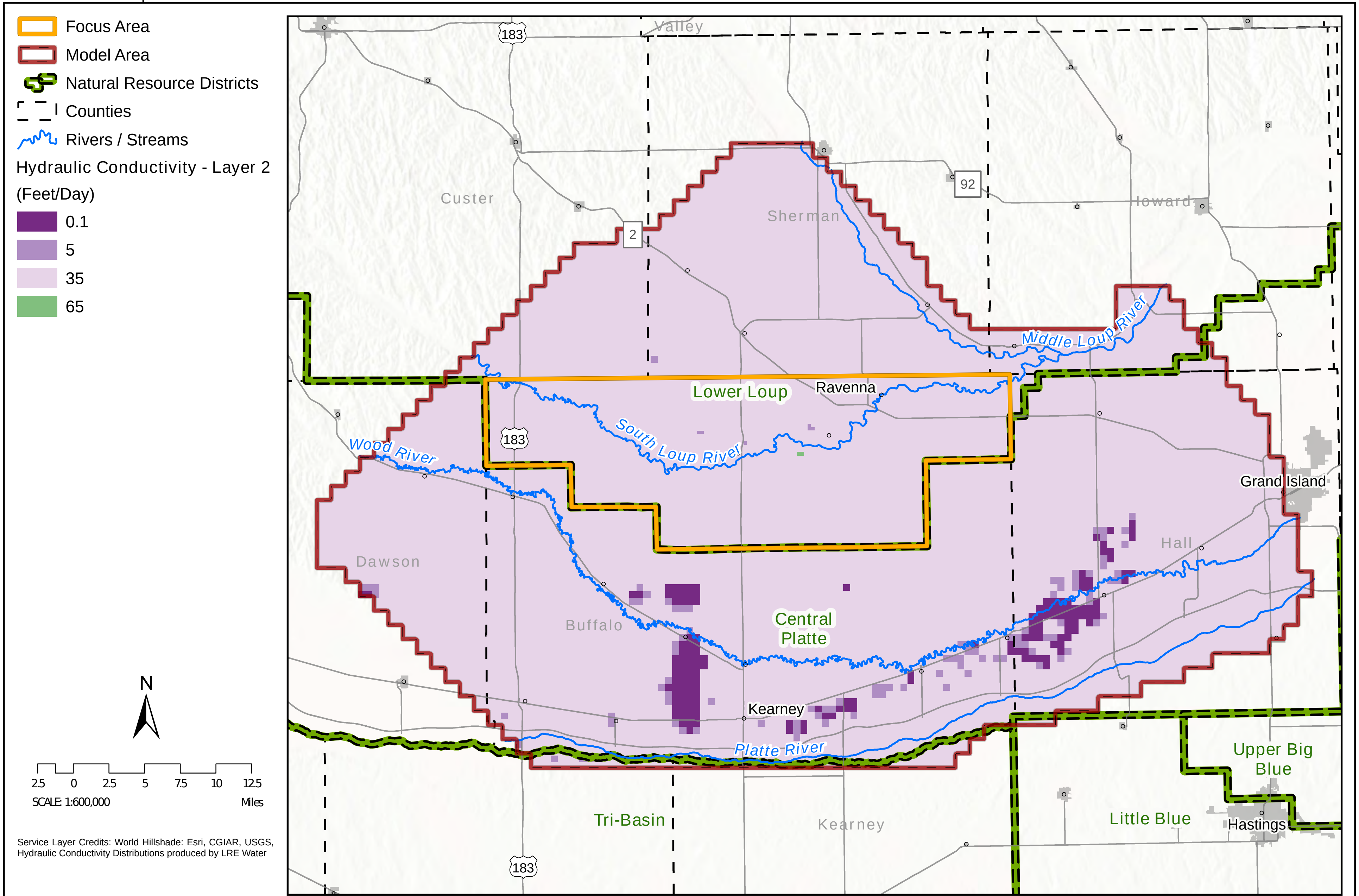

Prepared By:
LRE Water
Nebraska Office
Lincoln
(402) 416-4667

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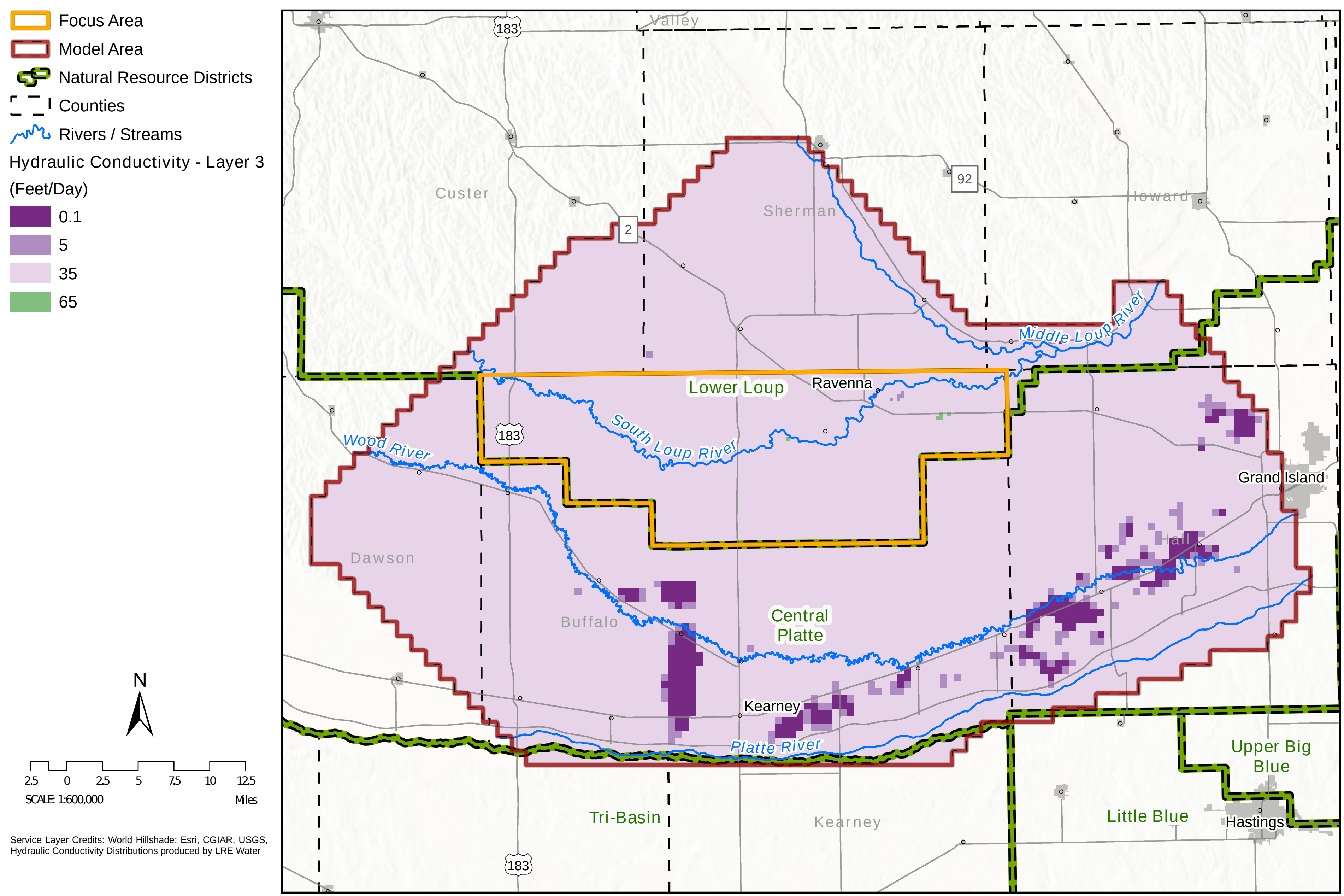
LAYER 2 K DISTRIBUTION

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx	DATE: 1/21/2025	FIGURE: 9



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LRE Water
Nebraska Office
Lincoln
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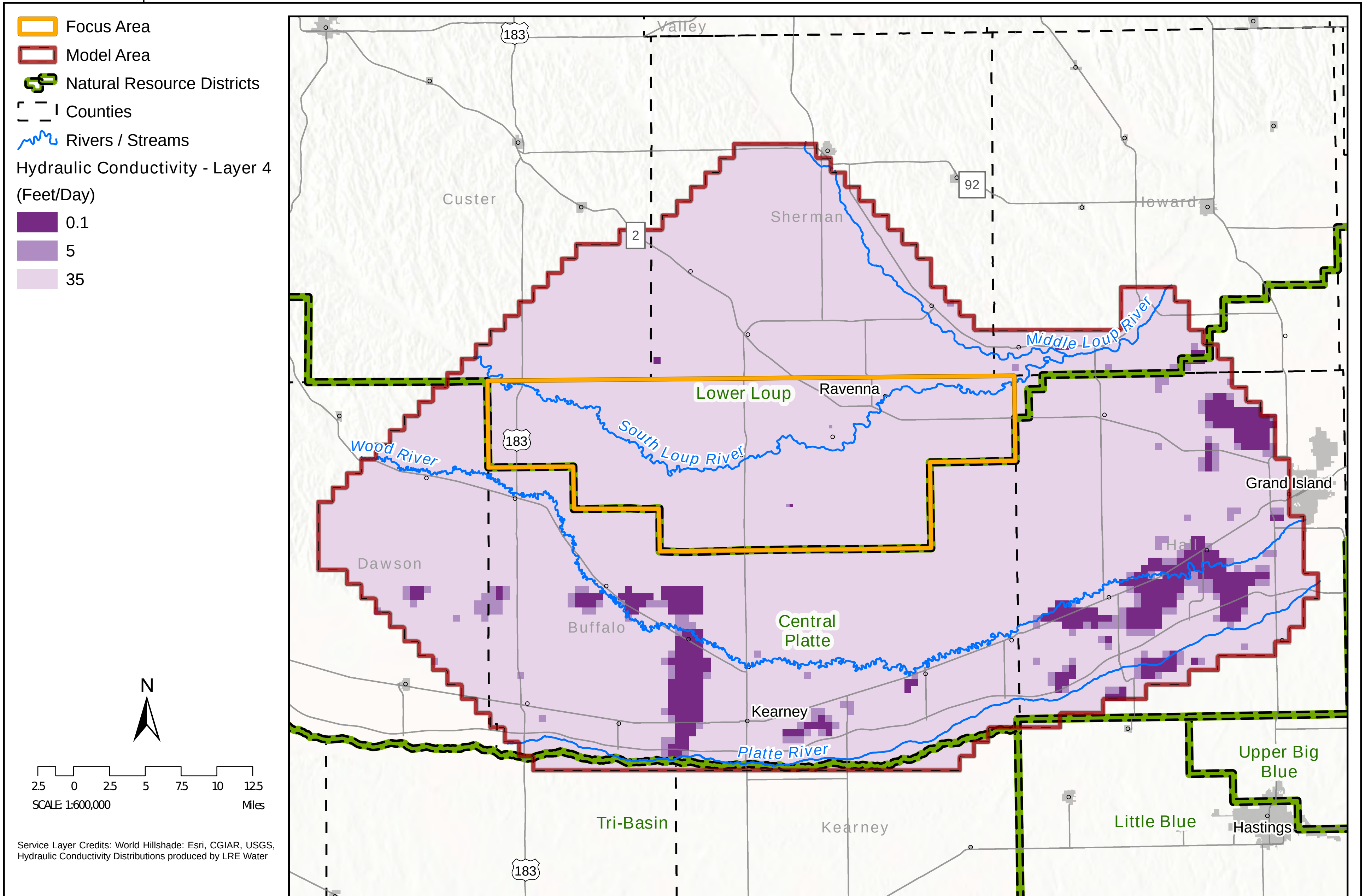
LAYER 3 K DISTRIBUTION

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/21/2025 | FIGURE: 10



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Nebraska Office
Lincoln
(402) 416-4667

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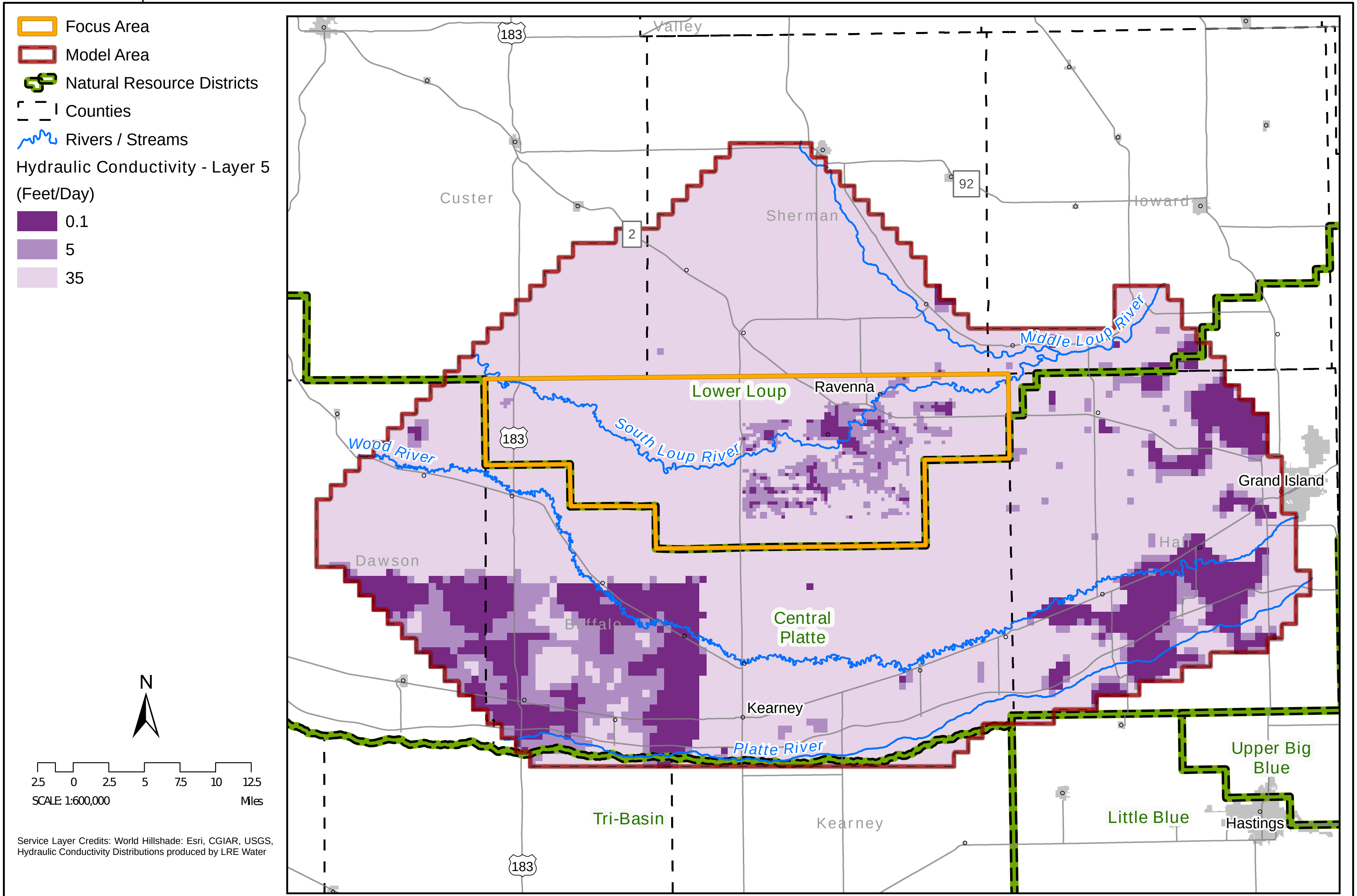
LAYER 4 K DISTRIBUTION

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/21/2025 | FIGURE: 11



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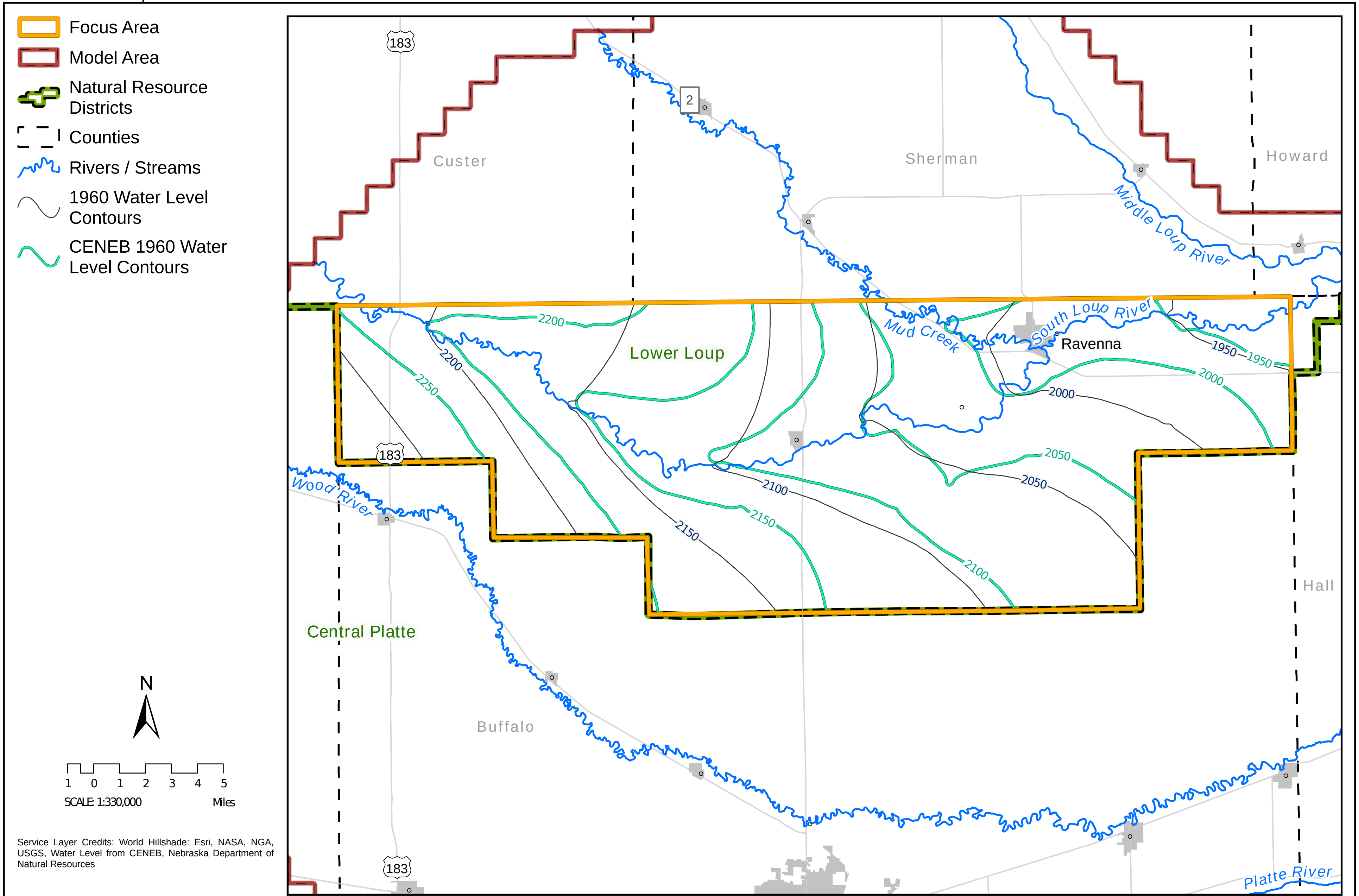
LAYER 5 K DISTRIBUTION

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx	DATE: 1/21/2025	FIGURE: 12



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Lincoln
(402) 416-4667

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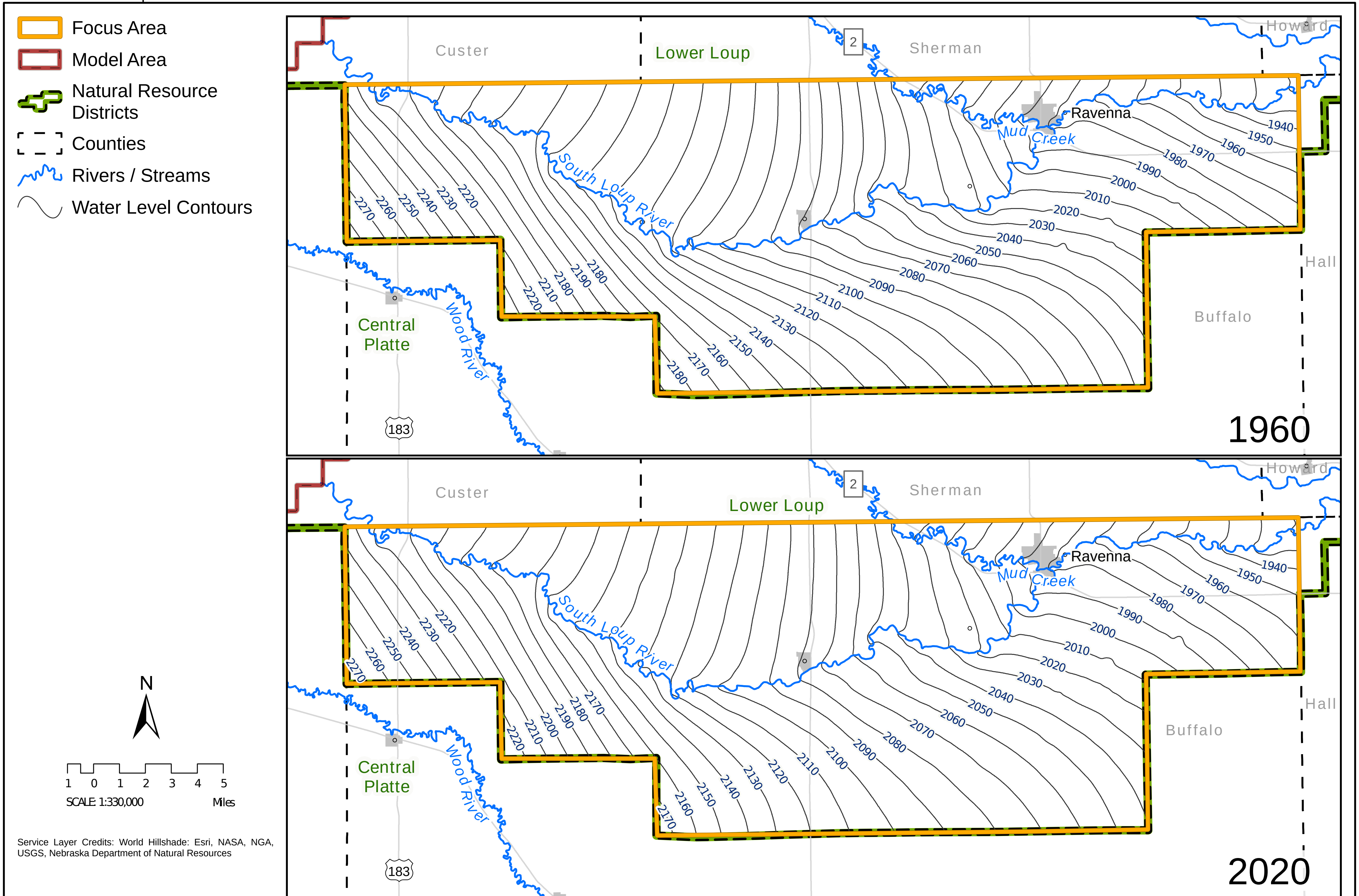
CALIBRATED MODEL CENEB 1960 WATER LEVEL COMPARISON

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/21/2025 | FIGURE: 13



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Nebraska Office
Lincoln
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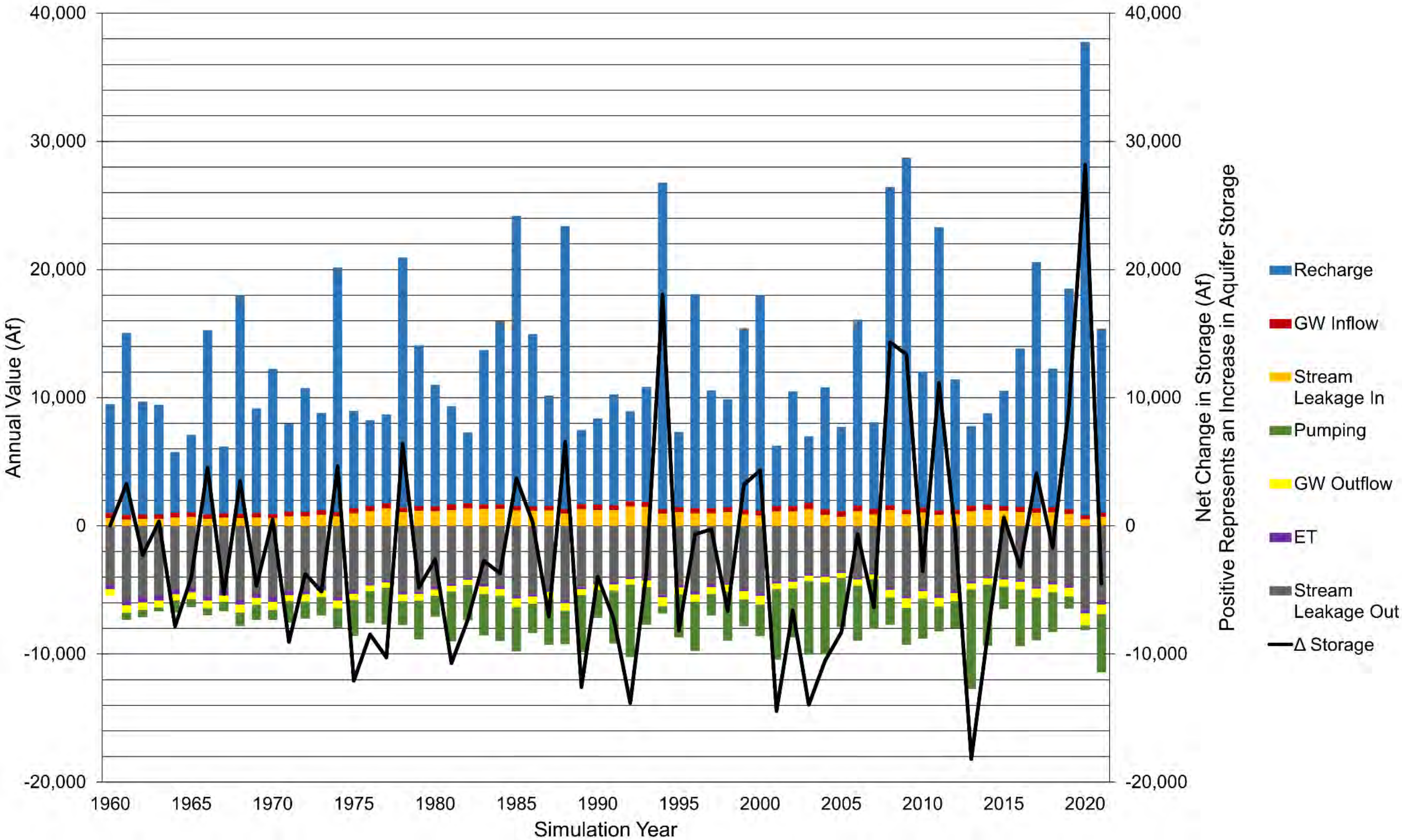
CALIBRATED MODEL 1960 AND 2020 WATER LEVEL CONTOUR COMPARISON

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 14



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MODEL WATER BUDGET THROUGH TIME

FILE: WaterBudget_Excel.xlsx | DATE: 1/21/2025 | FIGURE: 15

Focus Area
Model Area
Natural Resource Districts
Counties
Rivers / Streams
1960 - 2020 Water Level Change Contours

Water Level Change - 1960 to 2020

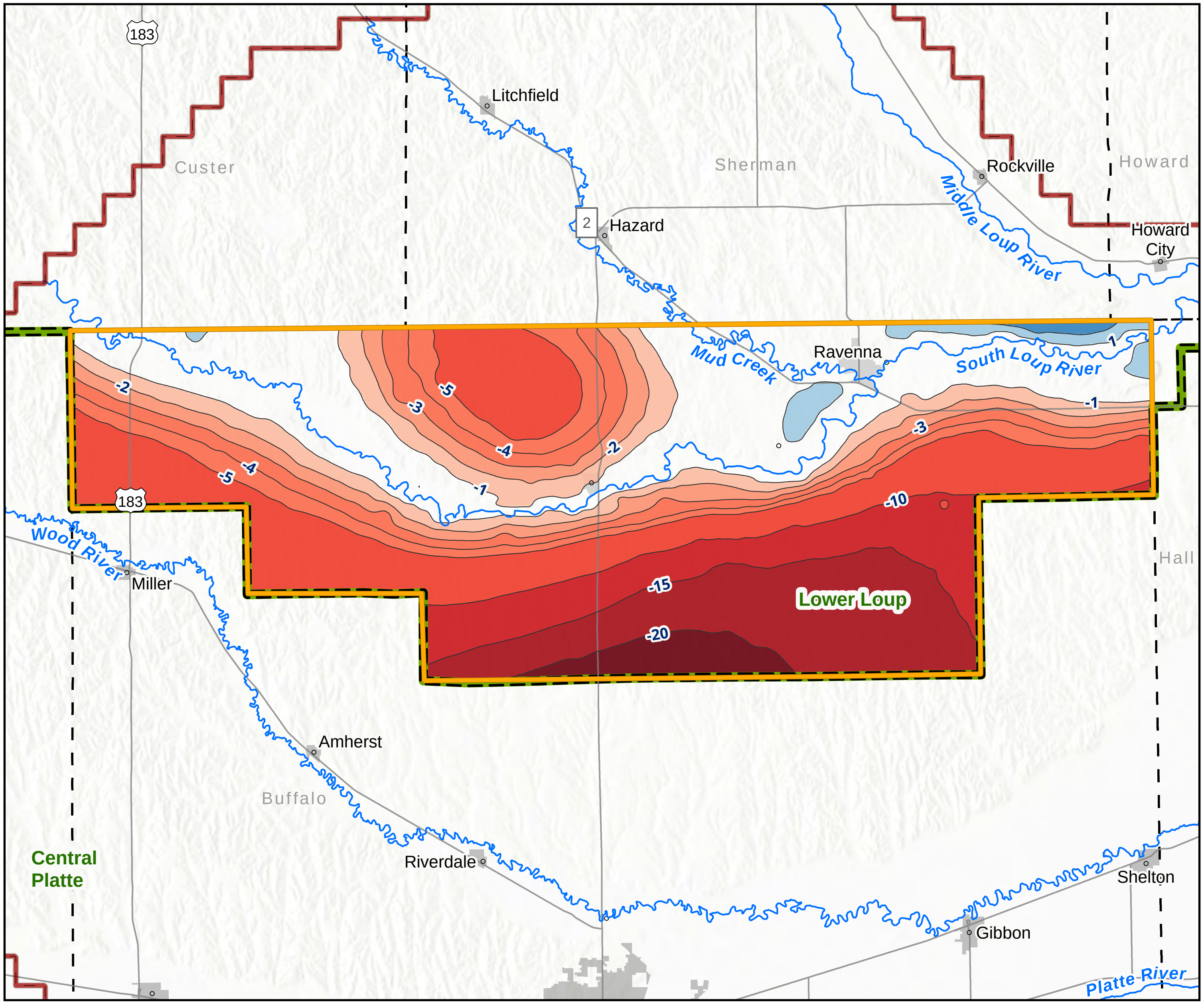
Total Change in Feet

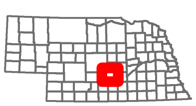
- > 2
- 1 to 2
- 1 to -1
- -1 to -2
- -2 to -3
- -3 to -4
- -4 to -5
- -5 to -10
- -10 to -15
- -15 to -20
- < -20

N

1 0 1 2 3 4 5
SCALE: 1:330,000 Miles

Service Layer Credits: World Hillshade: Esri, NASA, NGA, USGS, Well source (NeDRN), Nebraska Department of Natural Resources





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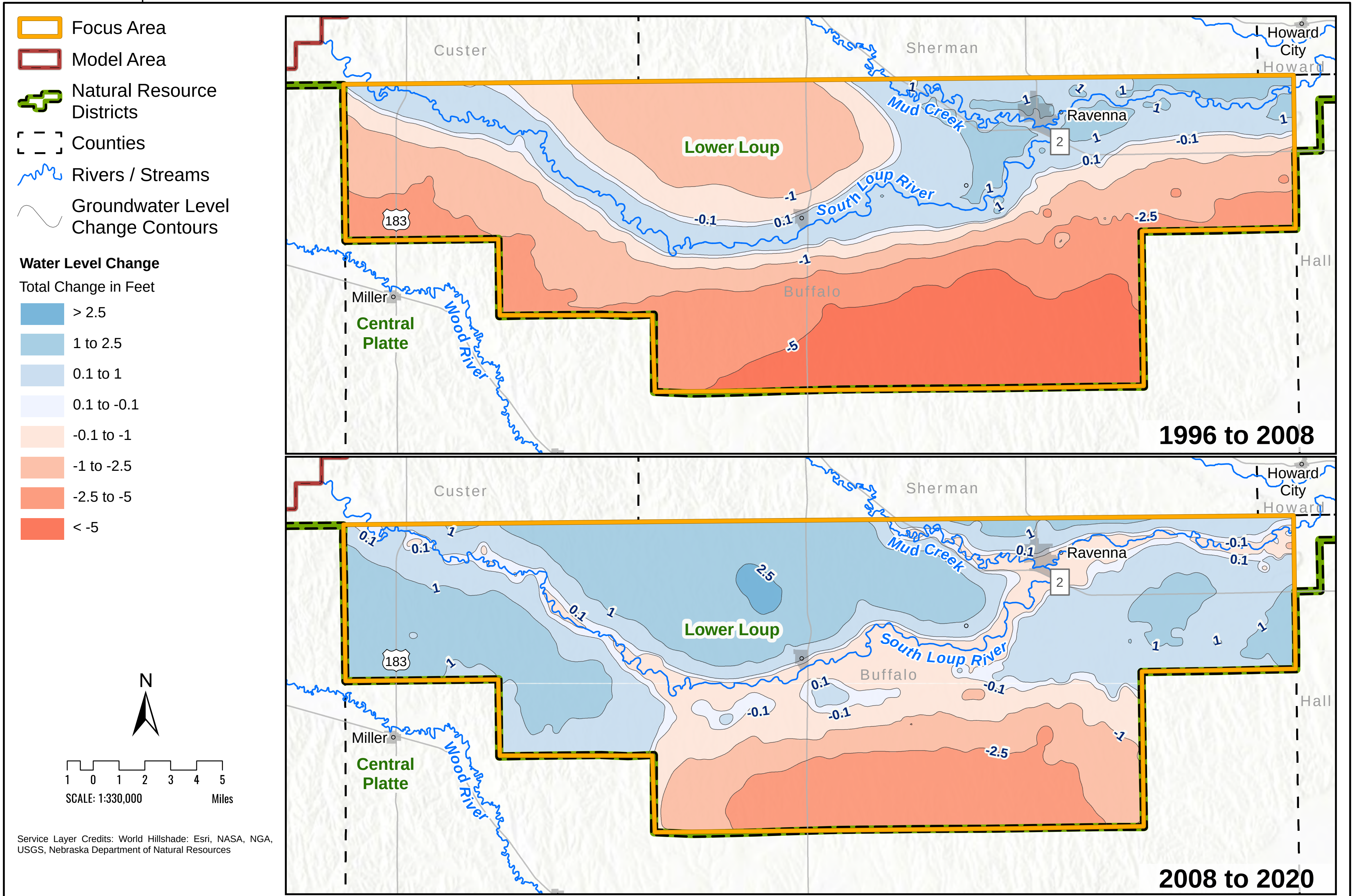
CHANGE IN GROUNDWATER ELEVATION FROM 1960 TO 2020

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 16



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LRE Water
Nebraska Office
Lincoln
(402) 416-4667

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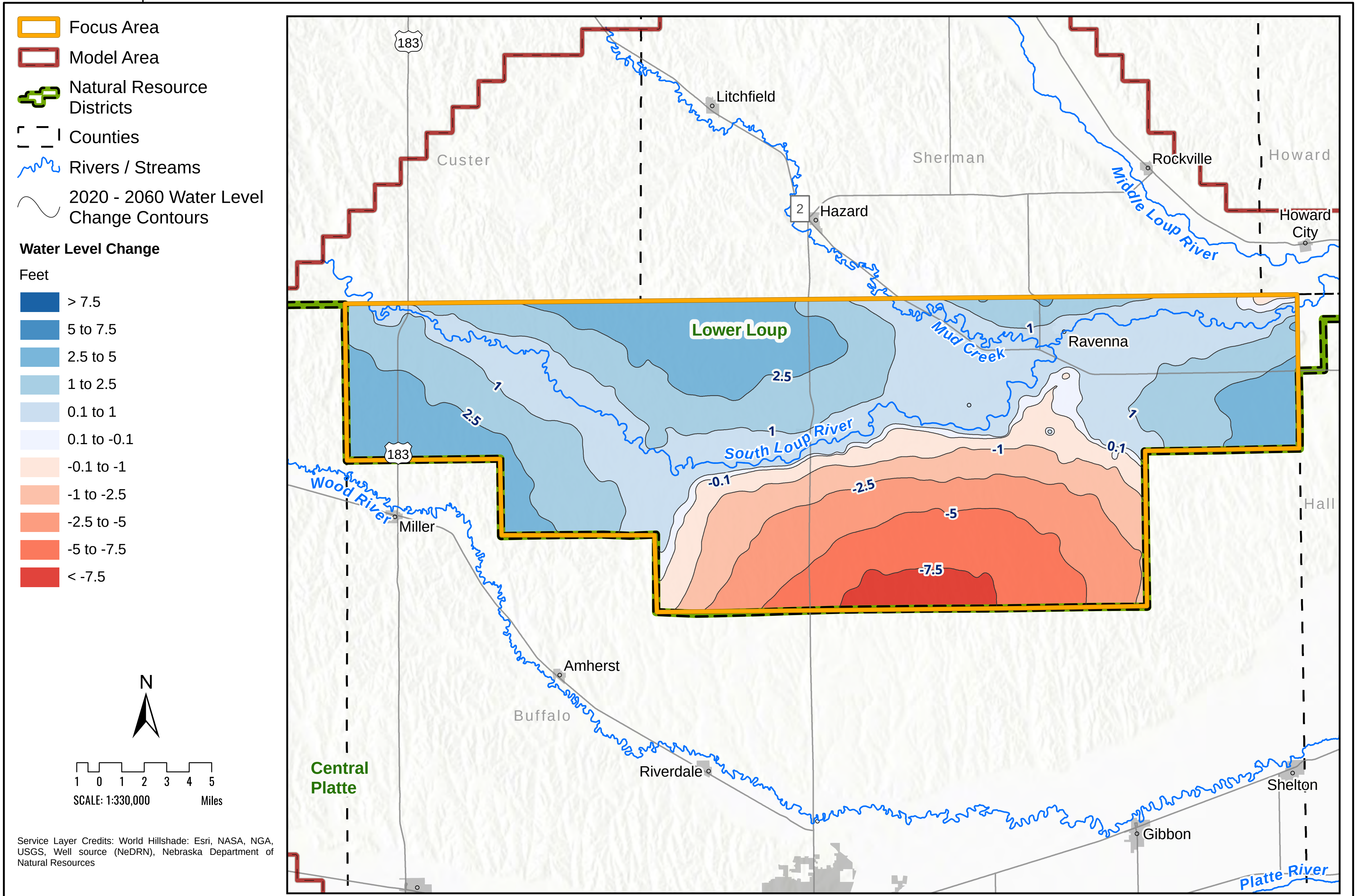
GROUNDWATER DECLINE COMPARISON FOR 1996-2008 and 2008-2020

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx	DATE: 1/22/2025	FIGURE: 17



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Nebraska Office
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FUTURE PREDICTED DRAWDOWN FROM 2020 THROUGH 2060

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 18

Focus Area
Model Area
Natural Resource Districts
Counties
Rivers / Streams
Mounding Contours

Water Level Change

Feet

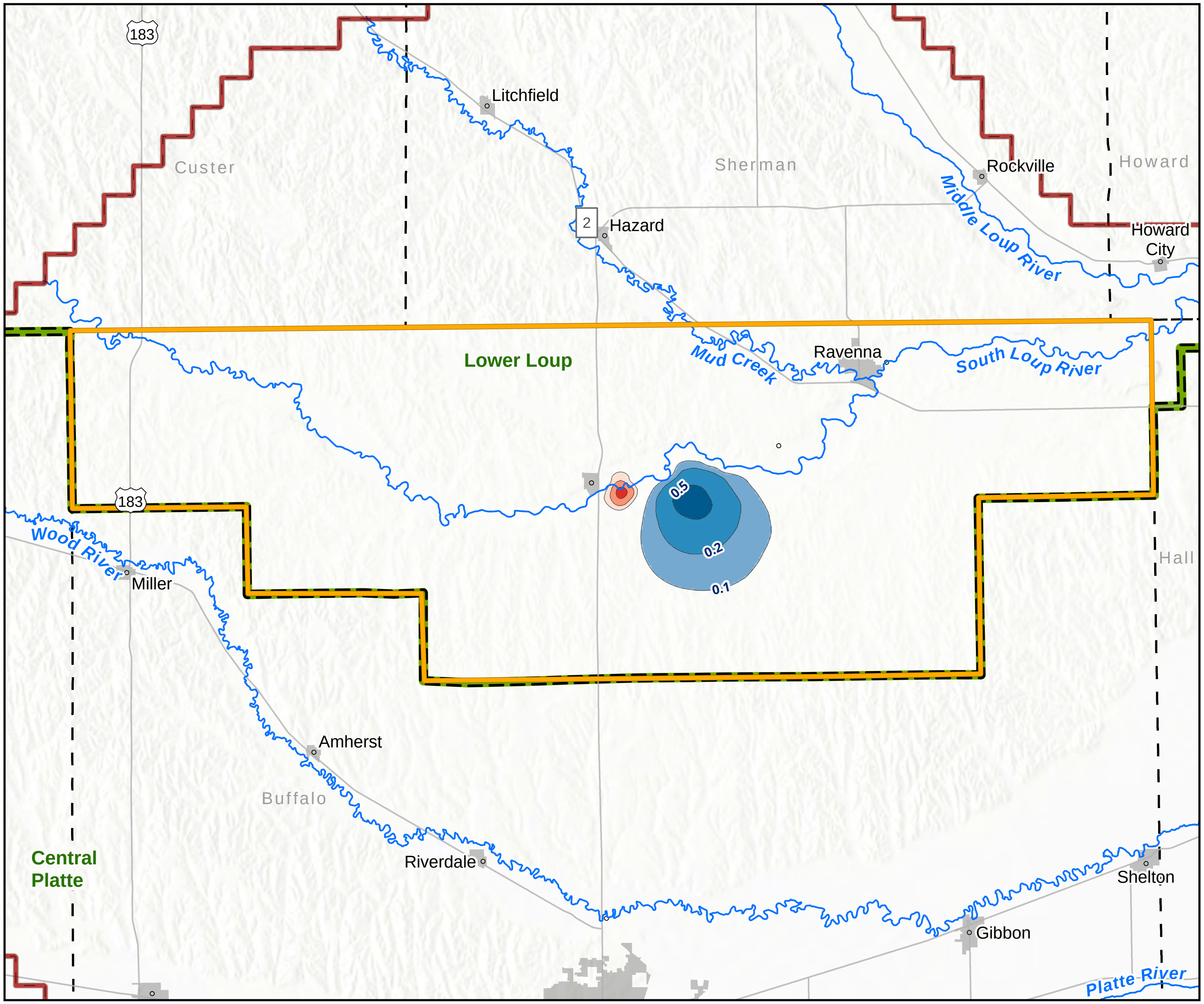
- > 0.5
- 0.2 to 0.5
- 0.1 to 0.2
- 0.1 to -0.1
- -0.1 to -0.2
- -0.2 to -0.5
- < -0.5

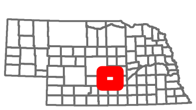
N

1 0 1 2 3 4 5

SCALE: 1:330,000 Miles

Service Layer Credits: World Hillshade: Esri, NASA, NGA, USGS, Nebraska Department of Natural Resources





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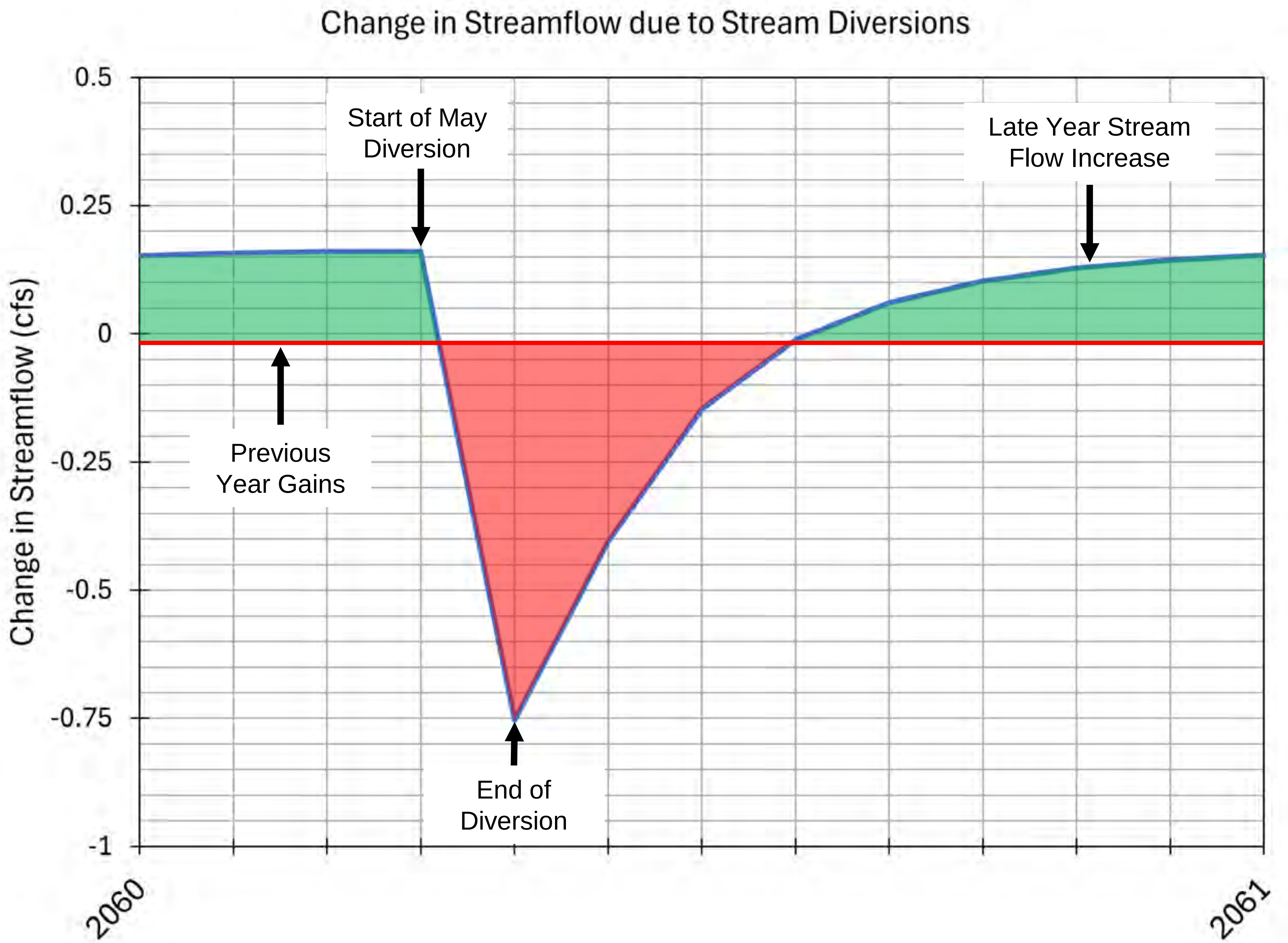
BUFFALO COUNTY, NE

STREAM DIVERSION WATER TABLE IMPACT

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 19



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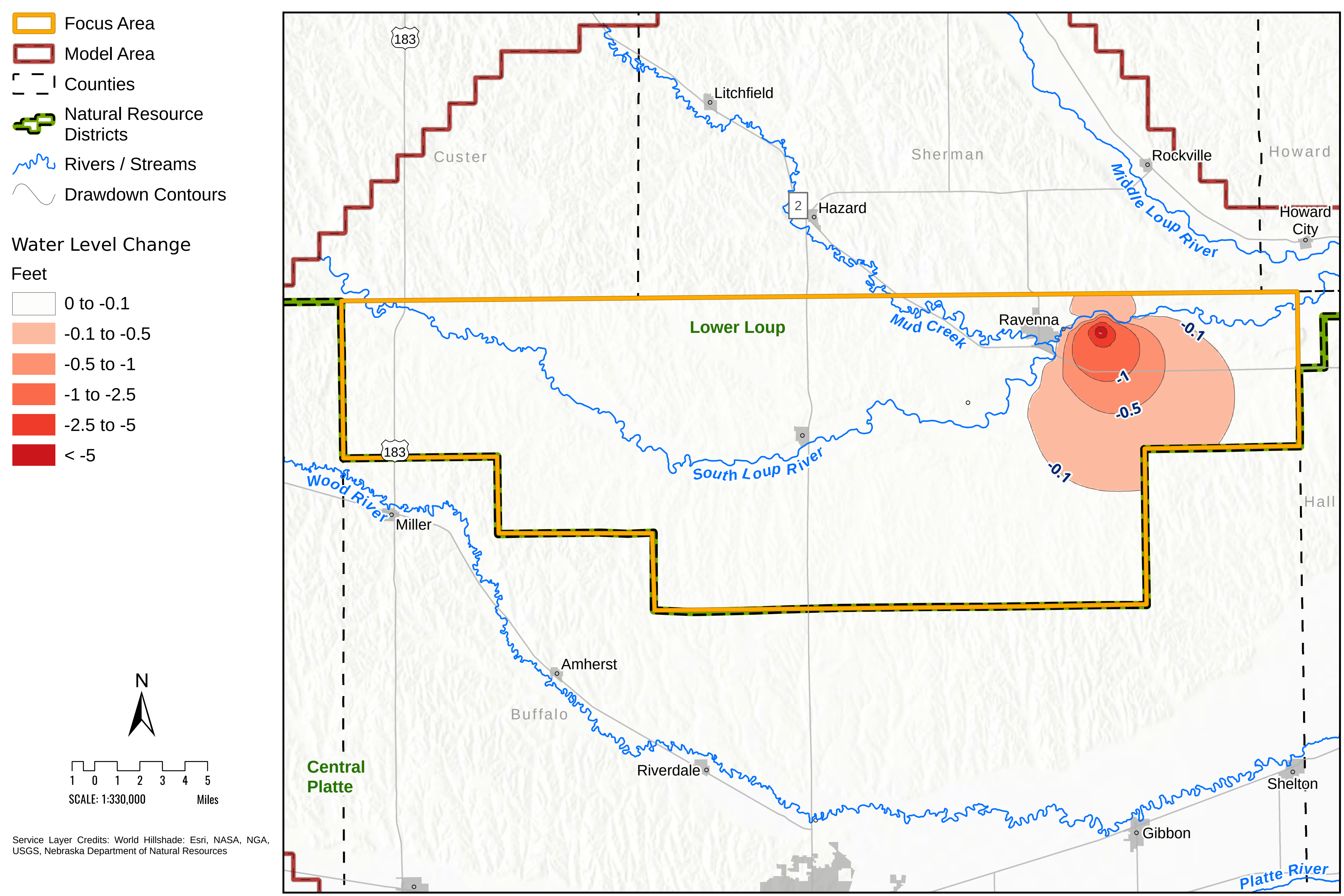
		STREAM DIVERSION STREAMFLOW IMPACT
		FILE: BC_SFR_Outputs.xlsx DATE: 1/21/2025 FIGURE: 20



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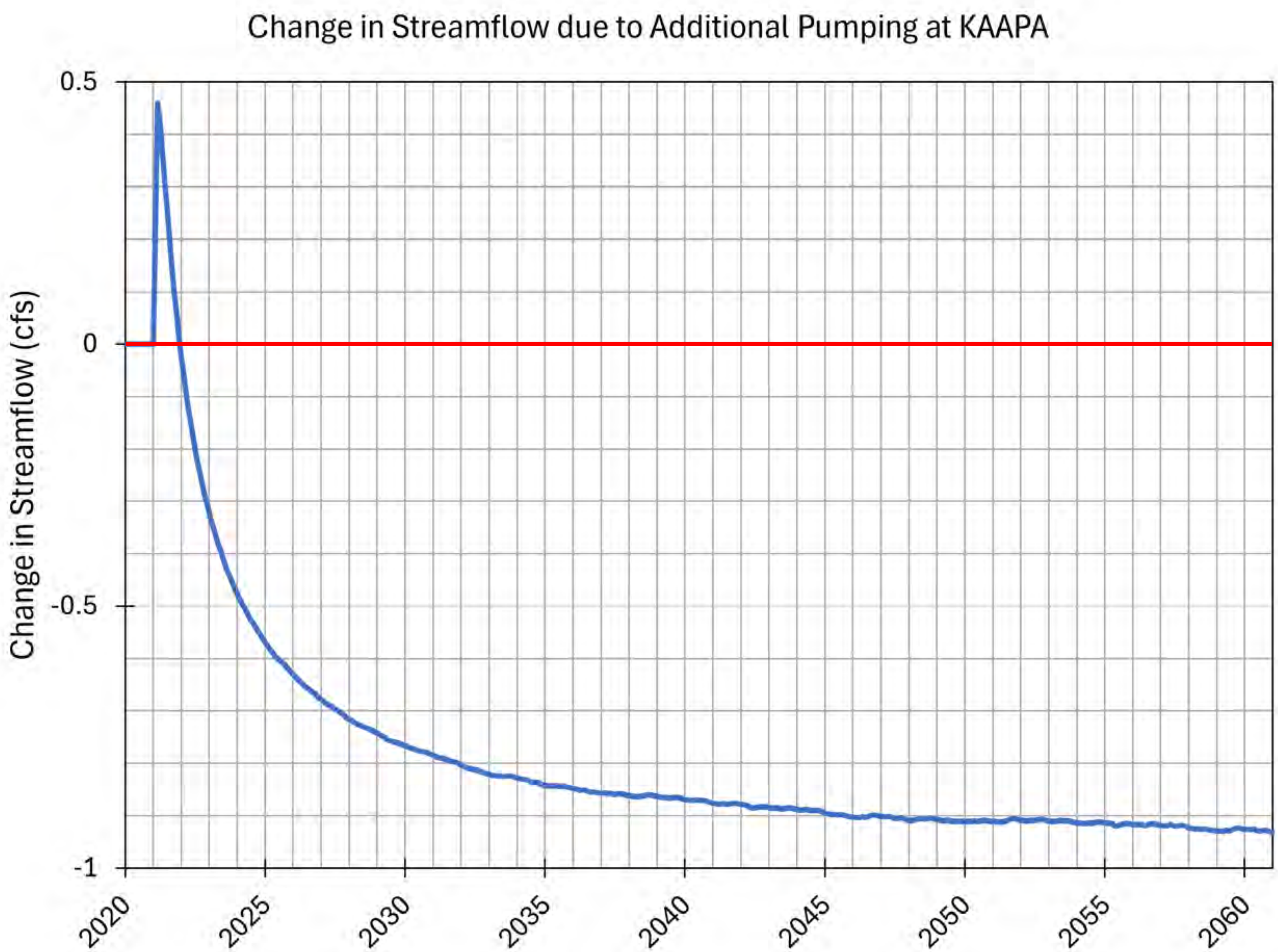
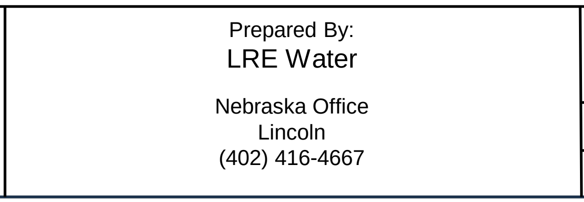
THEORETICAL PUMPING INCREASE WATER TABLE IMPACT

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 21





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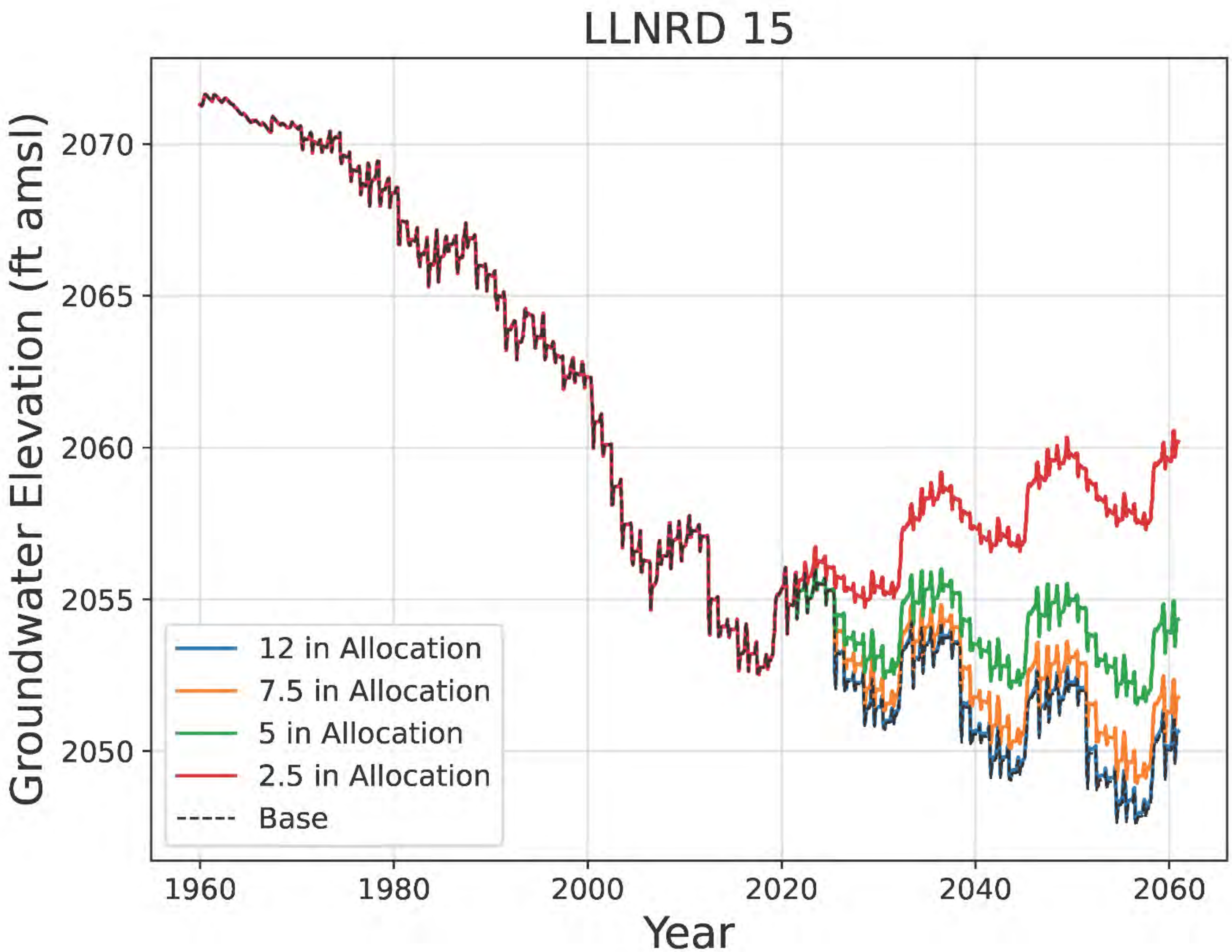
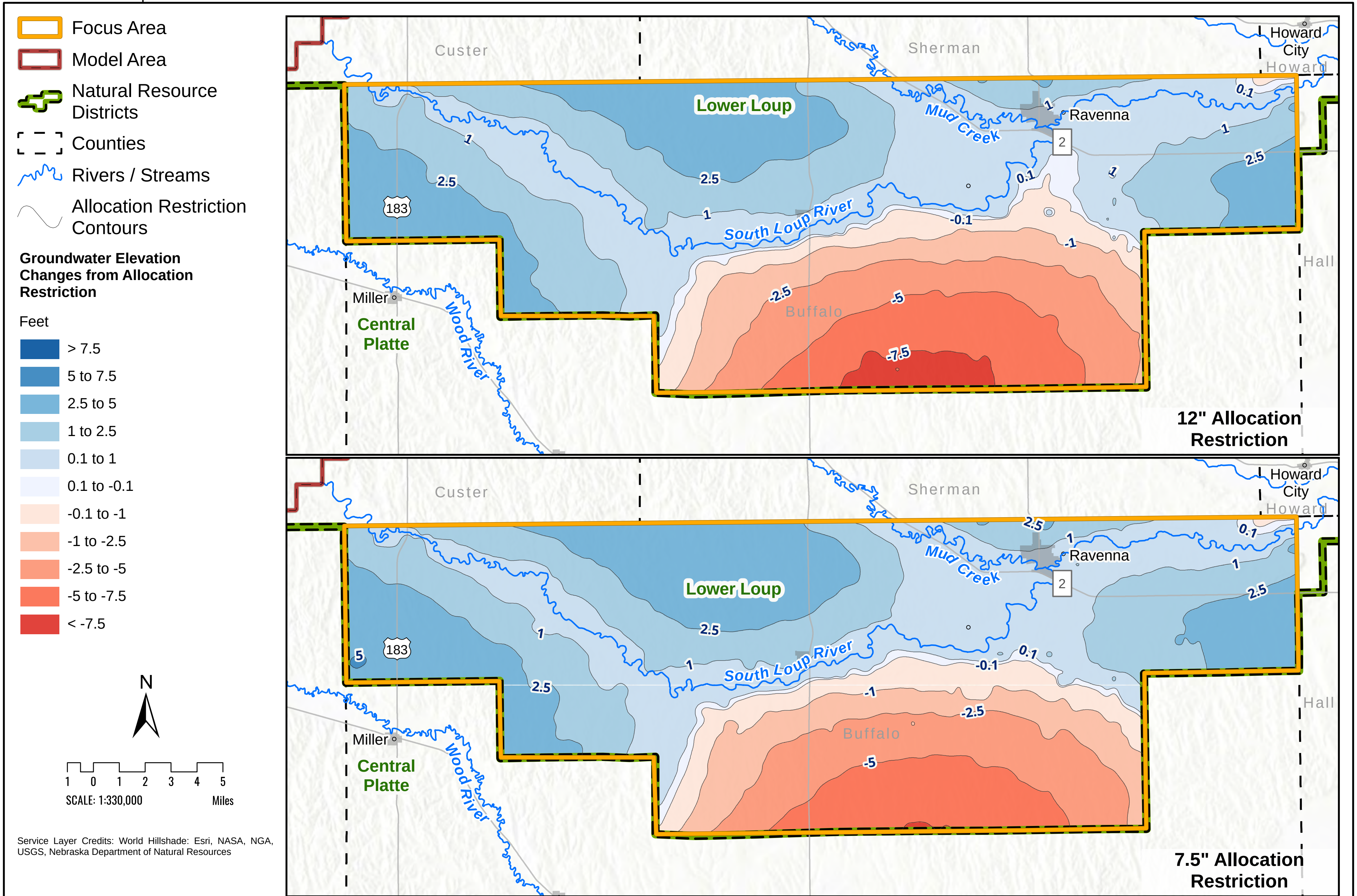
BUFFALO COUNTY AREA GROUNDWATER MODEL
BUFFALO COUNTY, NE

THEORETICAL PUMPING INCREASE STREAMFLOW IMPACT

FILE: BC_SFR_Outputs.xlsx	DATE: 1/21/2025	FIGURE: 22



LRE WATER CONNECTING WATER TO LIFE	Prepared By: LRE Water Nebraska Office Lincoln (402) 416-4667	LOWER LOUP NATURAL RESOURCES DISTRICT BUFFALO COUNTY AREA GROUNDWATER MODEL BUFFALO COUNTY, NE ALLOCATION IMPACT ON GROUNDWATER DECLINE TRENDS AT LLNRD 15 FILE: DATE: 1/21/2025 FIGURE: 23



Prepared By:
LRE Water
Nebraska Office
Lincoln
(402) 416-4667

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LOWER LOUP NATURAL RESOURCES DISTRICT
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BUFFALO COUNTY, NE

12- AND 7.5-INCH PUMPING ALLOCATION WATER TABLE IMPACT

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 24

- Focus Area
- Model Area
- Natural Resource Districts
- Counties
- Rivers / Streams
- Allocation Restriction Contours

Groundwater Elevation Changes from Allocation Restriction

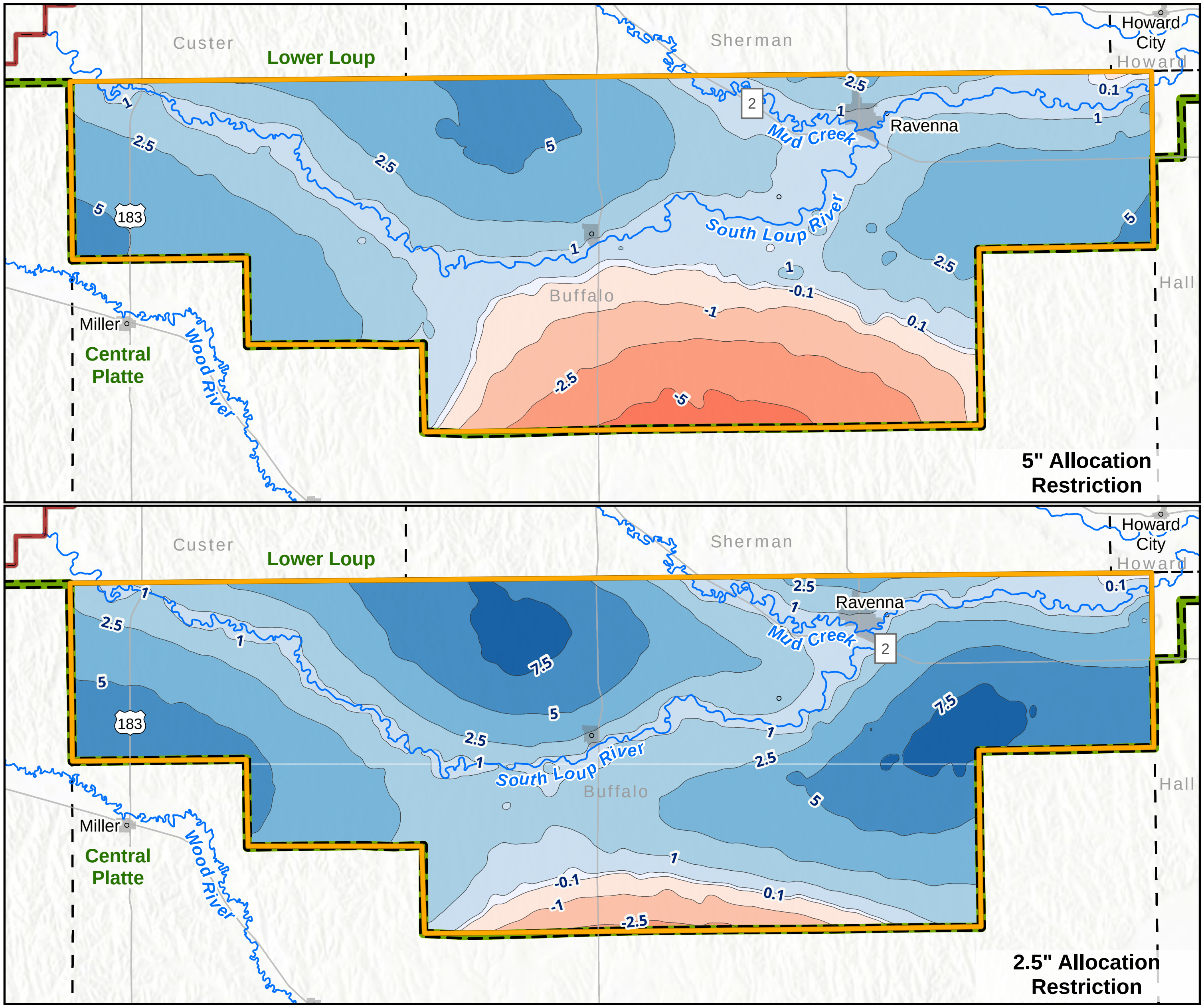
Feet

- > 7.5
- 5 to 7.5
- 2.5 to 5
- 1 to 2.5
- 0.1 to 1
- 0.1 to -0.1
- -0.1 to -1
- -1 to -2.5
- -2.5 to -5
- -5 to -7.5
- < -7.5

N

1 0 1 2 3 4 5
SCALE: 1:330,000 Miles

Service Layer Credits: World Hillshade: Esri, NASA, NGA, USGS, Nebraska Department of Natural Resources



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LRE Water
Nebraska Office
Lincoln
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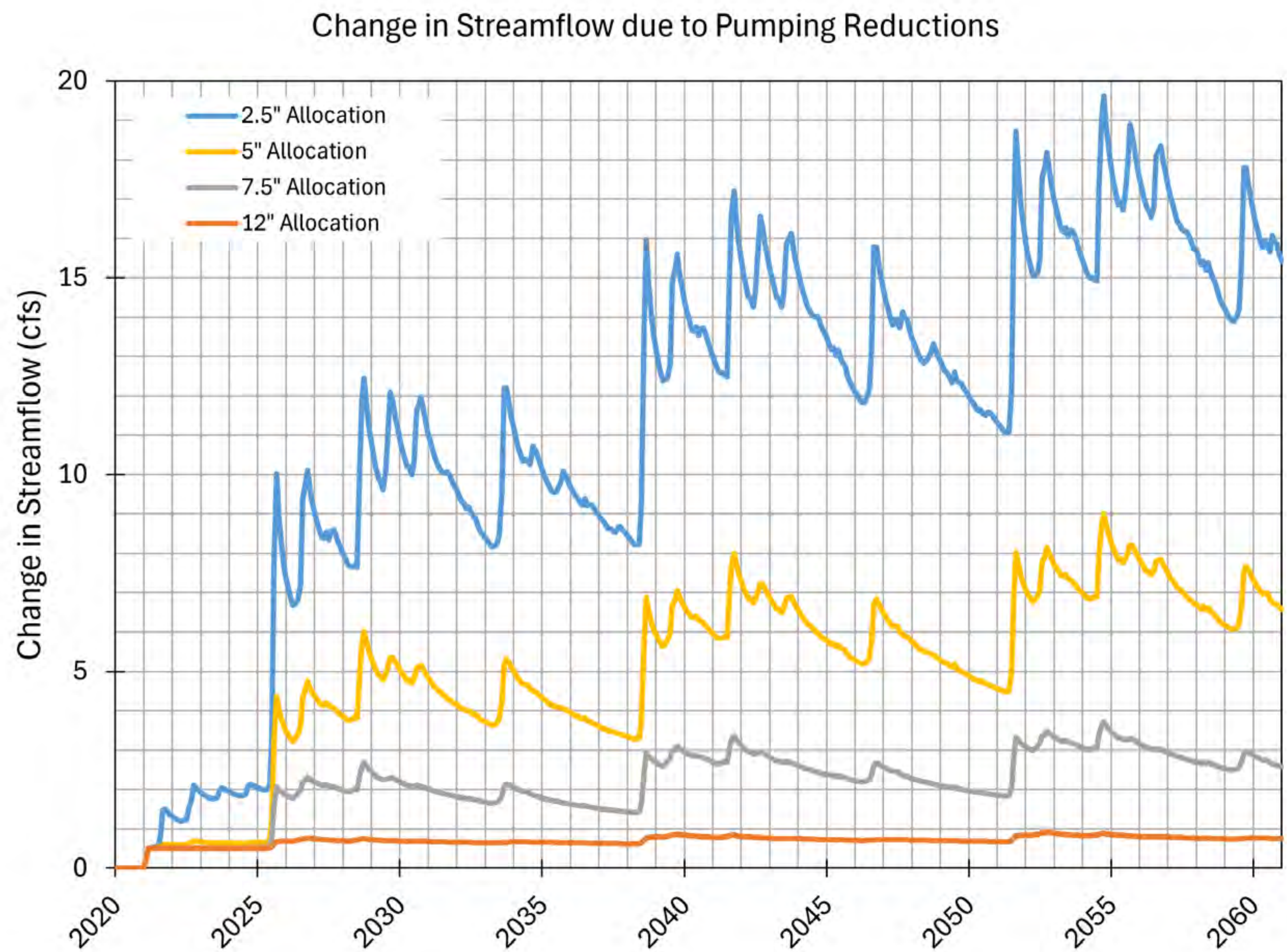
BUFFALO COUNTY AREA GROUNDWATER MODEL
BUFFALO COUNTY, NE

5- AND 2.5-INCH PUMPING ALLOCATION WATER TABLE IMPACT

FILE: 6002LLP02_LLNRD_BC_Model_Workspace_RTF.Aprx | DATE: 1/22/2025 | FIGURE: 25



LRE WATER CONNECTING WATER TO LIFE	Prepared By: LRE Water Nebraska Office Lincoln (402) 416-4667	LOWER LOUP NATURAL RESOURCES DISTRICT BUFFALO COUNTY AREA GROUNDWATER MODEL BUFFALO COUNTY, NE PUMPING ALLOCATION STREAMFLOW IMPACT FILE: BC_SFR_Outputs.xlsx DATE: 1/21/2025 FIGURE: 26

Appendix A
The Flatwater Group Report

January 2025

The Buffalo County Model:
Sub-Regional Soil Water Balance Model

Prepared for:

Lower Loup Natural Resources District

Prepared By:

THE FLATWATER GROUP INC.

January 2025

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Acronym Definitions

ac	Acre
ACIS Grid 1	Applied Climate Information System Interpolated Weather Station data
ACIS Grid 21	Applied Climate Information System PRISM weather data
AE	Application Efficiency
AF	Acre-feet
ASCE	American Society of Civil Engineers
AWDN	Automated Weather Data Network
BCM	Buffalo County Model
BRBM	Blue River Basin Model
CeNEB	Central Nebraska Regional Groundwater Model
CIR	Consumptive Irrigation Requirement
CNPPID	Central Nebraska Public Power and Irrigation District
CO	Comingled – irrigated by both groundwater and surface water
COD	Surface water irrigation deliveries to comingled lands
COHYST	Cooperative Hydrology Study
COP	Groundwater irrigation pumping on comingled lands
CPNRD	Central Platte Natural Resources District
CROPSIM	the soil water balance model used in the RSWB model
DP	Deep Percolation
ET	Evapotranspiration
ET Base	Evapotranspiration on an irrigated crop not attributed to the application of irrigation water
ET Gain	Evapotranspiration on an irrigated crop attributed to the application of irrigation water
GIR	Gross Irrigation Requirement
GW	Irrigated by groundwater only
GWC	Groundwater Concentration factor
GWP	Groundwater irrigation pumping on groundwater only lands
HPRCC	High Plains Regional Climate Center
I	Applied Irrigation Water
I_{net}	Applied Net Irrigation
in	inches
INSIGHT	Integrated Network of Scientific Information and GeoHydrologic Tools
IAD	Irrigation Application and Demand
IAS	Irrigation Application and Supply
LatSeep	Lateral Seepage – volume of transport inefficiency between main canal and field
LatLoss	Lateral Loss rate – rate of transport inefficiency between main canal and field
LBNRD	Little Blue Natural Resources District
LLNRD	Lower Loup Natural Resources District
LRE	LRE Water
LPRBC	Lower Platte River Basin Coalition

MLPPID	Middle Loup Public Power and Irrigation District
NeDNR	Nebraska Department of Natural Resources
NIR	Net Irrigation Requirement
NRCS	Natural Resources Conservation Service
NWS/Coop	National Weather Service Cooperative Observers Network
P	Precipitation
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCC-ACIS	Regional Climate Center – Applied Climate Information System
.RCH	Recharge file input for groundwater model
RO	Runoff at the edge of the field
RSWB	Regionalized Soil Water Balance model – Watershed Model
SL	Surface Loss – irrigation inefficiency attributed to evapotranspiration
SF	Runoff Contributions to stream flow
Statsgo2	Digital General Soil Map of the United States
STELLA	COHYST surface water operations model
SW	Irrigated by surface water only
SWC_i	Soil Water Content at time period i
ΔSWC	Change in Soil Water Content
SWD	Surface water irrigation deliveries to surface water only lands
TBNRD	Tri-Basin Natural Resources District
TFG	The Flatwater Group Inc.
TIN	Triangular Irregular Network
TPNRD	Twin Platte Natural Resources District
UBBNRD	Upper Big Blue Natural Resources District
USBR	United States Bureau of Reclamation
WBPs	Water Balance Parameters
.WEL	Well file input for groundwater model
WSPP	Water Supply Partitioning Program

1. Introduction

1.1. Authorization

The Flatwater Group, Inc. (TFG) has prepared this report as authorized under TFG's subcontract to LRE Water (LRE) through LRE project 153843 originally dated 20 June 2023. LRE is working under contract to the Lower Loup Natural Resources District (LLNRD) for the LLNRD Buffalo County Area Groundwater Model (BCM).

1.2. Purpose and Scope

The BCM is a sub-regional model being developed for use in evaluating water planning and integrated water resources management efforts within Buffalo County Nebraska and the LLNRD. The overall BCM consists of a groundwater flow model and a watershed model. Through this project, the models and their results are integrated to provide data and information which support future decisions that help achieve the NRDs' water management goals.

This report focuses on the processes and application of the watershed model, specifically the Regional Soil Water Balance Model (RSWB). It discusses the development, general methodologies, and how this model was applied across the project domain. Select summaries of the water balance, including pumping from groundwater and recharge depths are included in the results section.

The primary role of the watershed model is to ensure that the water supplies and uses were accounted for within a balanced water budget. The water budget is comprised of precipitation (P), applied irrigation water (I), evapotranspiration (ET), deep percolation (DP), runoff (RO), and changes in soil water content (ΔSWC).

2. Study Area

The BCM model domain consists of approximately 3.5 million acres (5,400 mi^2) in central Nebraska focusing on the drainage area of the South Loup River in Buffalo County. The extended model domain spans from the middle of Dawson County (~5 miles east of Cozad) in the west, to Merrick and Hamilton County in the East (~5 miles east of Grand Island), north to Broken Bow on line with the northern border of Sherman and Howard counties, and south to the middle of Phelps, Kearney, and Adams Counties (just north of Minden). The model area includes areas from parts of the Loup, Platte, and Blue Basin drainage areas.

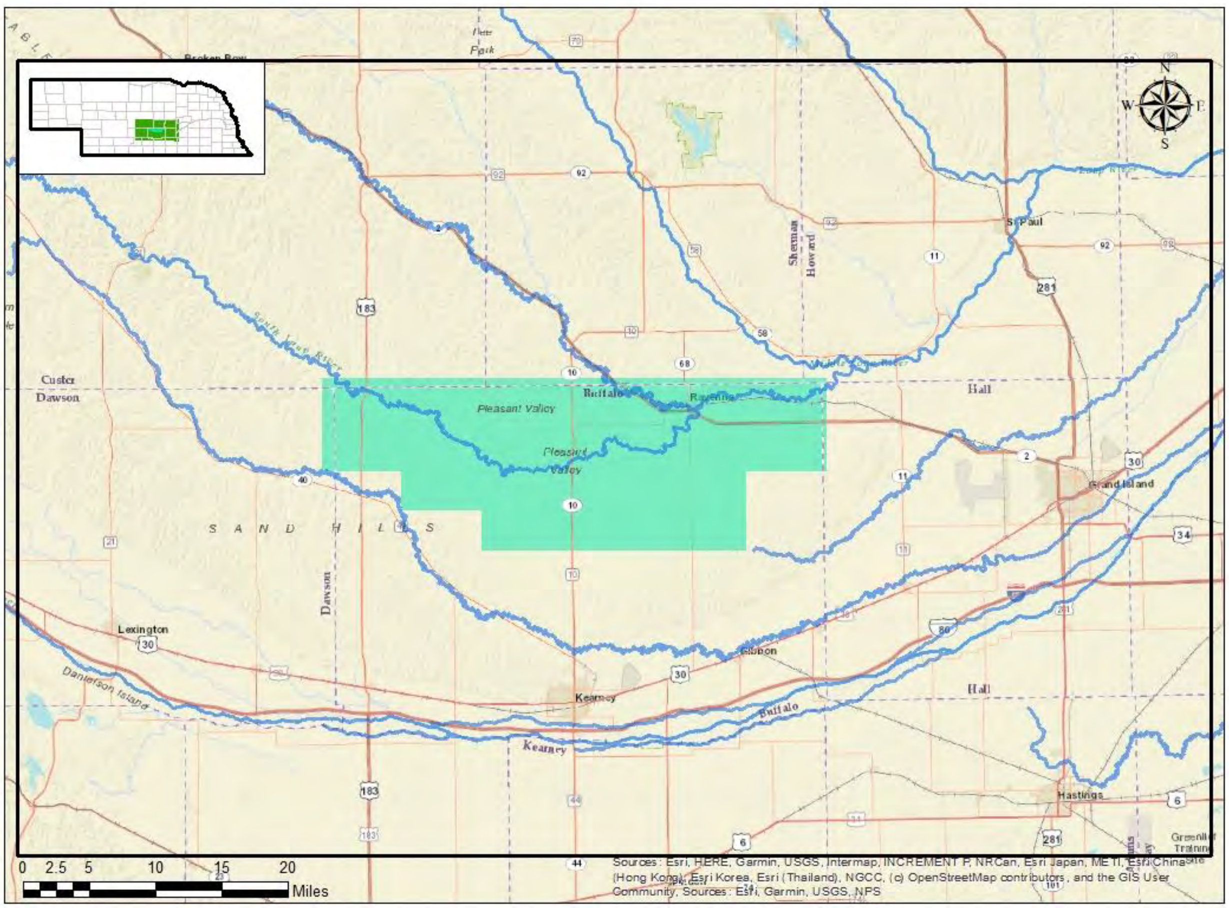

Figure 1. BCM focus area and model domain.

3. Conceptual Model

The hydrologic cycle, as modified by irrigation and other human activity, serves as the conceptual model for this project. Figure 2 is a schematic illustration of the hydrologic cycle for a system where the use of water for irrigation is important. This figure provides visual context for discussion of how the system is modeled.

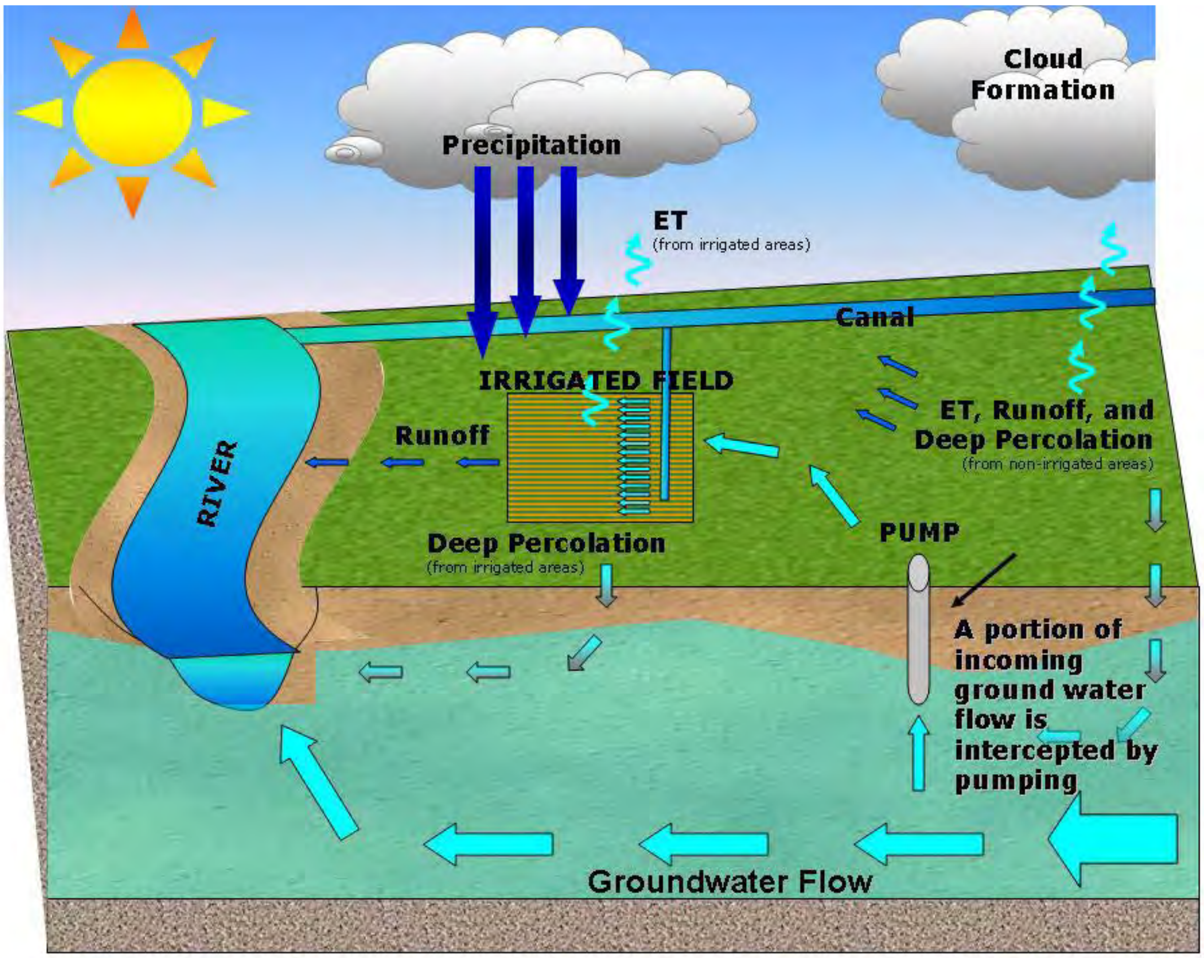

Figure 2. Illustration of hydrologic cycle in which irrigation is important.

The intended use of the model drives what physical characteristics of the study are important to properly represent. In the case of the RSWB model, information about the area's climate, soils, land use, and farming practices are important characteristics to address when attempting to evaluate available water supplies, demands, and uses. The model estimates the amount of water needed to irrigate crops, to develop estimates of the amount of groundwater recharge resulting from deep percolation, and to develop estimates of runoff contributions to total stream flow.

In general, Nebraska has a continental climate exhibiting large temperature variations both within a season as well as year to year. To account for the highly variable climate in the study area, the RSWB model incorporated a reference crop-based methodology. The reference crop (tall crop; alfalfa) was used to represent the evaporative demand of the climate, and in this process, provide a method to standardize crop water use to climatic conditions and to compute evaporative demand from the crops grown in the area and represented in the model.

Soils in the study area include loess, alluvium, and glacial till. Land use is often directly tied to soil type. Steeper upland areas are well suited to be used as rangeland while the more gently sloping soil and deeper loamy soils are well suited to crop production. To account for this variability, the RSWB model used an approach sensitive to key soil properties (water holding capacity, hydrologic soil group) and made use of annually updated land use files which reflected the area's development.

As land use has changed over the course of time in this area, so to have the related production practices. As technology has advanced, both the types of crops and the methods by which given crops are produced have evolved. This study includes evaluation of the changes which have occurred related to the irrigation application and management as well as residue management related to tillage practices.

Irrigation management in the area has seen a number of changes during the modeled timeframe. The use of groundwater as compared to surface water as a source for irrigation has increased. The methods by which irrigation water is applied to crops have changed and become generally more efficient in terms of the amount of irrigation water applied compared to the amount of irrigation water consumed by crops. The methods employed by the RSWB model attempted to capture the major effects of these changes.

Similarly, farming practices have also evolved over time. Traditionally, production practices involved a number of passes through the field in preparation for planting, but effectively removing or destroying any residue of the previous year's crop. Advancements in technology, equipment, and management practices have trended producers toward adopting reduced tillage and no-till practices, resulting in larger quantities of residue remaining on the soil surface. *Ceteris paribus*[1], one can expect residue on the soil surface to reduce runoff and increase infiltration. Additionally, the residue shades and protects the soil surface, reducing the rate of evaporation from the soil surface. The RSWB utilizes several methods to represent the changing farming practices and different methods of residue management.

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[1] All other things are not equal in real life. The modeling efforts showed that increases in residue tended to keep the level of soil water depletion lower at the end of the year and going into the rainy spring season. Meaning a precipitation event at this time may result in a higher runoff rate on the higher residue field. However, if we look at precipitation events later in the growing season when the level of soil water depletion is more pronounced, the expected trend is realized.

4. Watershed Model

The RSWB model represents one part of what is more broadly referred to as the watershed model. The primary purpose of the watershed model is to ensure that the water supplies, demands, and uses are accurately accounted for within a balanced water budget. For this purpose, the water budget is represented by precipitation (P), applied irrigation (I), evapotranspiration (ET), deep percolation (DP), runoff (RO), and change in soil water content (ΔSWC). The watershed model can be divided into four parts: a climate model, a soil water balance model, spatial and temporal distribution routines, and the Regionalized Soil Water Balance (RSWB) model (Figure 3).

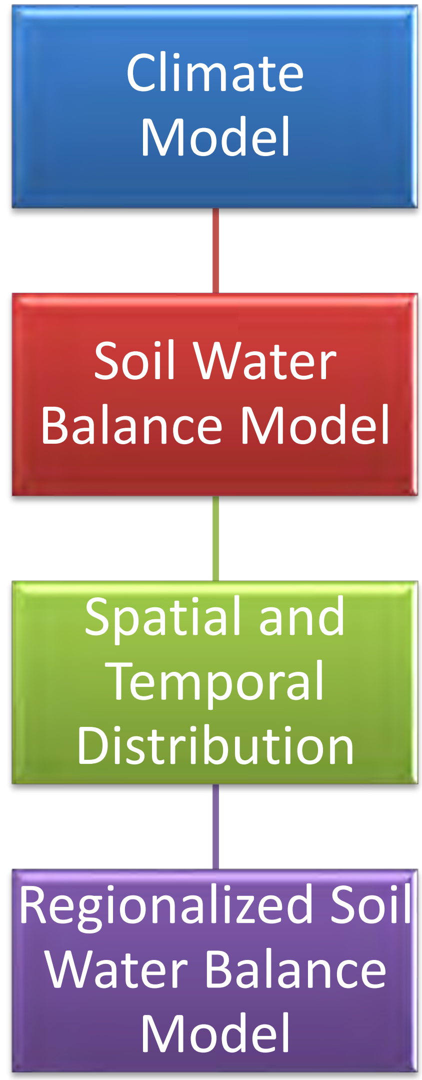

Figure 3. Components of the Watershed model.

4.1. The Climate Model

Weather data is a foundational input for the BCM watershed model, with the remaining parts of the model reflecting how the system reacts to the weather conditions. Precipitation, temperature, and reference ET are the necessary weather data inputs to the soil water balance model discussed in further detail below.

For the purposes of the BCM model, three sources of weather data were used:

1. National Weather Service Cooperative Observers Network (NWS/Coop) from the High Plains Regional Climate Center (HPRCC)[2] – weather station location
2. Interpolated Weather Station data (ACIS Grid 1) from the Regional Climate Center – Applied Climate Information System (RCC-ACIS)[3] – uniform grid of simulation points arranged in a 25-mile TIN
3. Parameter-elevation Regressions on Independent Slopes Model (PRISM; ACIS Grid 21) from the RCC-ACIS[3,4] – uniform grid of simulation points arranged in a 25-mile TIN

Weather data was collected at a selection of simulation points and weather stations in and around the BCM model domain. Further detail on the implementation of weather data in the model is available in Section 6.5.

[2] (High Plain Regional Climate Center, Retrieved 2013-2023)
[3] (Applied Climate Information System, Retrieved 2023)
[4] (PRISM Climate Group, Oregon State University, Retrieved 2023)

While precipitation and temperature are readily available from both the weather stations and the gridded products, reference ET must be calculated. There are multiple ways to calculate the Reference ET depending on the breadth of information available. The watershed model uses two approaches: the ASCE standardized Penman-Montieth (Allen, et al., 2005), and a modified Hargreaves-Samani (Hargreaves & Samani, 1985). The Penman-Montieth approach is considered to be more accurate, however, the method requires several meteorological parameters (wind speed, relative humidity, and net radiation) to calculate reference ET. Hargreaves-Samani, on the other hand, only requires the temperature measurements to estimate reference ET; the simplicity of this approach is evident in its results. Temperature only methodologies do not capture all of the driving factors of evapotranspiration, which can reduce precision and/or accuracy; however, the accuracy is adequate for long term regional planning models.

Up until the last couple of decades, the extended data set needed for the Penman-Montieth method was not readily collected. The dataset is limited both by the timeframe and the number of stations collecting this information. Within Nebraska, climate stations which collect the needed information for a Penman-Montieth based reference ET calculation are part of the Automated Weather Data Network (AWDN) and are maintained by the High Plains Regional Climate Center. As the temporal domain defining BCM modeling efforts extends more than half a century in the past, using the Penman-Montieth approach alone was not feasible. Rather, a calibrated Hargreaves-Samani approach was employed. Using available AWDN records, reference ET values using the Penman-Monteith method were computed and compared to the reference ET values computed using the Hargreaves-Samani methodology. A relationship was developed between the two estimates and the geographical location of the weather station to develop geographically linked coefficients for the Hargreaves-Samani method which could be applied for the entire period of record. This allows the use of the National Weather Service and Cooperative (NWS/Coop) network of weather stations. These stations usually collect less data but have been collecting the data for a longer period. Furthermore, this network of stations is relatively denser, refining the scale of influence any individual station exhibits. A more detailed description of this process can be found in the document entitled CROPSIM Net Irrigation Requirement (The Flatwater Group, Inc., 2014).

4.2. Soil Water Balance Model

The Soil Water Balance Model used by the watershed model is called CROPSIM. CROPSIM is a water driven point source model which uses weather data in combination with representative system characteristics (crop phenology, soils, management, and irrigation) to estimate the daily soil water balance (Martin, Watts, & Gilley, 1984). It was developed by Dr. Derrel Martin with the University of Nebraska-Lincoln's Department of Biological Systems Engineering to aid in the estimation of ET, DP, and runoff which occurs on a range of cropped and naturally vegetated systems in primarily agricultural regions. This report provides a short overview of the mechanics of the CROPSIM model, further information can be found in the CROPSIM documentation (Martin D.).

CROPSIM begins with a known amount of water in the soil profile (SWC_{i-1}). Precipitation (P) from the weather data is applied. The portion of the precipitation which infiltrates into the soil is determined with the remainder going to runoff (RO). This is accomplished using a modified curve number approach with considerations for soil moisture content and surface residue. The infiltrated precipitation is used to fill the top soil layer, and then continues to fill each subsequent layer until the infiltrated precipitation is assigned. If there is more infiltrating water than there is room in the soil profile, this water will drain out the bottom of the soil profile as deep percolation (DP).

The amount of water in the soil is calculated. For irrigated simulations[5], if the soil water content drops below a management specified level of depletion this triggers an irrigation event[6]. A gross amount of water is applied with a net amount of irrigation infiltrating into the soil profile. The net irrigation fills the top layers and continues to fill subsequent layers until the entire depth of net irrigation water is assigned.

Vegetative growth is simulated from the specified planting date, progressing through the phenologic development tracked by growing degree days. The development of the plant extends the root system deeper into the soil allowing for greater access to soil moisture. At the same time the development of the canopy expands the transpiration potential of the crop. Transpiration demands are determined using Basal crop coefficients. Next it is determined if there is sufficient water in the root zone. If there is sufficient water to meet the transpiration demands, the water is transpired; otherwise, the crop is stressed, and a reduced rate of transpiration is determined. Evaporation from the soil surface is also determined. The combination of the transpired and evaporated water is removed from the root zone through evapotranspiration (ET).

Finally, the amount and distribution of water in the soil profile is determined. If there is water in a soil layer in excess of field capacity, the water is moved to the ensuing layers. If there is no room in the profile below the water will drain as deep percolation (DP). These steps are used to calculate the ending soil water content (SWC_i) as shown by Equation 1.

$$SWC_i = SWC_{i-1} + P + I_{net} - RO - ET - DP \quad (1)$$

The daily calculations are compiled and written to monthly summaries.

Long term simulations were made subjecting a variety of vegetation types to the climatic conditions measured at selected weather stations. This process is repeated for a selection of crop categories (10), soils (20), and irrigation methods (irrigated and non-irrigated) at each weather station.

Simulated crops include corn, soybeans, sorghum, alfalfa, winter wheat, and pasture. Each of these vegetation types is modeled in a continuous pattern[7]. Fallow is derived from the dryland winter wheat

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[5] CROPSIM is capable of simulating several different types of irrigation. For the watershed model simulations irrigation volumes are based upon the level of depletion in the soils and sprinkler irrigation. Other techniques include fixed dates, precipitation forecasting, and precipitation and evapotranspiration forecasting.
[6] Under the simulation technique used, it is assumed that the producer will only irrigate when there is sufficient space in the soil profile to hold the depth of net irrigation.
[7] i.e. corn after corn

simulation when the year begins without a live crop growing. Two additional crop classes include corn and soybeans in rotation[8]. Two sets of simulations were created to ensure that each year had an estimate of corn after soybeans and soybeans after corn.

To capture the changing effect of improved technology, management, and farming practices, nine sets of CROPSIM runs were created. Three runs represent the tillage practices common in 1949, 1973, and 1998 respectively. Six runs represent the 2020 tillage categories defined in the COHYST Conservation Study – Phase IV: conventional tillage, reduced tillage, mulch tillage, ridge tillage, strip tillage, and no tillage.

4.3. Spatial and Temporal Distribution Model

The next portion of the watershed model is to interpolate between the points where CROPSIM was modeled from both a spatial and temporal standpoint.

The first step in this process is to create the 2020 set point. This was accomplished by combining the tillage scenario results proportional to the tillage type density in the model area as defined in the COHYST Conservation Study – Phase III: survey of conservation tillage[9]. Next, the CROPSIM results were time trended between each of the 1949, 1973, 1998, and 2020 tillage scenarios[10].

Finally, the results were spatially interpolated to the geographic extents of the watershed model domain defined by the groundwater model grid. The first step was to establish the three nearest simulation points[11] and their distance to the cell centroids. Next each cell was assigned a CROPSIM soil class based upon the dominant soil type of the underlying cell. Finally, the water balance parameters are interpolated between the three nearest simulation points using an inverse weighted distance technique and the assigned soil class. The results are a set of coverages of the water balance parameters (WBPs) (P, NIR, DP, RO, and ET) for each combination of crop and irrigation method (dry or irrigated).

*This process was completed as part of the COHYST Conservation Study Phase IV. The COHYST coverages were then sampled for the BCM model area. The BCM WBPs retained the underlying 160-acre cells of the COHYST model.

4.4. Regionalized Soil Water Balance Model (RSWB)

The primary purpose of the RSWB is to develop estimates of pumping and recharge and create the appropriate .WEL and .RCH files for inclusion in the groundwater model. To accomplish this, the RSWB determines precipitation, estimates irrigation demand, applies irrigation, and partitions the applied water while adjusting for non-idealized conditions. Additionally, the RSWB is used to further partition

[8] Corn-soybeans-corn and soybeans-corn-soybeans
[9] This project defined the types of tillage operations in the CPNRD, TPNRD and TBNRD counties. The tillage type in the periphery area of the COHYST model was set to 100% mulch tillage.
[10] This was accomplished using linear interpolation.
[11] First weather stations, then simulation points on a 25-mile TIN

field runoff between stream flow contribution, recharge, and ET. Furthermore, the RSWB is capable of incorporating miscellaneous sources of recharge and pumping into the .WEL and .RCH deemed significant but not readily determined within the construct of the RSWB model.

The remainder of this publication will describe the processes, inputs, and results of the Buffalo County RSWB model.

5. RSWB Model Construction

The RSWB consists of seven programs (listed below), which incorporate distributed CROPSIM results, develop irrigation estimates, make adjustments to the water balance parameters, organize the results into properly formatted groundwater model input files, and generate water balance summary reports. The programs relate to one another as show in Figure 4.

1. Irrigation Application and Demand (IAD)
2. District Demand
3. District Supply
4. Irrigation Application and Supply (IAS)
5. Water Supply Partitioning Program (WSPP)
6. Make Well
7. Make Recharge
8. Compile Well
9. Compile Recharge
10. Report Summary
11. Supplementary 'Create Recharge' Files

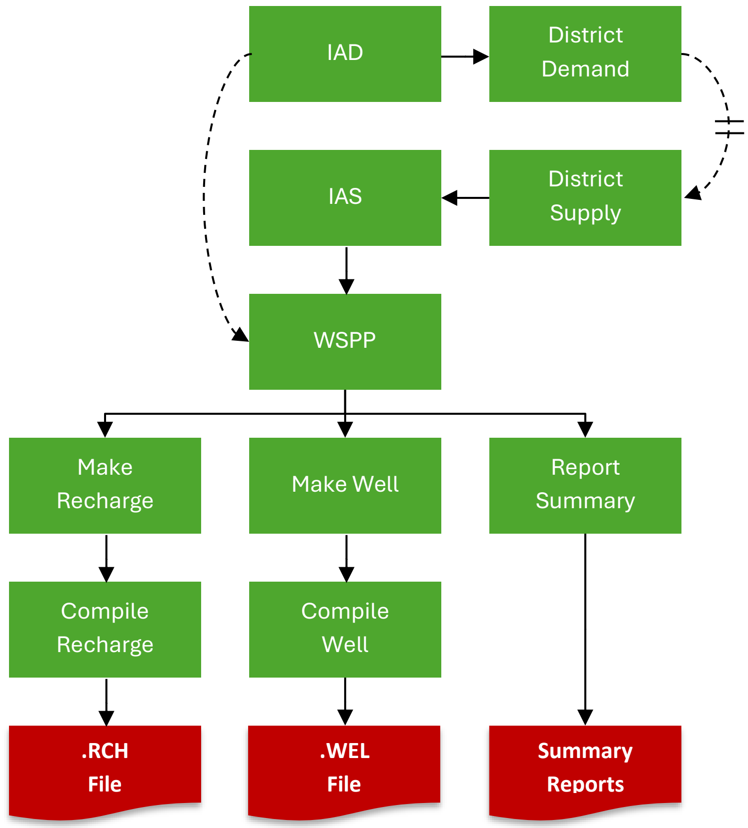


Figure 4. Process flow diagram for BCM RSWB Model.

The following chapter provides a general description of each program. Generalized schematics showing major conceptual components of the major programs are provided to assist a user interested in reviewing source code. The descriptions discuss in general terms the inputs required for each program.

5.1. Irrigation Application and Demand (IAD)

The IAD program (Figure 5) develops estimates of the irrigation demand volumes based upon land use classifications and irrigation source. The IAD uses the crop NIR, application efficiency (AE), and NIR target to estimate the gross volume of irrigation water demanded by each crop in each cell. The demands are passed to the District Demand program (supply runs) or directly implemented into the WSPP program (demand runs).

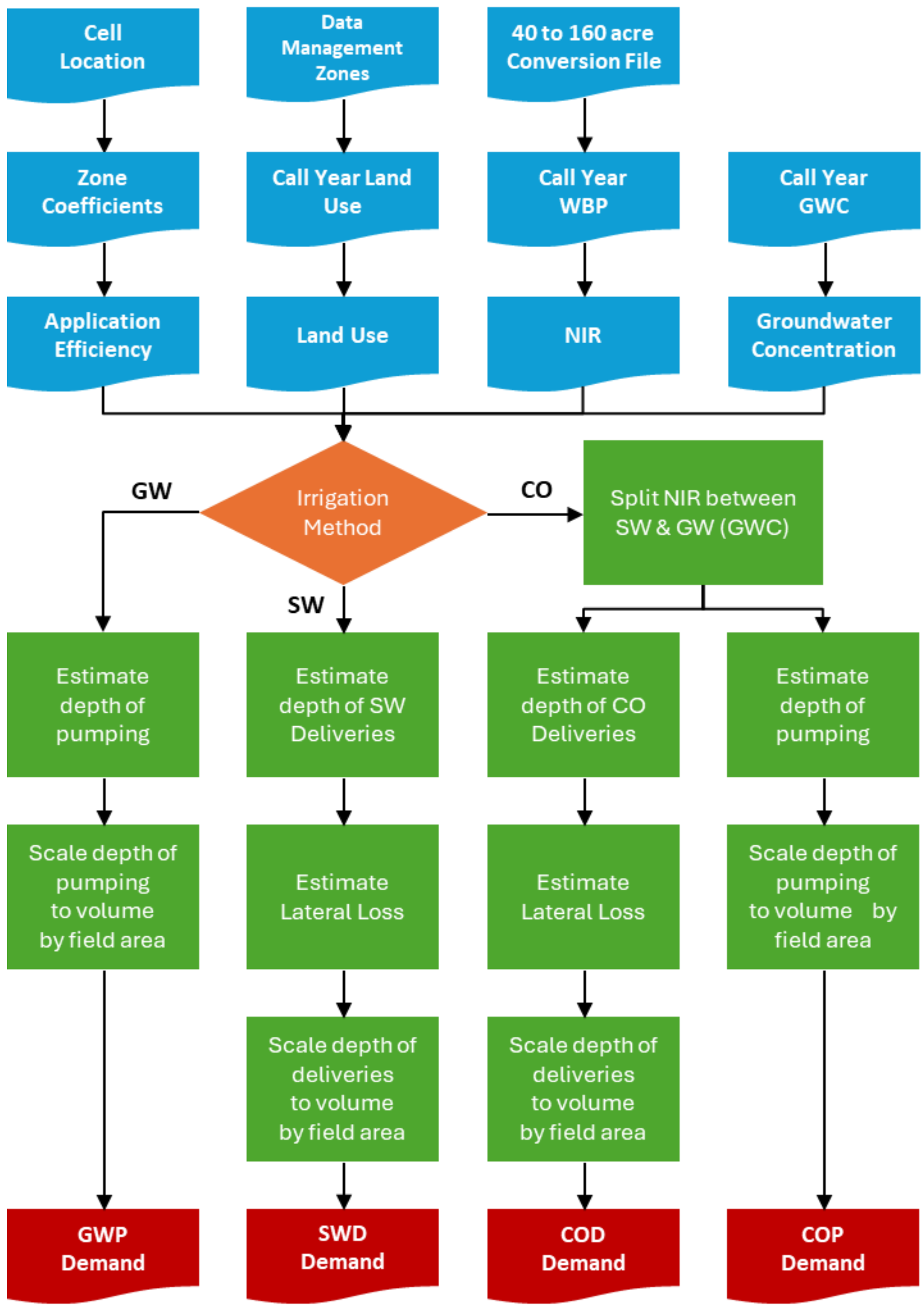


Figure 5. Flow chart depicting the inputs, outputs, and major functions of the IAD.

The depth of irrigation is estimated using the NIR from CROPSIM, adjusting it to a NIR target, and then adjusting to the gross irrigation depth using the application efficiency (Equation 2).

$$Irr_{crop,irr\ type} = NIR_{crop} * \frac{Target_{NIR}}{AE_{irr\ type}} \tag{2}$$

$Irr_{crop,\ irr\ type}$	Depth of irrigation water applied to the crop from an irrigation source (in)
NIR_{crop}	Net irrigation requirement for a given crop (in)
$Target_{NIR}$	Target indicating the portion of the full demand to be applied
$AE_{irr\ type}$	Application efficiency of the irrigation source
crop	Land use classification
irr type	Source of water; groundwater or surface water

The volume of water applied within a cell is computed by multiplying the per acre depth by the acres covered by the crop. This is repeated for each crop being grown in the cell (Equation 3).

$$Irr_{cell,irr\ type} = \sum\left(Irr_{crop,irr\ type} * Acs_{crop,irr\ type}\right) \tag{3}$$

$Irr_{cell,\ irr\ type}$	Volume of irrigation water applied to the cell from irrigation source (AF)
$Acs_{crop,\ irr\ type}$	Number of acres being grown of the crop type and from the irrigation source

For comingled lands (irrigated with both surface water and groundwater), irrigation demand was split between surface water and groundwater using the groundwater concentration factor (GWC). The GWC is used to represent the understanding of producers that the volume of available surface water is limited and may be insufficient to meet the full demand of their crop. The producer enters the irrigation season expecting to meet a portion of their irrigation needs on comingled lands with groundwater; thereby allowing a larger proportion of the available surface water to be applied to surface water only lands. The NIR value used in Equation 2 was weighted by the GWC to determine the portion of demand met by either groundwater pumping or surface water deliveries (Equations 4-5). A visual representation of this concept is shown in Figure 6.

$$NIR_{GW} = NIR * GWC \tag{4}$$

$$NIR_{SW} = NIR * (1 - GWC) \tag{5}$$

NIR	Net irrigation requirement (in)
NIR_{SW}	NIR met by surface water deliveries (in)
NIR_{GW}	NIR met by groundwater pumping (in)
GWC	Groundwater concentration factor
SW	Surface water source of irrigation
GW	Groundwater source of irrigation

The NIR parameter in Equation 2 was then replaced with NIR_{SW} and NIR_{GW} for calculations of demanded surface water or pumped groundwater, respectively.

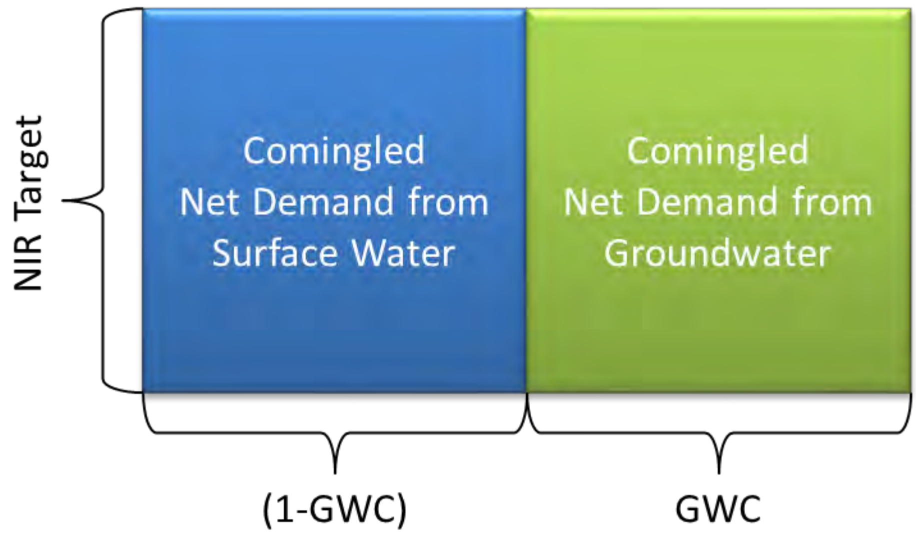


Figure 6. Division of demand for irrigation on comingled lands.

Finally, the demand for surface water is adjusted upwards to account for transport inefficiencies in the laterals between the main canal and the fields. The lateral seepage is a proportional amount related to the field demand (Equation 6).

$$SeepD_{Lat} = IrrD_{cell,SW} * LatLoss \tag{6}$$

$SeepD_{Lat}$	Seepage in the canal laterals from irrigation demands (AF)
$Irr_{cell,\ SW}$	Volume of surface water irrigation water demanded by the cell (AF)
LatLoss	Rate of transportation inefficiency of the canal's delivery system between the main canal and the field

5.2. District Demand

The district demand program combines each of the individual field demands for surface water within an irrigation district (Equation 7) and within the active BCM model domain. These district demands are compiled into a single district demand file.

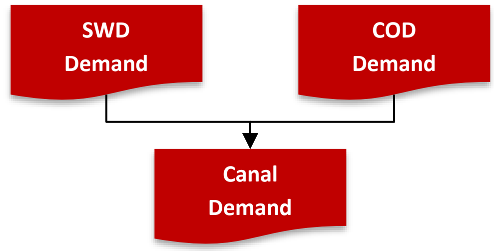


Figure 7. Flow Chart depicting the inputs, outputs, and major functions of the District Demand program.

$$IrrD_{district} = \sum(IrrD_{cell,SW} + SeepD_{Lat}) \quad (7)$$

$IrrD_{district}$	Irrigation District demands for surface water (AF)
$Irr_{cell,\,SW}$	Volume of surface water irrigation water demanded by the cell (AF)
$SeepD_{Lat}$	Seepage in the canal laterals from irrigation demands (AF)

5.3. District Supply

The District Supply program (Figure 8) defines the volume of deliveries to area of each surface water district in the active BCM model domain. Starting with the canal demand file, this program replaces the surface water irrigation district demand with available known volumes of irrigation district supply. The canal supplies are then passed to the IAS program.

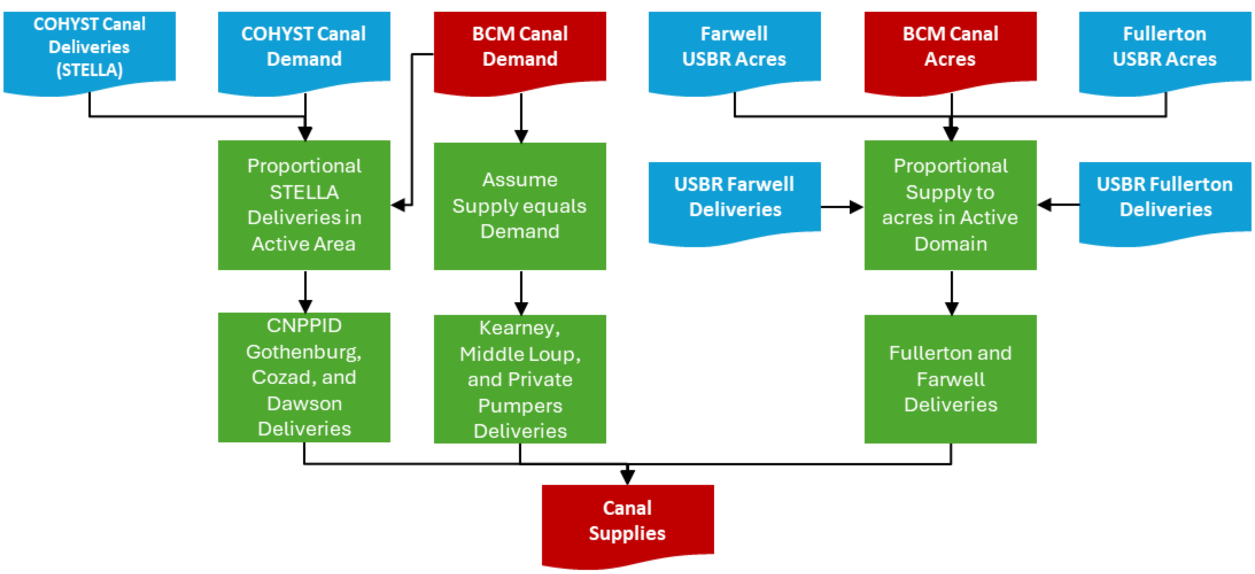


Figure 8. Flow Chart depicting the inputs, outputs, and major functions of the District Supply program.

Irrigation supplies can be divided into three categories.

1. Surface water supply volumes determined within the COHYST STELLA model
2. Surface water supply volumes retrieved from the United States Bureau of Reclamation (USBR) annual reports.
3. Surface water supply volumes are assumed to be equal to irrigation demands.

COHYST STELLA Volumes

The STELLA model provides surface water deliveries for the Gothenburg, Cozad, Dawson, and CNPPID irrigation districts[12]. These volumes are for the entire surface water district. However, only a portion of the area of each of these canals is located in the BCM model domain. The surface water supply was partitioned between the active and inactive area proportional to the demand for surface water in the active and inactive areas[13] (Equation 8).

$$IrrS_{district,active} = IrrS_{district,full} * \frac{IrrD_{district,active}}{IrrD_{district,full}} \quad (8)$$

$IrrS_{district,\ full}$	Surface water deliveries for the full area of the Irrigation District (AF)
$IrrS_{district,\ active}$	Surface water deliveries for the active area of the Irrigation District (AF)
$IrrD_{district,\ full}$	Surface water demands for the full area of the Irrigation District (AF)
$IrrD_{district,\ active}$	Surface water demands for the active area of the Irrigation District (AF)

USBR Annual Reports

The USBR annual reports provide records of the volumes of on-farm deliveries to surface water districts. Reports were available for the Farwell and Fullerton irrigation districts. These reports provided the deliveries for the entire surface water district and the total service area over which the water was applied. Only a portion of each surface water district is located within the active domain of the BCM model. The surface water deliveries in active area were proportioned relative to the district acres in the active area[14].

$$IrrS_{district,active} = IrrS_{district,full} * \frac{Acres_{district,active}}{Acres_{district,full}} \quad (9)$$

$IrrS_{district,\ full}$	Surface water deliveries for the full area of the Irrigation District (AF)
$IrrS_{district,\ active}$	Surface water deliveries for the active area of the Irrigation District (AF)
$Acres_{district,\ full}$	Surface water irrigated acres for the full district area from USBR

[12] STELLA supplies were retrieved from the baseline model of the 2023 Robust Review.
[13] Demand in the inactive area was derived from the total district demand from the COHYST model
[14] Surface water demands were only available for the active area. Information on the crop mix in the inactive area was not available, so supplies were partitioned only on service area in and outside the active domain.

$Acres_{district,\ active}$ Surface water irrigated acres in the active area of the Irrigation District[15]

In the event that the surface water irrigated acres in the model exceed the acres from the USBR report the entire volume of surface water deliveries is applied to the area in the active model.

Supplies equal Demands

Three irrigation districts fall in the BCM are assumed to receive supplies equal to demands; Kearney Canal, Middle Loup Public Power and Irrigation District (MLPPID), and private pumpers[16].

- The demands on the Kearney Canal are dominated by hydroelectric power. The relatively lower irrigation demands have yielded to the assumption that supplied are sufficient to cover demands.
- MLPPID is not managed by the USBR, thus the USBR did not have any diversion records.
- 'Private Pumpers' is a category of producers not affiliated with an irrigation district. They were not modeled within the STELLA model, nor were records available on the volume of irrigation applied to the field.

5.4. Irrigation Application and Supply (IAS)

The IAS program (Figure 9) distributes known volumes of irrigation supply to application areas and supplements this information with the target irrigation demands on areas with unknown irrigation supplies. Known supplies are distributed proportional to the demand on the areas over which they are supplied. Groundwater only supplies are assumed to meet demands and are estimated using the same techniques to estimate demand in the IAD (Equations 2-3, Section 5.1).

Surface water deliveries to either surface water only or comingled lands within each irrigation district are split between the individual crops and fields, weighted by NIR and acres (Equations 10-11).

$$IrrA_{crop,SW} = IrrS_{district,active} * \frac{\frac{IrrD_{crop,SW}}{12} * Acs_{crop,SW} * (1 + LatLoss)}{IrrD_{district,active}} \tag{10}$$

$$IrrA_{crop,CO} = IrrS_{district,active} * \frac{\frac{IrrD_{crop,CO}}{12} * Acs_{crop,CO} * (1 - GWC) * (1 + LatLoss)}{IrrD_{district,active}} \tag{11}$$

$IrrA_{crop,SW}$	Volume of surface water delivered to a crop in the surface water only field (AF)
$IrrA_{crop,CO}$	Volume of surface water delivered to a crop in the comingled field (AF)
$IrrS_{district,\ active}$	Surface water deliveries for the active area of the Irrigation District (AF)
$IrrD_{district,\ active}$	Surface water demands for the active area of the Irrigation District (AF)
$IrrD_{crop,XX}$	Depth of irrigation water demand by the crop from irrigation source (in)

[15] From BCM land use

[16] The implementation in Kearney Canal and for the private pumpers is consistent the COHYST model.

$Acs_{crop,XX}$	Number of acres of the specified crop type and irrigated from the irrigation source (acres)
GWC	Groundwater concentration factor
LatLoss	Rate of transportation inefficiency of the canal's delivery system between the main canal and the field
SW	Surface water
CO	Comingled

For comingled lands, pumping is calculated in two parts. First, the producer pumps the expected pumping demand defined using the GWC. Next, in the event that surface water deliveries were insufficient to meet the target irrigation demands, additional groundwater is pumped to cover the deficit (Figure 10, Equation 12-13)

$$IrrA_{crop,COP1} = \frac{NIR_{crop} * Target_{NIR}}{12 * AE_{GW}} * AC_{crop,CO} * (GWC) \quad (12)$$

$$IrrA_{crop,COP2} = \frac{NIR_{crop} * Target_{NIR} - IrrA_{crop,CODnet}}{12 * AE_{GW}} * AC_{crop,CO} * (1 - GWC) \quad (13)$$

$IrrA_{crop, COP1}$	Volume of comingled pumping on the portion of the comingled field expecting to apply groundwater first (AF)
$IrrA_{crop, COP2}$	Volume of comingled pumping necessary to account for deficit surface water deliveries (AF)
NIR_{crop}	Net Irrigation Requirement for a given crop (in)
$Target_{NIR}$	Representative target indicating the portion of the full demand expected to be applied by rational producers
$IrrA_{crop, CODnet}$	The net irrigation portion of the surface water deliveries to the field; deliveries minus lateral seepage minus application inefficiencies (in) (Equation 14)

$$IrrA_{crop,CODnet} = \frac{IrrA_{crop,COD}}{(1 + LatLoss) * AC_{crop,CO} * (1 - GWC)} * 12 * AE_{SW} \quad (14)$$

$IrrA_{crop,COD}$	Volume of surface water delivered to a crop in the comingled field (AF)
AE_{GW}	Application efficiency for groundwater pumping
$AC_{crop, CO}$	Crop acres for the comingled field (acres)
GWC	Groundwater concentration factor
LatLoss	Transportation efficiency of the canal's delivery system between the main canal and the field

The applied irrigation volumes are passed to the WSPP program.

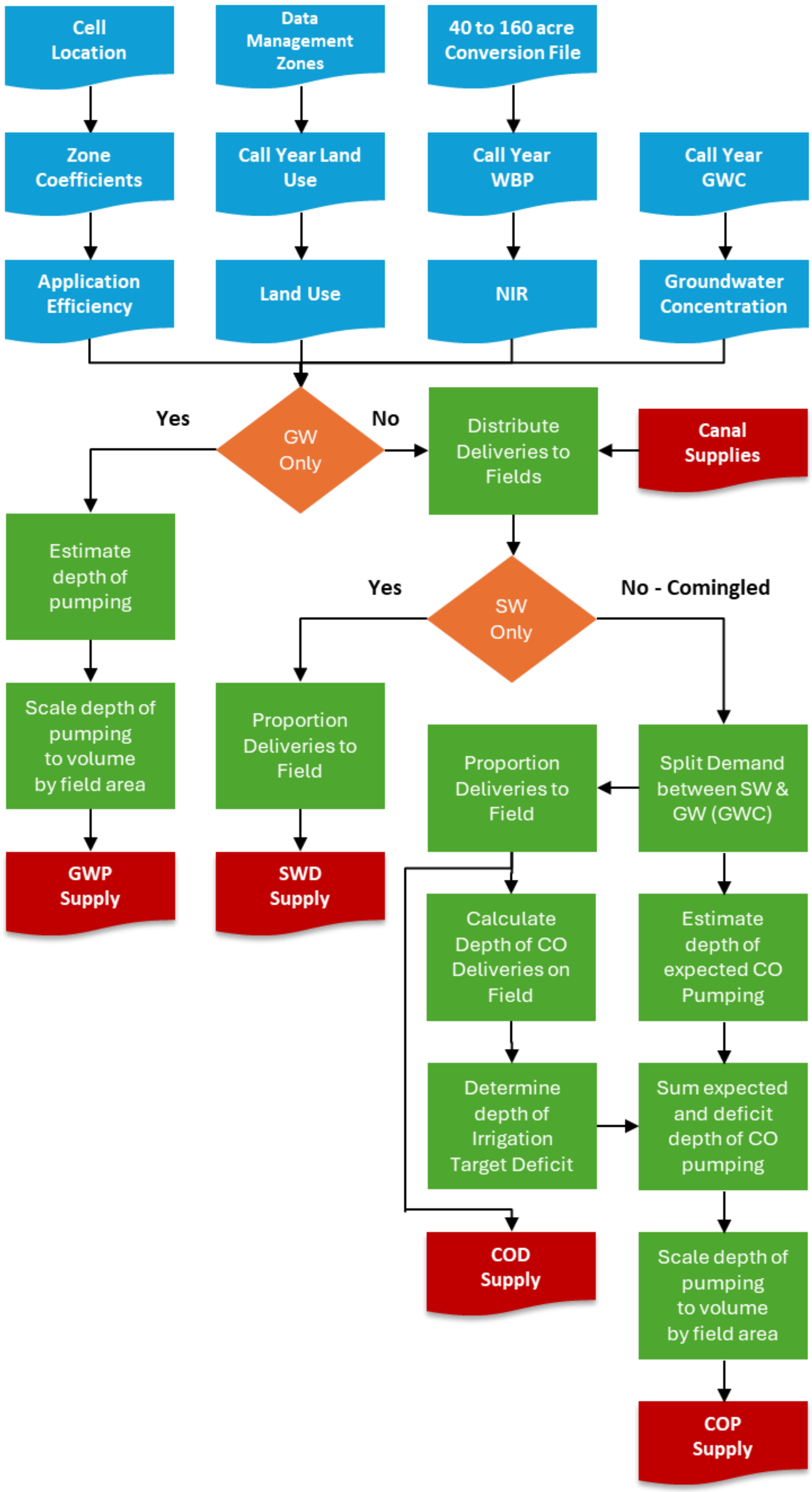


Figure 9. Flow chart depicting the inputs, outputs, and major functions of the IAS Program.

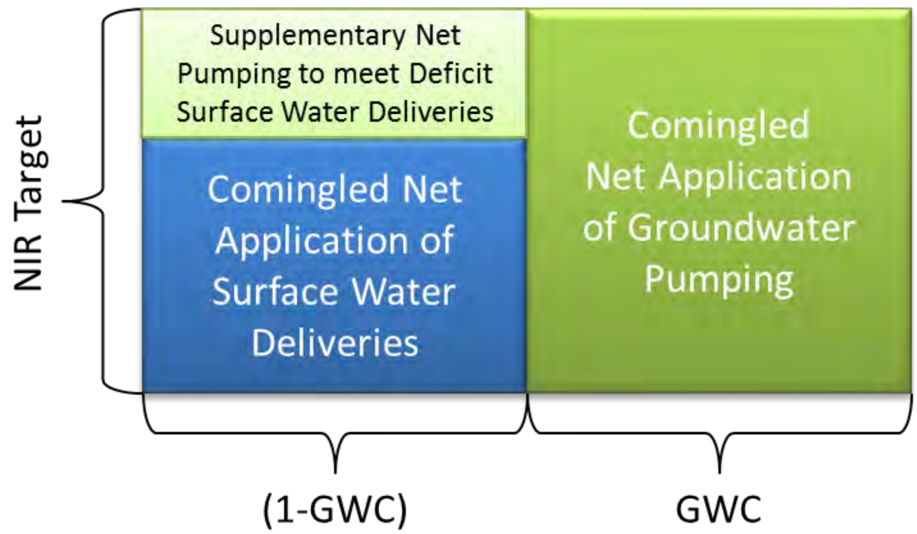


Figure 10. Depiction of the application of comingled irrigation when there is insufficient surface water deliveries to meet the demand for surface water.

5.5. Water Supply Partitioning Program (WSPP)

The purpose of WSPP is to partition precipitation and applied irrigation between evapotranspiration, recharge, runoff and change in soil water content. Additionally, WSPP is used to adjust the parameters of the water balance from the idealized conditions in CROPSIM, through calibration, to more accurately reflect the conditions experienced in the field. This is accomplished using the distributed water balance parameters, land use classification, and applied irrigation volumes (Figure 11). WSPP is capable of incorporating either the estimated irrigation amounts developed in the IAD, or an irrigation data set developed outside the model (e.g., metered well pumping records)[17].

All adjustments made to any water balance parameter must maintain the water balance shown in Equation 15. Precipitation and change in soil water content were kept constant throughout the process.

$$P + NIR - ET - DP - RO = \Delta SWC \tag{15}$$

P	Precipitation (in)
NIR	Net Irrigation Requirement (in)
ET	Evapotranspiration (in)
DP	Deep percolation (in)
RO	Runoff (in)
ΔSWC	Change in soil water content (in)

[17] For the BCM modeling, the irrigation estimates from the IAD were used.

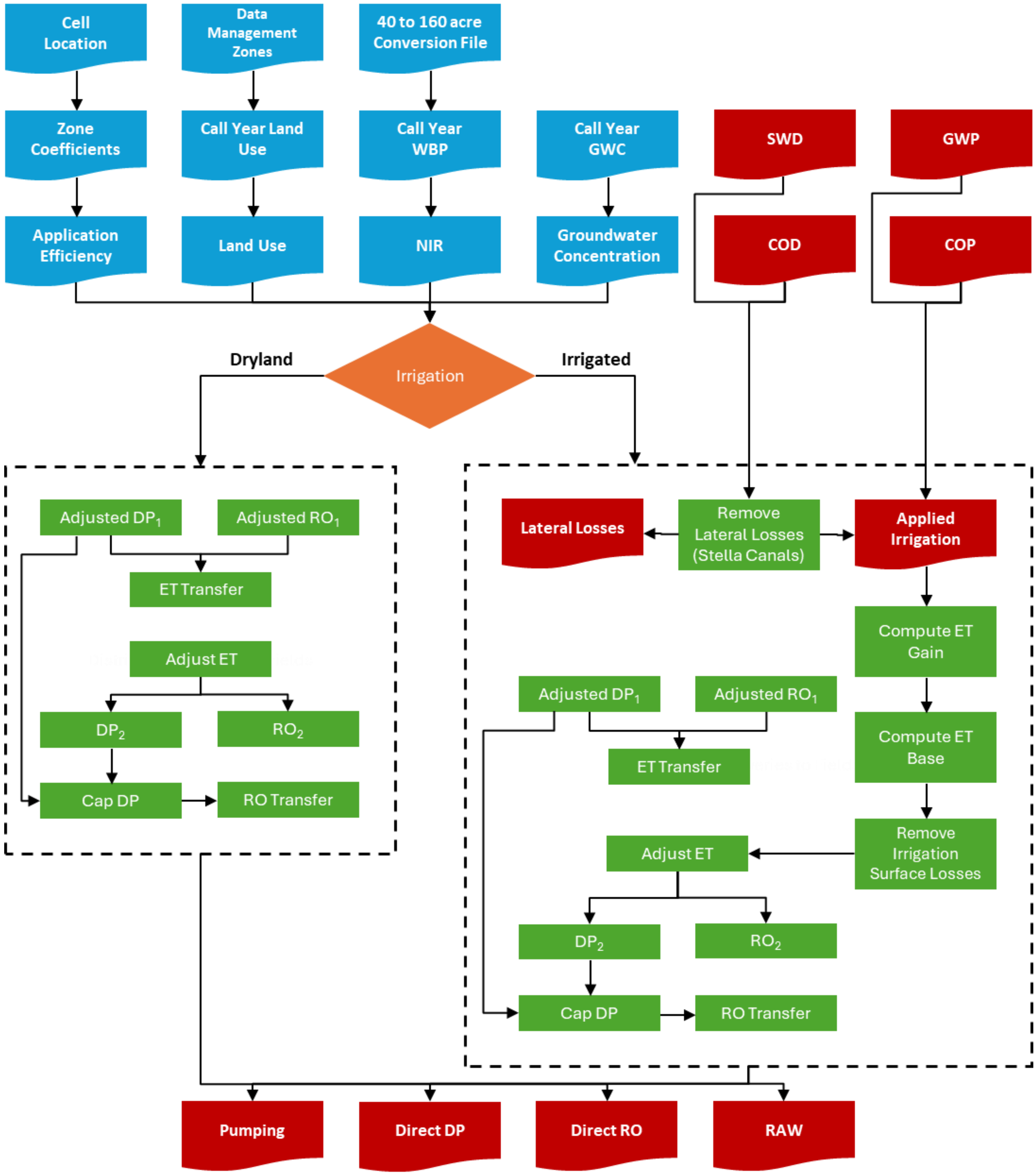


Figure 11. Flow chart depicting the inputs, outputs, and major functions of the WSPP Program.

Each crop type can be supplied by each irrigation source separately. Calculations are first made for rainfed conditions. An adjustment is made to the dryland ET to reflect the difference between the idealized conditions from CROPSIM and those observed in the field (Equation 16).

$$ET_{dry,adj} = ET * ADJ_{ET,dry} \tag{16}$$

ET	Evapotranspiration (in)
$ET_{dry, adj}$	Adjusted dryland ET (in)
$ADJ_{ET, dry}$	Dryland ET adjustment factor

The change in ET was converted to runoff and deep percolation (Equation 17-19).

$$\Delta ET_{dry} = ET - ET_{dry,adj} \tag{17}$$

$$RO_2 = \Delta ET_{dry} * DryET2RO \tag{18}$$

$$DP_2 = \Delta ET_{dry} - RO_2 \tag{19}$$

ET	Evapotranspiration (in)
$ET_{dry, adj}$	Adjusted dryland ET (in)
ΔET_{dry}	Change in dryland evapotranspiration; unassigned water (in)
RO_2	Additional runoff from the application of irrigation and movement to non-idealized conditions (in)
DP_2	Additional recharge from the application of irrigation and movement to non-idealized conditions (in)
DryET2RO	Partitioning factor used to divide unassigned water between runoff and deep percolation
dry	Not irrigated
adj	Adjusted

Likewise, runoff and deep percolation adjustment factors are available to calibrate the volume of either respective parameter coming out of CROPSIM. Changes in these parameters were converted to non-beneficial consumptive use (ET) (Equations 20-22).

$$RO_1 = RO * ADJ_{RO} \tag{20}$$

$$DP_1 = DP * ADJ_{DP} \tag{21}$$

$$ET_{trans} = (DP - DP_1) + (RO - RO_1) \tag{22}$$

RO	Runoff (in)
DP	Deep percolation (in)
RO_1	Adjusted runoff (in)
DP_1	Adjusted deep percolation (in)
ADJ_{RO}	Runoff adjustment factor
ADJ_{DP}	Deep percolation adjustment factor
ET_{trans}	Runoff and deep percolation from CROPSIM converted into non-beneficial ET

Finally, the WSPP program allows for upper limits to be applied to recharge rates. A diminishing returns function is employed such that after the annual rate of deep percolation exceed a lower threshold; as the depth of deep percolation goes to infinity, the depth realized by the model approaches the deep percolation cap (Equations 23-26). This routine was implemented to account for the fact that soils may be limited on their ability to drain water which has seeped below the modeled root zone, causing over estimation of recharge rates.

$$\lim_{DP_1+DP_2 \to \infty} DP_{dry,tot} = DP_{cap} \quad (23)$$

$$DP_{dry,tot} = DP_{ll} + \left(DP_{cap} - DP_{ll}\right) * \left(1 - \left(1 - \frac{(DP_1+DP_2)-DP_{ll}}{DP_{ul}-DP_{ll}}\right)^{\frac{1}{\alpha}}\right) \quad (24)$$

Where:

$$\alpha = \frac{DP_{cap}-DP_{ll}}{DP_{ul}-DP_{ll}} \quad (25)$$

$$DP2RO = DP_1 + DP_2 - DP_{dry,tot} \quad (26)$$

DP_1	Adjusted deep percolation (in)
DP_2	Additional recharge from the application of irrigation and movement to non-idealized conditions (in)
$DP_{dry\ tot}$	Model realized rate of deep percolation (in)
DP_{cap}	Maximum rate of realized deep percolation (in)
DP_{ul}	Theoretical point at which the realized rate of deep percolation meets the maximum rate or realized deep percolation, representative of infinity (in)
DP_{ll}	Rate of deep percolation at which the model begins to taper off the realized rate of deep percolation (in)
DP2RO	Recharge converted to runoff due to the recharge cap limit (in)

The recharge realized by the model and the additional runoff is distributed to monthly values proportional to the initial recharge rates.

Working forward from Equation 15, the water balance can be rewritten as shown in Equation 27 below[18].

$$P - ET_{dry,adj} - DP_{dry,tot} - DP2RO - RO_1 - RO_2 - ET_{trans} = \Delta SWC \qquad (27)$$

P	Precipitation (in)
$ET_{dry, adj}$	Adjusted dryland ET (in)
$DP_{dry\ total}$	Model realized rate of deep percolation (in)
DP2RO	Recharge converted to runoff due to the recharge cap limit (in)
RO_1	Adjusted runoff (in)
RO_2	Additional runoff from the application of irrigation and movement to non-idealized conditions (in)
ET_{trans}	Runoff and deep percolation from CROPSIM converted into non-beneficial ET (in)
ΔSWC	Change in soil water content (in)

To calculate the water balance parameters for irrigated crops, WSPP uses the distributed CROPSIM output for the irrigated crops, the dryland crop ET, and the volume of irrigation applied to the crop[19]. Similar to the dryland calculation, the water balance coming out of CROPSIM (Equation 15) is maintained, keeping precipitation and change in soil water content constant. Furthermore as described in Equations 20-22, a potential adjustment can be made to runoff and deep percolation.

ET gain is the increase in beneficial consumptive use from the application of irrigation water. Over the entire irrigation season, the marginal increase in ET gain from the application of additional irrigation water is subject to diminishing returns. This process is defined by Equation 28.

$$ET_{gain} = \begin{cases} CIR * \left(1 - \left(1 - \frac{Irr_{crop,irr\ type}}{GIR}\right)^{\frac{1}{\beta}}\right) & Irr_{crop,irr\ type} < GIR \\ ET_{sea,max,irr} - ET_{sea,max,dry} & Irr_{crop,irr\ type} \geq GIR \end{cases} \qquad (28)$$

ET_{gain}	Increase in ET from the application of irrigation water (in)
CIR	Consumptive irrigation requirement - the additional amount of ET that a plant must use to maximize its yield potential over a dryland crop; defined in Equation 29 (in)

$$CIR = ET_{sea,max,irr} - ET_{sea,max,dry} \qquad (29)$$

GIR	Gross irrigation requirement - the amount of water that needs to be applied in order to meet the net irrigation requirement (in)

[18] Note that NIR is equal to zero.

[19] For the BCM model, the irrigation volumes developed in the IAD program were used.

β — Water use efficiency term; defined by Equation 30

$$\beta = \frac{CIR}{GIR} \tag{30}$$

$Irr_{crop, irr type}$	Depth of irrigation water applied to the crop from an irrigation source (in)
$ET_{sea, max, irr}$	ET needed to meet the max yield potential for an irrigated crop during the growing season (in)
$ET_{sea, max, dry}$	Dryland ET utilized during the irrigation season (in)

The resultant ET gain was then distributed back to the months based upon: 1) Applied Water > 0 and $ET_{irr} > ET_{dry}$, 2) Applied Water > 0 and $ET_{irr} < ET_{dry}$, and finally any remaining ET gain by 3) Applied Water = 0 and $ET_{irr} > ET_{dry}$. The ET gain is added to the non-irrigated ET to determine the total ET. Finally, an adjustment of the irrigated ET was made to account for differences between the idealized conditions in CROPSIM and those observed in the field (Equation 31).

$$ET_{irr,adj} = ET_{irr} * ADJ_{ET,irr} \tag{31}$$

ET_{irr}	Irrigated ET[20] (in)
$ET_{irr, adj}$	Adjusted irrigated ET (in)
$ADJ_{ET, irr}$	Irrigated ET adjustment factor

Next a surface loss[21] was calculated to determine the portion of applied water that was lost directly to non-beneficial consumptive use. These losses are assumed to be a fixed percentage of the total applied volume. The remaining applied water in excess of the surface losses and ET, while maintaining the change in soil water content from the CROPSIM output, was divided between runoff (RO_2) and deep percolation (DP_2), defined by Equation 32. This water includes both the irrigation inefficiencies and the shift from idealized CROPSIM conditions.

$$RODP_{wt} = MIN\left(MAX\left(\frac{RO_fDP*RO_1}{RO_fDP*RO_1+DP_1}, RO_{min}\right), RO_{max}\right) \tag{32}$$

$RODP_{wt}$	Partitioning factor used to divide water between runoff and deep percolation
RO_fDP	Weighting factor to control the influence of runoff on the partitioning factor
RO_1	Adjusted runoff (in)
DP_1	Adjusted deep percolation (in)
RO_{min}	Minimum partitioning factor (in)
RO_{max}	Maximum partitioning factor (in)

[20] The irrigated ET is a function of applied water

[21] Surface loss in this context refers to irrigation water lost during application; drift, evaporation, interception, etc….

Finally, the WSPP program allows for upper limits to be applied to irrigated recharge rates in the same way they are applied to the dryland crops (Equations 23-26). The results from the irrigated calculations are summarized in Equation 33 and are equivalent to the results found in Equation 15 for an irrigated crop. The partitioning of the applied irrigation is further illustrated in Figure 12.

$$P + Irr_{crop,irr\ type} - SL - ET_{irr,adj} - DP_{irr,tot} - DP2RO - RO_1 - RO_2 - ET_{trans} = \Delta SWC \qquad (33)$$

P	Precipitation (in)
$Irr_{crop, irr\ type}$	Depth of irrigation water applied to the crop from an irrigation source (in)
SL	Surface losses (in)
$ET_{irr, adj}$	Adjusted irrigated evapotranspiration (in)
$DP_{irr, tot}$	Total irrigated deep percolation (in)
DP2RO	Recharge converted to runoff due to the recharge cap limit (in)
RO_1	Adjusted runoff (in)
RO_2	Additional runoff from the application of irrigation and movement to non-idealized conditions (in)
ET_{trans}	Runoff and deep percolation from CROPSIM converted into non-beneficial ET (in)
ΔSWC	Change in soil water content (in)

The results were then scaled to the cell level by multiplying the water balance results by the number of crop acres serviced by the irrigation method within the cell. Finally, the cell totals were calculated by summing all the crop irrigation method combinations present within the cell.

The WSPP program is also responsible for calculating and spatially distributing lateral losses for the irrigation districts represented in COHYST STELLA model[22]. The supply provided by the STELLA model includes lateral losses[23]. Prior to beginning the irrigated crop calculations in WSPP, the lateral losses are removed from the applied irrigation (Equation 34) and amassed at the cell. The volume of field deliveries is then converted to an applied depth per acre (Equation 35) and implemented in the WSPP irrigated field calculations.

[22] Dawson, Cozad, Gothenburg, CNPPID, and Kearney Irrigation Districts.
[23] The Loup River Irrigation District lateral losses were already separated from farm deliveries in the records from the USBR

$$LatSeep_{cell} = \sum IrrA_{crop,XX} * \frac{LatLoss}{1+LatLoss} \quad (34)$$

$$Irr_{crop,XX} = IrrA_{crop,XX} * \frac{1}{1+LatLoss} * \frac{12}{Acs_{crop,XX}} \quad (35)$$

$LatSeep_{cell}$	Transportation inefficiency of the canal's delivery system between the main canal and the filed (AF)
$IrrA_{crop,XX}$	Volume of surface water delivered to a crop (AF)
$Irr_{crop,\ XX}$	Depth of irrigation water applied to the crop from an irrigation source (in)
LatLoss	Rate of transportation inefficiency of the canal's delivery system between the main canal and the field
$Acs_{crop,\ XX}$	Number of acres of the specified crop type and irrigated from the irrigation source (acres)

The pumping, recharge, and water balance outputs of the WSPP program are then provided to the Make Recharge, Make Well, and WSPP Report programs. Lateral losses are provided to the Compile Lateral Loss program.

Partition of Applied Irrigation Water

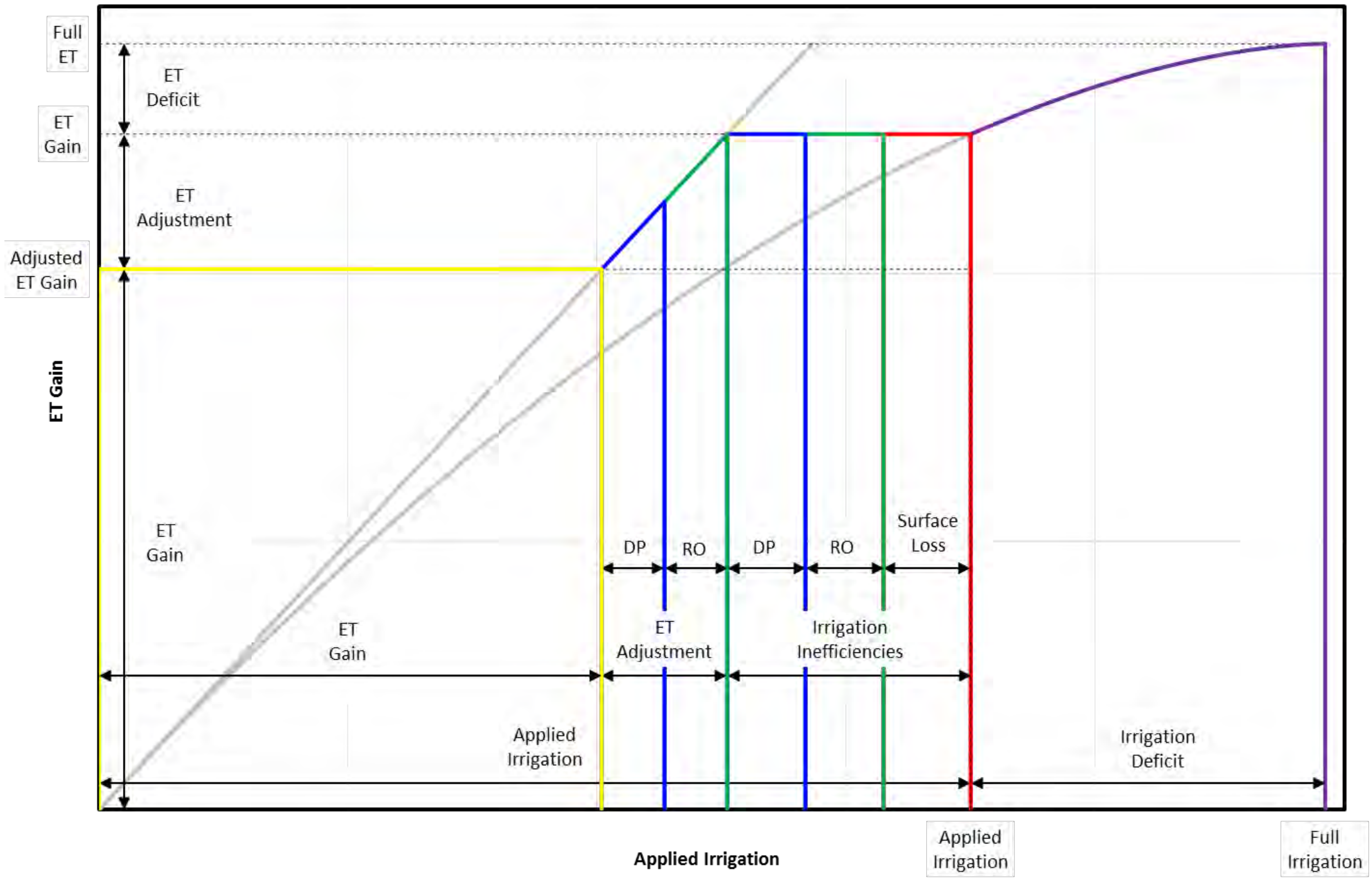


Figure 12. Partitioning a depth of applied irrigation between ET, RO, DP, and surface losses.

5.6. Make Well

The primary purpose of the Make Well program combines the various forms of agricultural pumping data into a set of annual files developed for the groundwater model in the .WEL format. During this process, depicted in Figure 13, the program combines all sources of pumping in each active BCM RSWB cell. Next, the program converts the pumping from a cell basis to a node basis. This is accomplished by summing the cell pumping for each cell located within the node as defined by the link between the groundwater model nodes and watershed model cells.

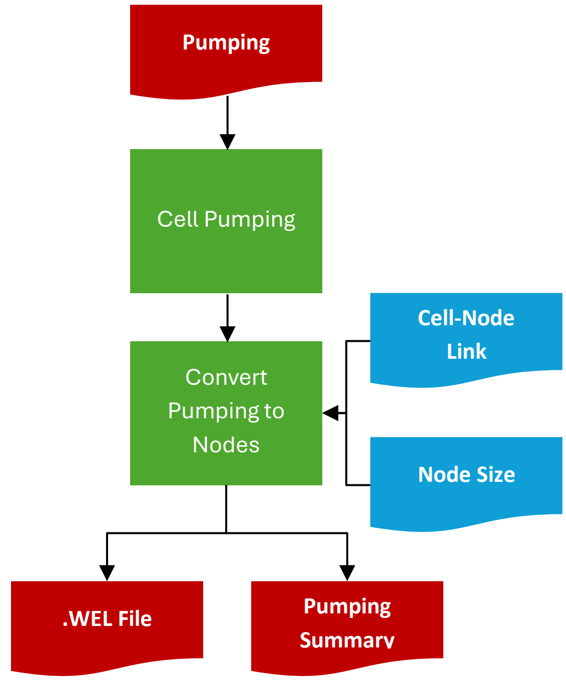


Figure 13. Flow chart depicting the inputs, outputs, and major functions of the Make Well program.

5.7. Compile Well

The Compile Well program was a simple program developed to combine the annual pumping files with the correct headers into a single file ready for use in the groundwater model. A program Schematic would not materially assist in reviewing the Compile Well's source code.

5.8. Make Recharge

The Make Recharge program combined the various forms of recharge data into a set of annual files formatted for use in the groundwater model in the .RCH format using the methodology shown in Figure 14. The sources of recharge in the BCM model include direct agricultural recharge and indirect agricultural recharge resulting from runoff transmission losses.

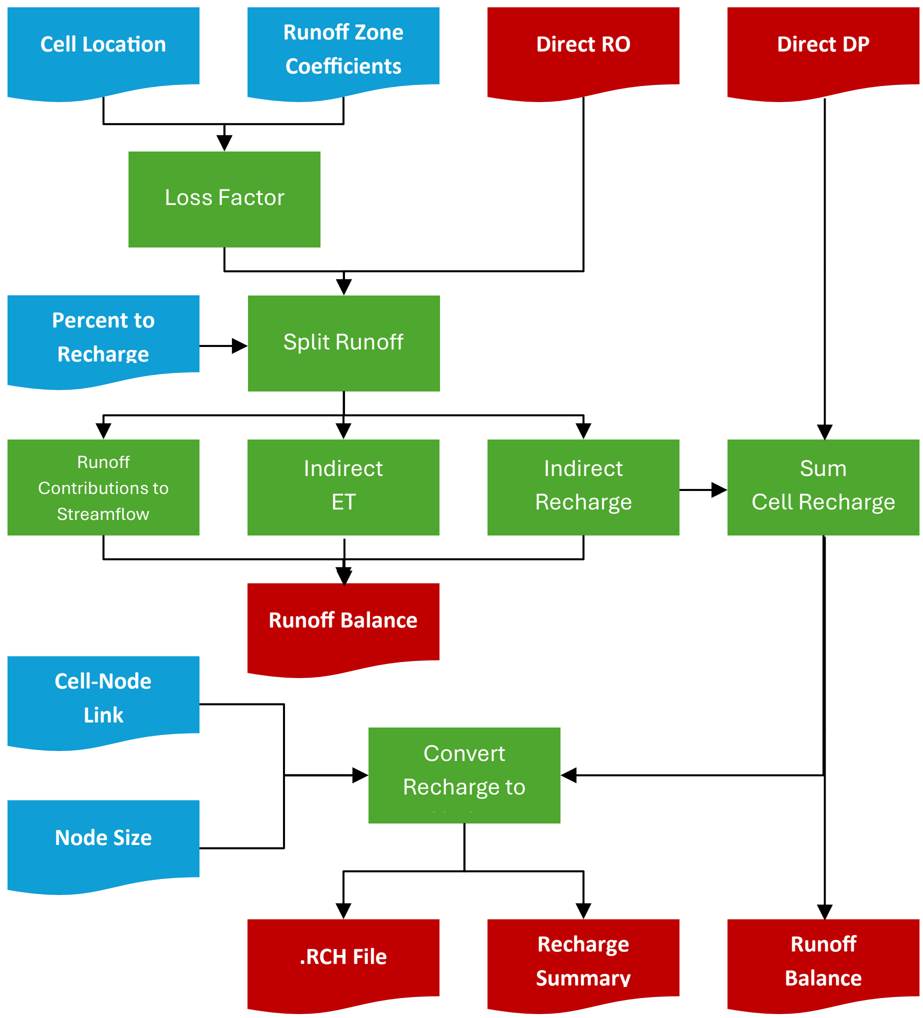


Figure 14. Flow chart depicting the inputs, outputs, and major functions of the Make Recharge program.

The Make Recharge program is responsible for estimating the indirect recharge. Indirect recharge is the additional recharge resulting from transmission losses between the field and the stream gauge. It is a function of direct agricultural runoff from a cell, a loss per mile rate, soil type, and the distance from the cell to the stream gauge at the end of the runoff zone. The runoff transmission loss is divided into non-beneficial consumptive use (ET) and recharge (Equations 36-39).

$$RO = SF + RO2DP + RO2ET \quad (36)$$
$$SF = RO * (1 - LossFactor) \quad (37)$$
$$RO2DP = RO * LossFactor * \%2Rch \quad (38)$$
$$RO2ET = RO * LossFactor * (1 - \%2Rch) \quad (39)$$

RO	Runoff (AF)
SF	Runoff contributions to streamflow (AF)
RO2DP	Runoff transmission losses to recharge (AF)
RO2ET	Runoff transmission losses to non-beneficial consumptive use (AF)
LossFactor	Portion of field runoff lost to recharge or ET during transit from field to stream gauge; calculated using Equation 40

$$LossFactor = Min(1 - e^{-lpm*Mi2Gauge}, 1.0) \quad (40)$$

%2Rch	Partitioning factor splitting the transmission losses between recharge and ET
Lpm	Loss per mile factor (%/mi)
Mi2Gauge	Distance between the centroid of a cell and the stream gauge identifying the accumulation point of the basin (mi)

Finally, the total recharge for each node is determined. This is accomplished by summing the cell recharge for each cell located within the node as defined by the link between the groundwater model nodes and watershed model cells.

5.9. Compile Recharge

The Compile Recharge program is a simple program developed to combine the annual .RCH files with the appropriate headers into single files to be provided for input into the groundwater Model. A program schematic would not materially assist in reviewing the Compile Recharge's source code.

5.10. WSPP Report

The WSPP Report program is also a simple program developed to compile the water balance parameters into annual summary files. Summaries are created on a defined geographic area. Within each of these areas annual and monthly summaries are created for combinations of soil, crop, and irrigation source.

5.11. Create Canal Seepage and Lateral Loss .RCH files

Loup River Canal Seepage - This program takes the canal seepage volumes for each canal and distributes it along the length of the canal. Then creates a node based .RCH file for canal seepage for each Farwell, Fullerton, and MLPPID irrigation districts in the active BCM domain.

Platte River Canal Seepage - This program takes the takes the canal seepage data from the COHYST STELLA program, distributes the volume along the length of the canal, determines the volume in the active model domain, and creates a node based .RCH file for input into the groundwater model.

Platte River Lateral Seepage - This program takes the distributed lateral seepage results from the RSWB and compiles it into a node based .RCH file for input into the groundwater model.

Farwell Canal Lateral Seepage - This program distributes the USBR lateral seepage data across the area serviced by the Farwell Canal. Seepage data was distributed proportional to the area of surface water only and comingled lands in a cell relative to the total surface water only and comingled lands serviced by the irrigation district.

6. RSWB Model Inputs

6.1. Model Grid

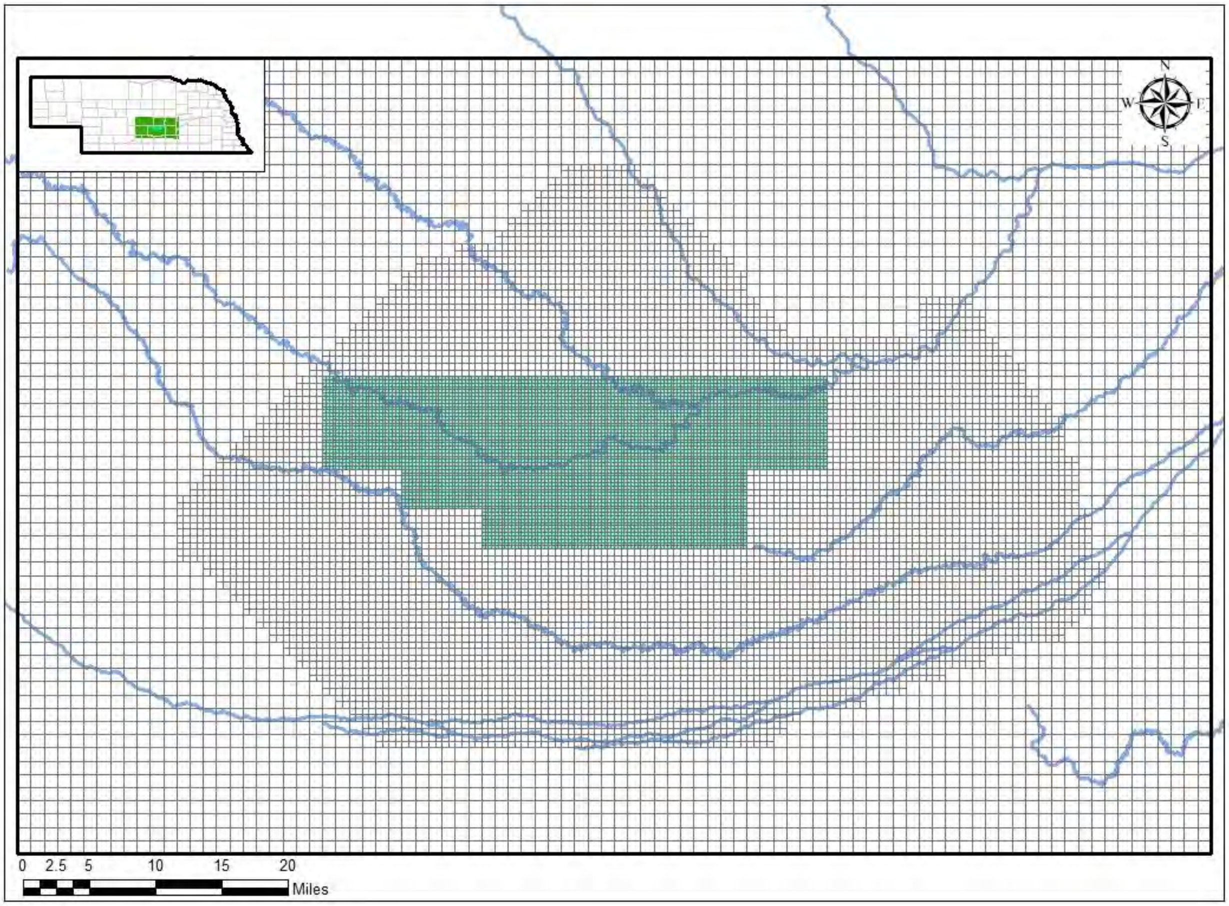


Figure 15. Network of nodes in the BCM.

Defining the area to be modeled is a first step in model development. For the BCM RSWB, three sets of grids were used to define the model area: the groundwater model node network, the BCM 40-acre grid, and a sampled portion of the COHYST 160-acre grid.

The BCM groundwater model employs an unstructured grid containing 16,386 nodes (Figure 15). The size of the model nodes varies between 40 acres, 160 acres, and 640 acres across the active model domain. The RSWB uses the node network to compile, organize, and share model results with the groundwater model.

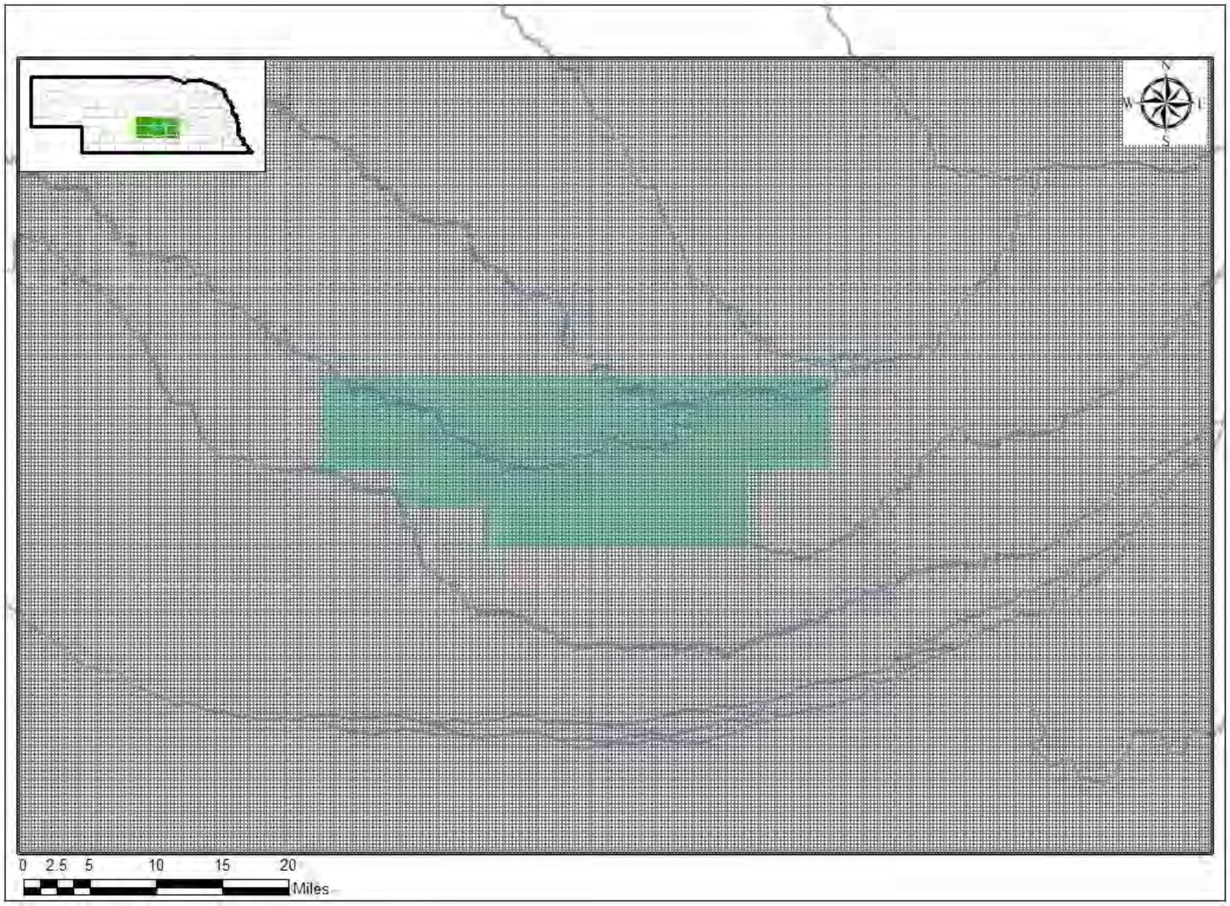


Figure 16. 40-acre BCM grid network

The BCM 40-acre grid (Figure 16) was used to create and organize the RSWB model inputs[24]. The grid consists of 86,400 cells of 40 acres organized in 240 rows and 360 columns.

[24] The 40-acre cell is the smallest sized groundwater model node size.

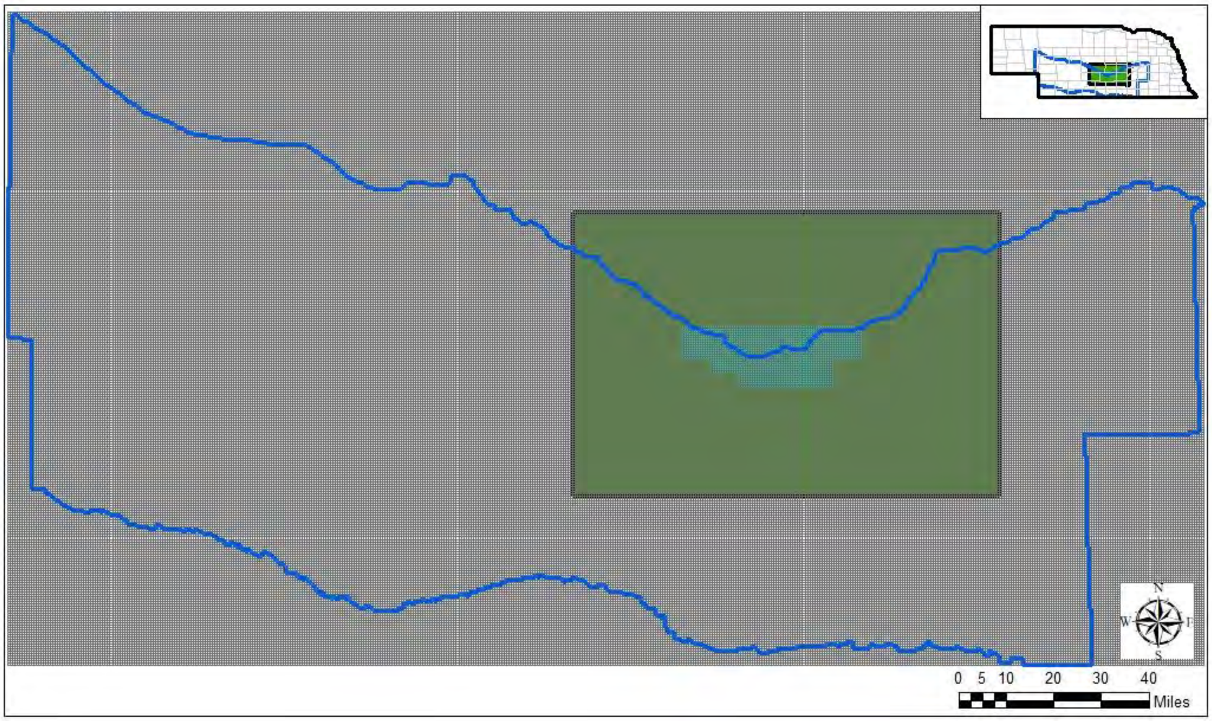


Figure 17. The BCM 160-acre grid overlaying the COHYST model grid.

The BCM 160-acre grid (Figure 17) was developed to organize the Water Balance Parameter (WBP) directly from the COHYST model. It consists of 21,600 cells with a one-to-one relationship with the COHYST model cells overlaying the BCM model domain.

6.2. Model Period

The BCM model was developed from January 1960 through December 2020. The BCM model includes 732 monthly stress periods.

6.3. Data Management Zones

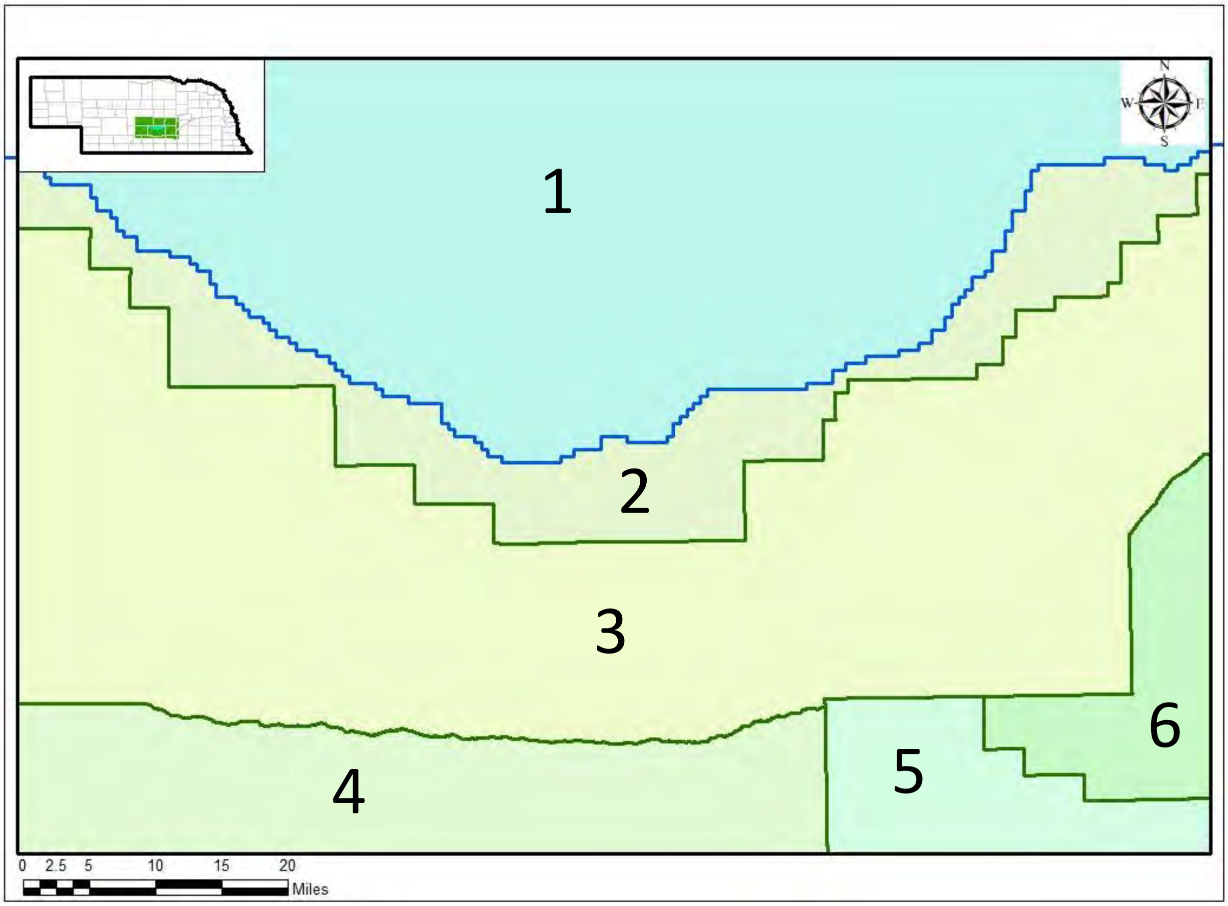


Figure 18. BCM Data Management Zones

The purpose of Data Management Zones is to organize the extents of the model based upon available input sources. For the BCM the primary driving input is the shape, form, and temporal extent of the available land use. The result is six data management zones (Figure 18).

1. Lower Loup Natural Resource District – Inactive COHYST model area
   - Defined by the political boundary of the LLNRD, the COHYST active area and the BCM model boundary
2. Lower Loup Natural Resource District – Active COHYST model area
   - Defined by the political boundary of the LLNRD, the COHYST active area, and the BCM model boundary
3. Central Platte Natural Resources District
   - Defined by the political boundary of the CPNRD and the BCM model boundary
4. Tri-Basin Natural Resources District in the Little Blue River drainage area
   - Defined by the political boundary of the TBNRD and the BCM model boundary
5. Little Blue Natural Resources District
   - Defined by the political boundary of the LBNRD and the BCM model boundary

6. Upper Big Blue Natural Resources District
   - Defined by the political boundary of the UBBNRD and the BCM model boundary

6.4. Soils

Soil characteristics influence how crops respond to climatic and management conditions. Soils can be thought of acting like miniature reservoirs that store and release water for vegetative growth (ET), allow the water to drain as recharge, or restrict the water from infiltrating resulting in runoff.

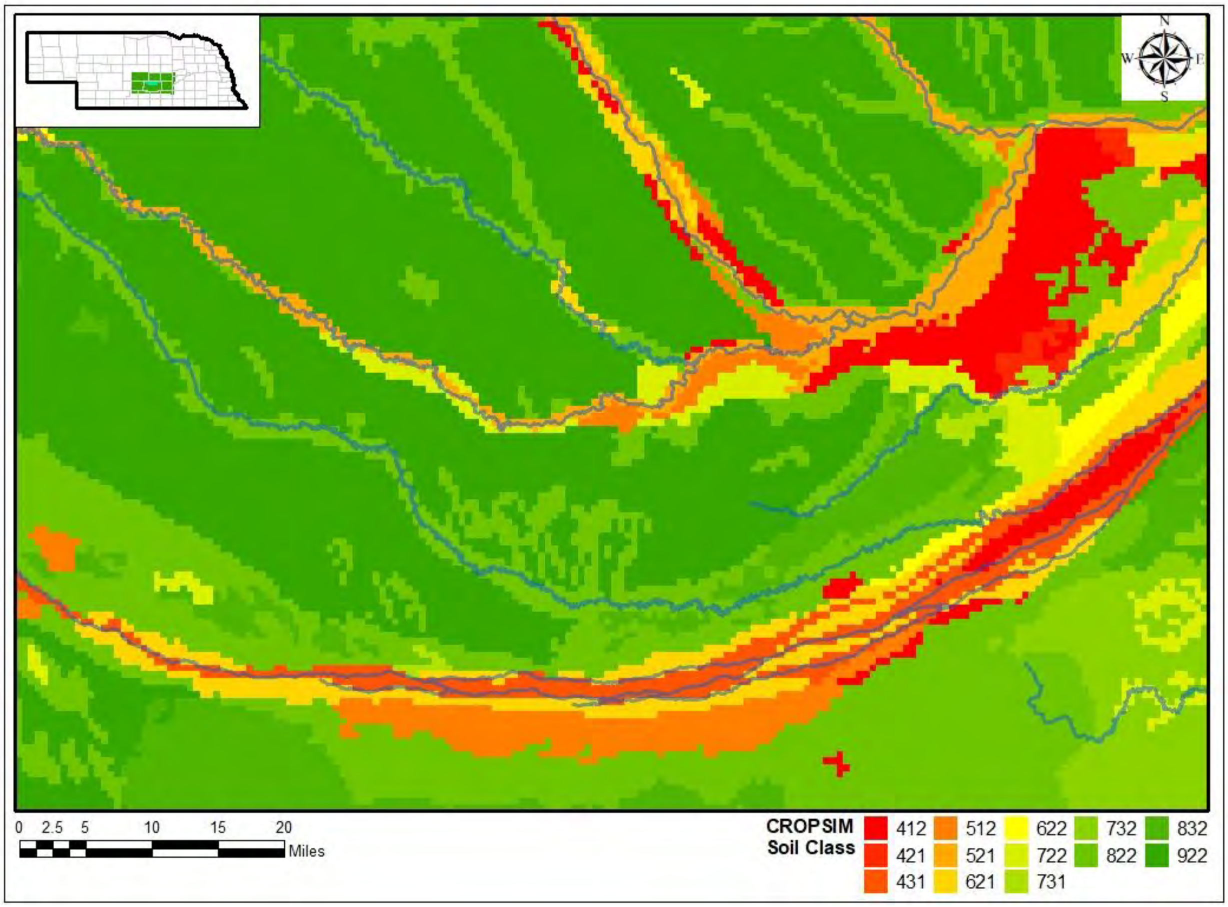


Figure 19. BCM soil – CROPSIM soil class on 160-acre cell.

Within the RSWB model, a cell's assigned soil type served as a link to the results from the CROPSIM model. To build this link, each cell was assigned a CROPSIM soil class. This was accomplished in a three-step process. The first step was to identify the soils present in the model domain. Statsgo2, from the Natural Resources Conservation Service (NRCS), is a database which contains the spatial distribution of soils. Within the model domain, numerous Statsgo2 soils classifications are present. To simplify the modeling process, the soils were grouped together with other soils which exhibit similar properties. To maintain congruency with the CROPSIM modeling practices, three characteristics were used: water holding capacity, hydrologic soil group, and distance to groundwater. Next the predominant soil class within each cell was determined. This was accomplished by overlaying the COHYST model grid, computing the area of each soil within each cell, and identifying the prominent class. Finally, the COHYST soils map was sampled to retrieve the BCM soils map. This process resulted in 13 soil classes (Figure 19).

6.5. Climate

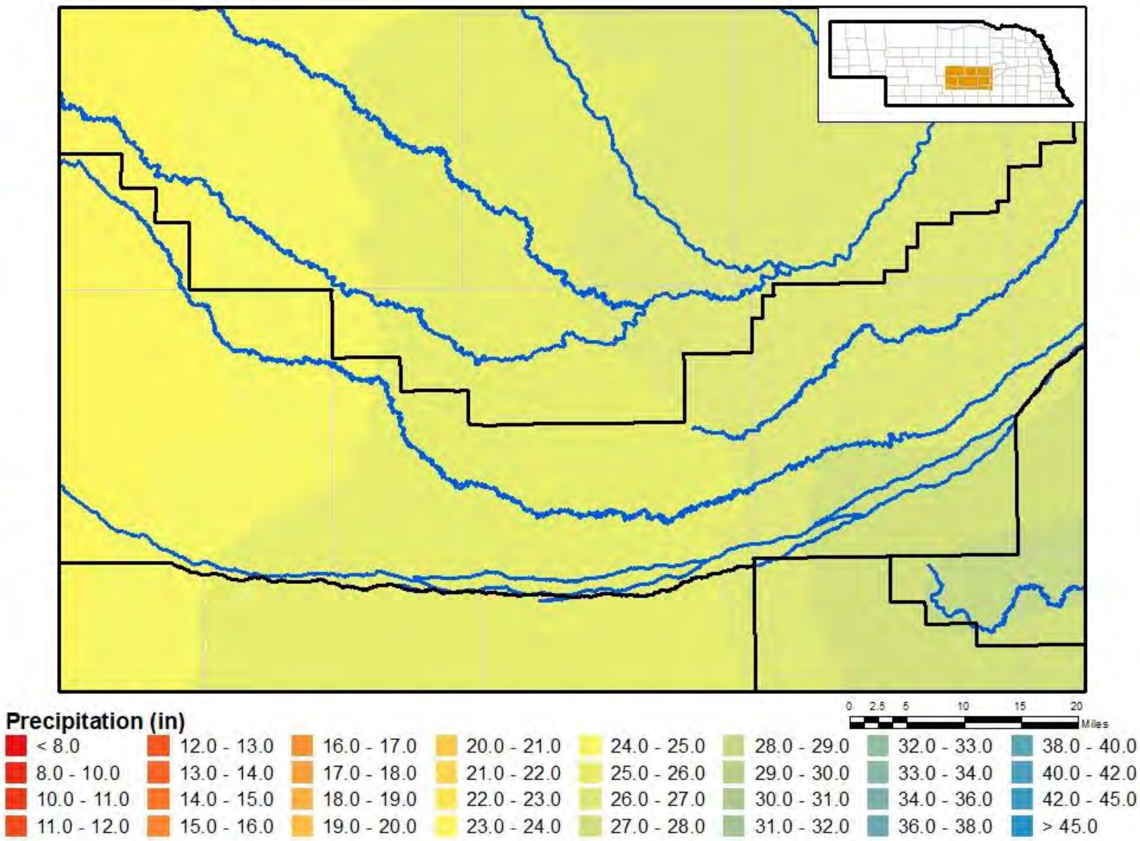


Figure 20. Average annual precipitation in the BCM 1960-2020 (in).

Climate conditions greatly influence vegetive growth; and thus, are a significant input into the CROPSIM model. Average annual precipitation in the model domain ranges from 23.0 to 28.0 inches and 24.7 to 26.5 in the focus area, with Figure 20 showing the distribution of the average annual precipitation.

The BCM model uses the same climate input as the Robust Review 2023 COHYST model[25]. This process utilizes three different sources of weather data:

1. National Weather Service and Cooperative Observers Program Stations (NWS\COOP) – 1960-1996
    - Sampled at weather station location
2. NRCC Interpolated Grid (ACIS Grid 1) – 1997-2001
    - Sampled on a 25-mile TIN

[25] Further information on the retrieval and development of this information can be found in Chapter 5 of the COHYST 2010 documentation and the COHYST Climate Analysis documentation.

3. PRISM (ACIS Grid 21) – 2002-2020
    - Sampled on a 25-mile TIN

Precipitation, maximum temperature, and minimum temperature were retrieved from each source. The NWS\COOP weather data was retrieved at the physical location of the station. PRISM and ACIS grid 1 each consist of a continuous spatial coverage. To retrieve the weather data, the spatial coverage is sampled at a series of locations in and surrounding the active model domain. A TIN spaced 25 miles apart was chosen for the pattern of simulation points. This distribution of simulation points was then used to sample the data from PRISM and ACIS grid 1.

Upon retrieving the data from either source, the weather data was reviewed for completeness and quality. Following the quality control efforts, the information was run through the climate model and prepared into .WEA files for use in the CROPSIM model. Figure 20 shows this information interpolated between the three nearest simulation points for each BCM model 160-acre cell.

6.6. Water Balance Parameters (WBPs)

The weather data from each simulation point was run through the CROPSIM model to simulate the water balance for each crop, soil, tillage category, and irrigation as described in Section 4.2. The spatial and temporal distribution model in conjunction with the soils distribution, was used to distribute the

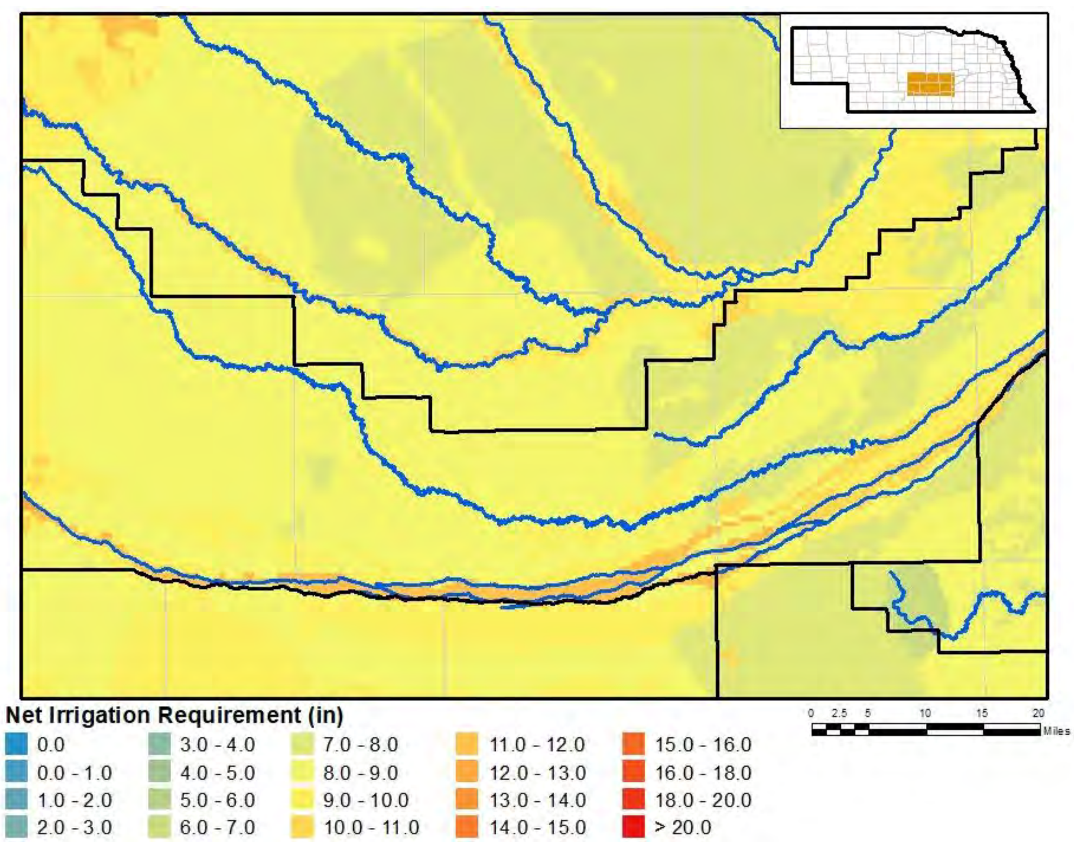


Figure 21. Average net irrigation requirement for corn in the BCM model domain 1960-2020.

water balance results of the CROPSIM model to each cell in the COHYST model grid. This process created annual files for each WBP (precipitation, NIR, ET, RO, DP) for each combination of crop and irrigation method. Figure 21 represents this process by showing the average annual NIR for corn in units of ac-in/ac (which reduces to inches). Within the model domain, values range from 6.8 to 12.3 in with an average of 8.4 in[26]; this range narrows to 7.8 to 10.5 inches in the focus area with an average of 8.5 in. The image depicts the influence of both weather data and soil class by mimicking the patterns in Figure 20 and Figure 19 respectively.

6.7. Land Use

Land use inputs specify the area and types of crops being grown in the watershed; as well as if they are being irrigated and from which source type (dryland, groundwater only, surface water only or comingled). In addition to the source type, surface water only and comingled lands are linked to the servicing surface water irrigation district. This definition is used to determine surface water irrigation supplies, the initial water balance parameters, and scale the point results to the field level.

The BCM includes ten crop classes.

1. Corn
2. Soybeans
3. Sorghum
4. Alfalfa
5. Winter Wheat
6. Pasture
7. Corn after soybeans in rotation
8. Soybeans after corn in rotation
9. Fallow
10. Miscellaneous

Within the BCM each Data Management zone has a corresponding set of land use input files. The input data sets were developed combining the information from a variety of regional watershed models. The data sources and temporal scope of the data are as follows[27]:

1. Lower Loup Natural Resource District – Inactive COHYST model area
    - 1960-2012 CeNEB Model
    - 2013-2020 LPRBC INSIGHT (2021)
2. Lower Loup Natural Resource District – Active COHYST model area
    - 1960-2010 COHYST Model
    - 2011-2012 consisted of repeating the 2010 land use

[26] This is an estimate of the expected amount of net irrigation needed by the crop if grown in the location, it does not imply that the crop is being grown there.
[27] For repeated land use inputs, the acres in the crop classes in the corn-soybean rotation are swapped.

- 2013-2020 LPRBC INSIGHT (2021)

3. Central Platte Natural Resources District
   - 1960-2010 COHYST Model
   - 2011 consisted of repeating the 2010 land use
   - 2012-2020 2023 Robust Review COHYST update
4. Tri-Basin Natural Resources District in the Little Blue River drainage area
   - 1960-2010 COHYST Model
   - 2011-2020 2023 Robust Review COHYST update
5. Little Blue Natural Resources District
   - 1960-2009 COHYST Model
   - 2010-2018 BRBM Model
   - 2019-2020 consisted of repeating the 2018 land use
6. Upper Big Blue Natural Resources District
   - 1960-2009 COHYST Model
   - 2010-2018 BRBM Model
   - 2019-2020 consisted of repeating the 2018 land use

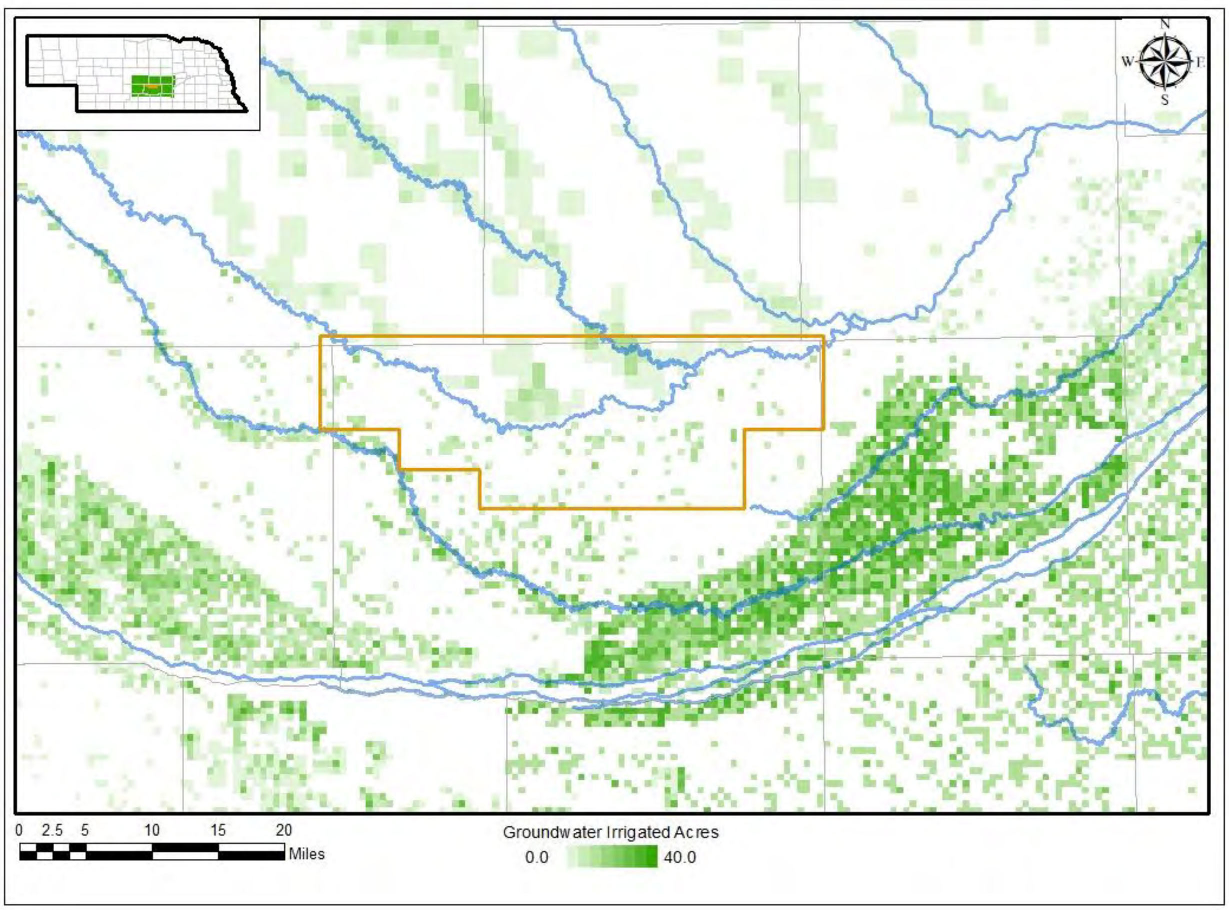


Figure 22. Development of groundwater only irrigated acres – BCM model 1960.

Over the historical period of the model, the area in the BCM has seen a significant increase in irrigation development. Since 1960 (Figure 22), irrigated acres have increased from 360,000 to just under 1.4 million acres in 2020 (Figure 23), with approximately 90% of this increase from groundwater only acres (Figure 24).

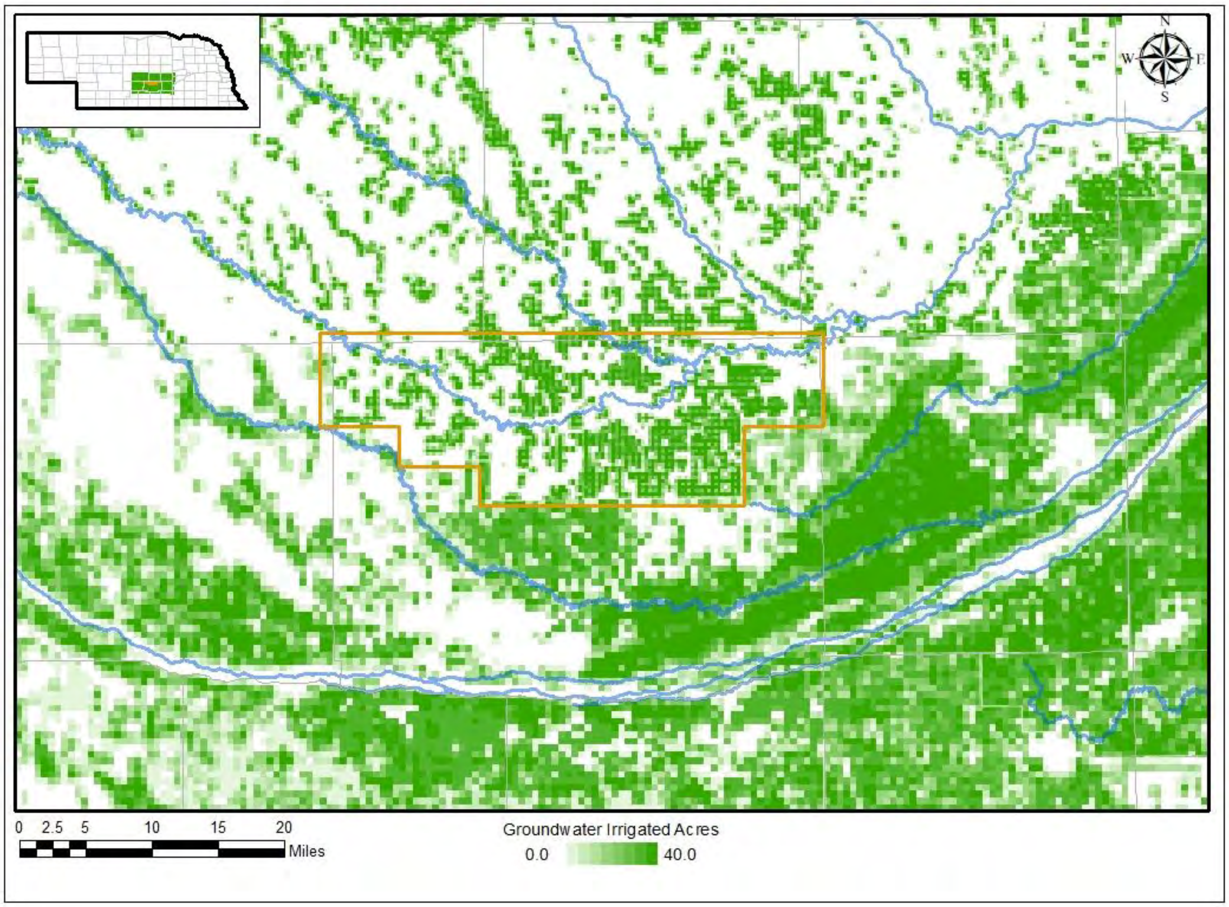


Figure 23. Development of groundwater only irrigated acres – BCM model 2020.

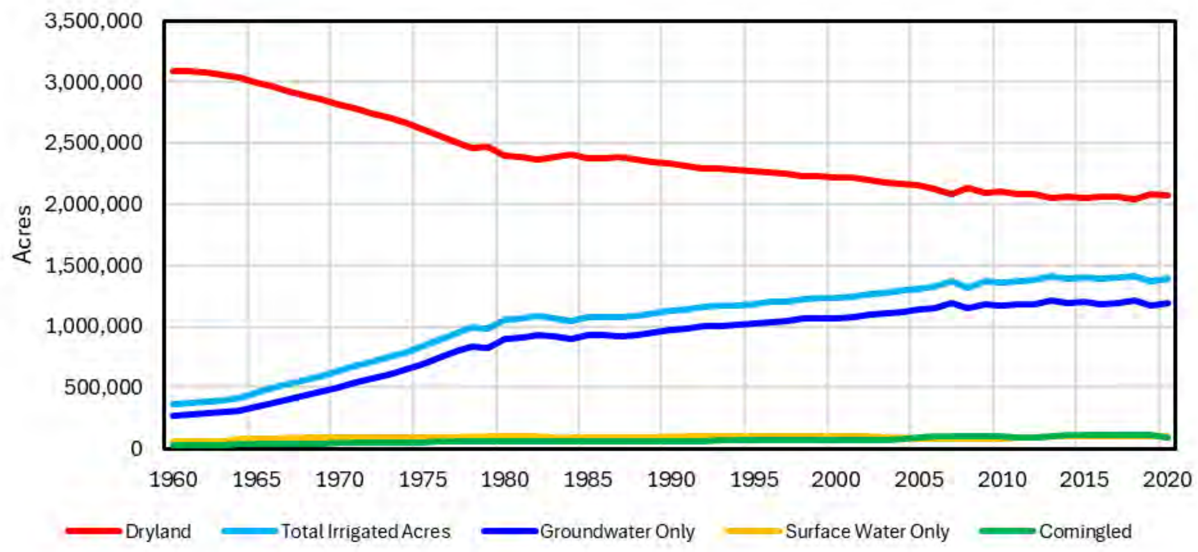


Figure 24. Development of irrigated acres within the BCM model domain.

Examining only the BCM focus area (Buffalo County in the LLNRD, Figure 25), irrigate land use increased from just under 8,000 acres in 1960 to approximately 85,000 acres in 2020.

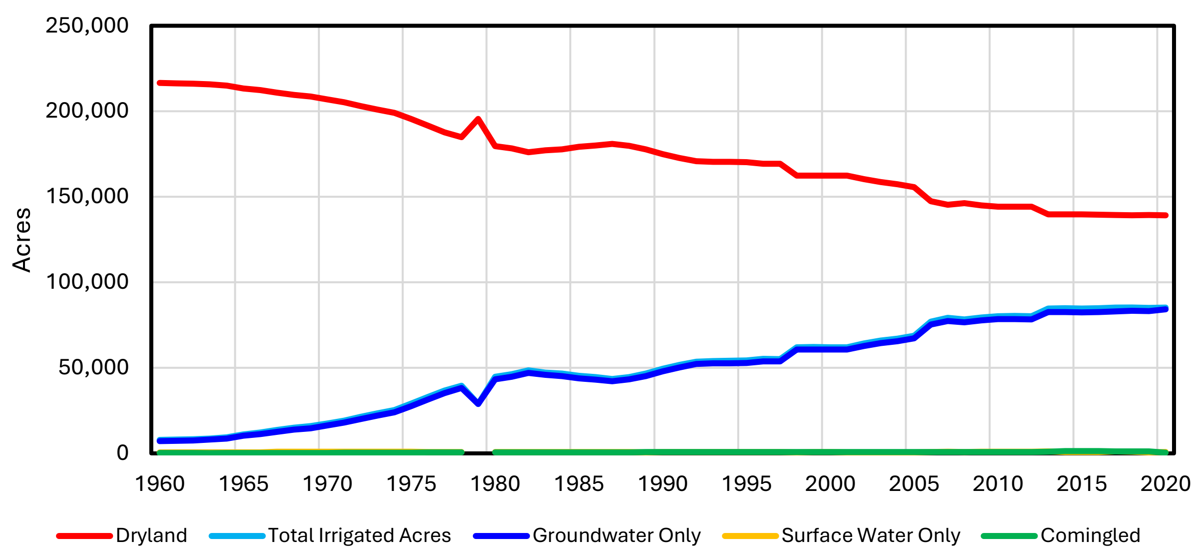


Figure 25. Development of irrigated acres in the model focus area: Buffalo County within the LLNRD

6.8. Model Regions

The RSWB employs input regions to aid in the spatial calibration of the model. The input regions allow for adjustments to sub-areas, independent of the rest of the model domain, to reflect significant localized conditions. The RSWB uses two types of input regions: runoff zones, and coefficient zones.

6.8.1. Runoff Zones

Runoff zones represent a delineation of the model domain by select drainage basins. These areas consist of the land area which drains to a specific point designated by a stream gauge. The BCM RSWB model consists of sixteen runoff zones (Figure 26) with the balance of the model domain assigned to a generic zone.

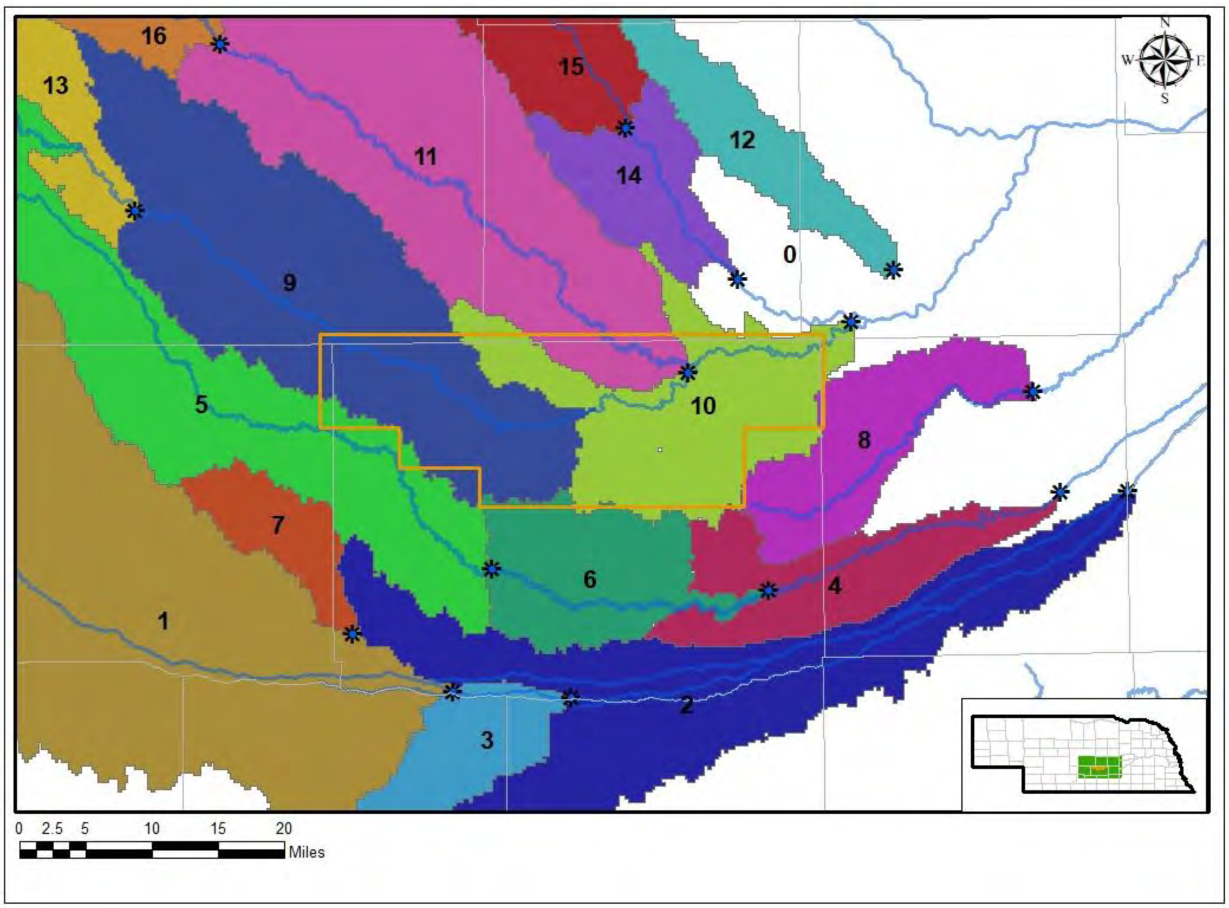


Figure 26. BCM Runoff Zones.

The runoff zones are used to calibrate the portion of the field runoff which contributes to stream flow. The runoff zones use the loss per mile parameters to regulate the rate at which runoff is lost during transit from the field to the stream gauge. The runoff totals for each zone are compiled for each stress period and provided for use in the surface water operations model and the groundwater model. It is combined with the simulated baseflow for total flow analysis in the river.

6.8.2. Coefficient Zones

Coefficient Zones represent a geographical group of cells which exhibit similar water balance responses. The BCM RSWB adopted the COHYST coefficient zone definition. COHYST includes eighteen coefficient zones, of which seven zones are present in the BCM model domain (Figure 27). Zones 2-4, and fifteen represent Platte River surface water irrigation district service areas. Zone 17 is a two-mile buffer around the Platte River. Zone 1 is the remaining area north of the drainage basin divide between the Platte River Basin and the Republican and Blue River Basins. Zone 16 is the remaining area to the south of this divide. These zones were created to capture the unique local conditions and represent control areas for a variety of model functions.

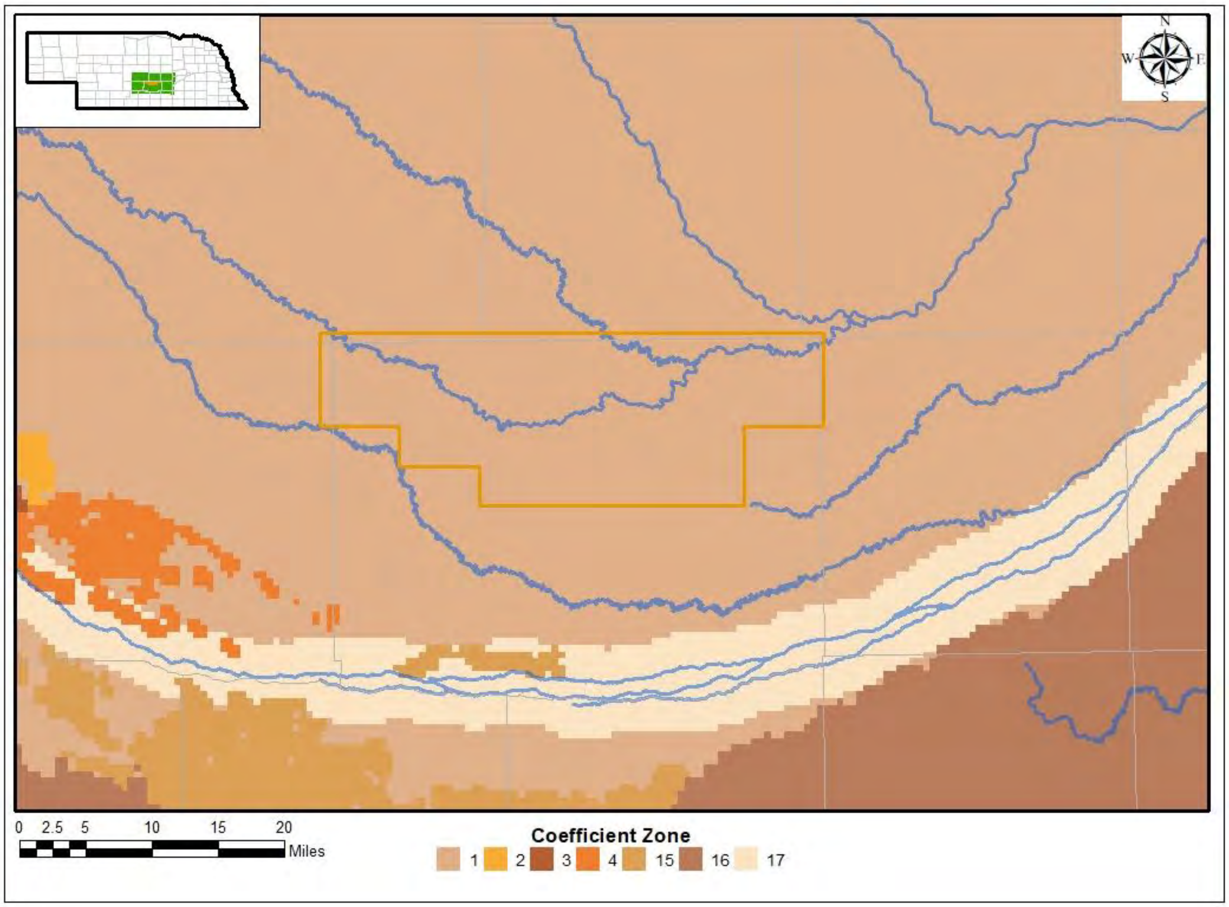


Figure 27. BCM coefficient zones.

Application Efficiency

The application efficiency of an irrigated system is the ratio of net irrigation to gross irrigation. It is dependent upon the techniques used to physically apply water to the field. Within the BCM RSWB model, the method for applying irrigation to individual fields was not defined, therefore application efficiency was assigned based upon irrigation source type (groundwater or surface water).

The RSWB allows the application efficiency to trend over time within each coefficient zone (Equation 41). This allows the model to capture the influence of improved technology and impact of better irrigation management practices as well as differing rates of adoption on the spatial scale. The trending process uses two flat values book-ending a trended period between two defined years.

$$AE = \begin{cases} AE_{ini} & year \leq YR_{AE,ini} \\ AE_{ini} + \left(AE_{fin} - AE_{ini}\right)\left(\frac{year - YR_{AE,ini}}{YR_{AE,fin} - YR_{AE,ini}}\right) & YR_{AE,ini} < year < YR_{AE,fin} \\ AE_{fin} & year \geq YR_{AE,fin} \end{cases} \quad (41)$$

AE	Application efficiency
AE_{ini}	The initial application efficiency
AE_{fin}	The final application efficiency
Year	The relevant year
$YR_{AE,\,ini}$	The year the trending process begins
$YR_{AE,\,fin}$	The year the trending process ends

Application efficiency is controlled by the coefficient zone. The BCM adopted the AE definitions from the COHYST model, summarized in Table 1.

Table 1. Application Efficiency Terms

Zone	Irrigation Source Type	Initial AE	Final AE	Beginning Trend Year	Ending Trend Year
1-7, 15, 16	GW	0.70	0.85	1970	1993
1-7, 15, 16	SW	0.65	0.65	1970	1993
17	GW	0.65	0.70	1970	1993
17	SW	0.65	0.65	1970	1993

Runoff Partitioning Factor

The runoff partitioning factor (Equations 38-39) controls the partitioning of runoff transmission losses between ET and recharge. This partitioning factor is controlled separately for each coefficient zone.

Zone Coefficients

Each coefficient zone is further sub-divided by soil type and crop. Each coefficient zone sub-group contains a set of RSWB adjustment coefficients used during calibration of the watershed model. There are thirteen different adjustment coefficients (described below). The BCM adopted the coefficient values from the COHYST model.

1. Irrigation Target ($Target_{NIR}$): Specifies the portion of the net irrigation requirement to be met by irrigation when volumes are simulated.

2. Dryland ET Adjustment Factor ($ADJ_{ET, dry}$): Adjusts ET for the difference between the results from the soil water balance model and realized field conditions for dryland crops

3. Irrigated ET Adjustment Factor ($ADJ_{ET, irr}$): Adjusts ET for the difference between the results from the soil water balance model and realized field conditions for irrigated crops

4. Surface Loss Fraction – Groundwater (FSL_{GW}): Specifies a percentage of applied ground water irrigation that is lost to non-beneficial consumptive use

5. Surface Loss Fraction – Surface water (FSL_{SW}): Specifies a percentage of applied surface water irrigation that is lost to non-beneficial consumptive use

6. Dryland ET to Runoff ($DryET_2RO$): Specifies the portion of the dryland ET adjustment that is converted to runoff with the remainder becoming deep percolation

7. Deep Percolation Adjustment (ADJ_{DP}): Adjusts the deep percolation results from the soil water balance model with the change being converted to non-beneficial consumptive use

8. Runoff Adjustment (ADJ_{RO}): Adjusts the runoff results from the soil water balance model with the change being converted to non-beneficial consumptive use

9. Maximum Partitioning Factor (RO_{max}): Maximum value of the irrigated partitioning factor ($RODP_{wt}$) used to divide unassigned water between runoff and deep percolation

10. Minimum Partitioning Factor (RO_{min}): Minimum value of the irrigated partitioning factor ($RODP_{wt}$) used to divide unassigned water between runoff and deep percolation

11. Deep Percolation Lower Threshold (DP_{ll}): Sets the lower limit at which the RSWB model begins to taper off annual deep percolation rates

12. Deep Percolation (DP_{cap}): Sets the maximum rate of deep percolation the program will allow

13. Runoff Weighting Factor (RO_fDP): Weighting factor used to influence the effect of runoff on the irrigation partition factor ($RODP_{wt}$)

6.9. Surface Water Irrigation Districts

Surface water irrigation districts represent a collection of irrigated lands which have a defined water right and collectively extract water from one or more points of diversion from the river. The RSWB uses the collection definitions to amass estimates of demands for surface water irrigation and distribute surface water deliveries from the headgate to the fields. Within the BCM there are eight surface water irrigation districts located wholly or partially within the active domain (Figure 28). Of these districts, three are sourced from the Loup Rivers and five divert from the Platte River.

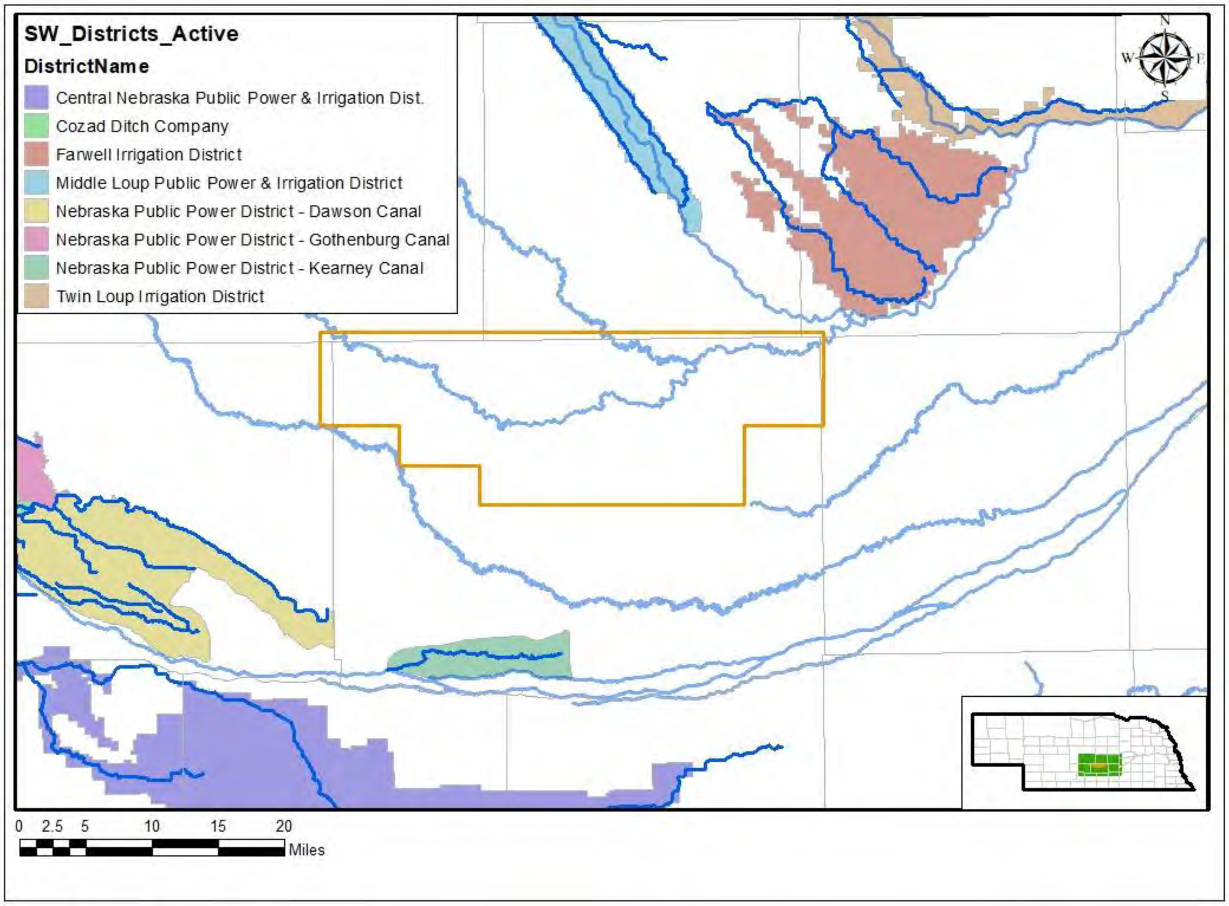


Figure 28. Surface Water Irrigation Districts in the BCM active area.

Within the RSWB there are three components of the water balance specifically related to the surface water irrigation districts: field deliveries, canal seepage, and lateral losses. The methodology used to implement this information varied with the districts.

6.9.1. Platte River Canals

The source material for the canals diverting from the Platte River is derived from the COHYST STELLA model results[28]. The STELLA model includes five canals which divert from the Platte River: Cozad, Dawson, Gothenburg, Kearney, and CNPPID.

Within COHYST, the demand for the entire surface water irrigation district was estimated. These demands were provided to the STELLA model, which determined the available supply of water in the river which was diverted at each headgate. It further divided this supply between main canal seepage, on-farm deliveries, and returns. Main canal seepage was distributed along the canal reaches[29]. The on-farm deliveries were provided to the watershed model to be distributed to the lands serviced by the district; these volumes also include the volume of lateral losses between the main canal and the fields.

Within the BCM, only a portion of the total surface water irrigation district service areas and canals fall within the active domain. To accommodate this, the total COHYST supply is prorated between the BCM and non-BCM areas.

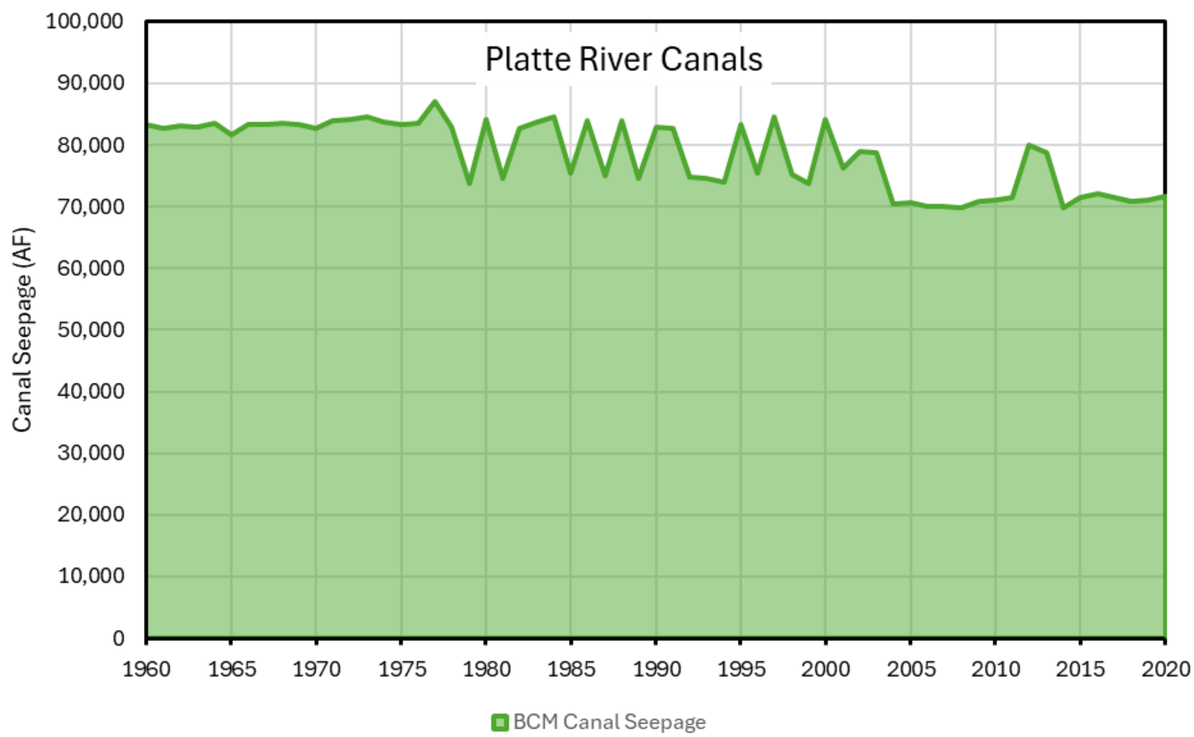


Figure 29. Platte River canal seepage within the BCM model domain.

[28] 2023 Robust Review Stella Model
[29] Multiple reaches can exist on a single canal.

Canal seepage was distributed to the active BCM cells proportional to the length of the reach in a cell to the total length of the reach[30] (Equation 42). Canal Seepage from the Platte River canals included in the BCM are shown in Figure 30.

$$Canal\ Seepage_{cell} = Canal\ Seepage_{reach} * \frac{Canal\ Length_{cell}}{Canal\ Length_{reach}} \quad (42)$$

The on-farm delivery supplies were prorated proportional to the canal's irrigation demand in the active BCM area to the total irrigation demand in the canal (Equation 43). Figures 30-34 show portion of the COHYST deliveries applied in the BCM model domain.

$$Canal\ Deliveries_{BCM} = Canal\ Deliveries_{COHYST} * \frac{Canal\ Demand_{BCM}}{Canal\ Demand_{COHYST}} \quad (43)$$

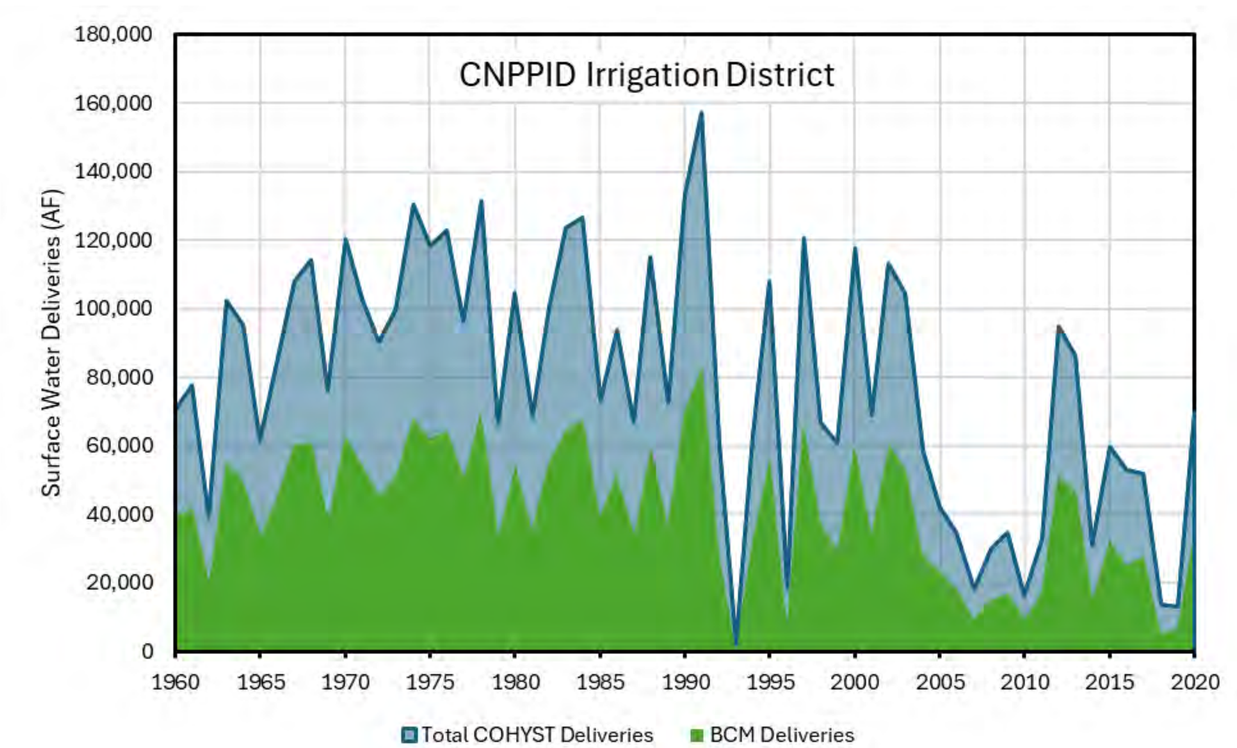


Figure 30. Surface water deliveries in the CNPPID Irrigation District within the BCM.

[30] Note: this is a deviation from the COHYST model where the total canal seepage in a reach is divided evenly amongst the underlying cells regardless of the length of the canal within the cell.

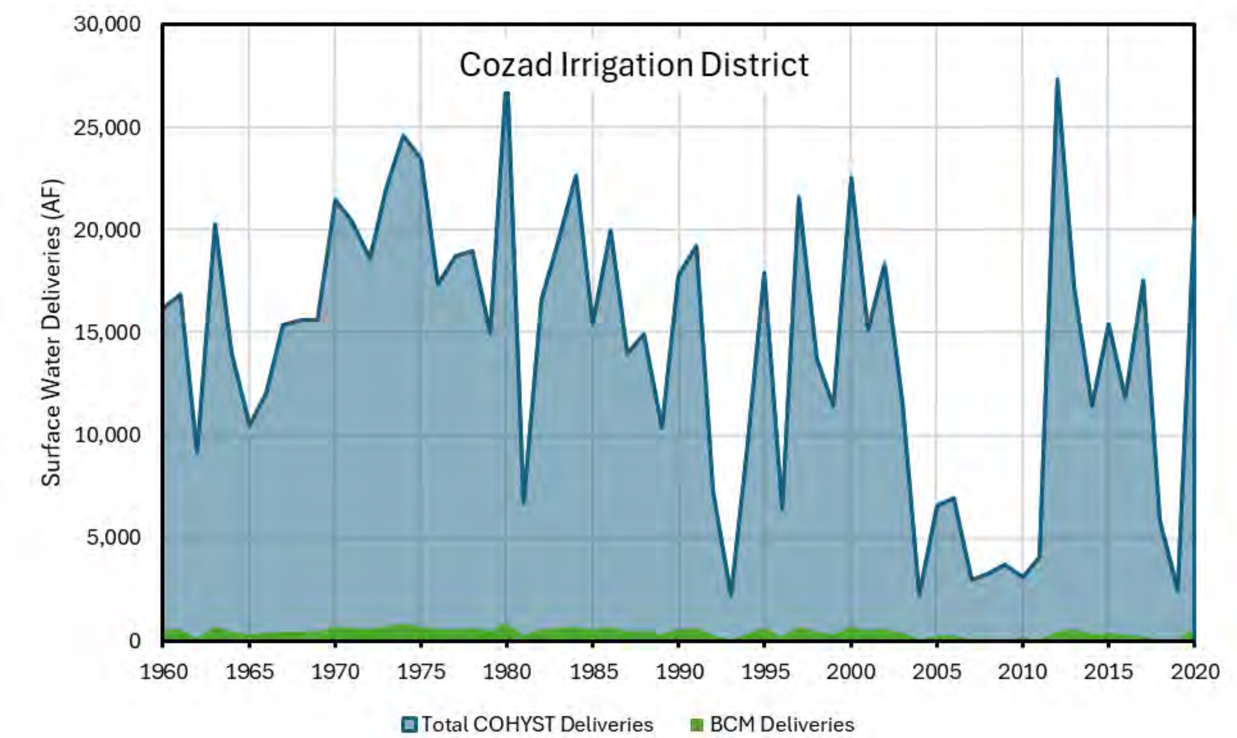


Figure 31. Surface Water deliveries in the Cozad Irrigation District within the BCM.

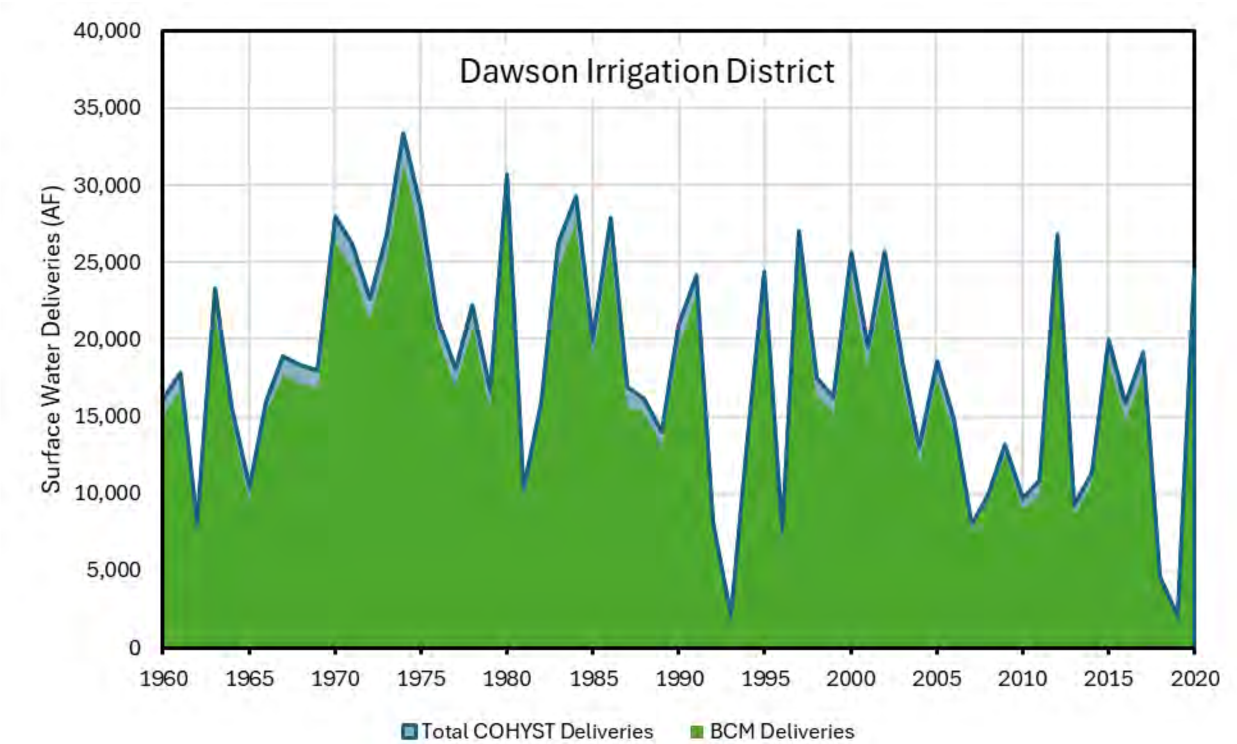


Figure 32. Surface Water deliveries in the Dawson Irrigation District within the BCM.

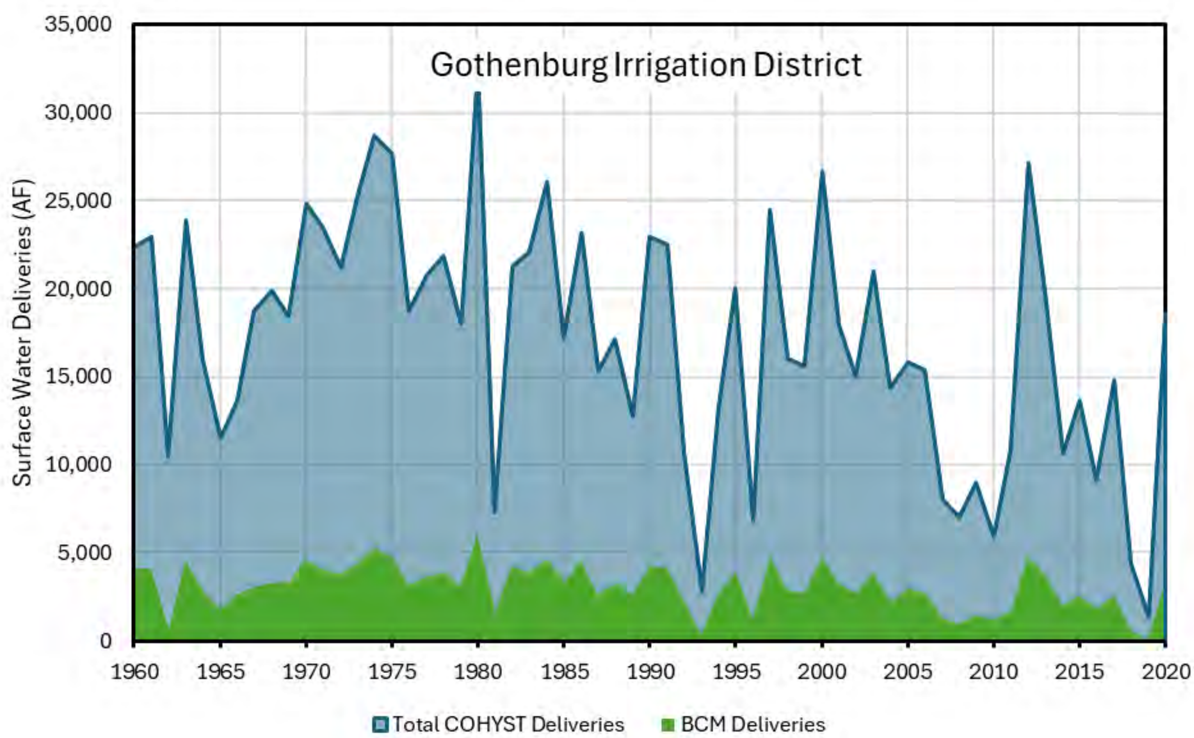


Figure 33. Surface Water deliveries in the Gothenburg Irrigation District within the BCM.

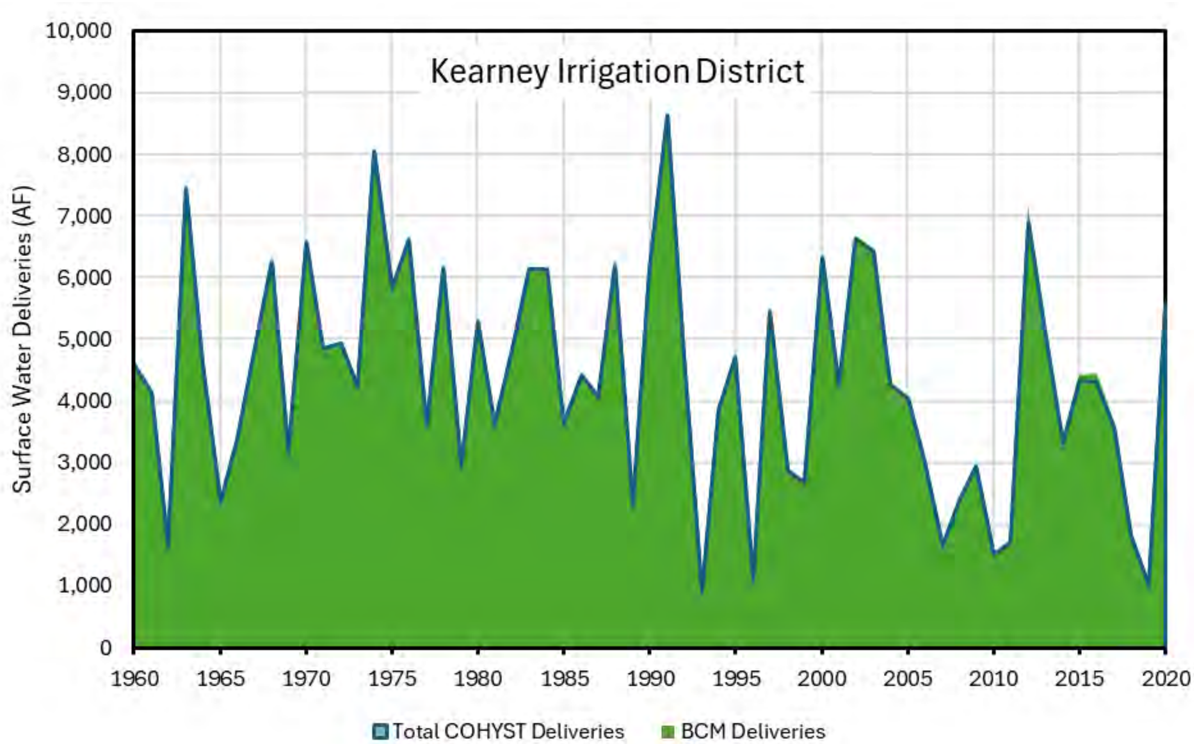


Figure 34. Surface Water deliveries in the Kearney Irrigation District within the BCM.

6.9.2. Farwell Irrigation District

The Farwell Irrigation District is located in central Nebraska, diverting from the Middle Loup River and the Sherman Reservoir. The source material for the Farwell Irrigation District was the United States Bureau of Reclamation annual reports. From the reports three items were extracted: on-farm deliveries (column 14), main canal losses (column 8) and lateral losses (column 11). Additionally, the reports included the serviced area. The USBR reports included data from 1967[31]-2002 and 2012-2018.

The missing annual volumes and the monthly distribution of those volumes were estimated from the available data (2003-2011; 2019-2020). The 2012-2018 serviced area was not included in the report. This area was estimated at 49,000 acres; the average number of acres reported 1993-2002. The per-acre depth of irrigation was computed for each year. Next, the annual precipitation rates (in/ac) were determined for the service area.

Multiple relationships between the precipitation and irrigation depth were analyzed (Figure 35), similar trends were observed over multiple dataset time periods. Ultimately, the 2012-2018 trend was chosen. The deciding factor was that the precipitation data for this trend used the same source[32] as the period being filled. Using this same period of time, the monthly distribution of deliveries was calculated from the average proportional deliveries in these years. This distribution is defined in Table 2.

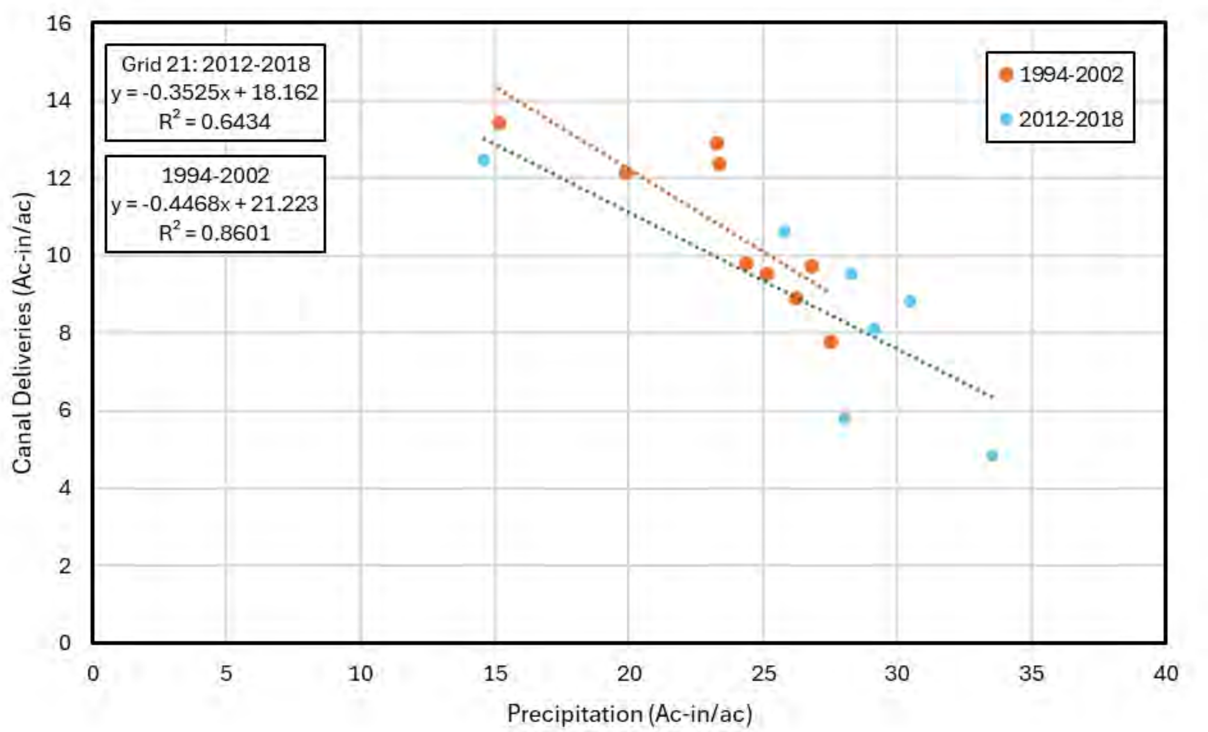


Figure 35. Relationship between precipitation and irrigation depth in the Farwell Irrigation District.

[31] 1967 is consistent with the completion of the Sherman Reservoir.

[32] ACIS Grid 21 PRISM

Table 2. Distribution of annual deliveries to month for filled data.

Month	Proportion of Deliveries
January	0.0
February	0.0
March	0.0
April	0.0
May	0.0
June	0.079
July	0.478
August	0.331
September	0.112
October	0.0
November	0.0
December	0.0

The next step in the process is to determine the volume of water applied within the BCM model domain. This was accomplished by comparing the USBR reported irrigated area to the surface water irrigated acre serviced by the canal in the BCM land use data set. If the BCM acres were less than the USBR acres, the volume was adjusted downward, otherwise the entire volume was applied over the serviced acres (Equation 44). The total and BCM applied volumes are shown in Figure 36.

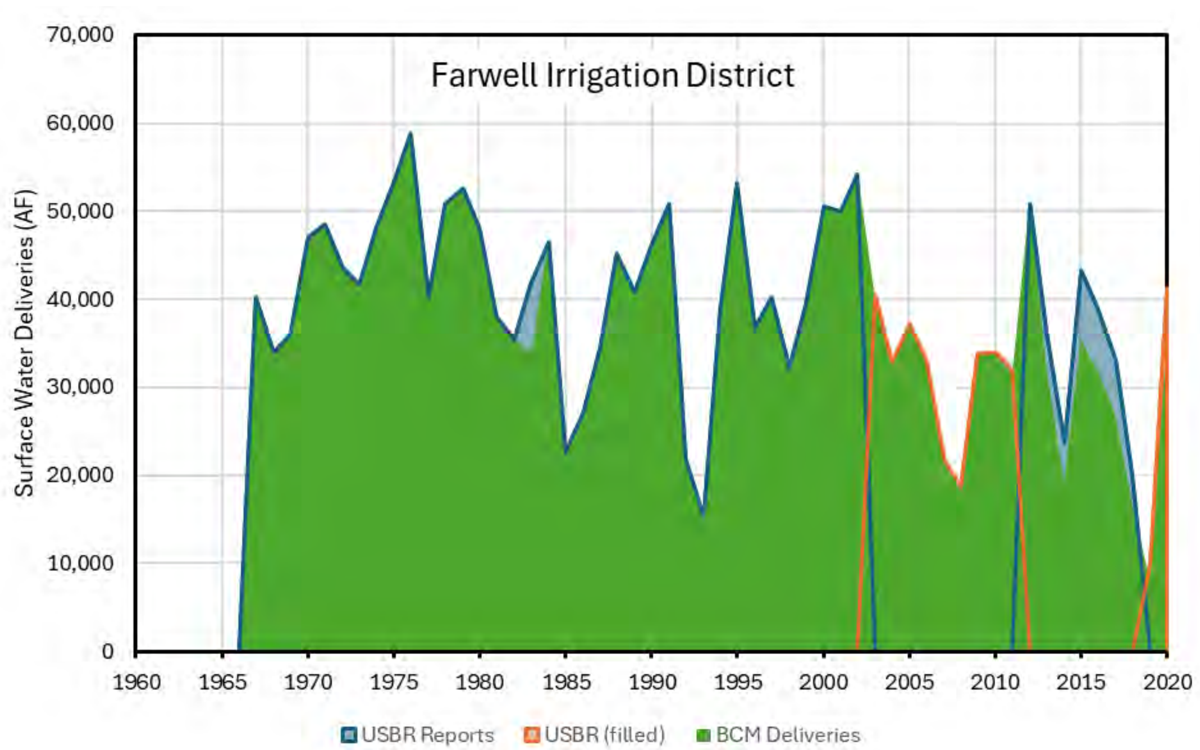


Figure 36. Surface Water deliveries from the Farwell Irrigation District applied within the BCM.

$$Canal\ Deliveries_{BCM} = Canal\ Deliveries_{Total} * \frac{Canal\ Acres_{BCM}}{Canal\ Acres_{total}} \quad (44)$$

Canal Deliveries	On-farm deliveries (AF)
Canal Acres	Area serviced by the district (acres)
BCM	Within the BCM model domain
Total	Canal totals

In the same manner, main canal seepage values were filled for the years 2003-2011 and 2019-2020. To estimate canal seepage volumes a relationship was developed between the canal on-farm deliveries and the canal seepage from the USBR data (Figure 37). This relationship was then applied to the canal deliveries estimate previously developed to fill the missing canal seepage values. These values were then distributed to monthly values using a distribution derived from the average 2012-2018 monthly distribution of canal seepage (Table 3).

The canal seepage was then distributed to the model grid along the length of the canals[33] proportionate to the length of the canal within a cell relative to the overall length of the canal (Equation 42). The annual volumes of Farwell canal seepage applied in the model relative to the total Farwell canal seepage are shown in Figure 38.

Table 3. Distribution of annual canal seepage to month for filled data.

Month	Proportion of Canal Seepage
January	0.0
February	0.0
March	0.0
April	0.0
May	0.03
June	0.40
July	0.30
August	0.21
September	0.06
October	0.0
November	0.0
December	0.0

[33] Main Canal, Central Canal, and South Canal.

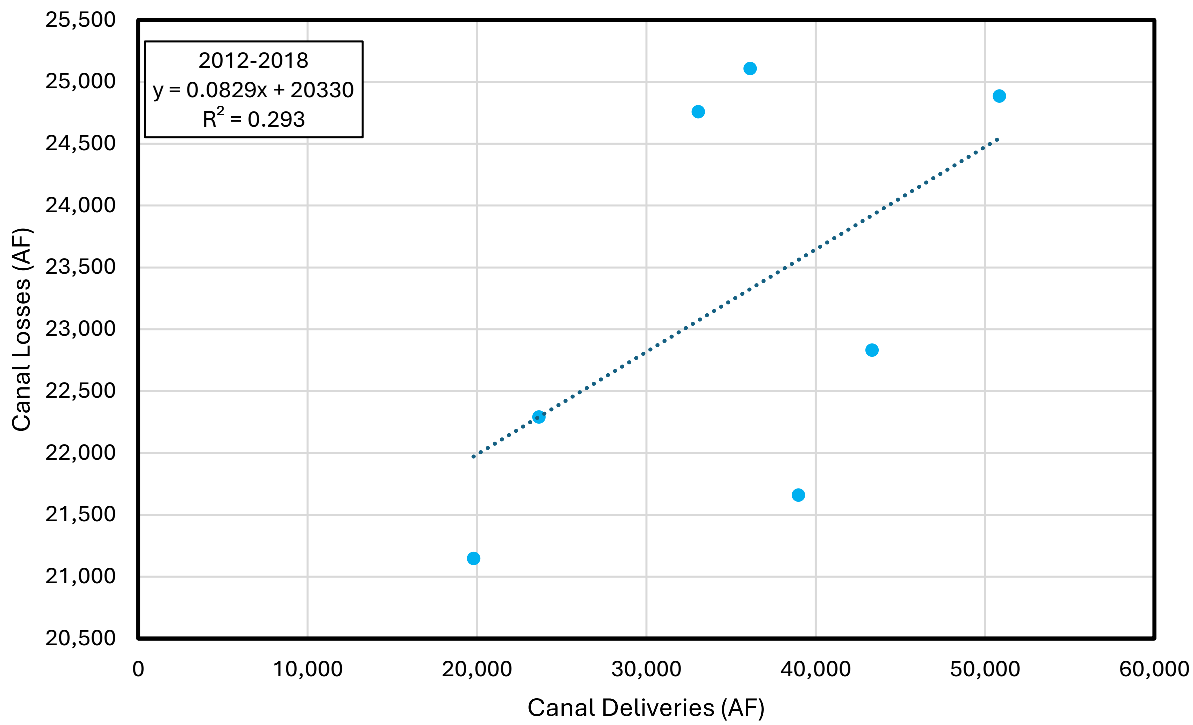


Figure 37. Relationship between canal deliveries and main canal seepage in the Farwell Irrigation District.

Finally, lateral seepage was also filled for the 2003-2011 and 2019-2020. To estimate lateral seepage volumes a linear relationship was developed between the canal on-farm deliveries and the canal lateral seepage from the USBR data (Figure 39). Investigation of the data showed that the pre-2002 data was higher than the post 2012 data. The data showed a change in pattern of the lateral seepage rates (AF/ac) during the 2012-2018 period; where the beginning of this period had seepage rates more consistent with the 1993-2002 period and the end of the period exhibited lower rate. Therefore, to fill the 2002-2011 period, the estimate was based upon the 1993-2002 data; and the 2019-2020 period was estimated using the 2012-2018 data. The estimated annual volumes were then distributed to monthly values based upon the average distribution during each of these periods (Table 4).

Table 4. Distribution of annual canal seepage to month for filled data.

Month	Proportion of Later Losses 1993-2002	Proportion of Later Losses 2012-2018
January	0.00	0.00
February	0.00	0.00
March	0.00	0.00
April	0.00	0.00
May	0.00	0.00
June	0.33	0.42
July	0.36	0.29
August	0.25	0.22
September	0.06	0.07
October	0.00	0.00
November	0.00	0.00
December	0.00	0.00

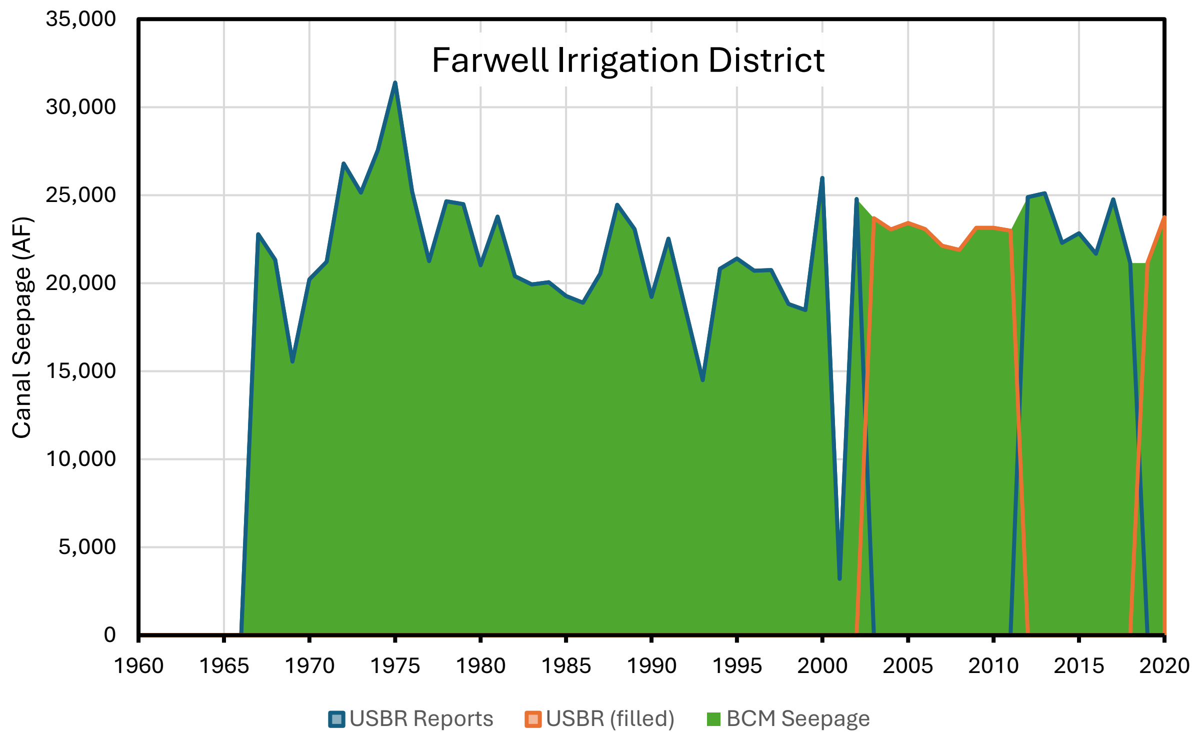


Figure 38. Main canal seepage in the Farwell Irrigation District applied in the BCM.

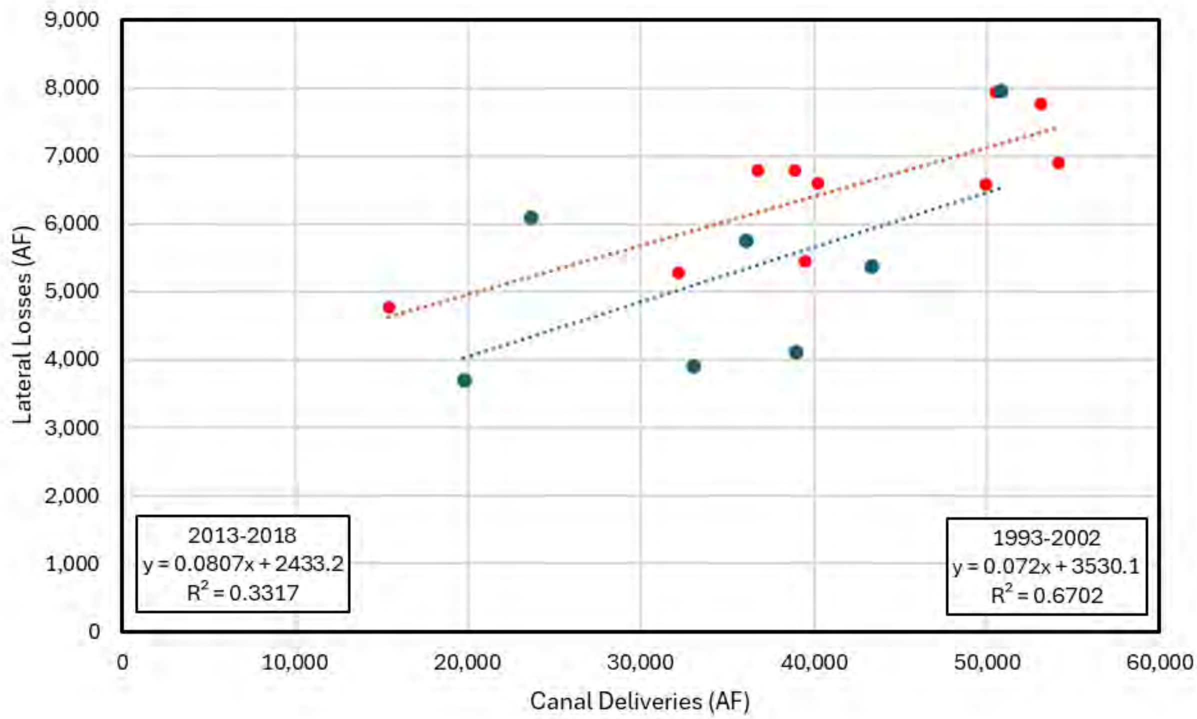


Figure 39. Relationship between canal deliveries and lateral seepage in the Farwell Irrigation District.

The lateral seepage was then distributed to the model grid. The seepage was applied in the same cell where the surface water irrigation was applied. The volume of seepage in each cell was proportioned by the quantity of surface water acres in the cell relative to the total number of surface water irrigated acres in the canal service area[34] (Equation 45). Total lateral loss volumes applied in the BCM area shown in Figure 40.

$$Lateral\ Loss_{cell} = Lateral\ Loss_{canal} * \frac{Acres_{cell}}{Acres_{canal}} \tag{45}$$

$Lateral\ Loss_{cell}$	Lateral loss placed in the cell (AF)
$Lateral\ Loss_{canal}$	Lateral loss total for the canal (AF) from USBR data[35]
$Acres_{cell}$	Surface water only or comingled acres serviced by the canal in the cell RSWB land use input
$Acres_{canal}$	Total surface water irrigation district serviced acres from USBR data

[34] Acres were used as the demand for surface water was unavailable for any area outside the BCM.
[35] The USBR acres data was used to account for irrigated acres which may fall outside the BCM model domain.

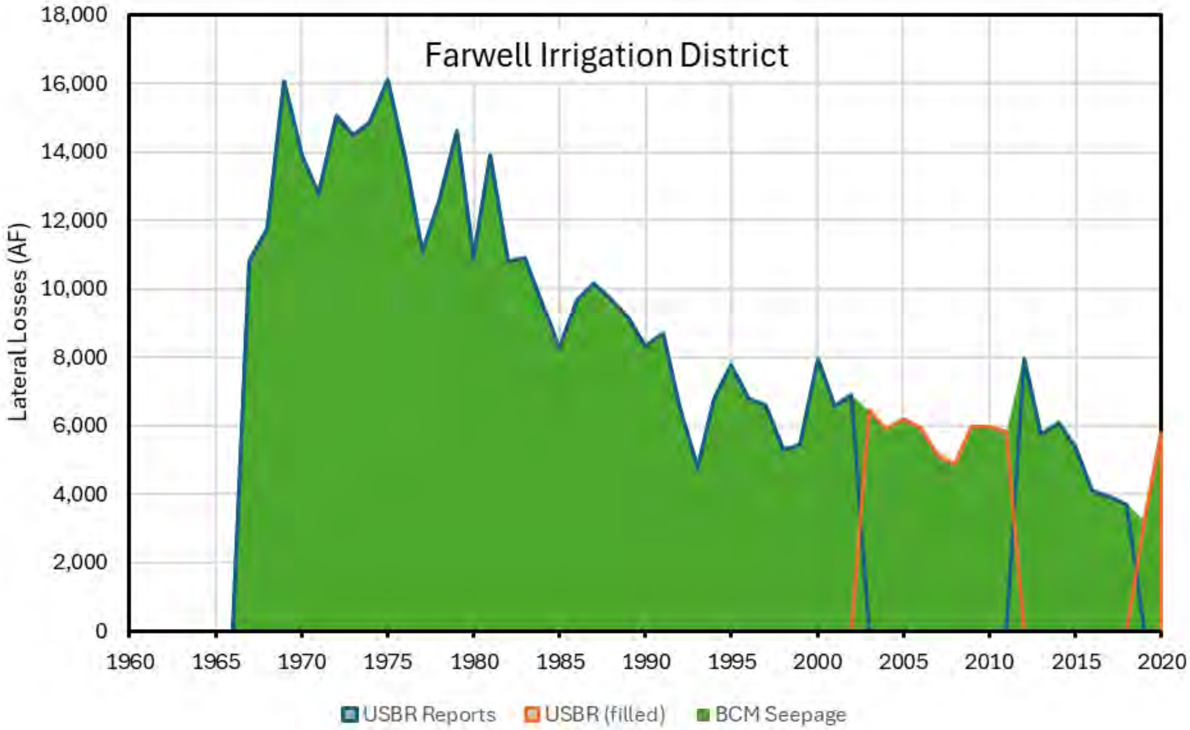


Figure 40. Lateral loss seepage in the Farwell Irrigation District applied in the BCM.

6.9.3. Fullerton Irrigation District

The Fullerton Canal is located in central Nebraska and part of the Twin Loups Irrigation District sourcing water from the Davis Creek Reservoir. The source material for the Fullerton Irrigation District was the United States Bureau of Reclamation annual reports. From the reports two items were extracted: on-farm deliveries (column 14) and main canal losses (column 8); no lateral losses (column 11) were reported for the canal. Additionally, the reports included the total serviced area. The USBR reports included data from 1992[36]-2020.

Only a portion of the Fullerton Canal service area is located within the BCM model domain. To account for this, the reported surface water delivery volumes were partitioned proportionally to the serviced acres within the model domain (Equation 44). The total and BCM applied volumes are shown in Figure 41.

Main canal seepage volumes were distributed to the model grid along the length of the canal proportionate to the length of the canal within a cell relative to the overall length of the canal (Equation 42). The annual volumes of canal seepage in the Fullerton Canal applied in the model relative to the total Fullerton Canal seepage area shown in Figure 42.

[36] 1992 is consistent with the completion of the Davis Creek Reservoir.

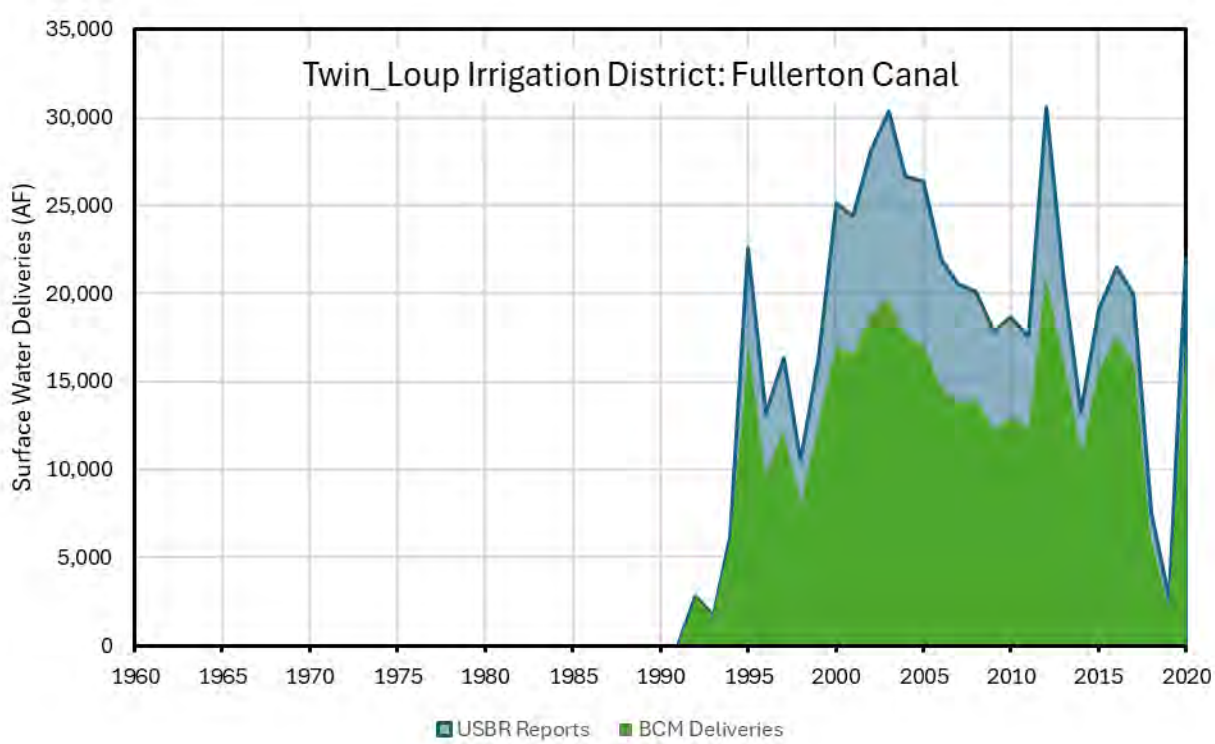


Figure 41. Surface water deliveries from the Fullerton Irrigation Canal applied within the BCM.

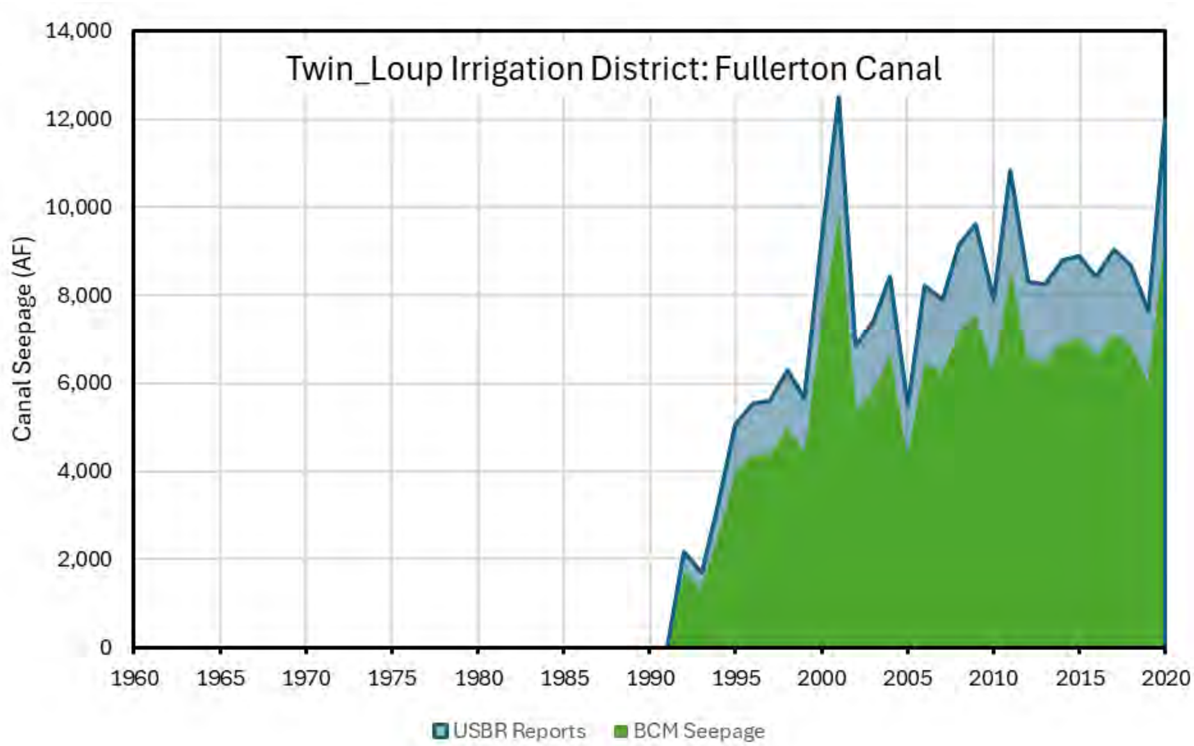


Figure 42. Main canal seepage in the Fullerton Irrigation Canal applied within the BCM.

6.9.4. Middle Loup Public Power and Irrigation District (MLPPID)

The Middle Loup Public Power and Irrigation District is located in central Nebraska, diverting from the Middle Loup River. MLPPID consists of four canals, with portions of Canals 3 & 4 overlaying the active BCM domain. MLPPID records were not available from the USBR. Therefore, irrigation supplies were assumed to meet estimated irrigation demands. The irrigation district has surface water rights dating back to the 1930s, therefore it was assumed that the canals were in operation during the entire modeled period. Surface water supplies applied on the MLPPID canals in the BCM domain are shown in Figure 43.

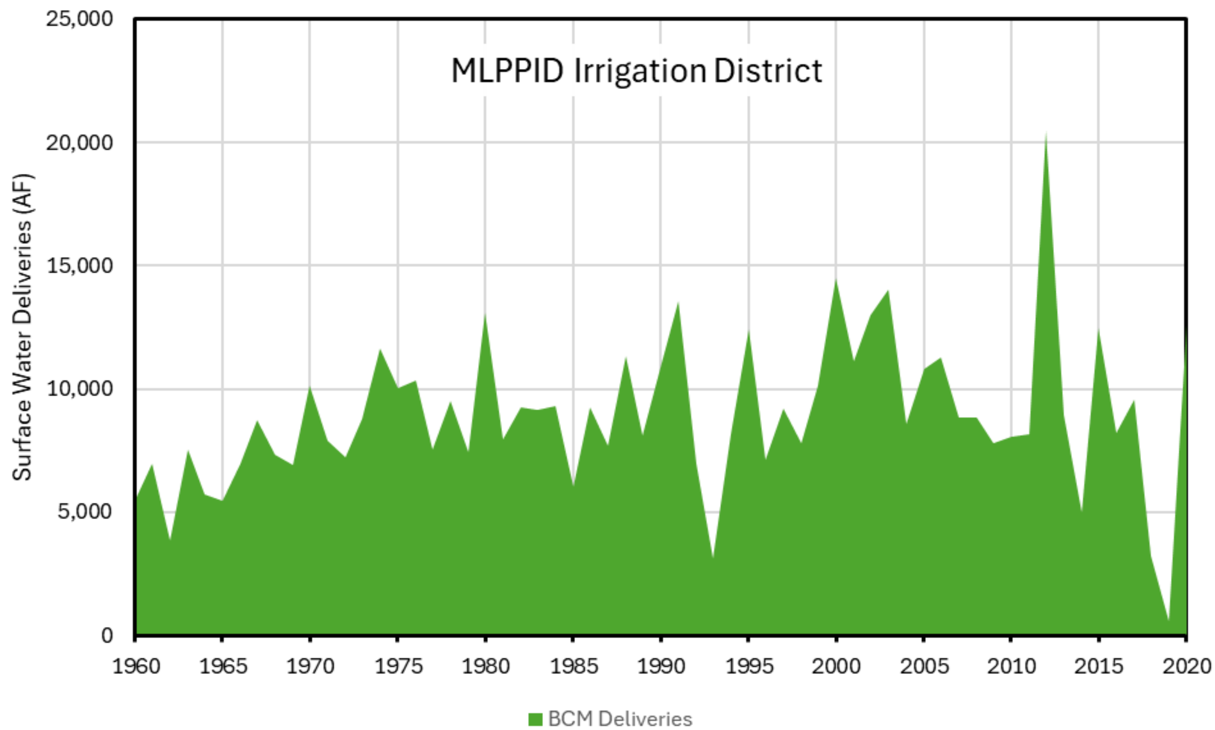


Figure 43. Surface water deliveries in the MLPPID Canal applied within the BCM.

Canal Seepage in the BCM's MLPPID canal area was estimated from the annual delivery estimates in the same area. The canal seepage rate was estimated from the main canal seepage data in the Fullerton Canal as the average annual ratio of canal seepage to canal deliveries[37] (Equation 46); this ratio was 55% (i.e. for every 100 AF delivered to the fields, an additional 55 AF is lost to seepage in the main canals). The distribution of the canal seepage throughout the year was derived from the average monthly distribution of canal seepage in Fullerton canal. The distribution can be found in Table 5. This canal seepage estimate is only for the area in the BCM model domain. The estimate is applied to the length MLPPID canals in model domain proportional to the length of the canals in the cell to the total length of

[37] 1992-2020

the canals in the active BCM model area[38] (Equation 47). Total canal seepage for the MLPPID canals in the BCM are shown in Figure 44.

$$Canal\ Seepage\ Rate = \frac{\sum \frac{Canal\ Seepage}{Canal\ Deliveries}}{nyears} \quad (46)$$

$$Canal\ Seepage_{cell} = Canal\ Seepage_{active} * \frac{Canal\ Length_{cell}}{Canal\ Length_{active}} \quad (47)$$

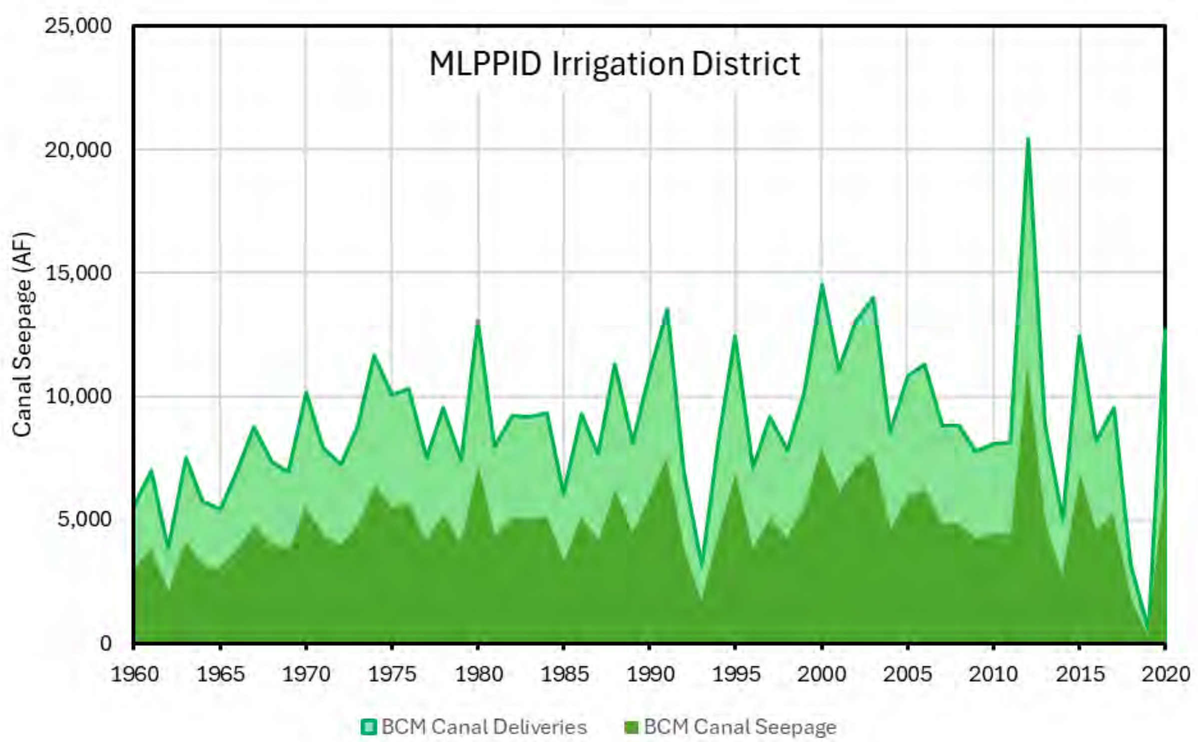


Figure 44. Main canal seepage in the MLPPID applied in the BCM active area.

Note: The properties of the Fullerton Canal were chosen to create estimates for the MLPPID canal. This choice was made over the Farwell canal because of the general shape and position of the canals. Both Fullerton Canal and MLPPID Canal service areas are long thin service areas along a single river, while Farwell Irrigation district is more spread out filling the area between the Middle and North Loup Rivers.

[38] Not the total length of the canals.

Table 5. Distribution of annual canal seepage to month for MLPPID canals.

Month	Proportion of Deliveries
January	0.0
February	0.0
March	0.0
April	0.0
May	0.192
June	0.268
July	0.236
August	0.230
September	0.074
October	0.0
November	0.0
December	0.0

7. Results

The watershed model can produce a wide variety of results on a number of different scales. The following section will describe a selection of these results to provide insight into the watershed model output on a global, regional, and focus area level. This section contains results depicting average conditions, snapshots of a single point in time, and time series values. The results presented are from the BCM RSWB model Run: BCM_40_006, which provided the calibrated pumping, recharge, and runoff contributions to streamflow to the BCM groundwater model.

7.1. Global Water Balance

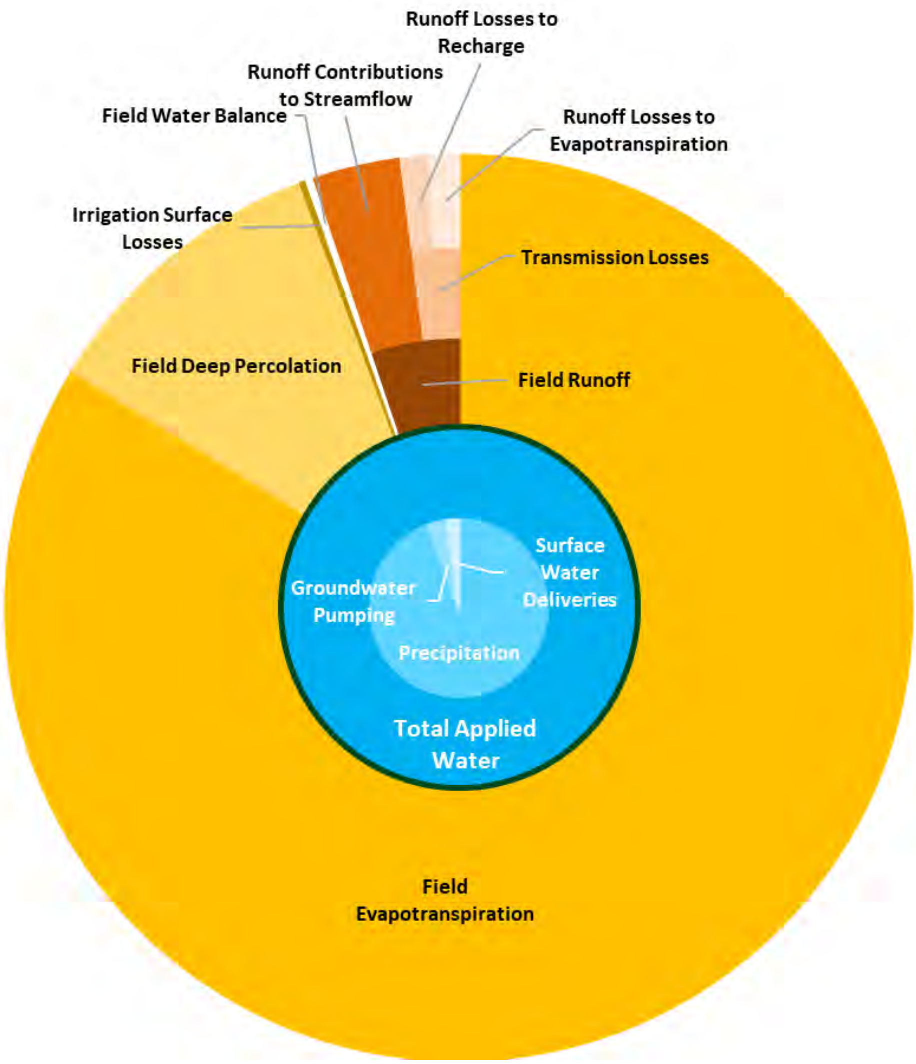


Figure 45. Sources and distributions of the BCM model water balance.

This section presents selected results from the entire model domain. Figure 45 shows a relative breakdown of the sources and distributions of the water balance components proportional to the total volume of applied water. The numerical breakdown of the long-term average annual water balance is provided in Table 6. The depth values in this table represent the average volume divided by the area of the entire model domain. The applied irrigation is further broken down in Table 7 to show the depth of applied irrigation only on irrigated lands.

Table 6. Long-term average annual water balance for the BCM (1960-2020).

Parameter	Run: BCM_40_006		
	Volume (AF)	Depth (in)	% of Total Applied Water
Acres	1,481,789		
Precipitation	3,151,567	25.52	94.5%
Groundwater Pumping	117,966	0.96	3.5%
Surface Water Deliveries	66,547	0.54	2.0%
Total Applied Water	3,336,079	27.02	100.0%
Field Evapotranspiration	2,810,159	22.76	84.2%
Field Deep Percolation	354,712	2.87	10.6%
Field Runoff	172,726	1.40	5.2%
Irrigation Surface Losses	7,895	0.06	0.2%
Field Water Balance	(9,413)	(0.08)	(0.3%)
Field Runoff	172,726	1.40	5.2%
Runoff Contributions to Streamflow	104,651	0.85	3.1%
Runoff Losses to Recharge	34,037	0.28	1.0%
Runoff Losses to Evapotranspiration	34,037	0.28	1.0%
Net Recharge	270,784	2.19	8.1%
Net Impact to Rivers	375,435	3.04	11.3%

Table 7. Long-term average annual applied irrigation in the BCM (1960-2020).

Parameter	Volume (AF)	Acres	Depth (in/ac)
Groundwater Pumping	707,060	952,414	8.9
Surface Water Deliveries	128,361	157,666	9.8

The RSWB produces water balance results on a variety of local geographic areas. For the BCM, the primary objective is concentrated on the focus area of Buffalo County in the LLNRD. Tables 8-9 show the long-term water balance and average annual applied irrigation (1960-2020) within the focus area.

Table 8. Long-term average annual water balance for the BCM focus area Buffalo County in the LLNRD (1960-2020).

Parameter	Run: BCM_40_006		
	Volume (AF)	Depth (in)	% of Total Applied Water
Acres	224,460		
Precipitation	480,987	25.71	93.4%
Groundwater Pumping	32,794	1.75	6.4%
Surface Water Deliveries	1,350	0.07	0.3%
Total Applied Water	515,130	27.54	100.0%
Field Evapotranspiration	432,079	23.10	83.9%
Field Deep Percolation	53,706	2.87	10.4%
Field Runoff	29,111	1.56	5.7%
Irrigation Surface Losses	1,680	0.09	0.3%
Field Water Balance	(1,447)	(0.08)	(0.3%)
Field Runoff	-	0.00	0.0%
Runoff Contributions to Streamflow	29,111	1.56	5.7%
Runoff Losses to Recharge	20,274	1.08	3.9%
Runoff Losses to Evapotranspiration	4,419	0.24	0.9%
Net Recharge	25,331	1.35	4.9%
Net Impact to Rivers	45,605	2.44	8.9%

Table 9. Long-term average annual applied irrigation for the BCM focus area Buffalo County in the LLNRD (1960-2020).

Parameter	Volume (AF)	Acres	Depth (in/ac)
Groundwater Pumping	32,794	48,719	8.1
Surface Water Deliveries	1,373	1,441	11.4

7.2. Groundwater Pumping

Groundwater pumped for irrigation reflects the extraction of water from the aquifer for agricultural production. The pumping rate is a function of the net irrigation requirement, an NIR target, and the application efficiency. These values are developed with consideration for weather conditions, soils, crops, timing of water needs, irrigation system, and assumptions about management characteristics. On average, the BCM saw 0.96 inches per year[39] of pumping, while the BCM focus area averaged 1.75 inches per year[40]. Figure 46 shows the average annual rate of pumping in each BCM model cell. While Figures 47-48 show the increase in pumping density between the beginning (1960) and the end (2020) of the modeled period respectively. Figure 49 shows the annual depth of groundwater pumping per irrigated acre in the BCM domain relative to the annual rate of precipitation. Figure 50 shows the total volume of agricultural pumping in the BCM.

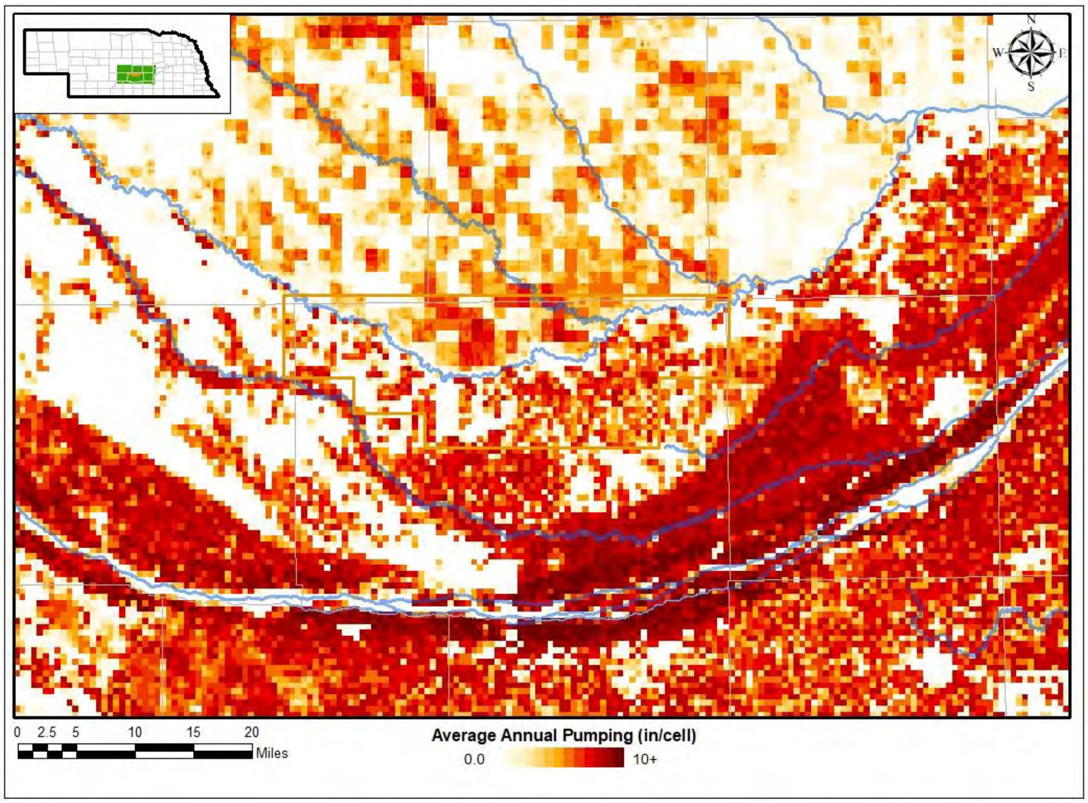


Figure 46. Average annual depth of agricultural pumping in the BCM model area 1960-2020.

[39] Applied at a rate of 8.9 inches per irrigated acre.
[40] Applied at a rate of 8.1 inches per irrigated acre.

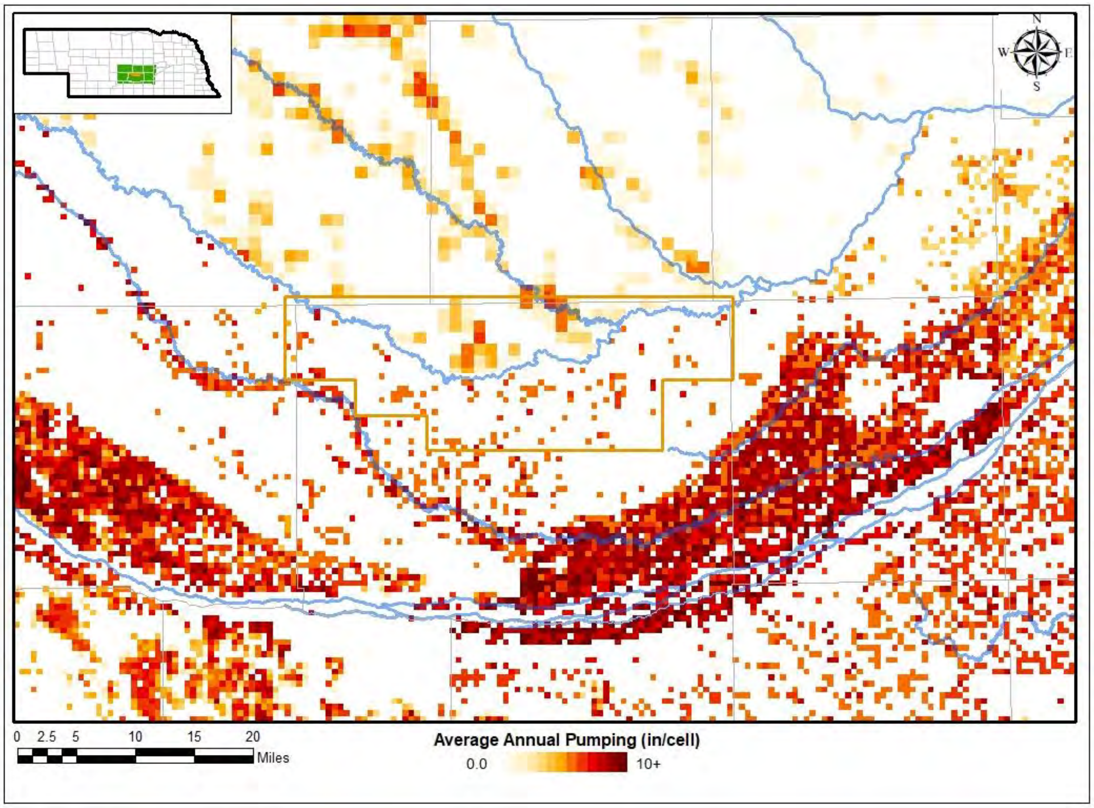


Figure 47. Extent of agricultural groundwater pumping 1960.

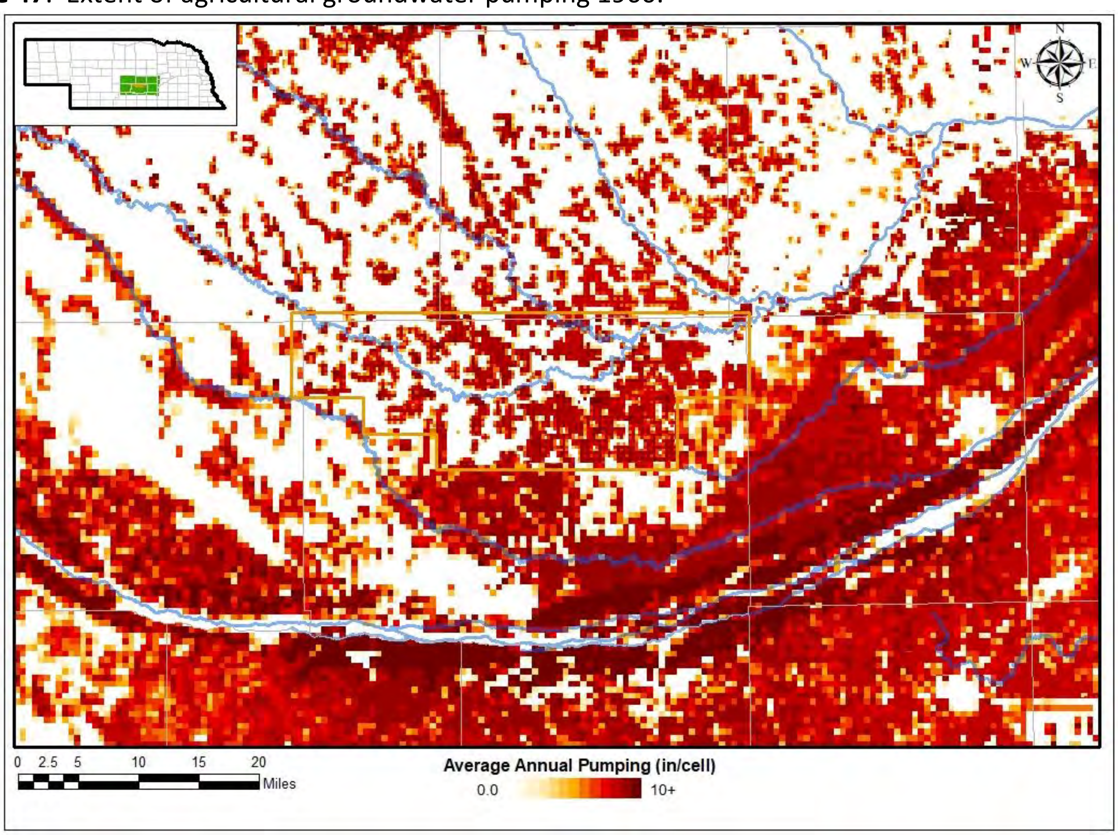


Figure 48. Extent of agricultural groundwater pumping 2020.

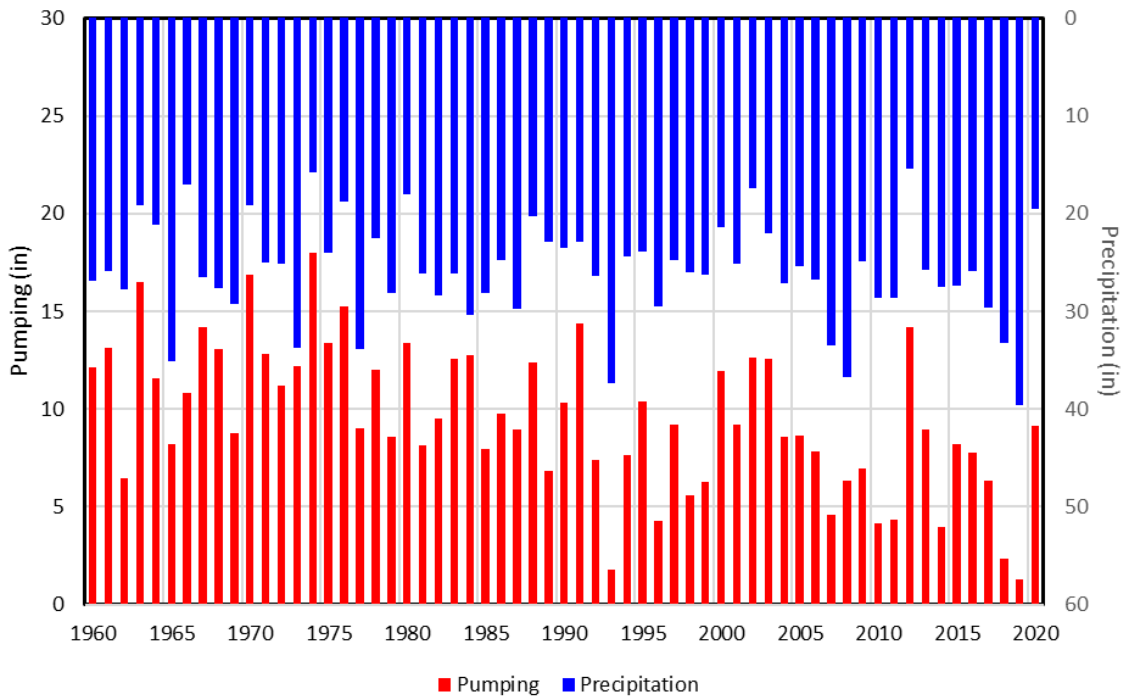


Figure 49. Average depth of agricultural pumping relative to precipitation for the BCM model domain.

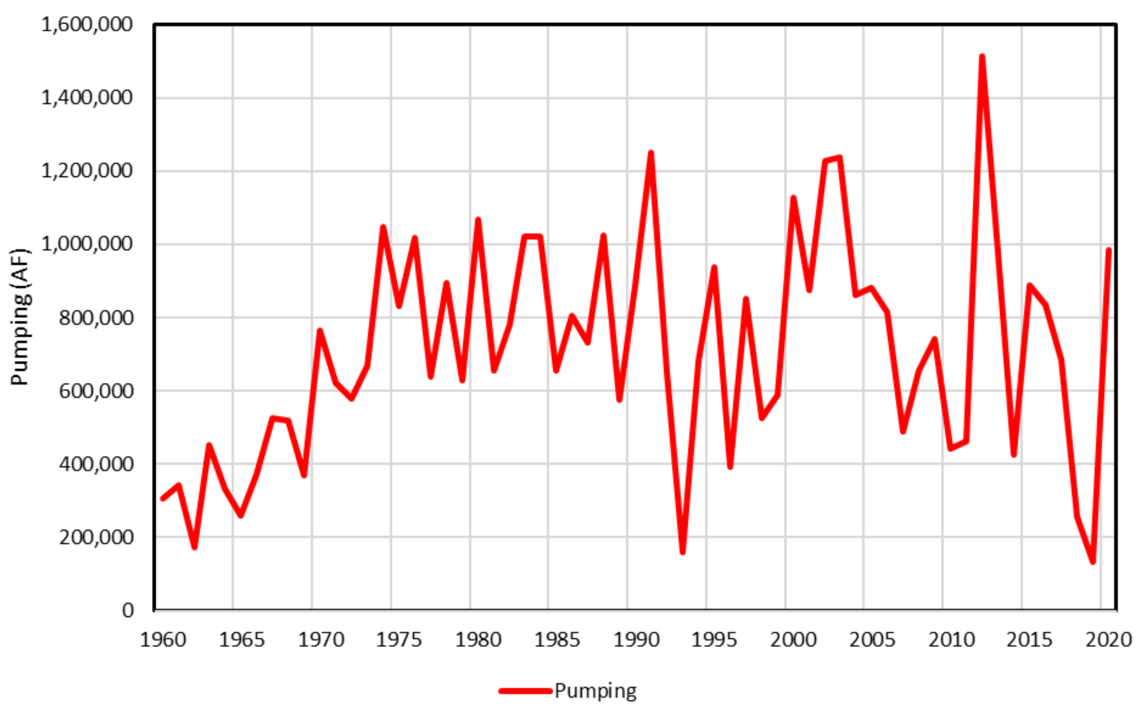


Figure 50. Annual Volume of agricultural pumping for the BCM model domain.

Figures 51-52 show the annual depth and annual volume of pumping in the BCM focus area.

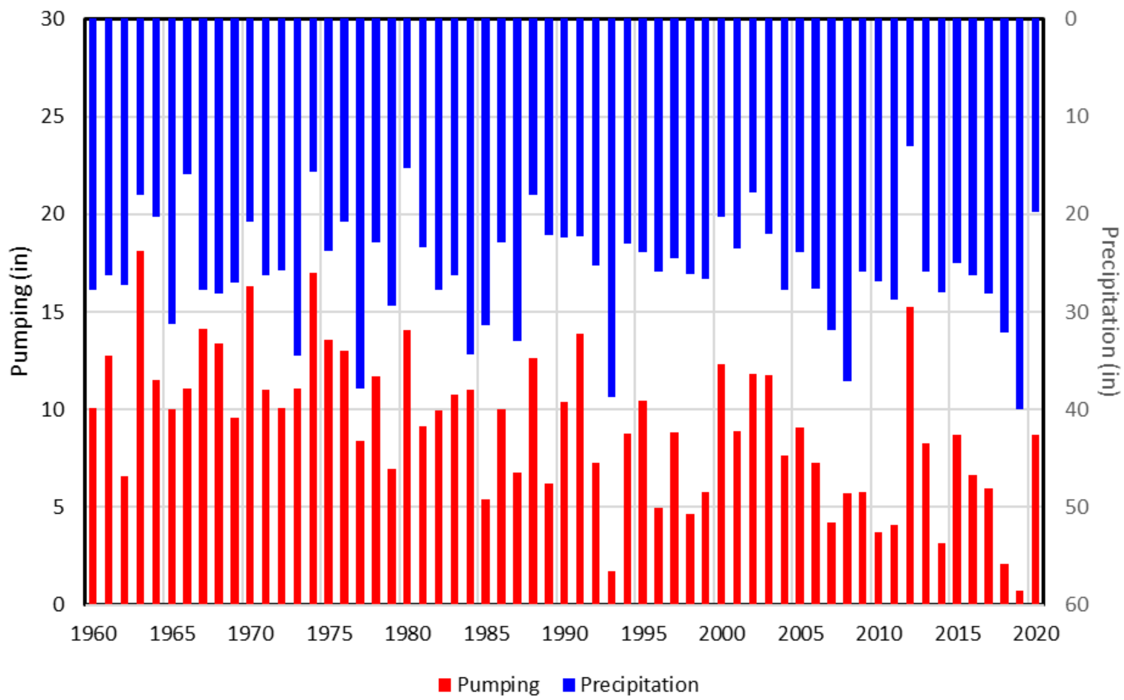


Figure 51. Average depth of agricultural pumping relative to precipitation for the BCM focus area.

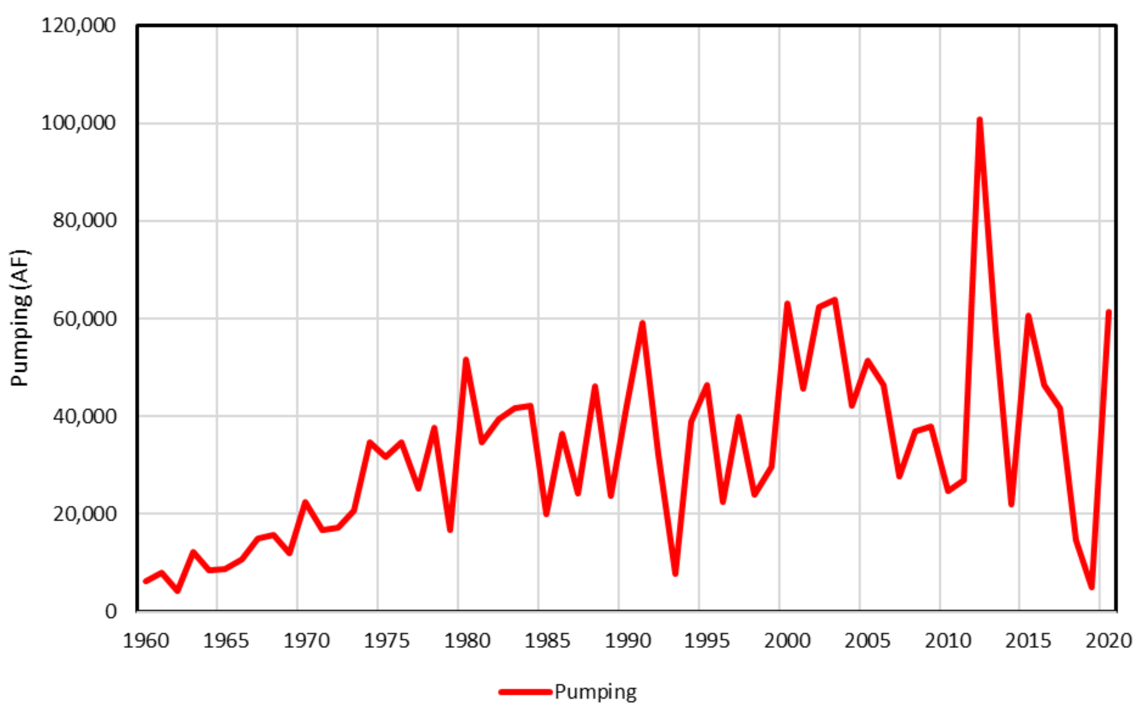


Figure 52. Annual Volume of agricultural pumping for the BCM focus area.

Metered Pumping

The evaluation of the model included comparing the model pumping estimates to metered pumping records from the LLNRD. Overall, the modeled pumping estimates closely followed the sample of available metered records. Figure 53 shows the distribution of all LLNRD metered pumping from 2010-2020 and where the modeled average sits in comparison to the metered average and median pumping rates.

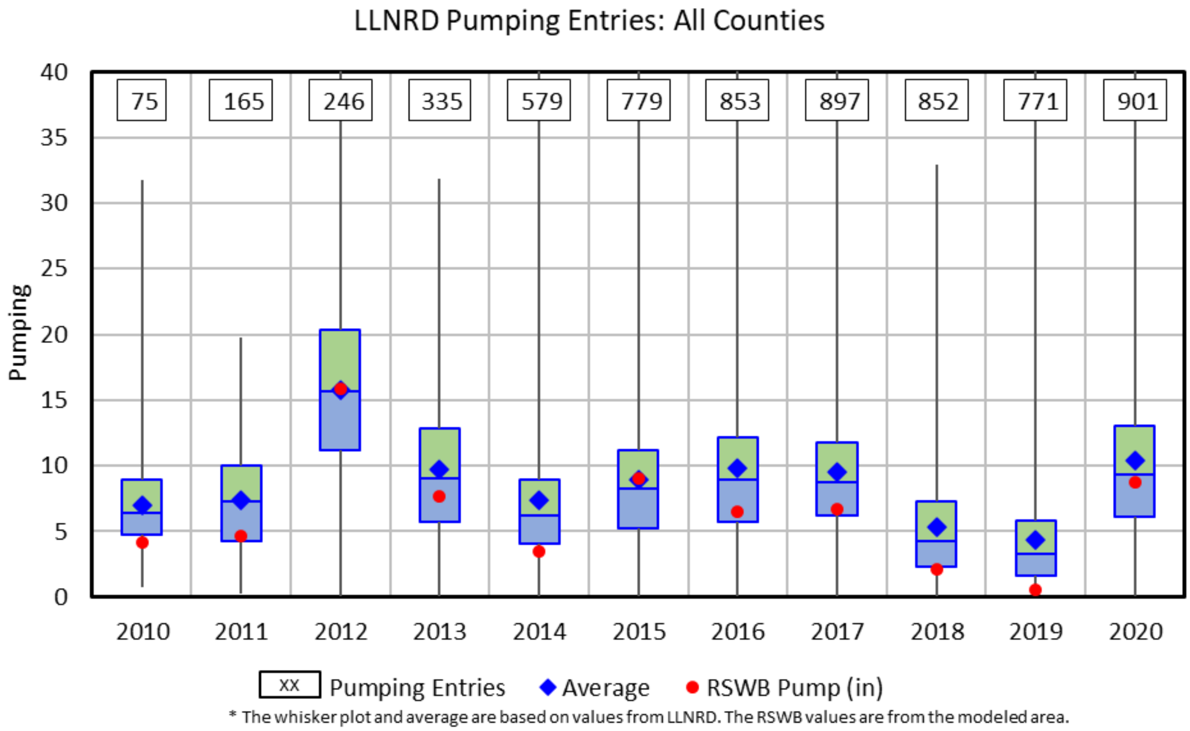


Figure 53. Comparison of model pumping to metered records in the LLNRD.

Figures 54-55 show how the range of model pumping compares to the range of metered pumping in 2013 and 2020 respectively. The metered pumping line depicts the rank of each metered record. The modeled line depicts the acre weight depth of applied pumping. Overall, the model data has a tighter range, the metered data exhibits greater variability, but for the average pumper the estimate is reasonable.

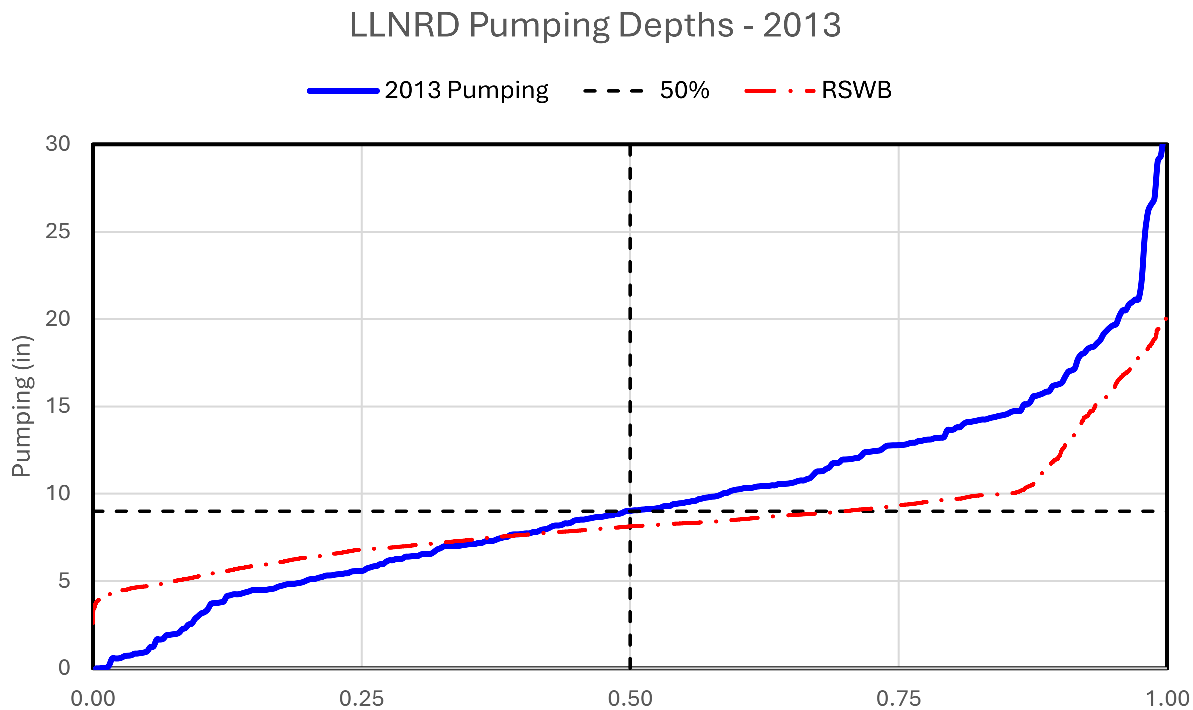


Figure 54. Cumulative Distribution Function plot of the LLNRD metered pumping and BCM model pumping in the LLNRD – 2013.

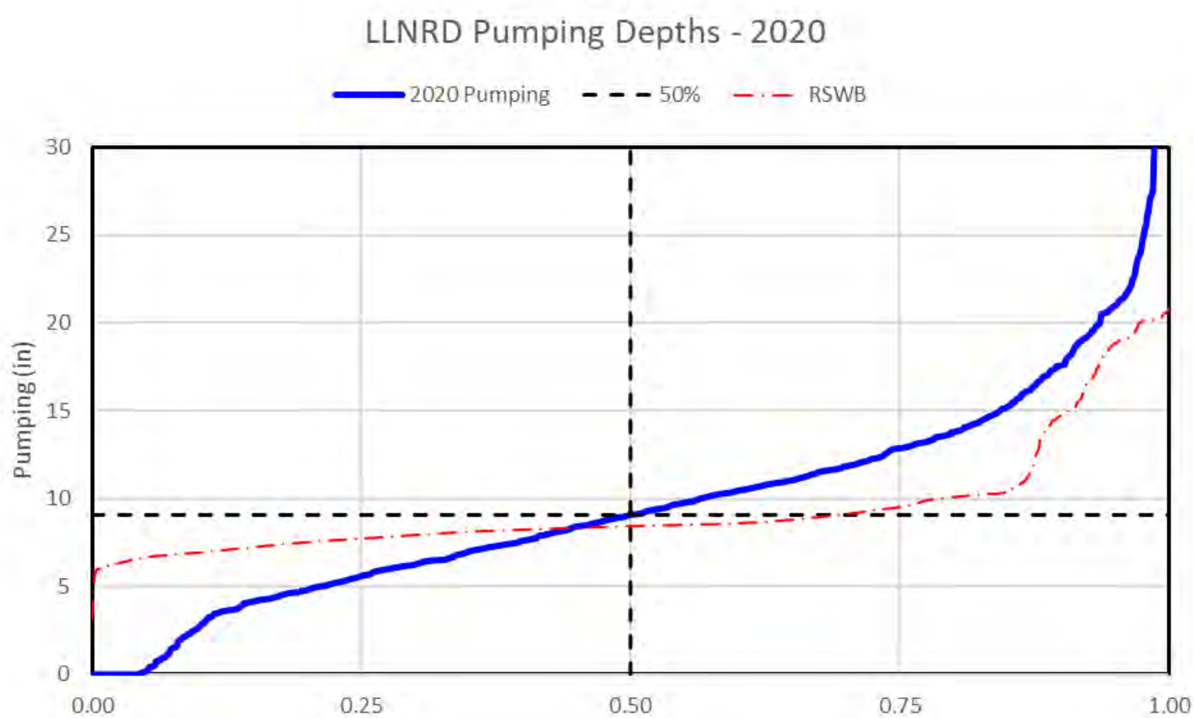


Figure 55. Cumulative Distribution Function plot of the LLNRD metered pumping and BCM model pumping in the LLNRD – 2020.

The metered pumping comparison was also completed for the focus area. Figure 56 shows how closely the modeled pumping represents the metered data within Buffalo County in the LLNRD. The average estimated pumping is close to the average metered pumping, it should be noted that this comparison is made with a small sample.

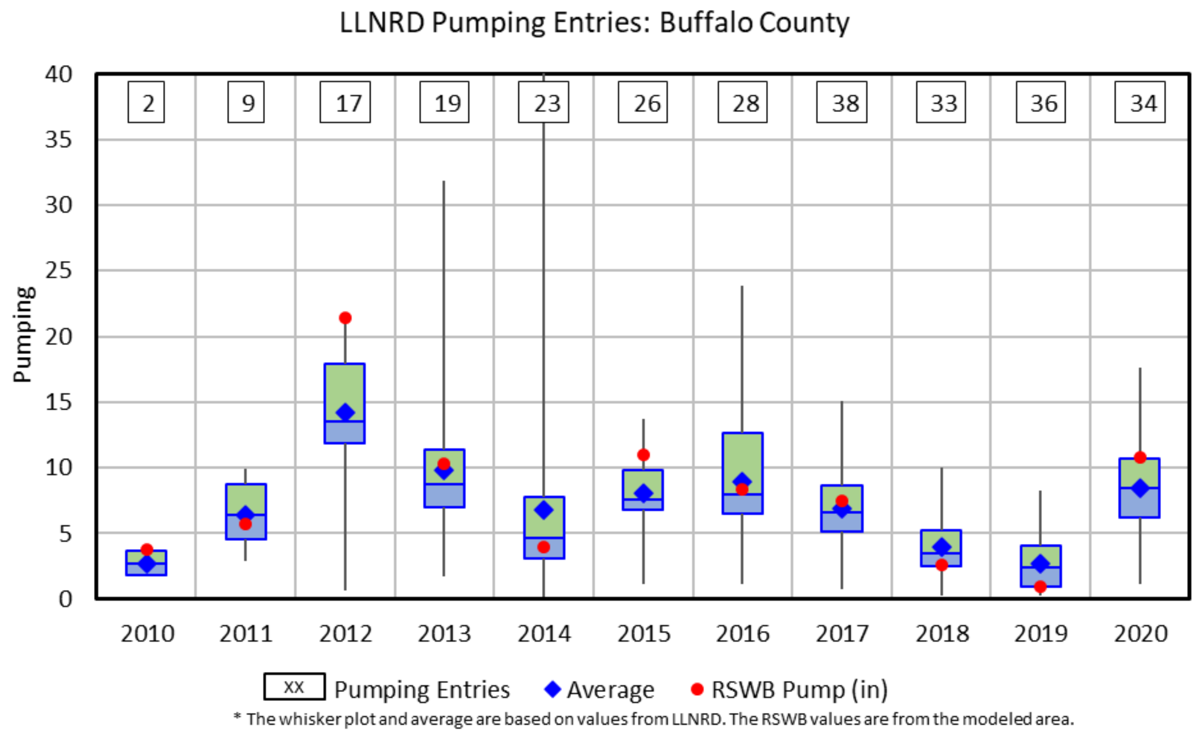


Figure 56. Comparison of model pumping to metered records in Buffalo County and LLNRD.

7.3. Recharge

Recharge is the portion of water which drains past the root zone and reaches the aquifer below. There was on average approximately 3.15 inches of recharge per year in the BCM model domain. Direct field recharge accounted for 2.87 inches and runoff transmission losses were responsible for the other 0.28 inches. Within the focus area the estimated recharge decreases to 3.11 inches. Field recharge rates stayed about the same as the greater model area, but runoff losses in the area decreased the indirect recharge rates. A map of the average annual recharge rates in the BCM are shown in Figure 57. While Figures 58–59 show the volumes of recharge over time in the BCM and BCM focus area respectively.

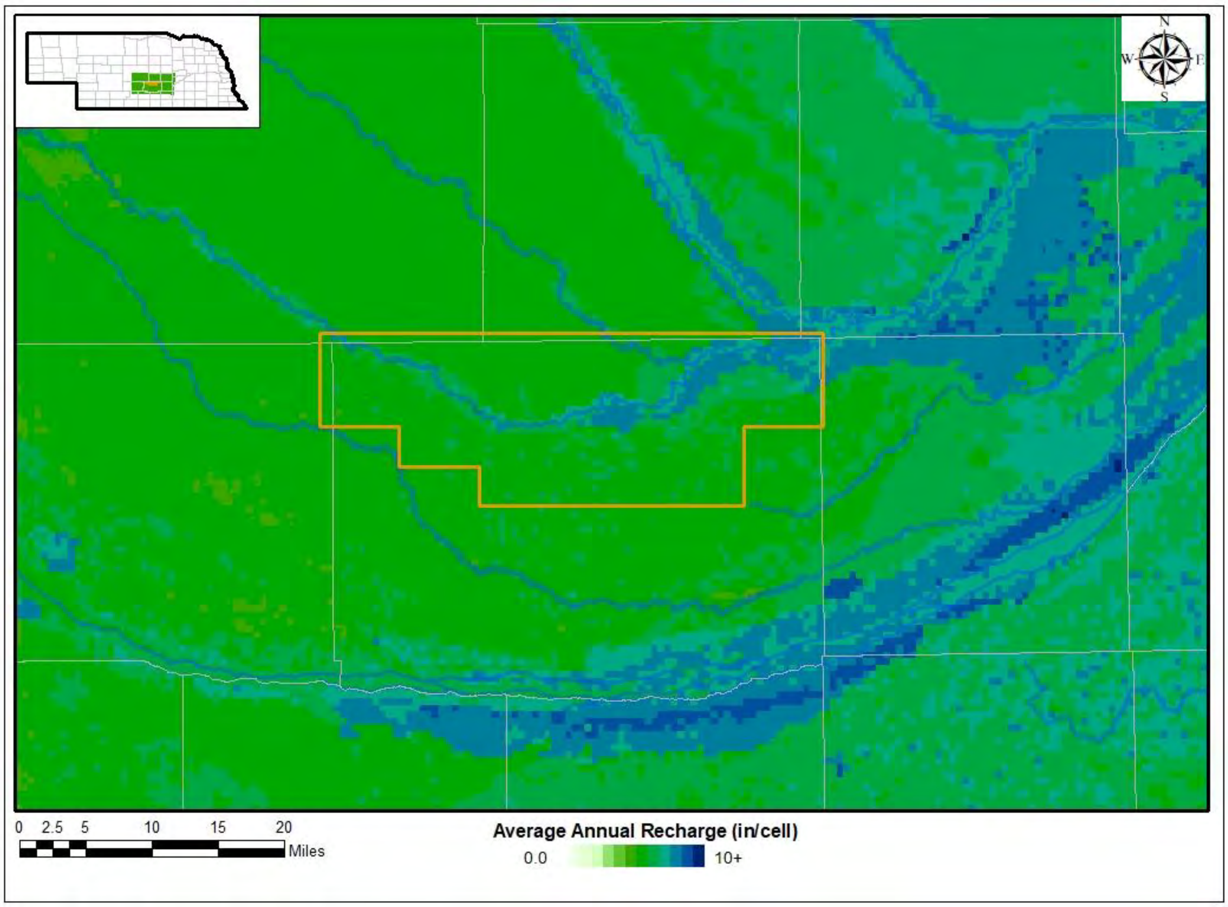


Figure 57. Average annual recharge in the BCM model area.

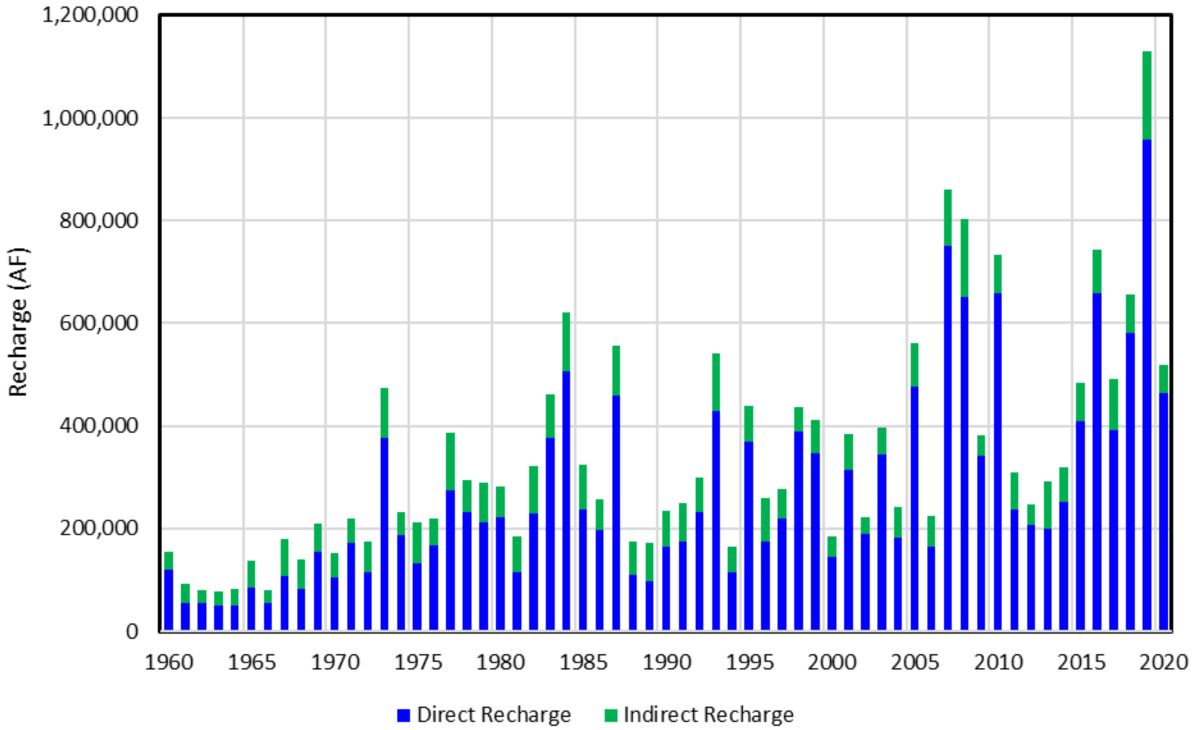


Figure 58. Average annual recharge across the entire BCM model area.

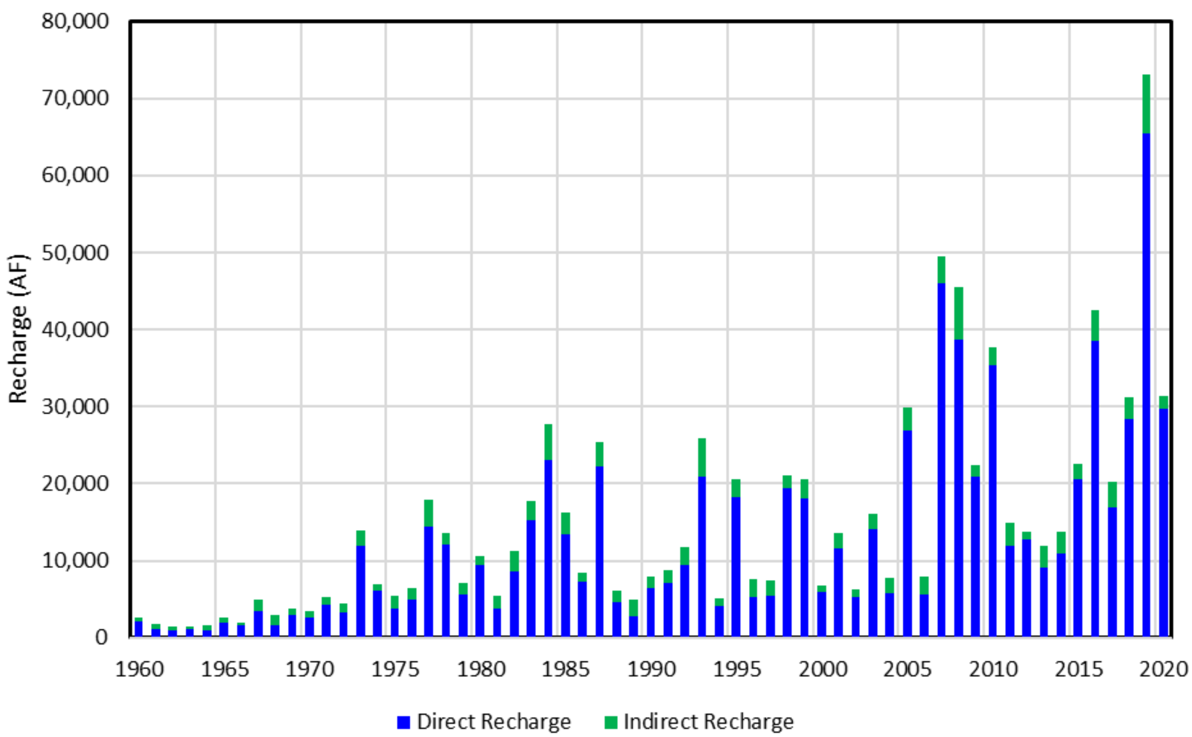


Figure 59. Average annual recharge within the BCM model focus area.

7.4. Net Recharge

Net Recharge represents the cumulative flux into the aquifer. It considers recharge to the aquifer (+) and the pumping being extracted (-) which is reflected in Figure 60. Within the BCM there was an average of 2.19 inches of net recharge. The BCM focus area experienced 1.35 inches of net recharge.

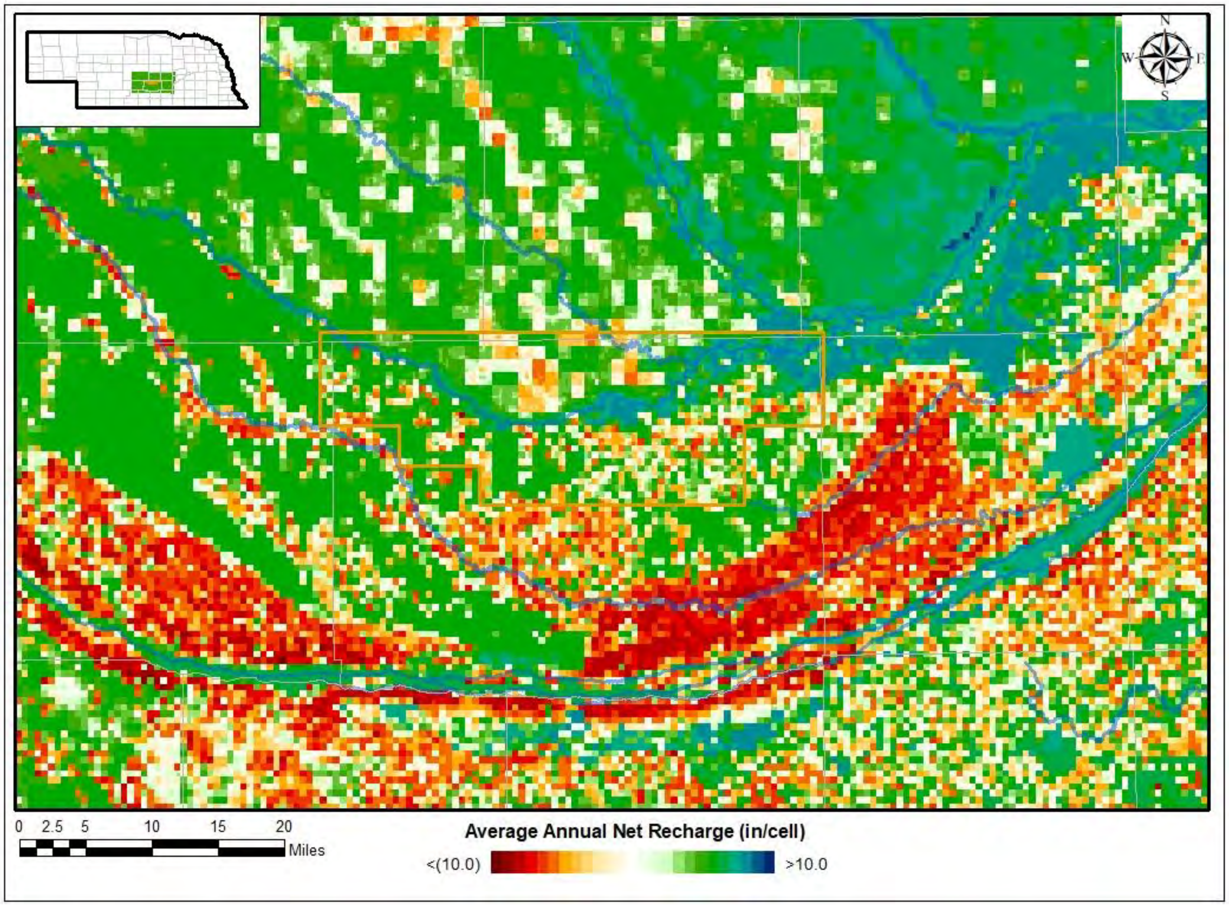


Figure 60. Average annual net recharge in the BCM model area.

References

Allen, R. G., Walter, I. A., Elliott, R. L., Howell, T. A., Itenfisu, D., Jensen, M. E., & Snyder, R. L. (2005). *The ASCE Standardized Reference Evapotranspiration Equation.* American Society of Civil Engineers.

Applied Climate Information System. (Retrieved 2023). *ACIS*. Retrieved from https://www.rcc-acis.org/

Hargreaves, G. H., & Samani, Z. A. (1985). Reference crop evaporation from temperature. *Transaction of ASAE, 1*(2), 96-99.

High Plain Regional Climate Center. (Retrieved 2013-2023). *NWS/Coop Weather Data*. Retrieved from https://hprcc.unl.edu/

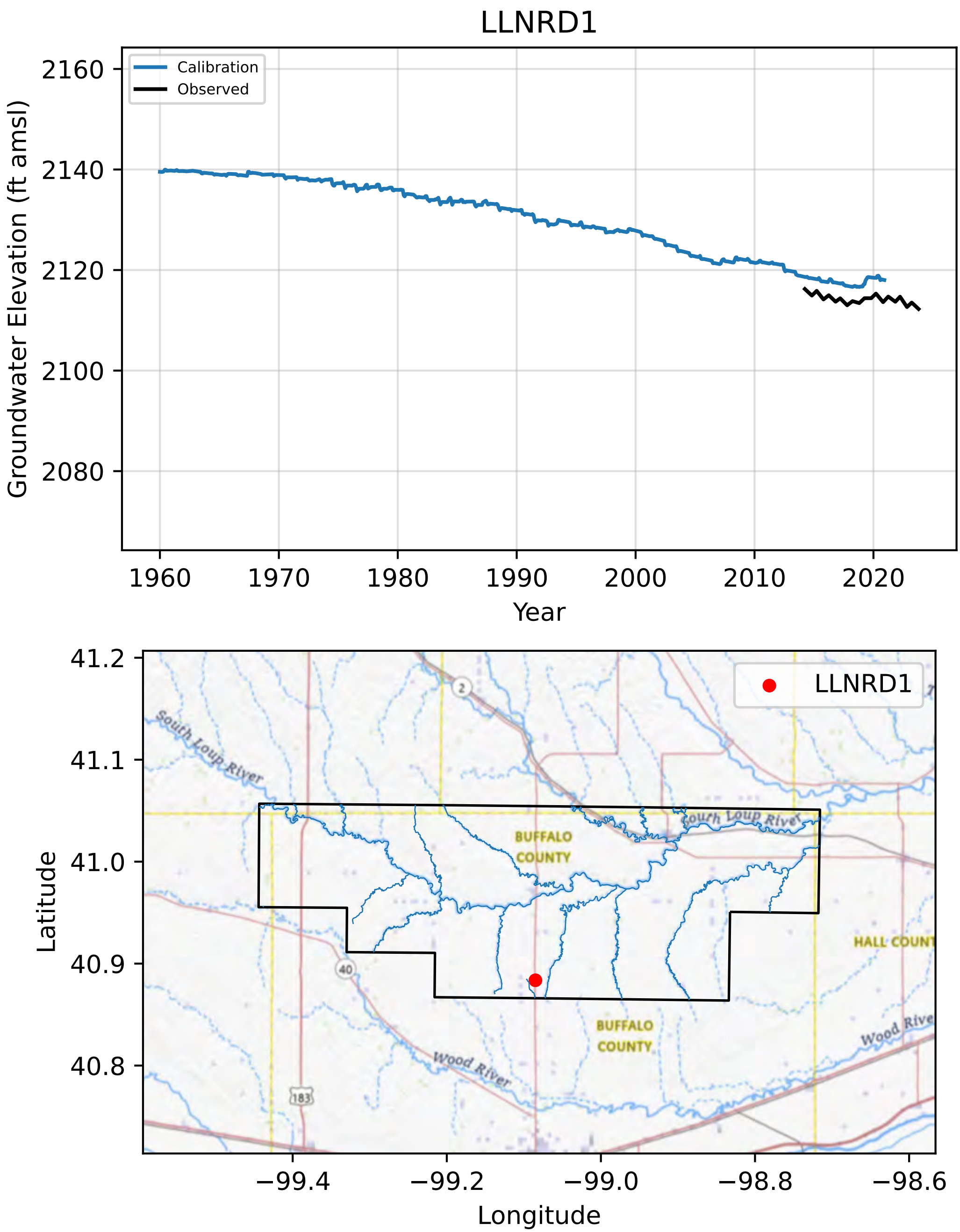
Martin, D. (n.d.). CROPSIM A Crop Simulation Program.

Martin, D. L., Watts, D. G., & Gilley, J. R. (1984). Model and production function for irrigation managment. *J. Irrig. Drain. Eng., 110*(2), 149-164.

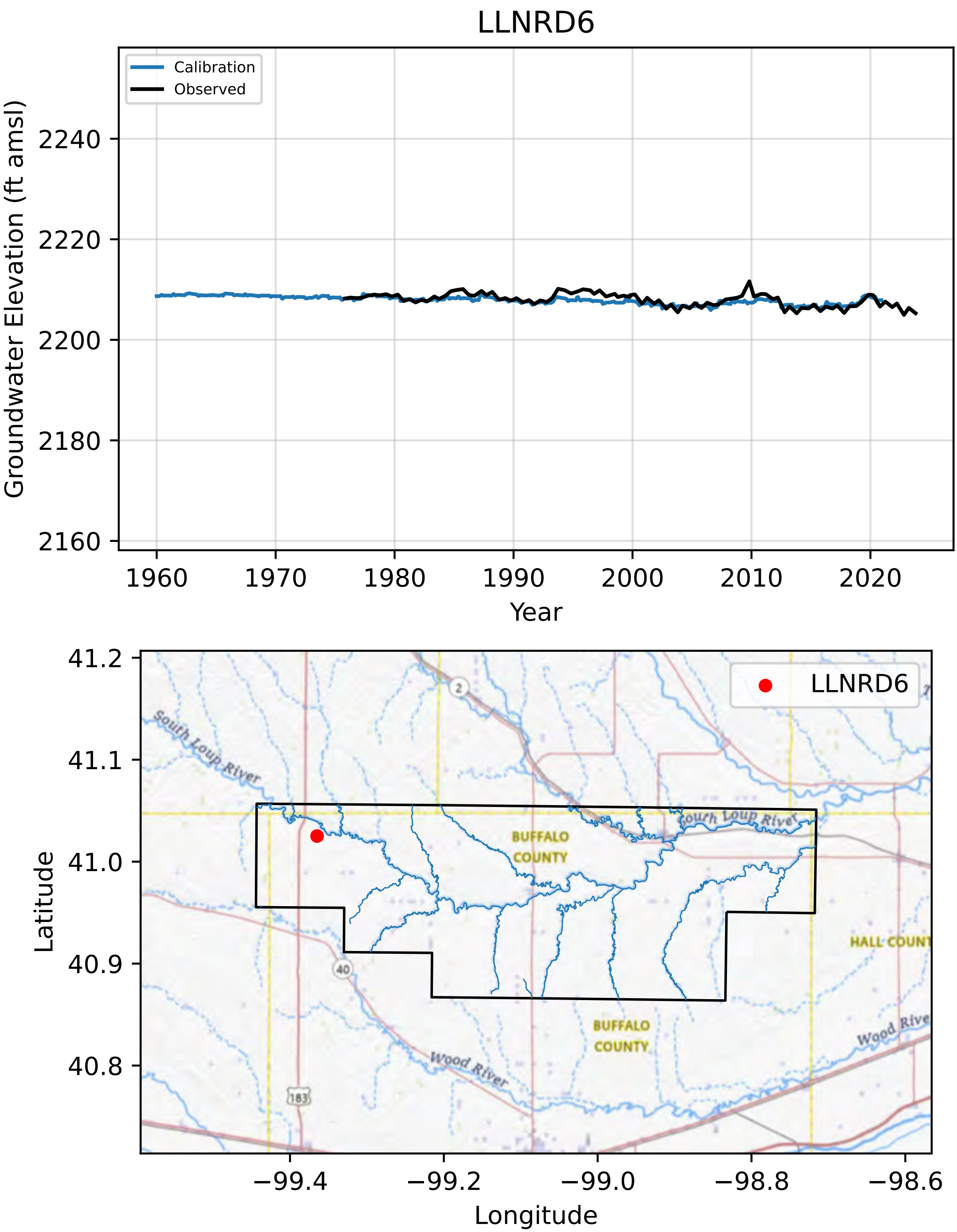
PRISM Climate Group, Oregon State University. (Retrieved 2023). Retrieved from https://prism.oregonstate.edu

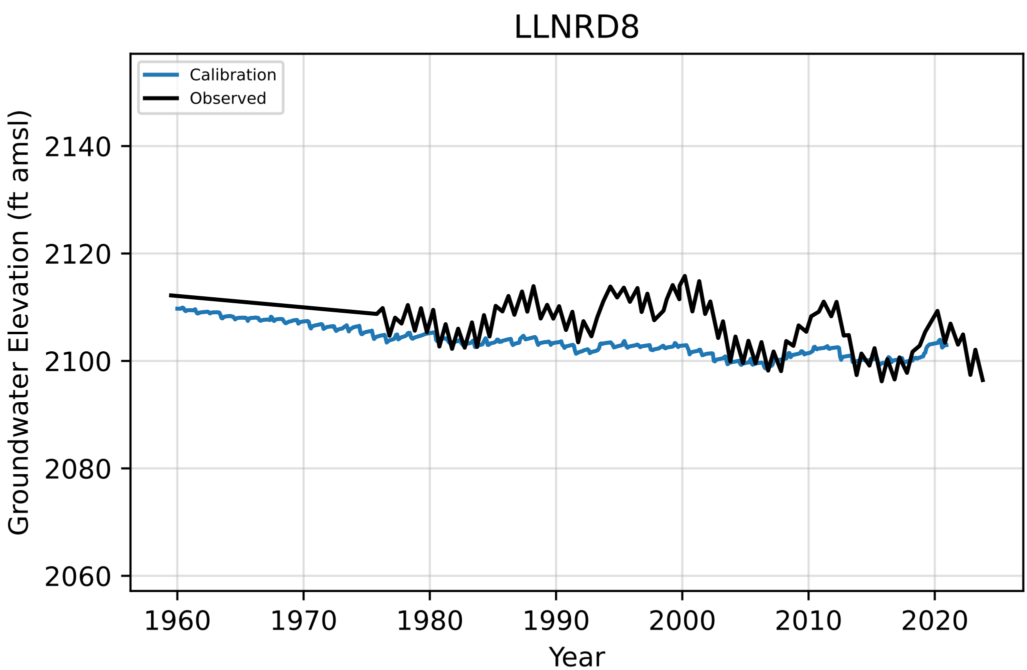
The Flatwater Group, Inc. (2014). *CROPSIM Net Irrigation Requirement; Draft.*

Appendix C
Hydrographs for Base Case

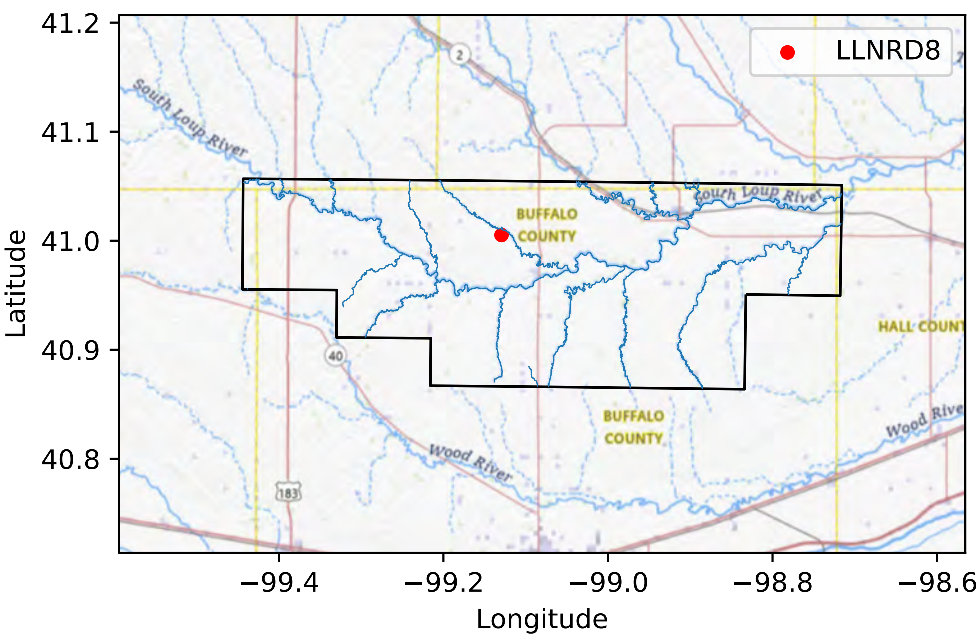


LLNRD1
Calibration
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD1
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive
2
40
183

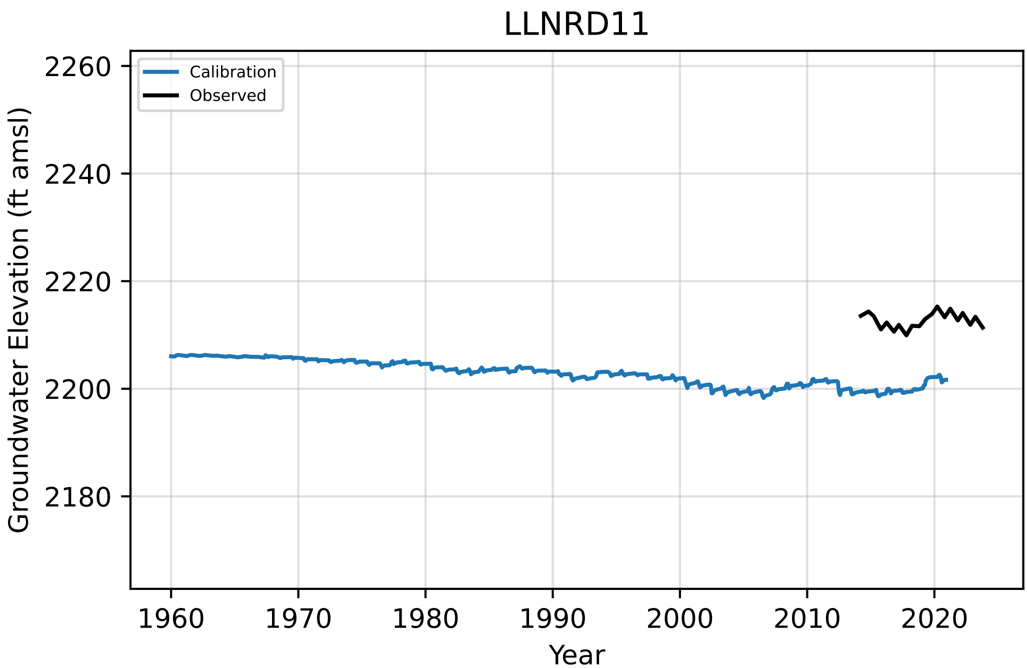

LLNRD6
Calibration
Observed
Groundwater Elevation (ft amsl)
2240
2220
2200
2180
2160
1960
1970
1980
1990
2000
2010
2020
Year
41.2
41.1
41.0
40.9
40.8
LLNRD6
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

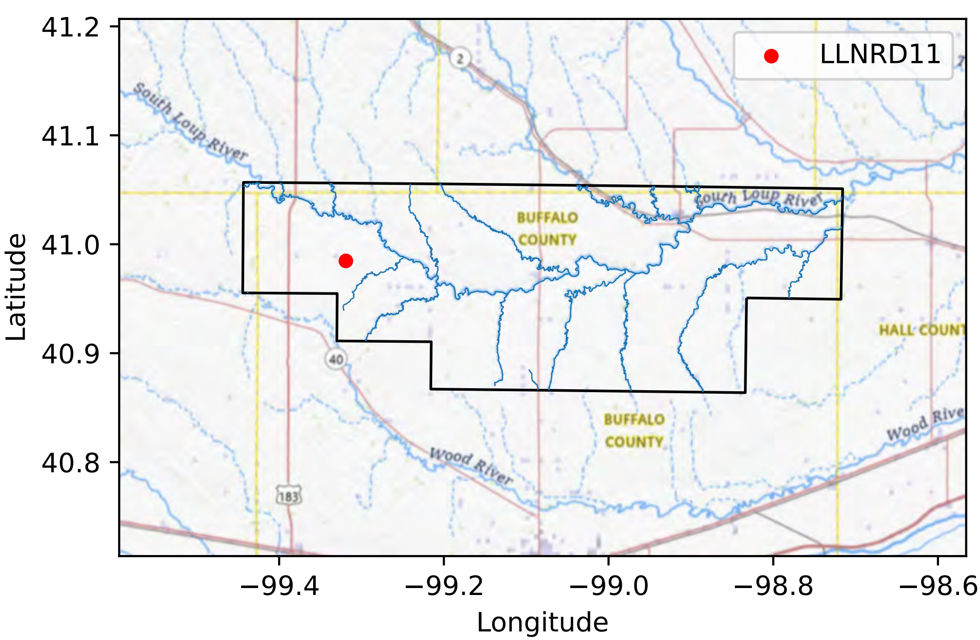


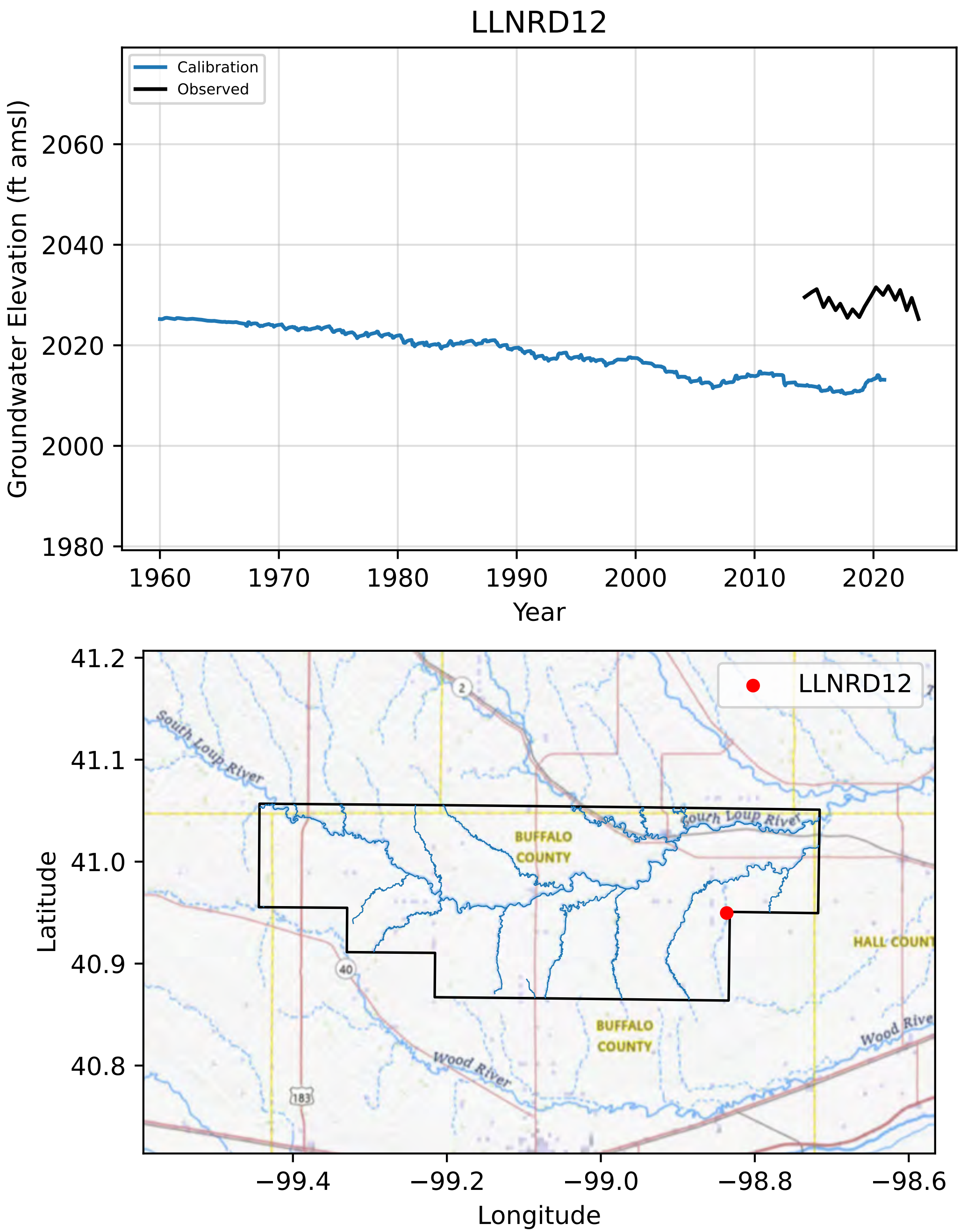
LLNRD8
Calibration
Observed
Groundwater Elevation (ft amsl)
2140
2120
2100
2080
2060
1960
1970
1980
1990
2000
2010
2020
Year



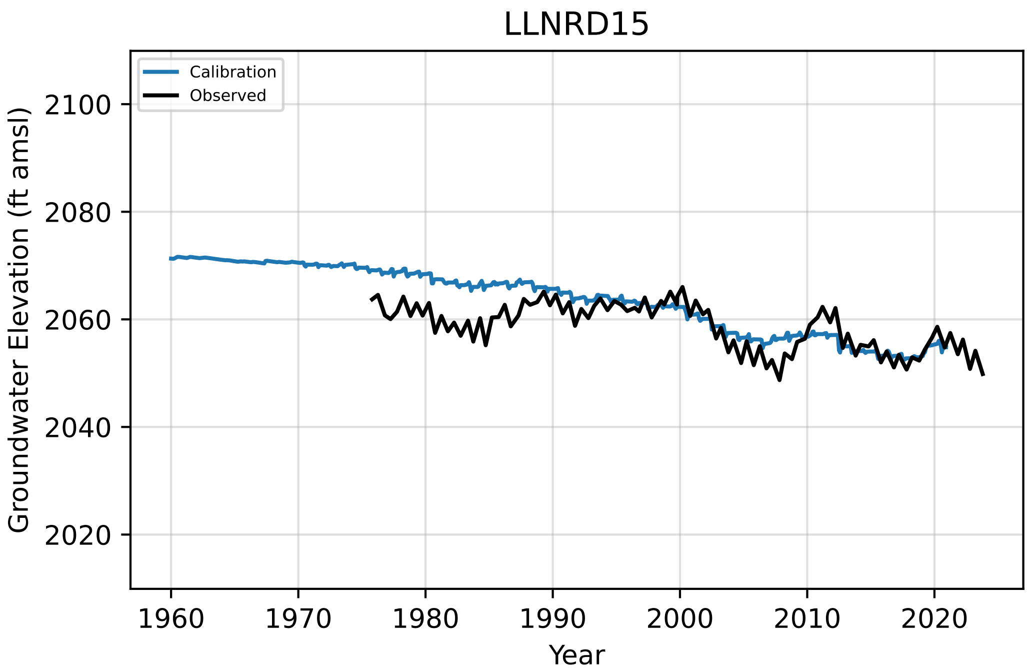
LLNRD8
South Loup River
BUFFALO
COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD11
Calibration
Observed
Groundwater Elevation (ft amsl)
2260
2240
2220
2200
2180
1960
1970
1980
1990
2000
2010
2020
Year

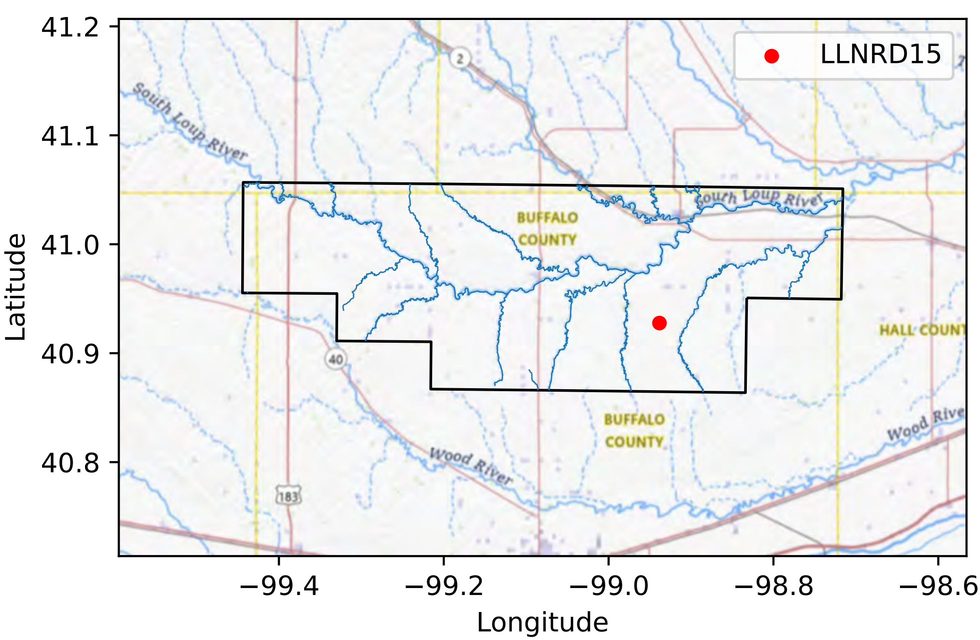

LLNRD11
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River



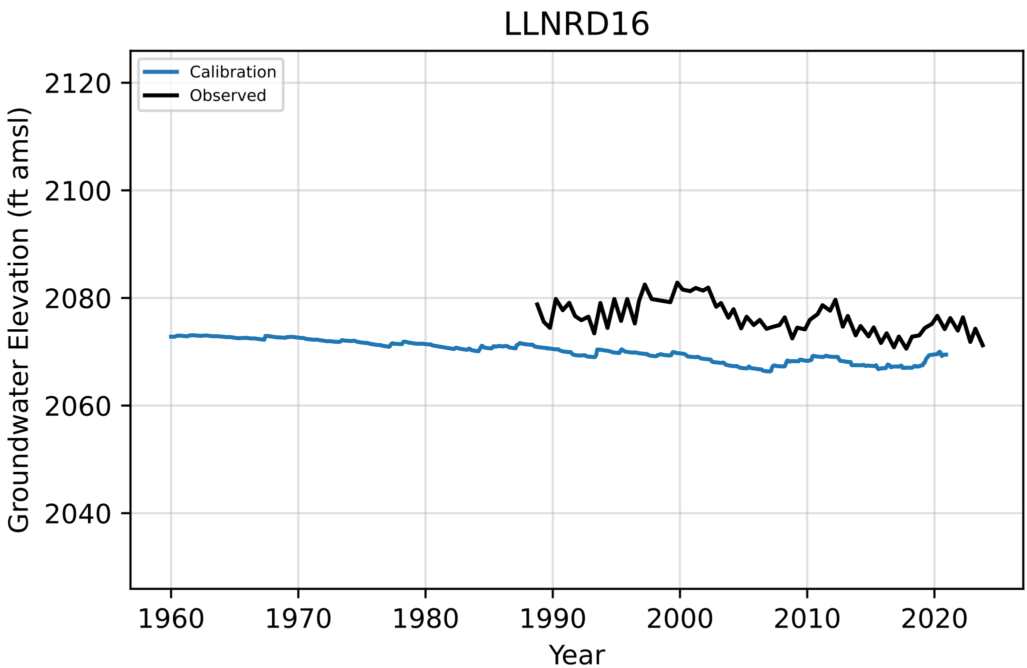
LLNRD12
Calibration
Observed
Groundwater Elevation (ft amsl)
2060
2040
2020
2000
1980
1960
1970
1980
1990
2000
2010
2020
Year
41.2
41.1
41.0
40.9
40.8
Latitude
LLNRD12
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

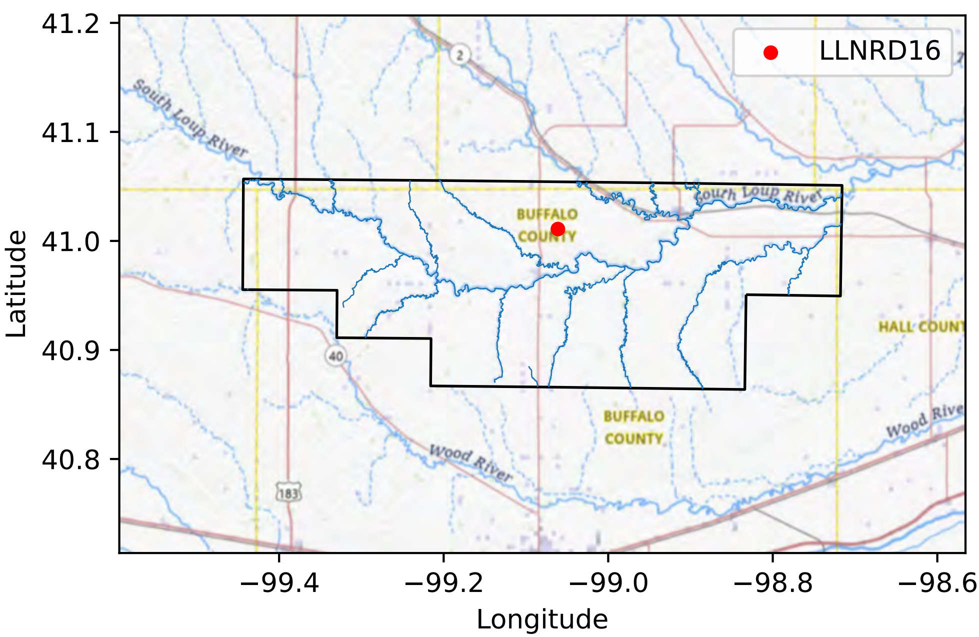


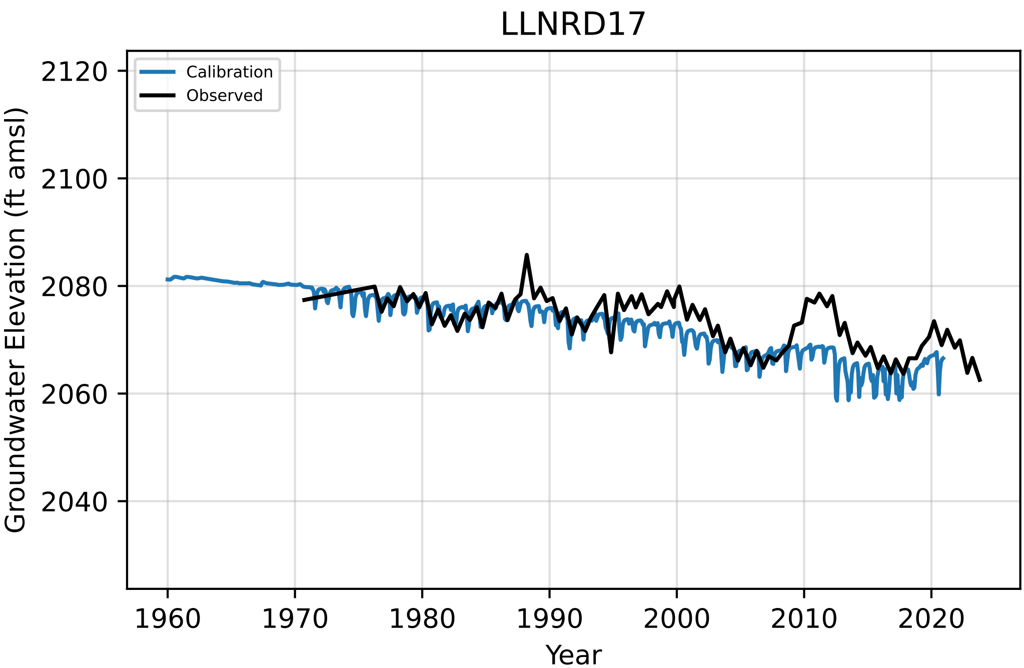
LLNRD15
Calibration
Observed
Groundwater Elevation (ft amsl)
2100
2080
2060
2040
2020
1960
1970
1980
1990
2000
2010
2020
Year



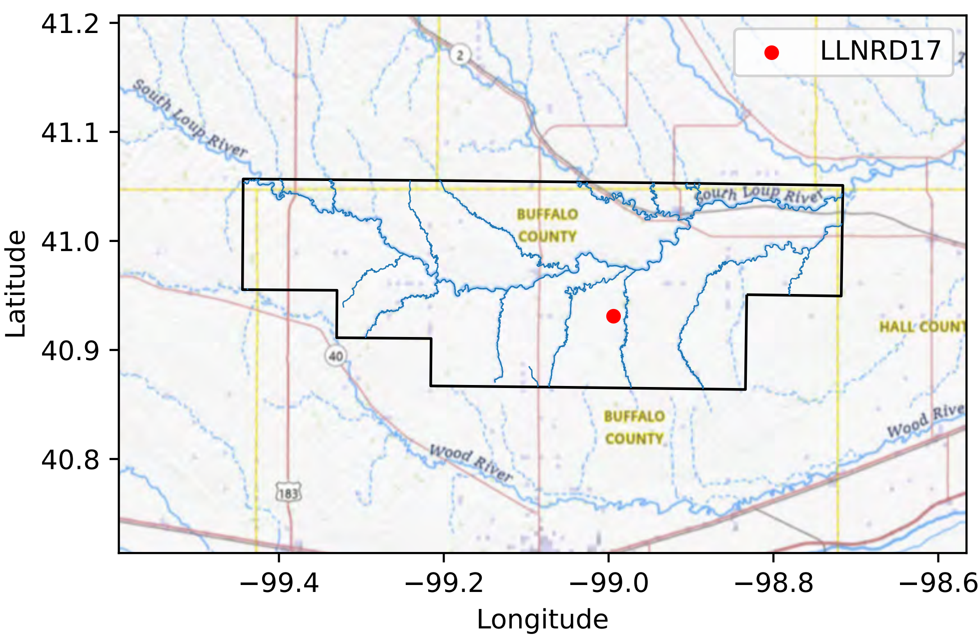
LLNRD15
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive


LLNRD16
Calibration
Observed
Groundwater Elevation (ft amsl)
2040
2060
2080
2100
2120
Year
1960
1970
1980
1990
2000
2010
2020

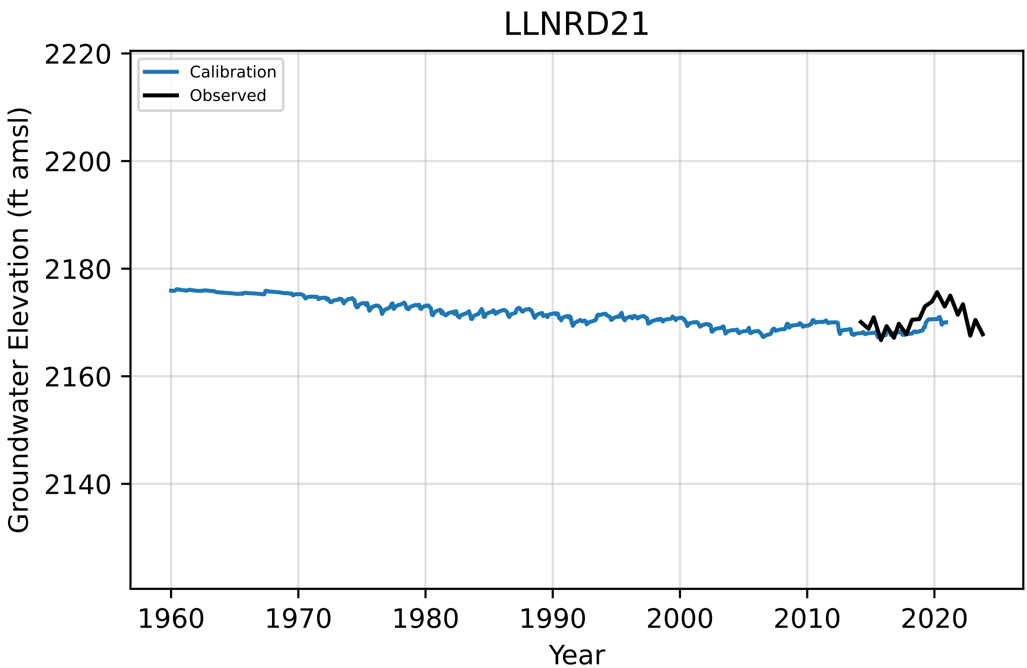

LLNRD16
Latitude
41.2
41.1
41.0
40.9
40.8
Longitude
−99.4
−99.2
−99.0
−98.8
−98.6
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
Wood River
2
40
183

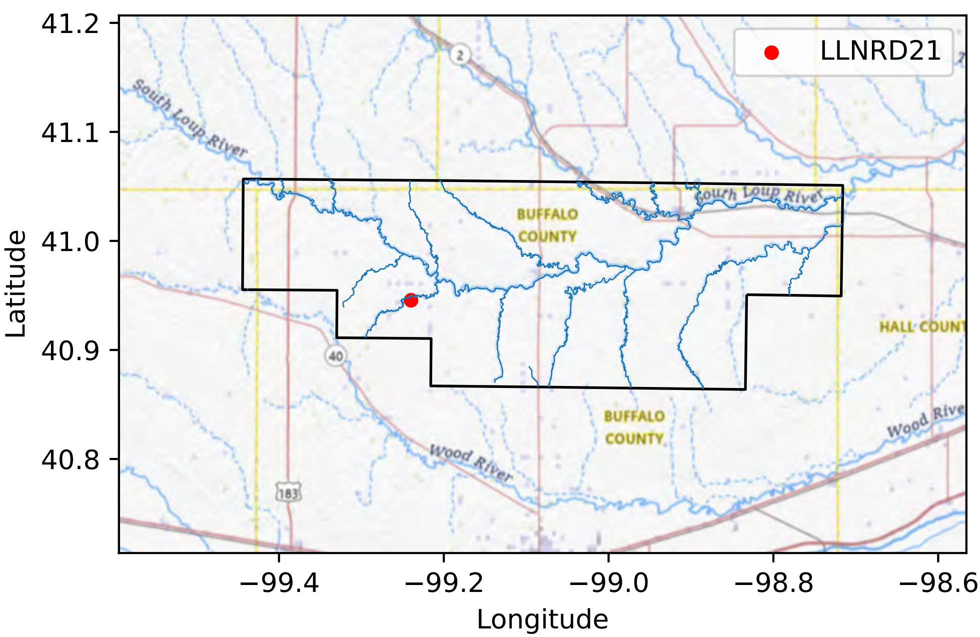


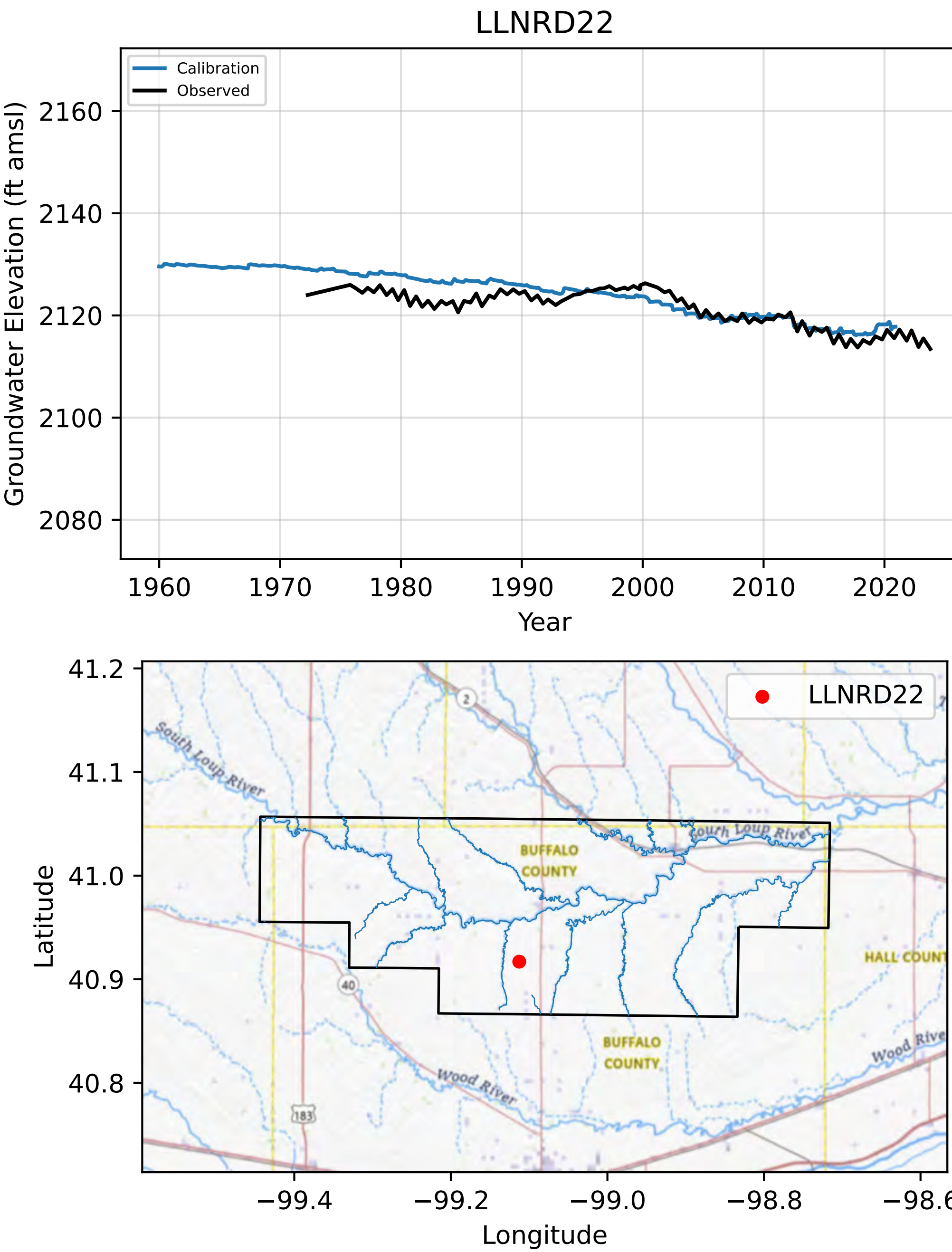
LLNRD17
Calibration
Observed
Groundwater Elevation (ft amsl)
2120
2100
2080
2060
2040
1960
1970
1980
1990
2000
2010
2020
Year



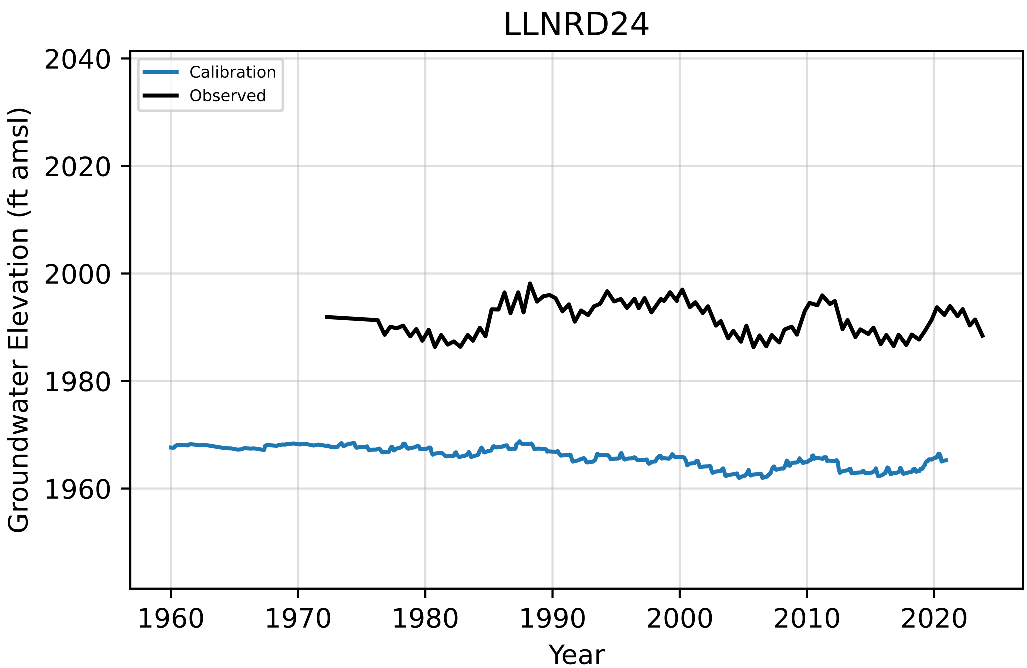
LLNRD17
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
South Loup River
HALL COUNT
BUFFALO COUNTY
Wood River
Wood River


LLNRD21
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year

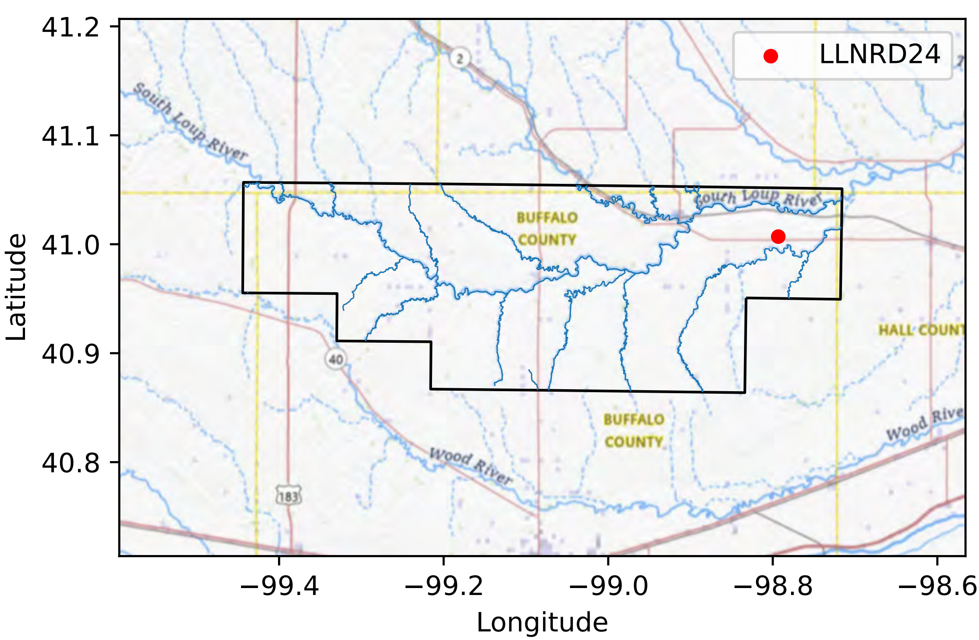

LLNRD21
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



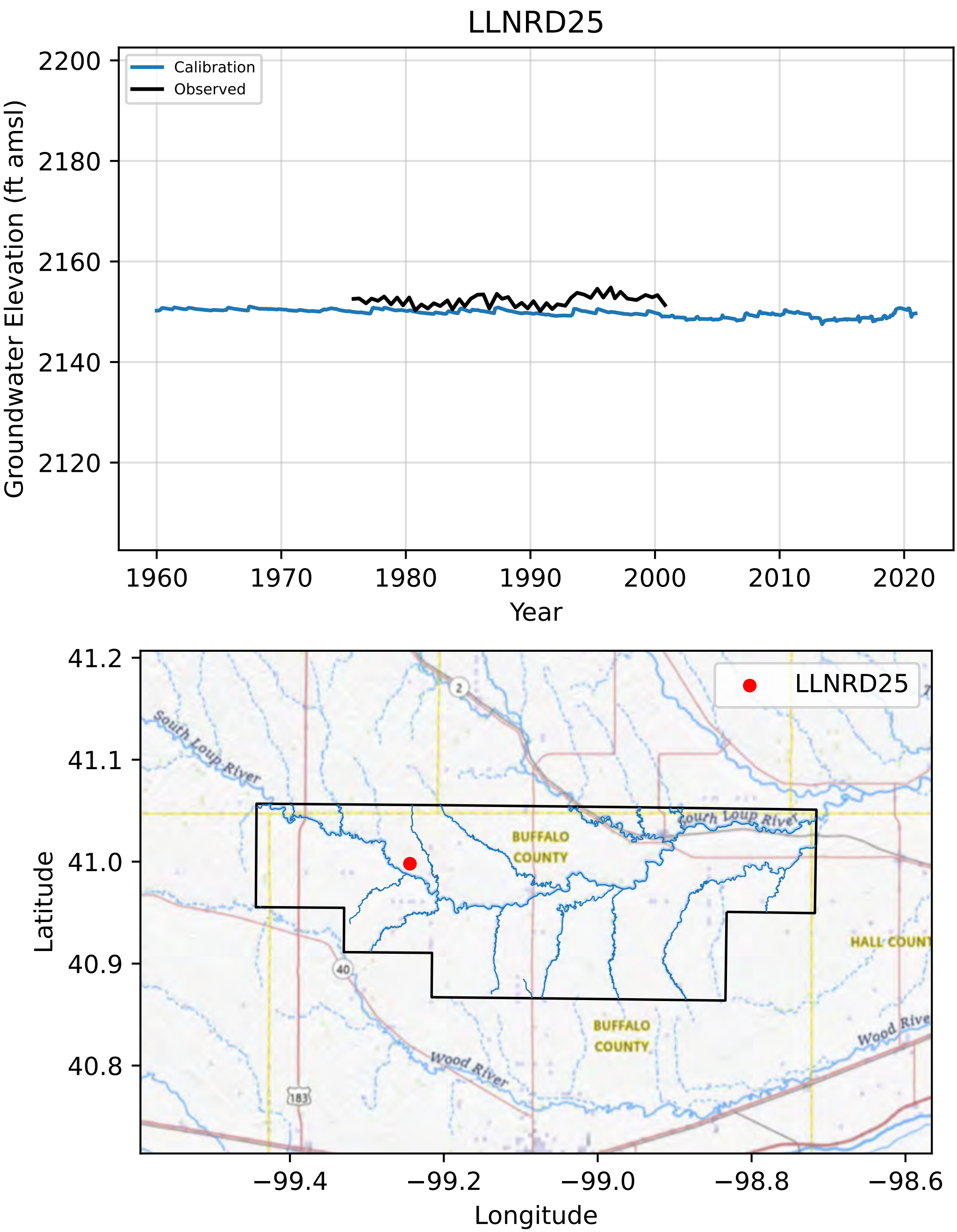
LLNRD22
Calibration
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD22
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River

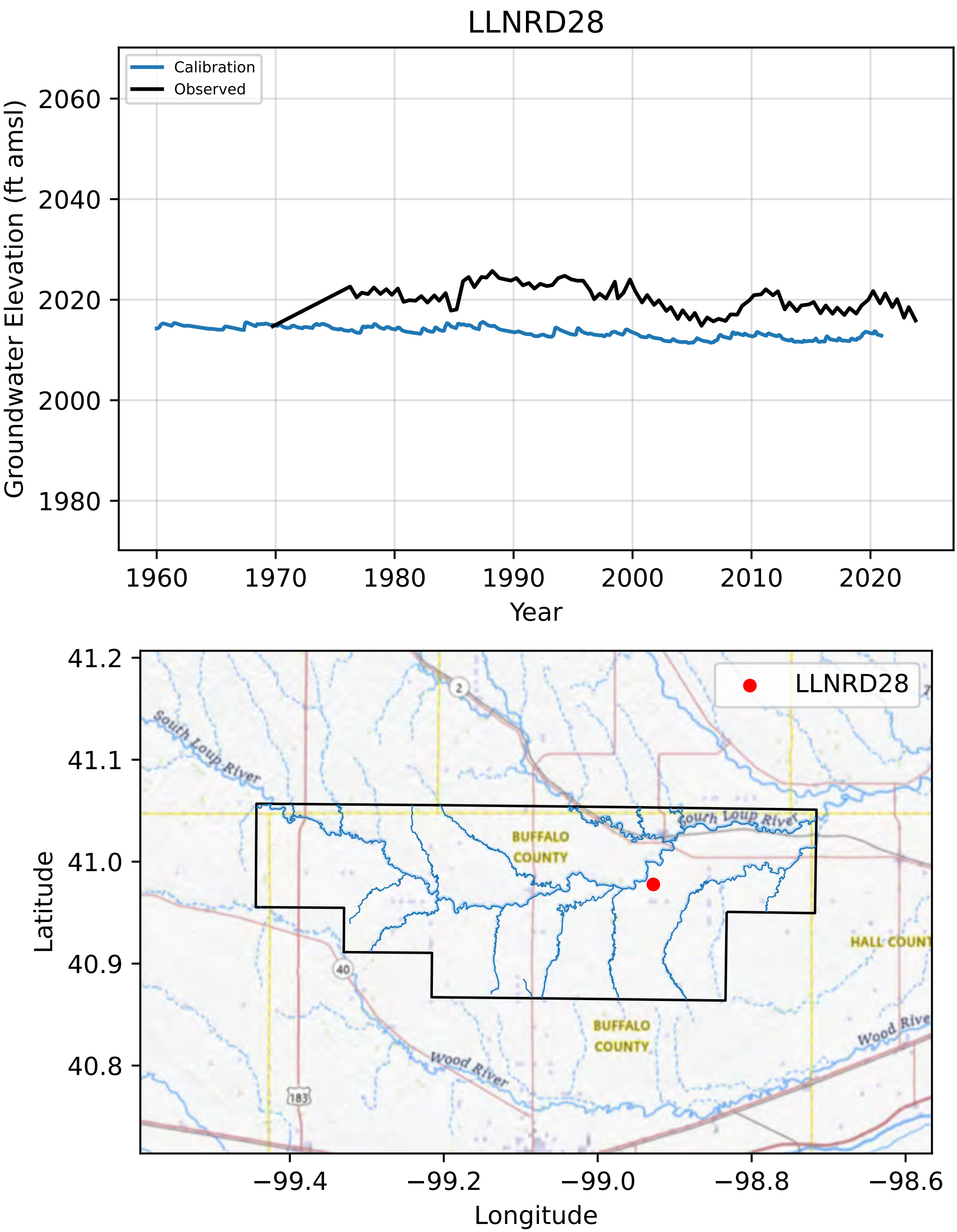


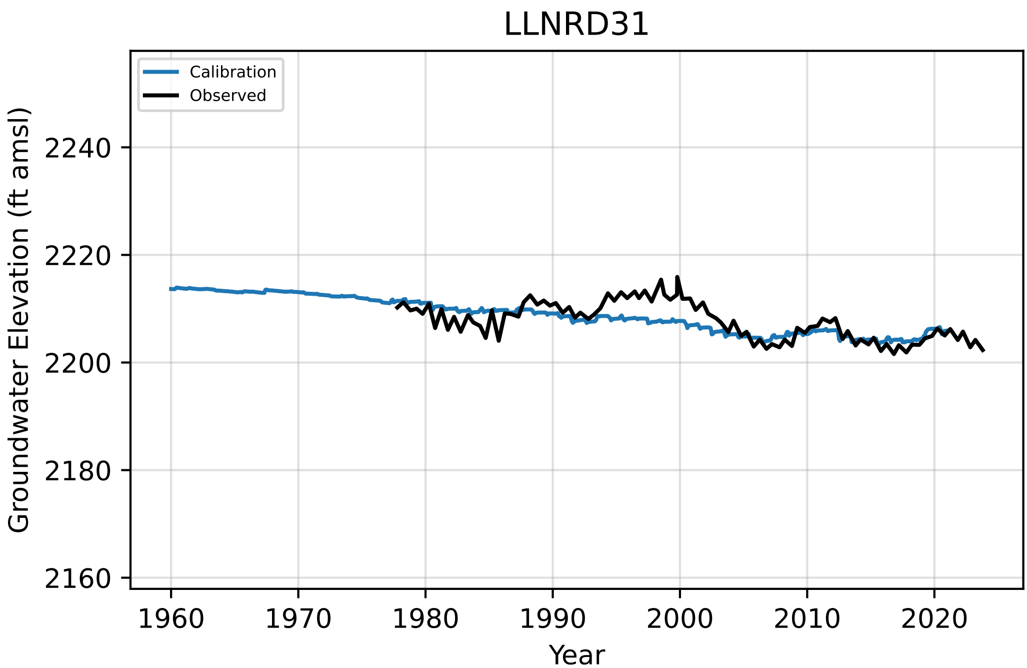
LLNRD24
Calibration
Observed
Groundwater Elevation (ft amsl)
2040
2020
2000
1980
1960
1960
1970
1980
1990
2000
2010
2020
Year

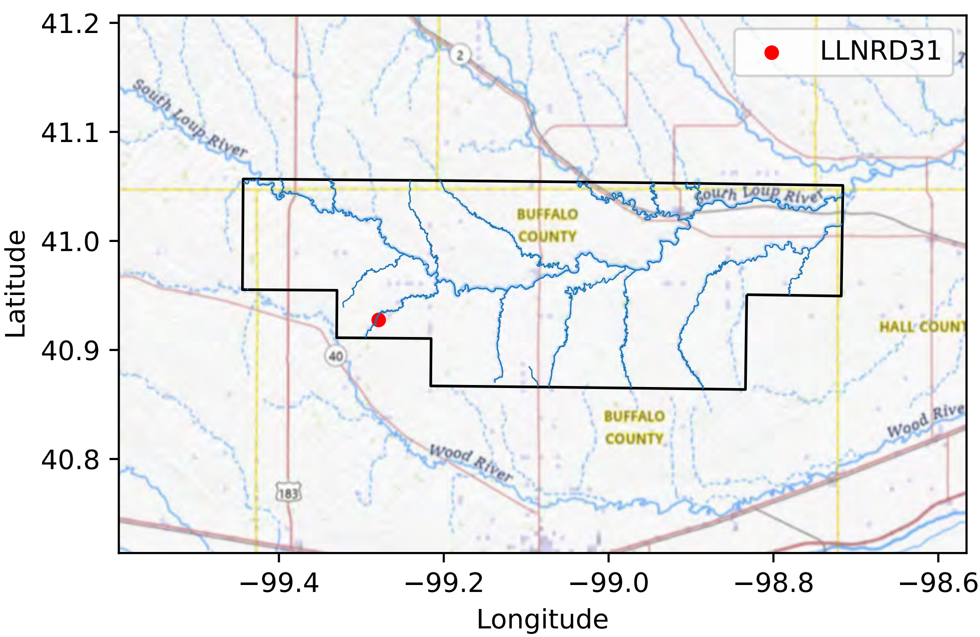


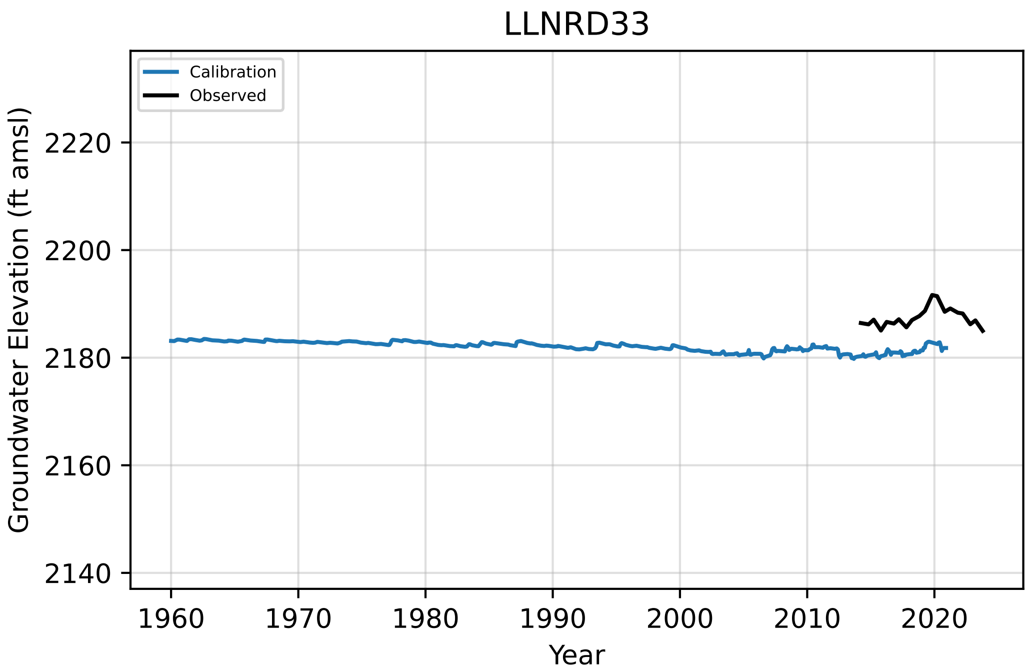
LLNRD24
South Loup River
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD25
Calibration
Observed
Groundwater Elevation (ft amsl)
2200
2180
2160
2140
2120
1960
1970
1980
1990
2000
2010
2020
Year
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
LLNRD25
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
Wood River

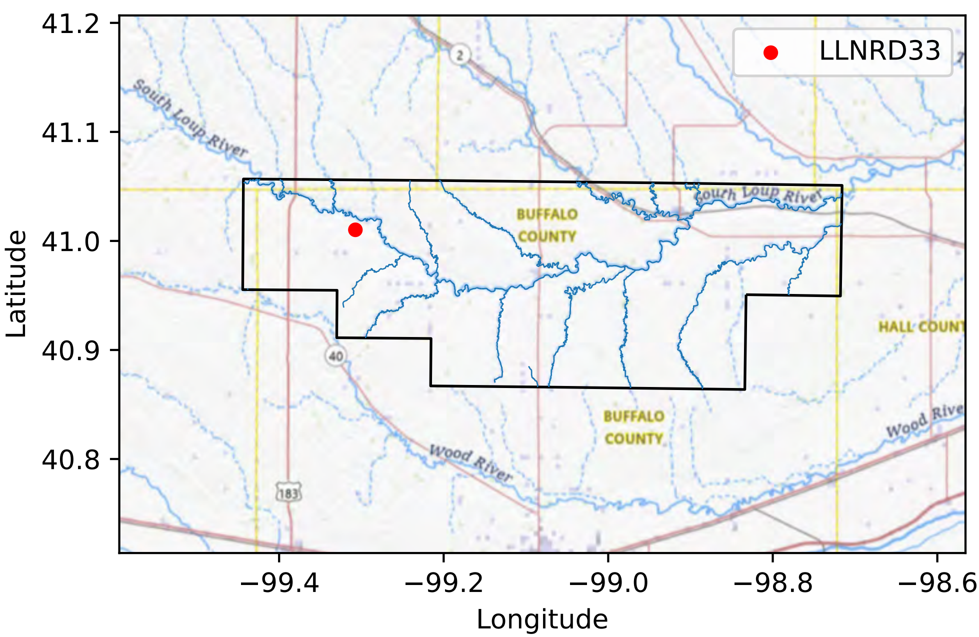

LLNRD28
Calibration
Observed
Groundwater Elevation (ft amsl)
2060
2040
2020
2000
1980
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD28
South Loup River
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD31
Calibration
Observed
Groundwater Elevation (ft amsl)
2240
2220
2200
2180
2160
1960
1970
1980
1990
2000
2010
2020
Year

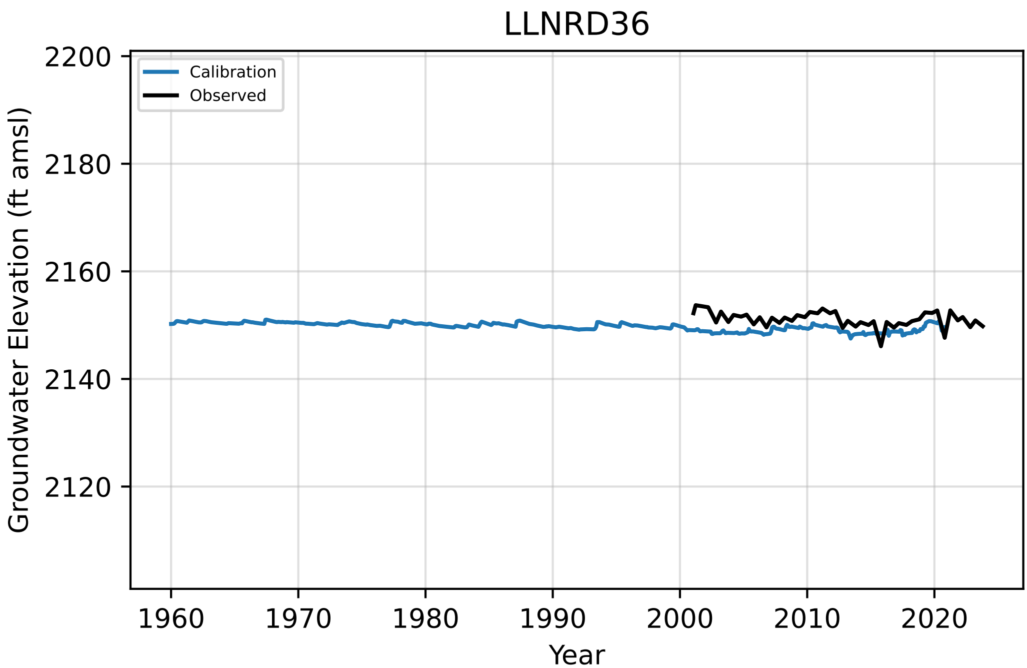

LLNRD31
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive



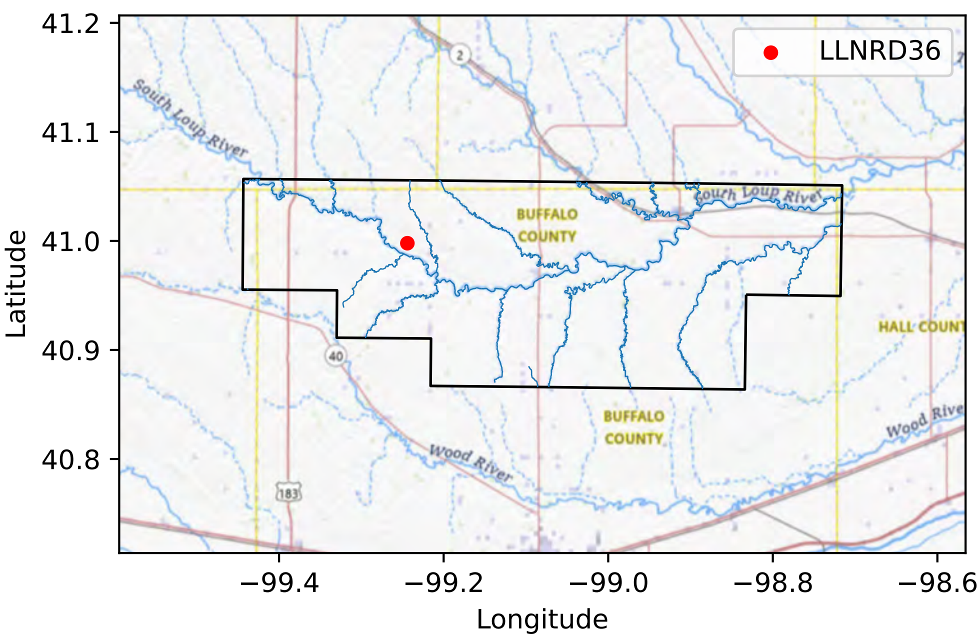
LLNRD33
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year



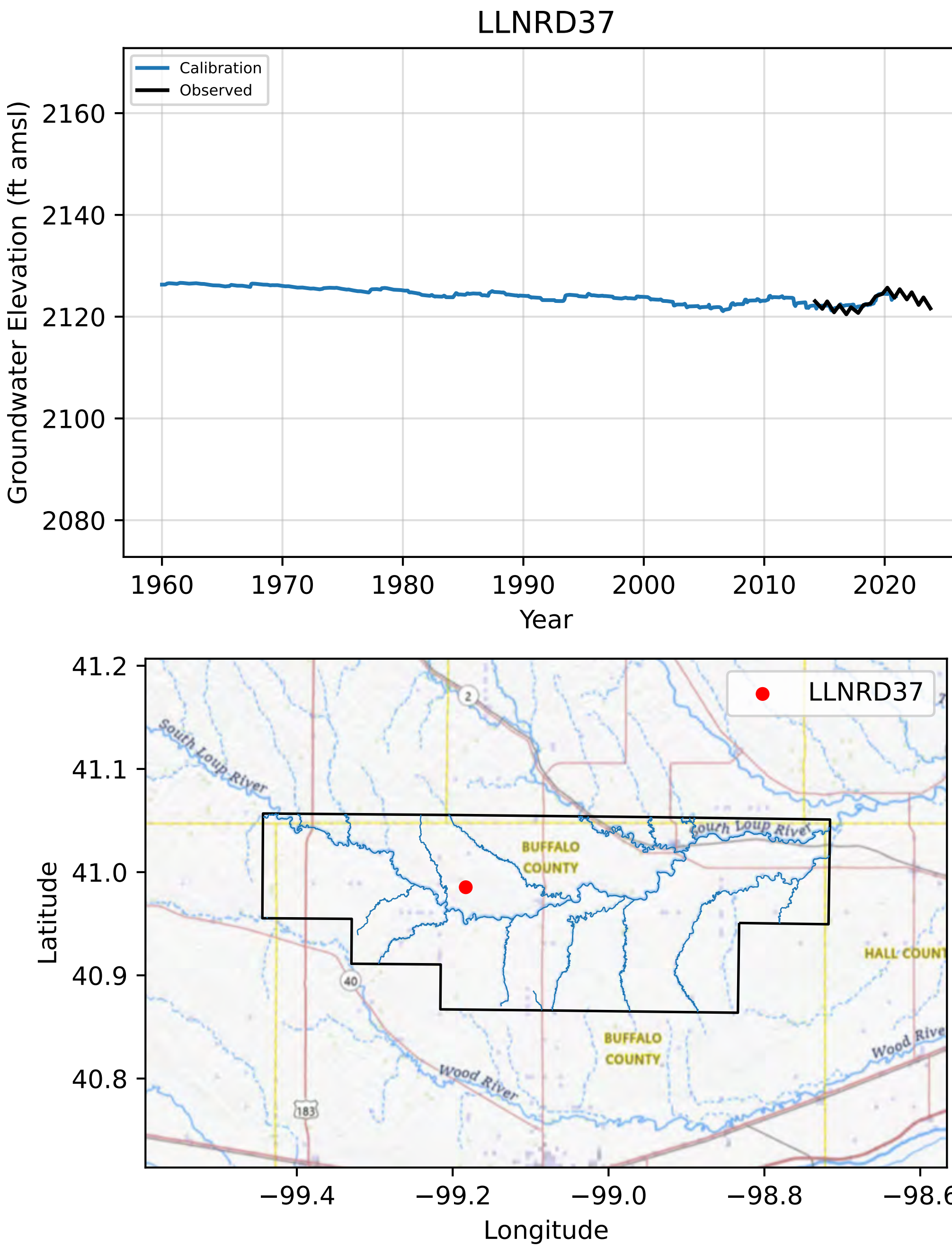
LLNRD33
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



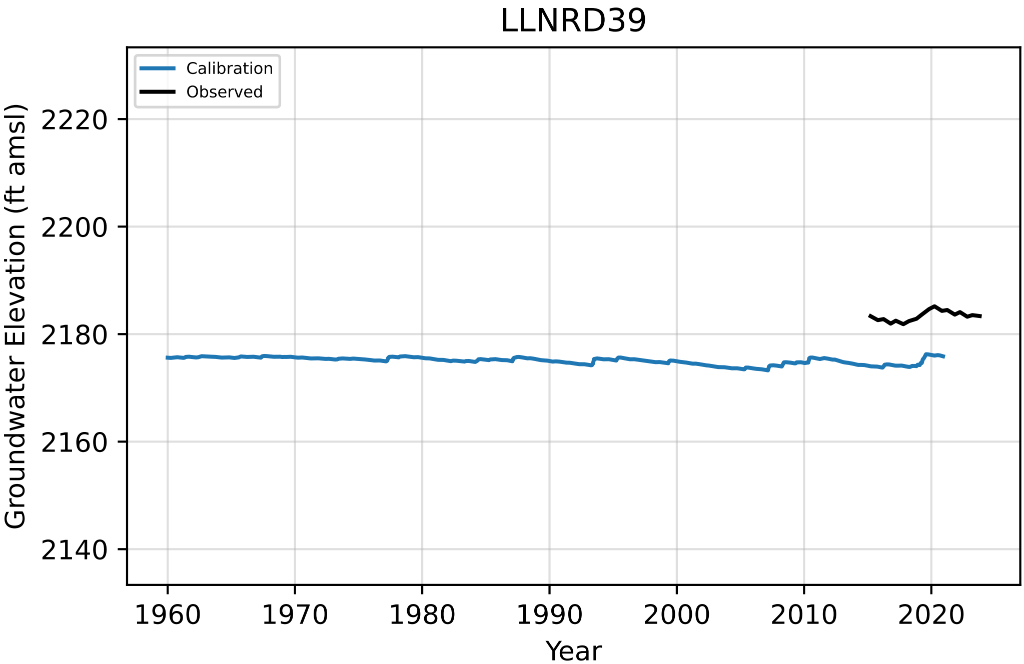
LLNRD36
Calibration
Observed
Groundwater Elevation (ft amsl)
2200
2180
2160
2140
2120
1960
1970
1980
1990
2000
2010
2020
Year



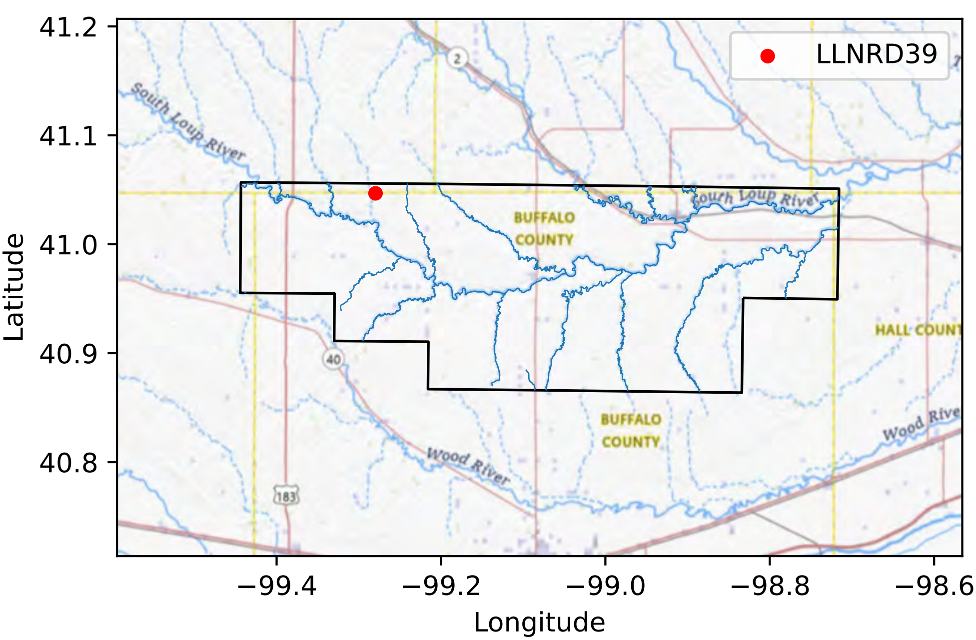
LLNRD36
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River



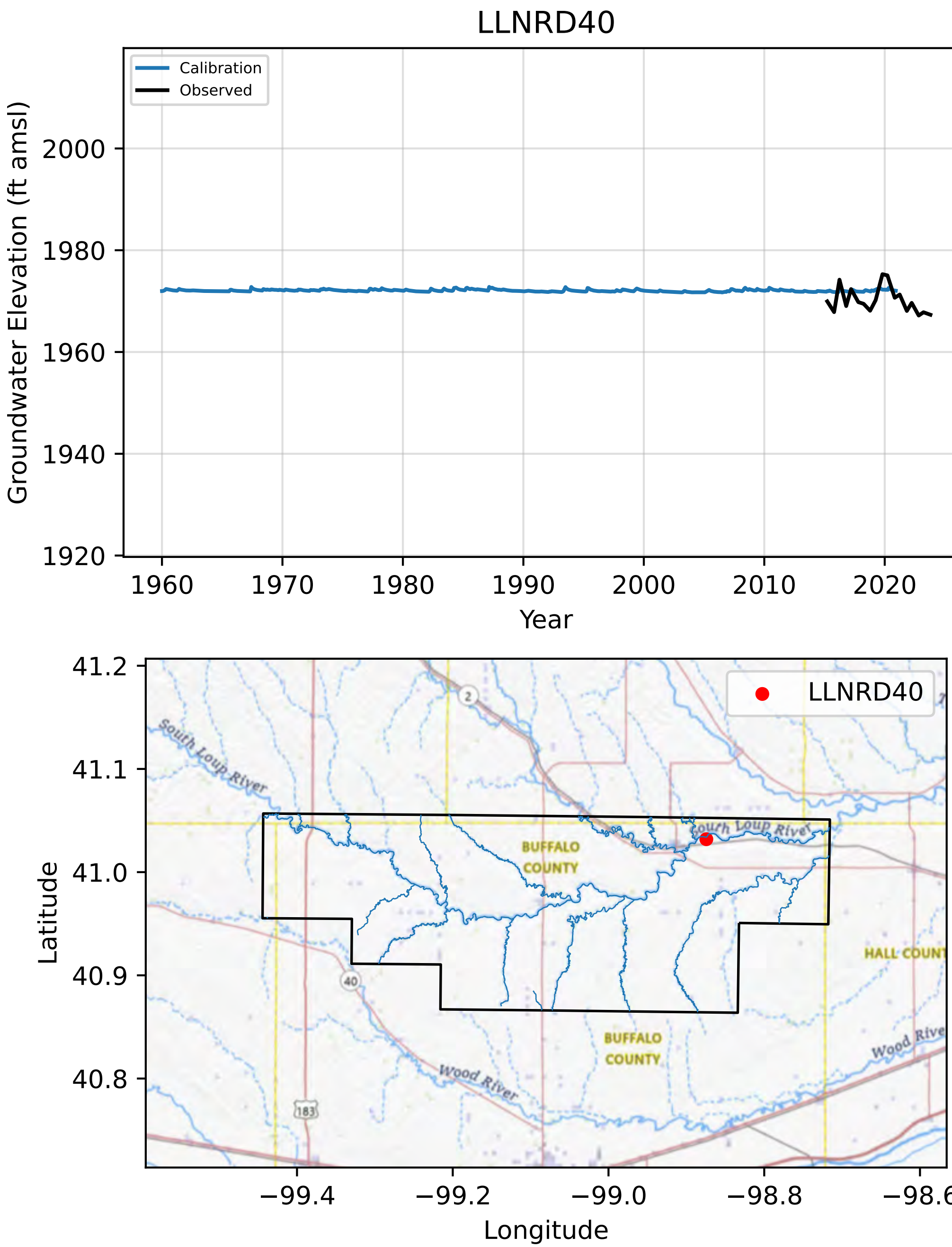
LLNRD37
Calibration
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
LLNRD37
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
40
183
2

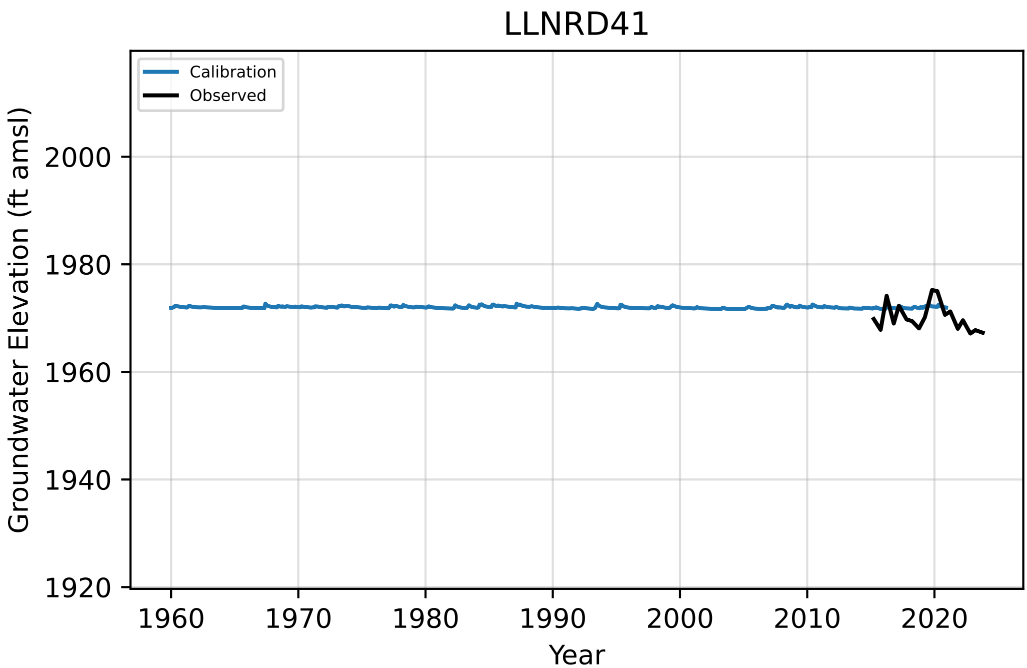


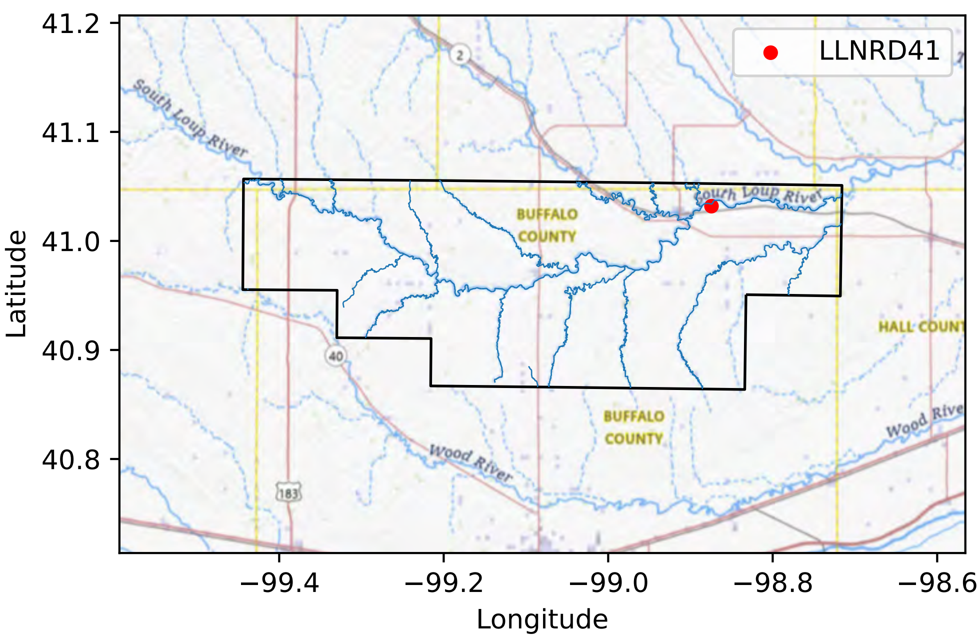
LLNRD39
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year

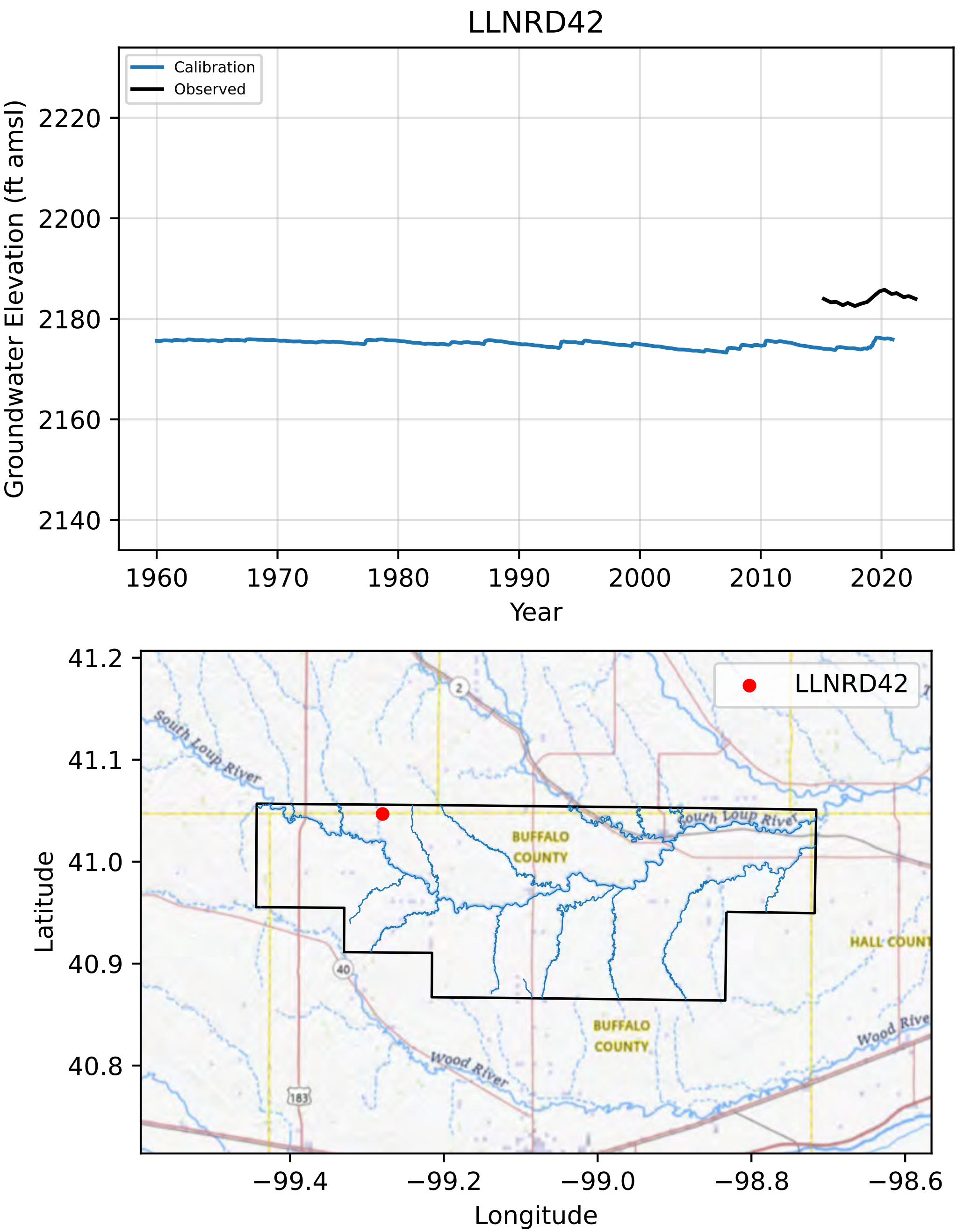


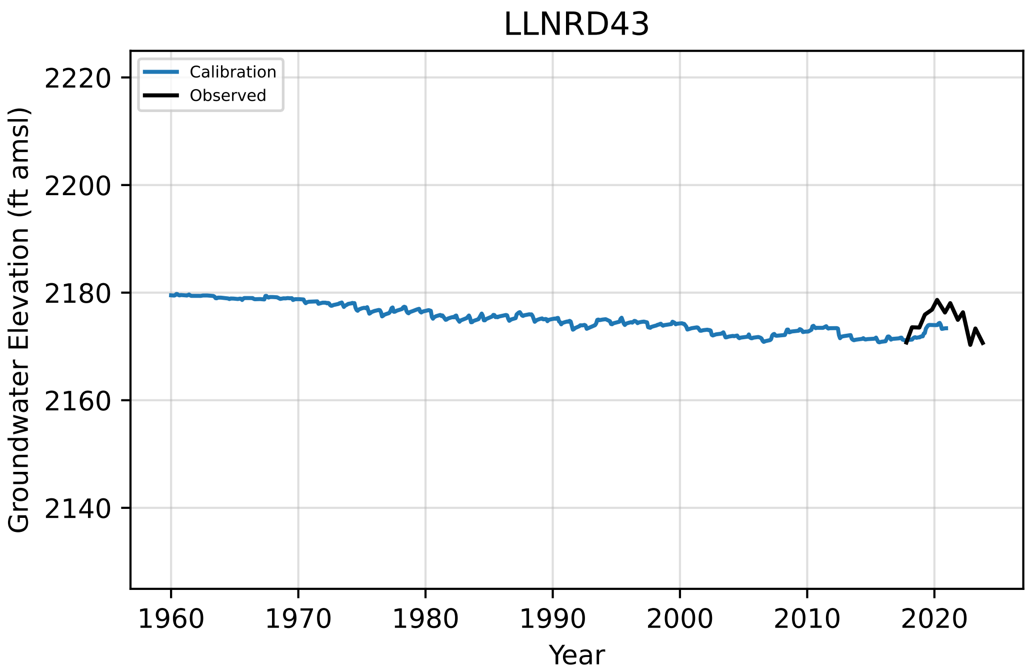
LLNRD39
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River


LLNRD40
Calibration
Observed
Groundwater Elevation (ft amsl)
2000
1980
1960
1940
1920
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD40
South Loup River
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River
2
40
183
Latitude
41.2
41.1
41.0
40.9
40.8
-99.4
-99.2
-99.0
-98.8
-98.6
Longitude

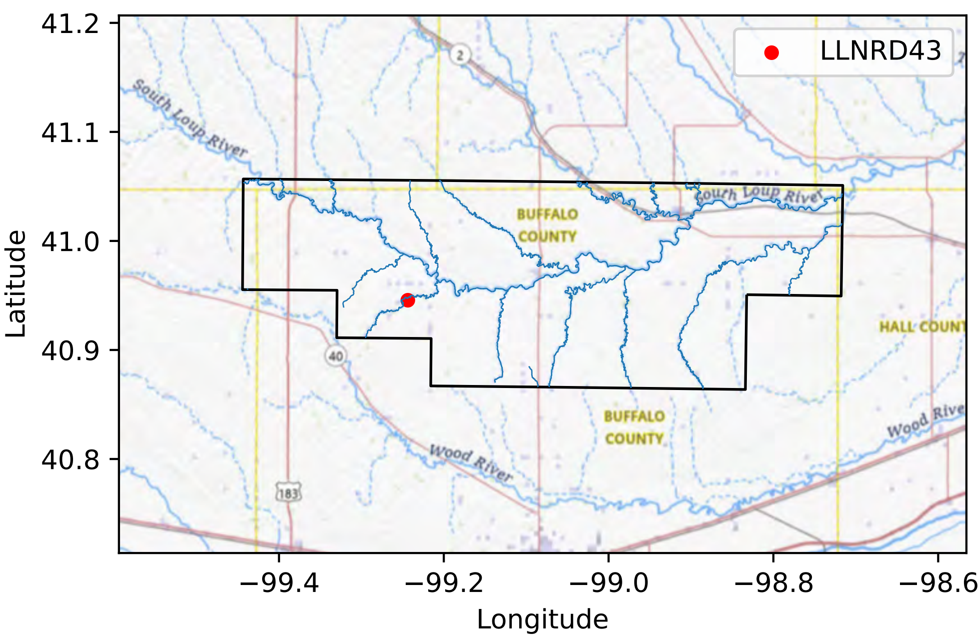

LLNRD41
Calibration
Observed
Groundwater Elevation (ft amsl)
Year


LLNRD41
Latitude
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River

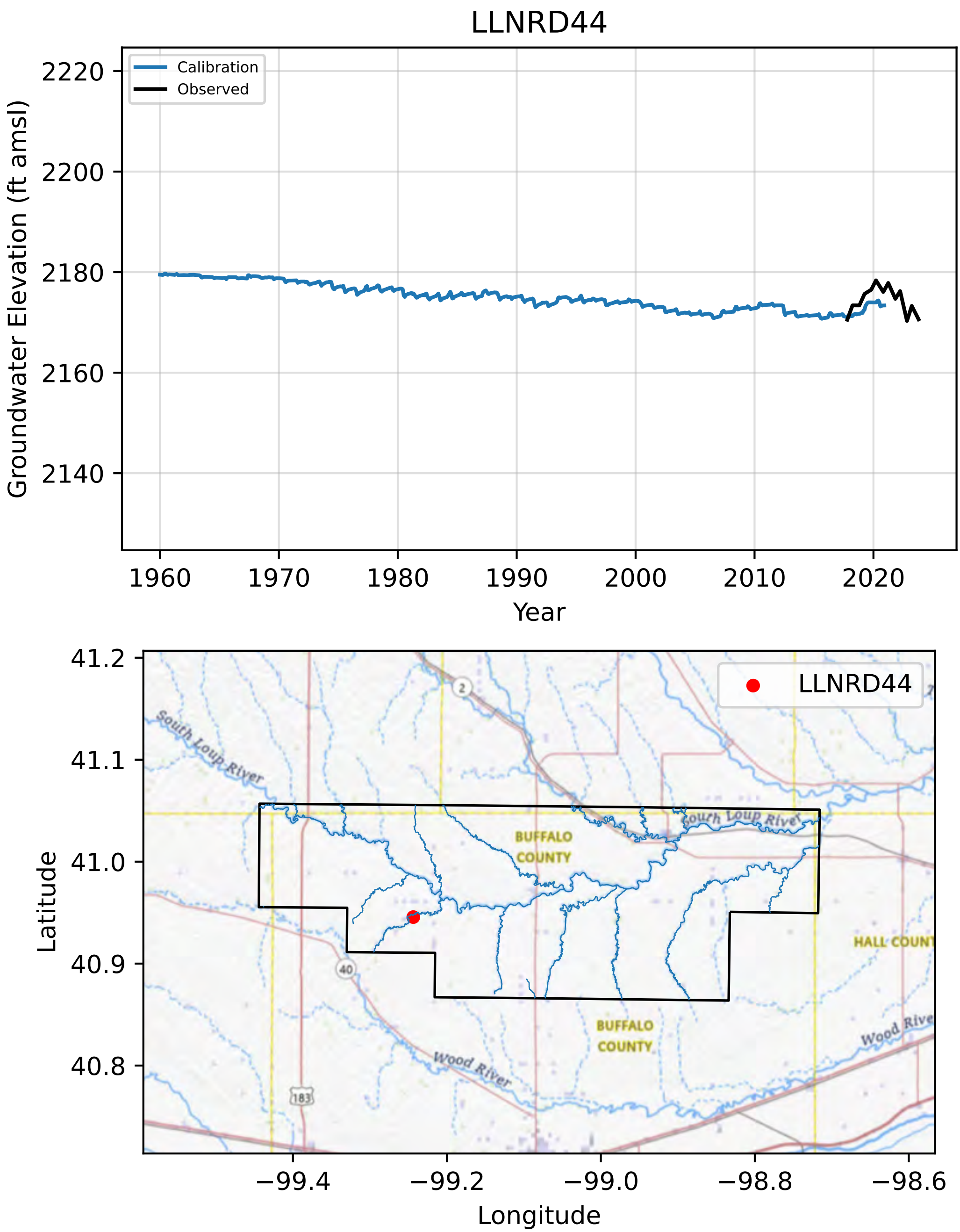

LLNRD42
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD42
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River

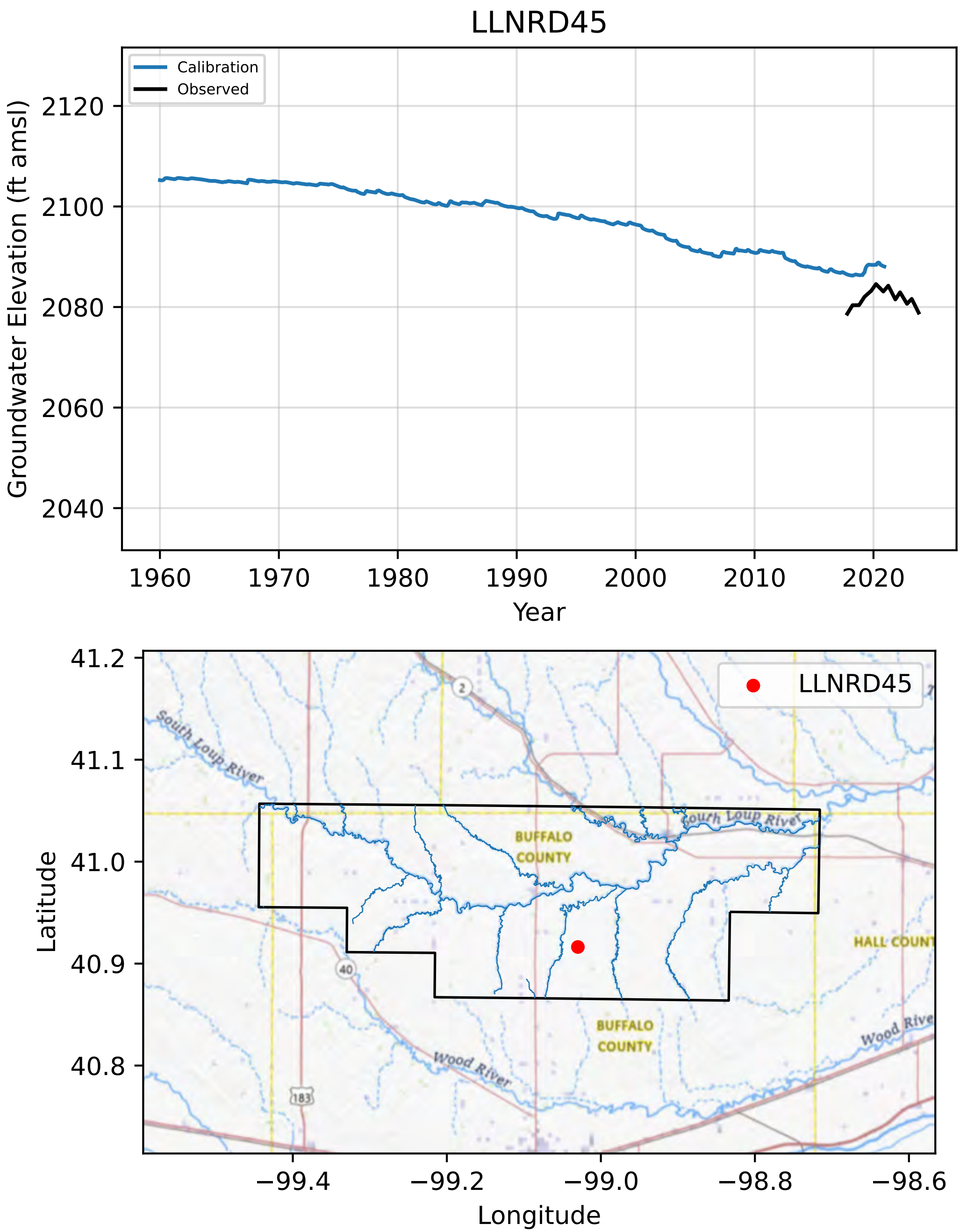


LLNRD43
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year

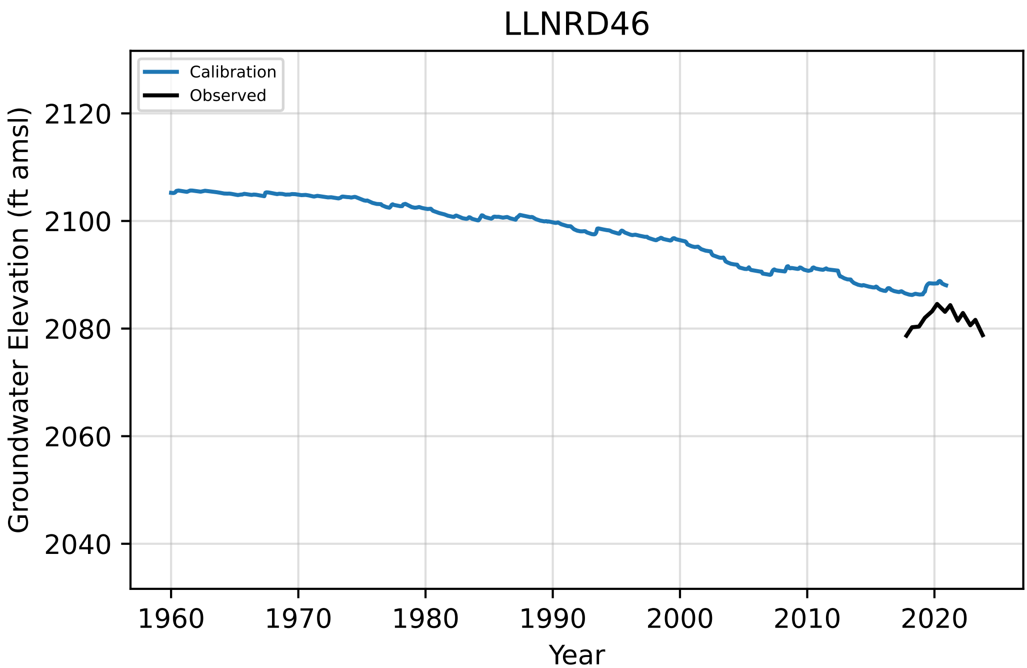


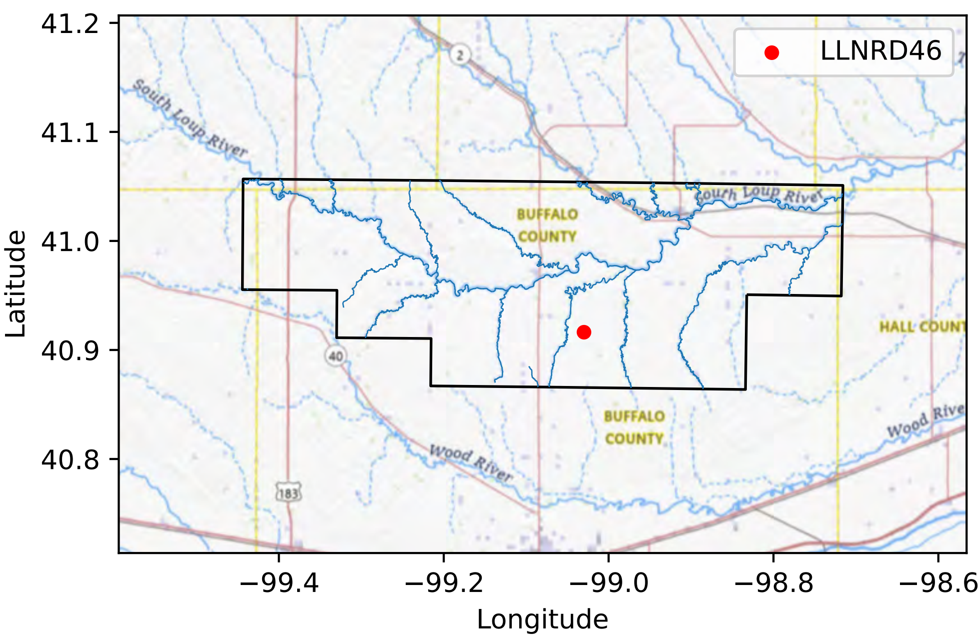
LLNRD43
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

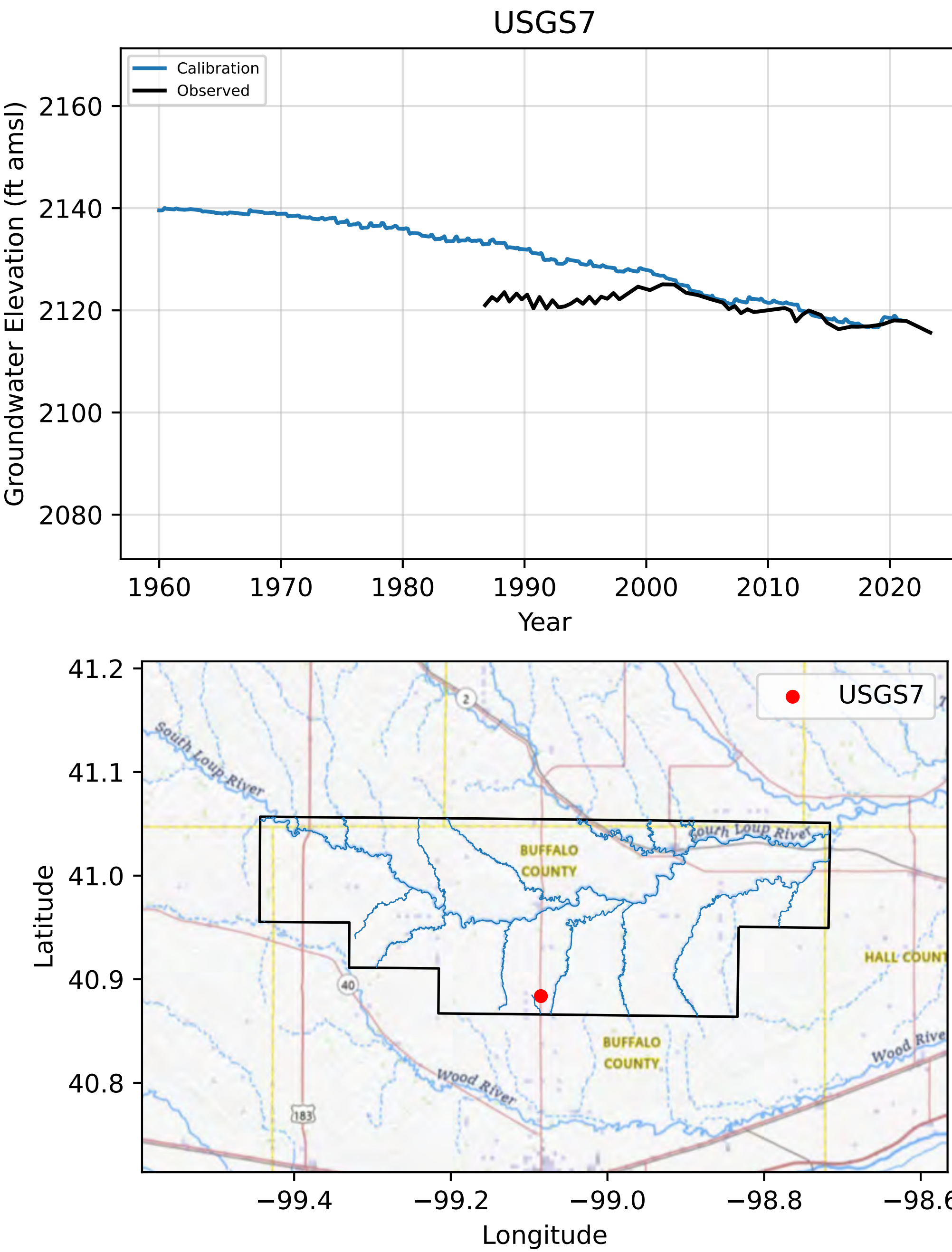

LLNRD44
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD44
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO
COUNTY
HALL COUNT
Wood River
183
40
2

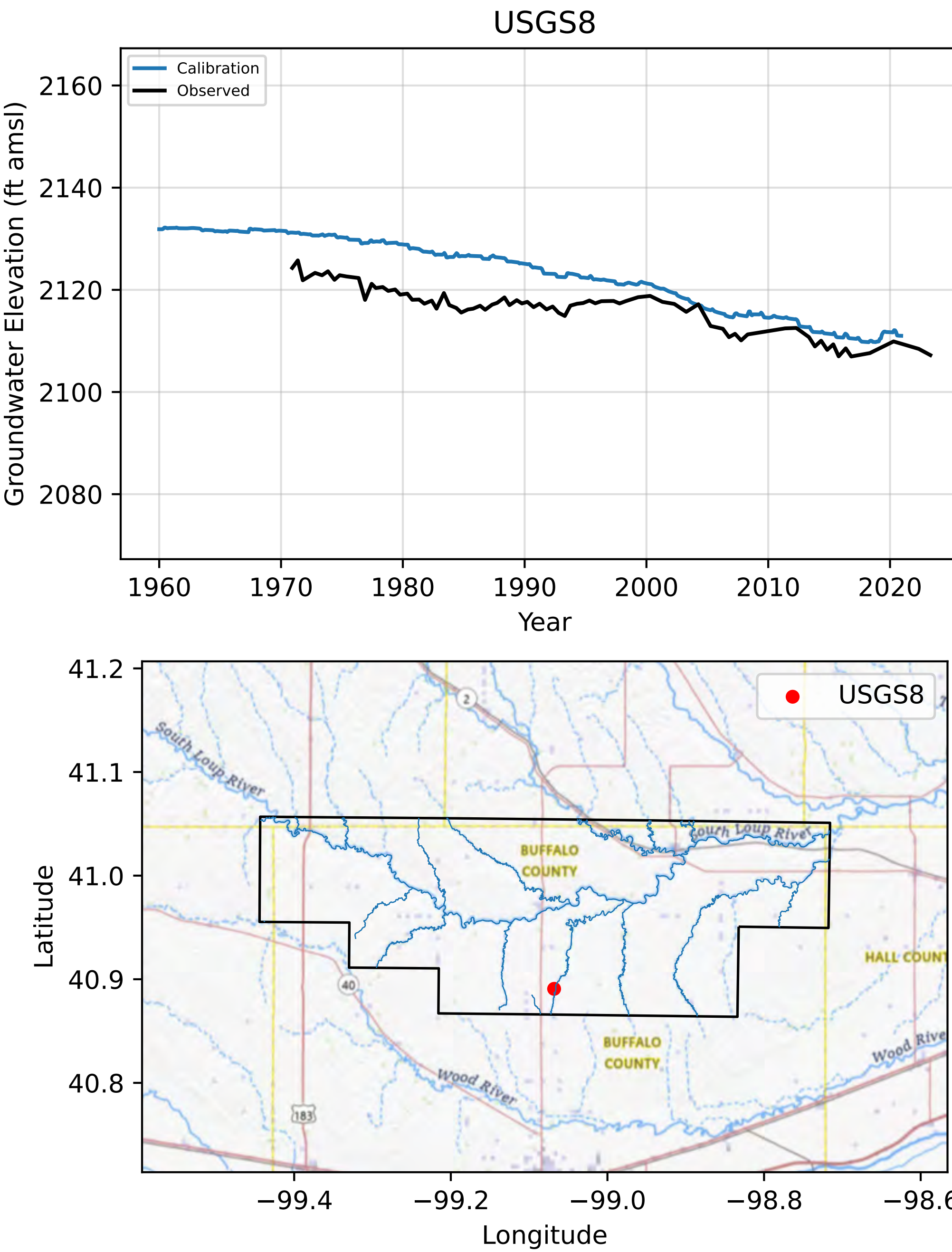


LLNRD45
Calibration
Observed
Groundwater Elevation (ft amsl)
2120
2100
2080
2060
2040
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD45
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River

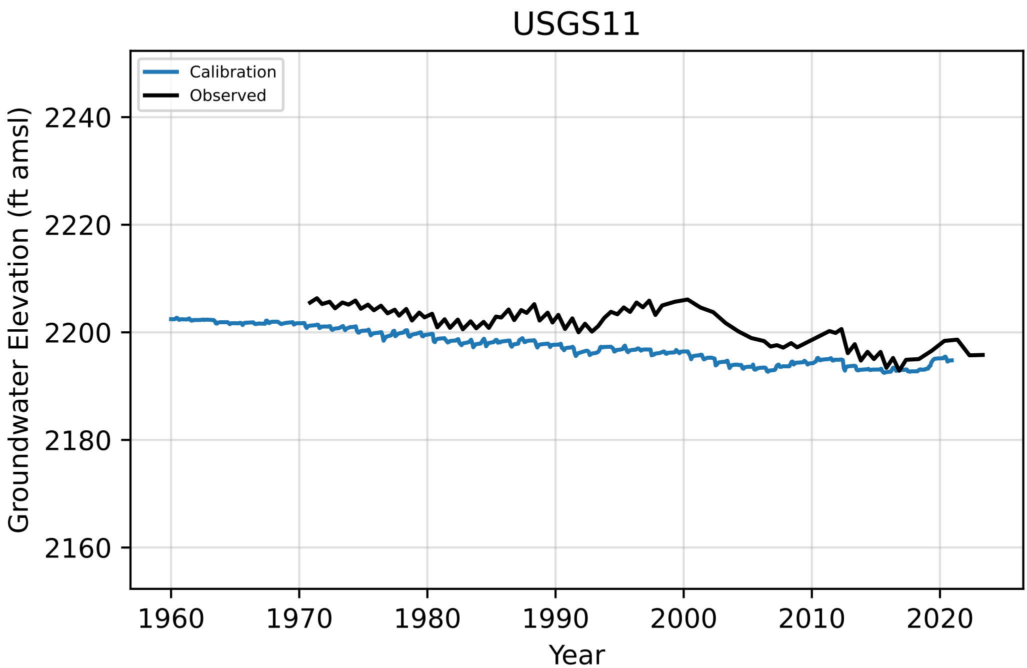

LLNRD46
Calibration
Observed
Groundwater Elevation (ft amsl)
2120
2100
2080
2060
2040
1960
1970
1980
1990
2000
2010
2020
Year


LLNRD46
South Loup River
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River
2
40
183
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

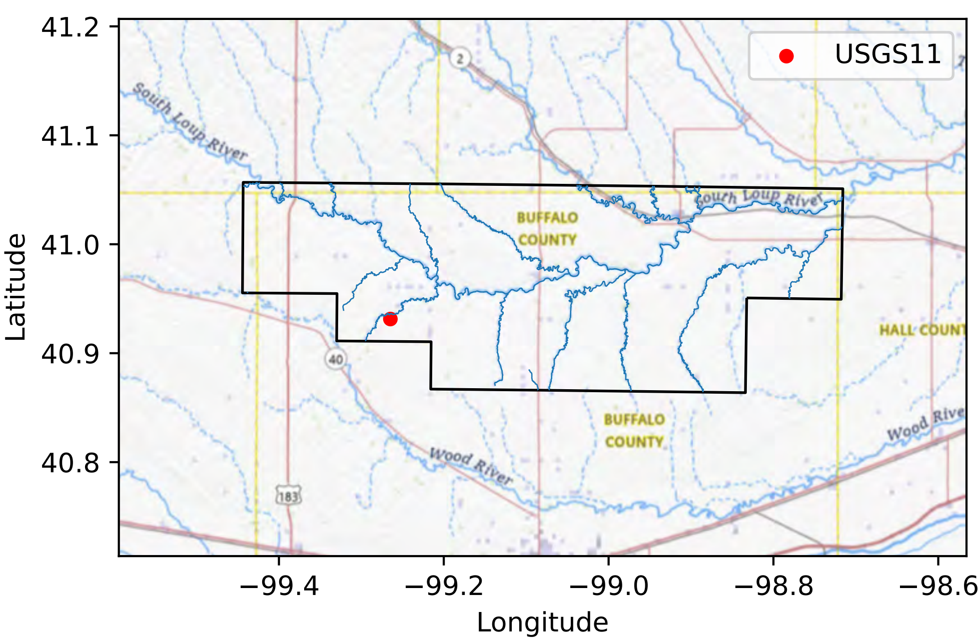

USGS7
Calibration
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
USGS7
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River
2
40
183



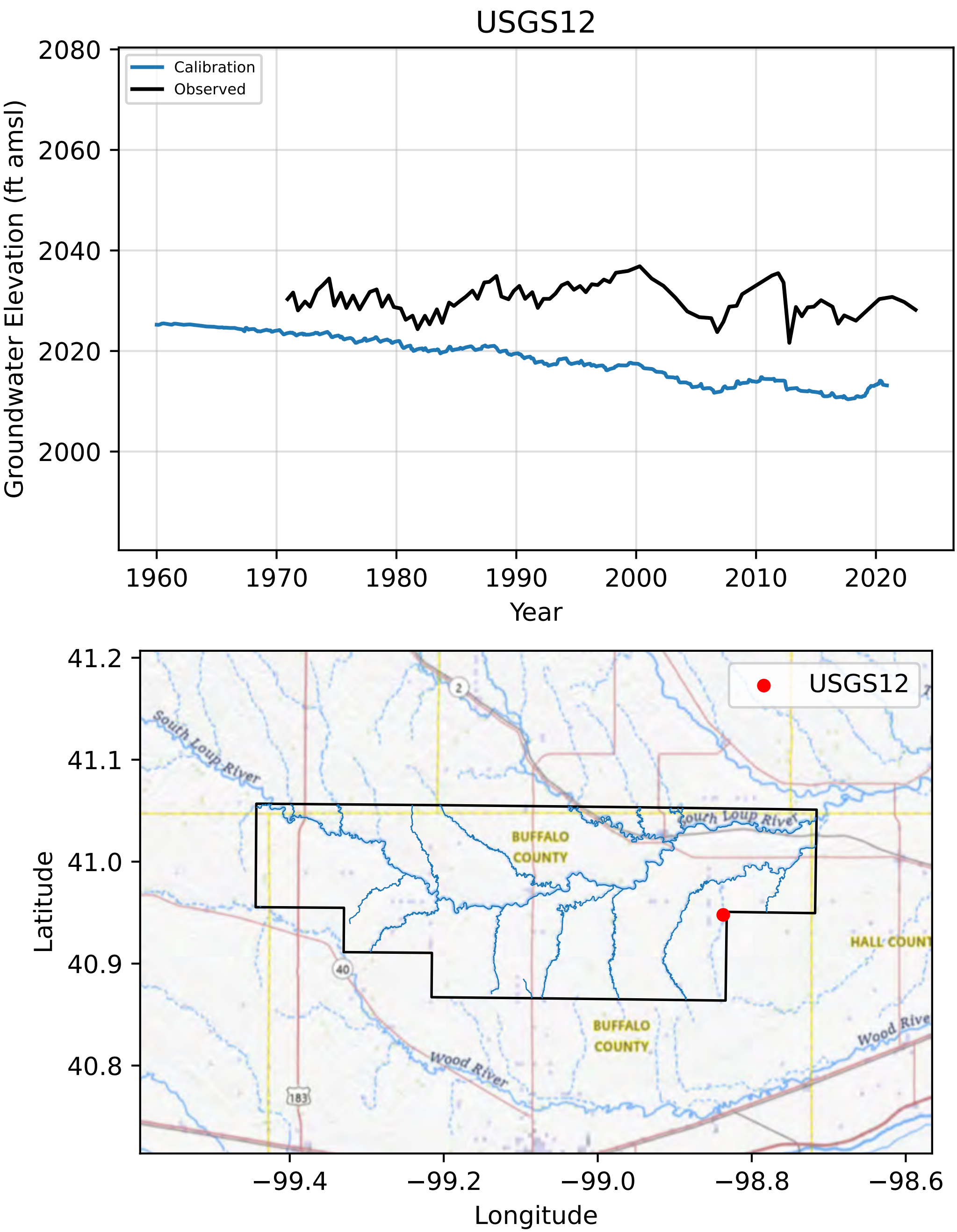
USGS8
Calibration
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year
USGS8
South Loup River
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River
2
40
183
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

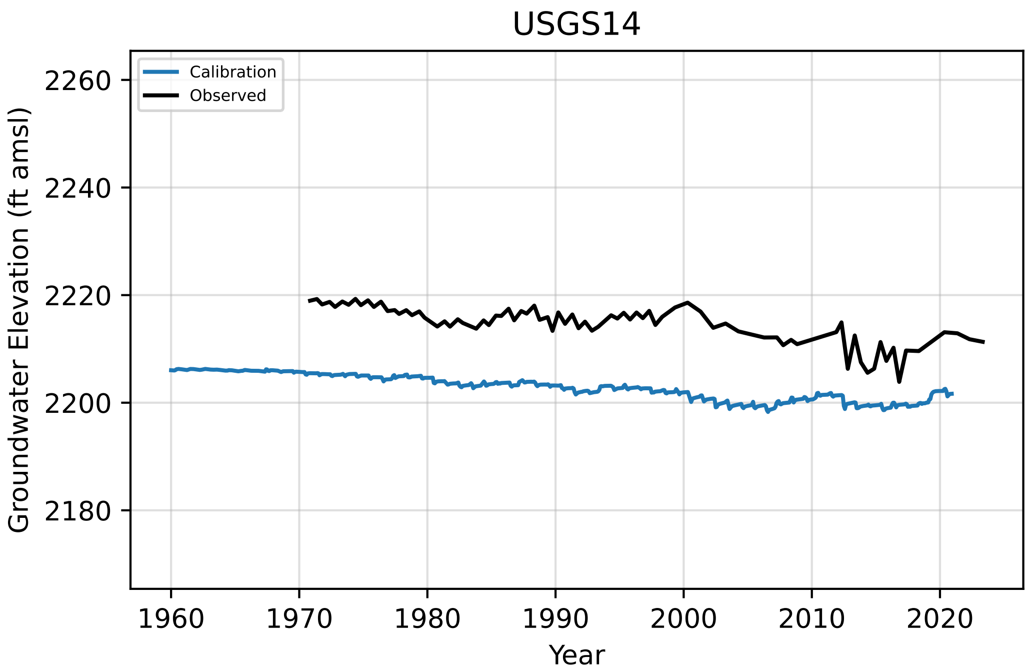


USGS11
Calibration
Observed
Groundwater Elevation (ft amsl)
2160
2180
2200
2220
2240
1960
1970
1980
1990
2000
2010
2020
Year

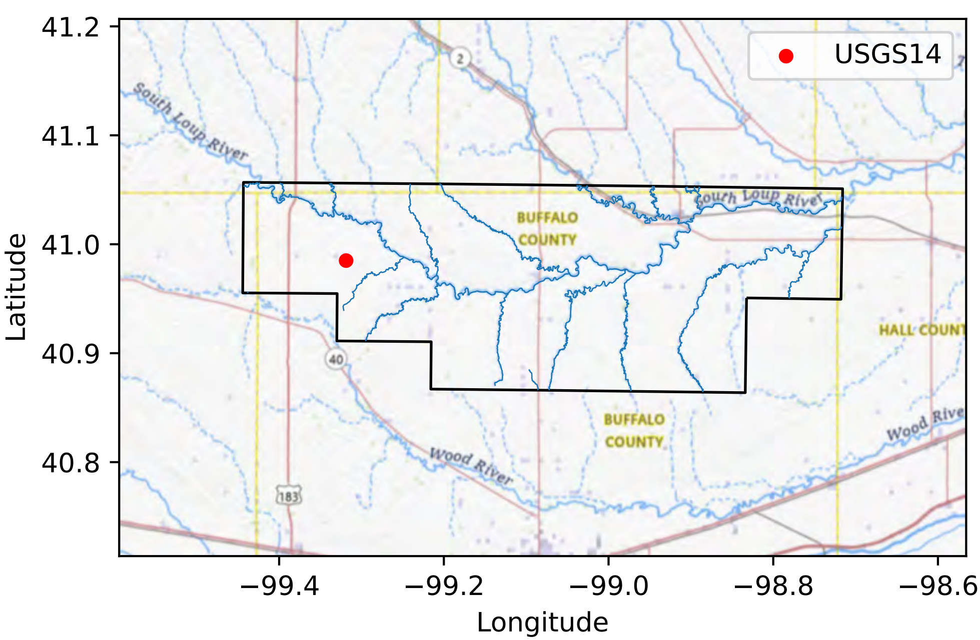


USGS11
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

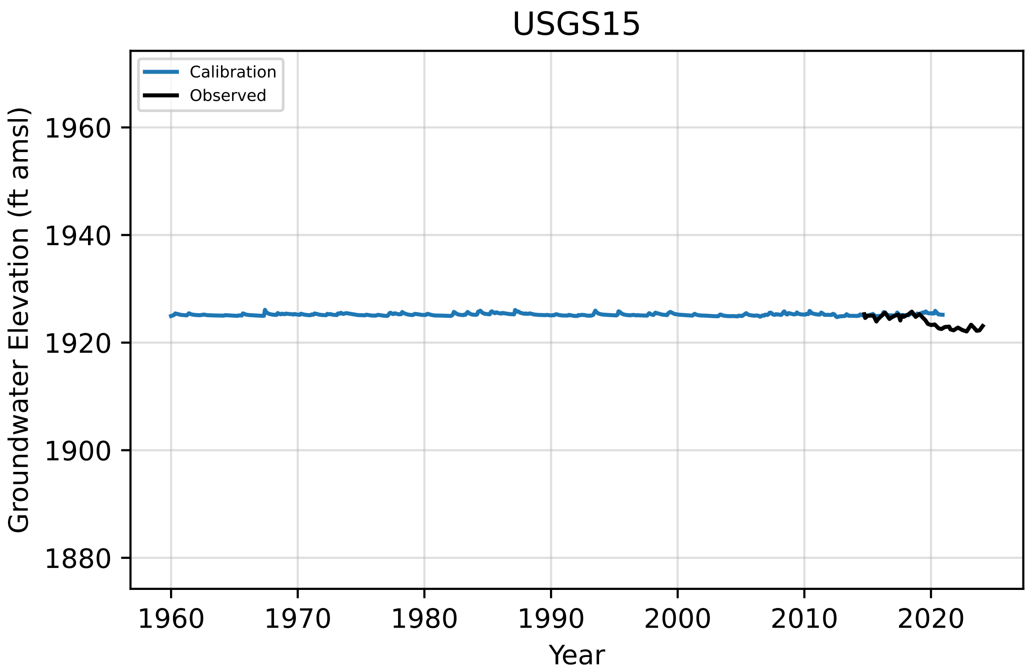

USGS12
Calibration
Observed
Groundwater Elevation (ft amsl)
2080
2060
2040
2020
2000
1960
1970
1980
1990
2000
2010
2020
Year
USGS12
South Loup River
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

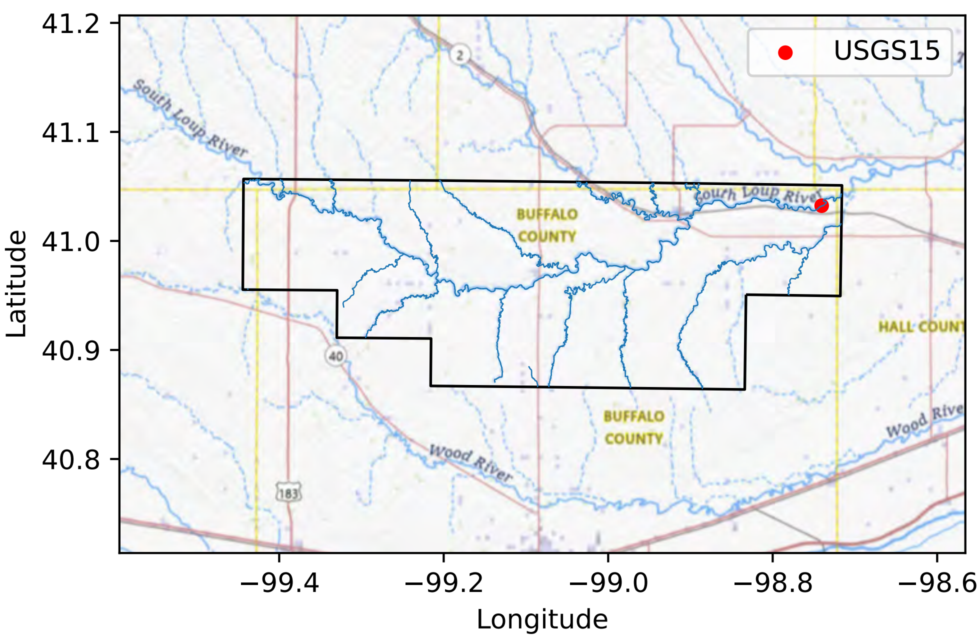


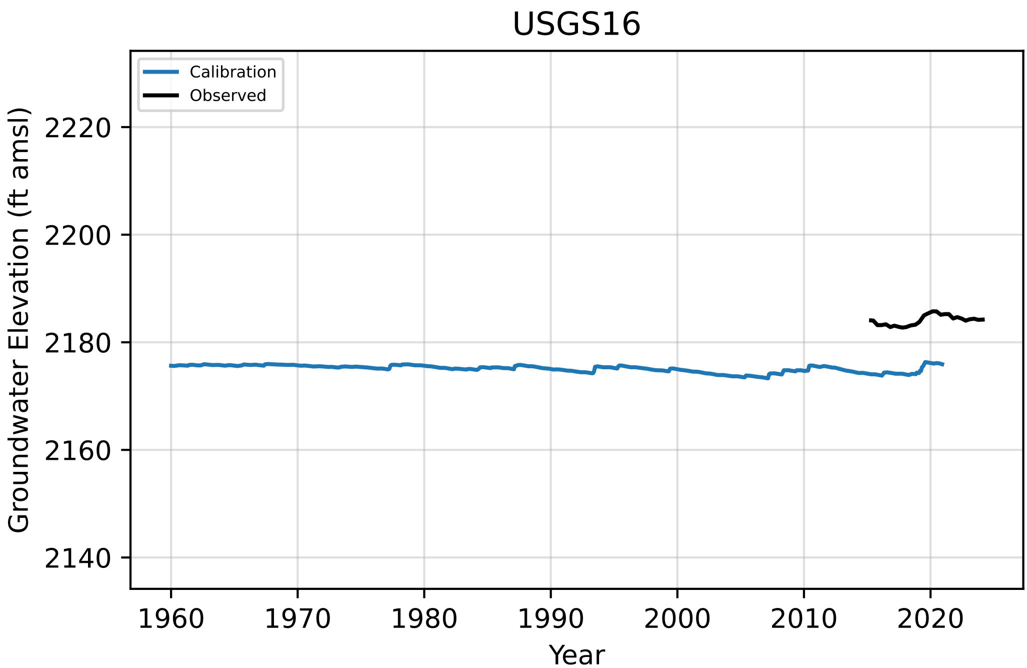
USGS14
Calibration
Observed
Groundwater Elevation (ft amsl)
2260
2240
2220
2200
2180
1960
1970
1980
1990
2000
2010
2020
Year



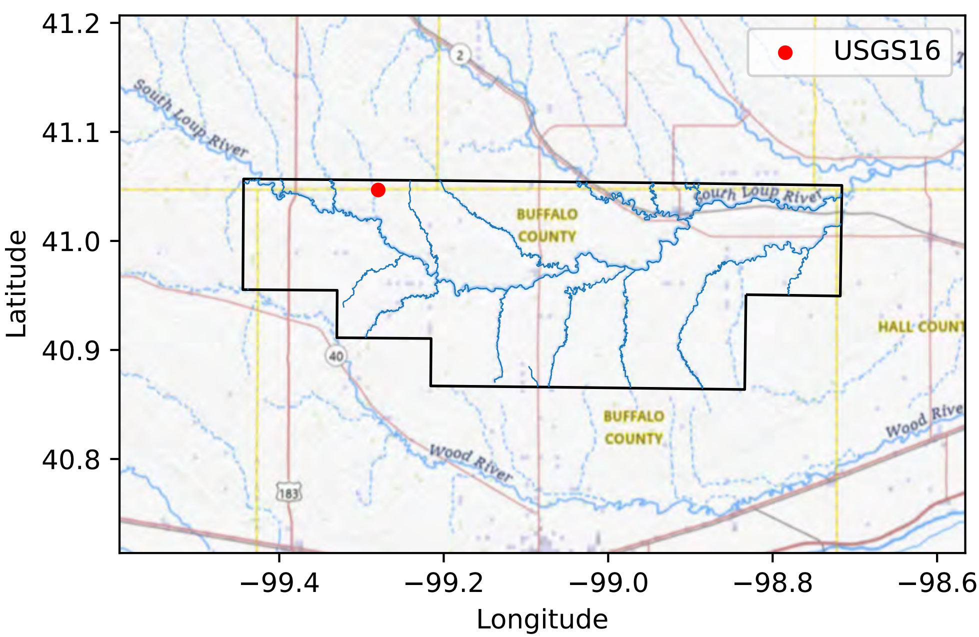
USGS14
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River


USGS15
Calibration
Observed
Groundwater Elevation (ft amsl)
1960
1940
1920
1900
1880
1960
1970
1980
1990
2000
2010
2020
Year


USGS15
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
Wood River
HALL COUNT

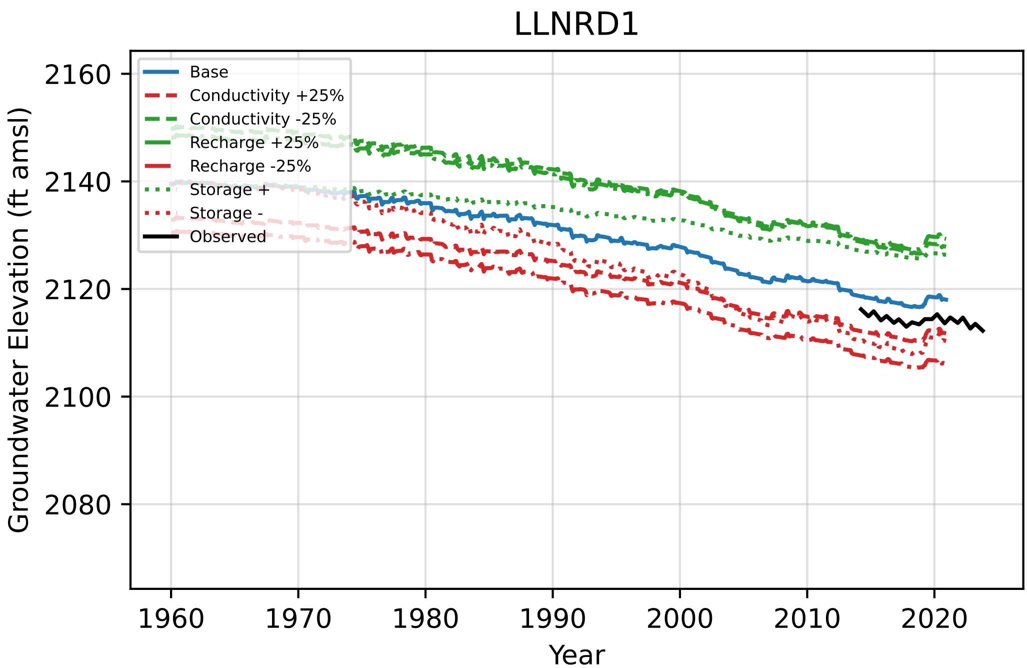


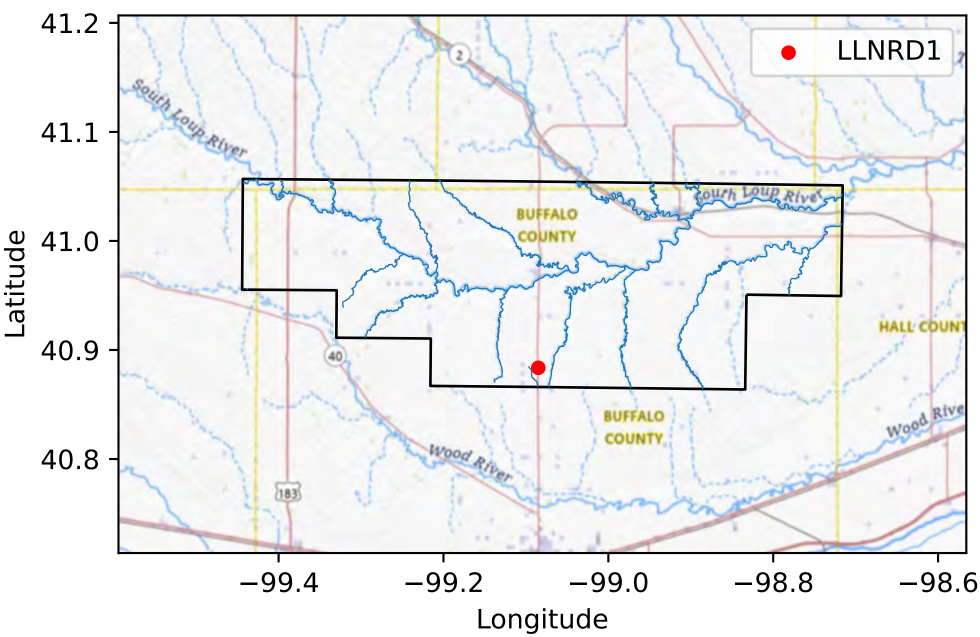
USGS16
Calibration
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year

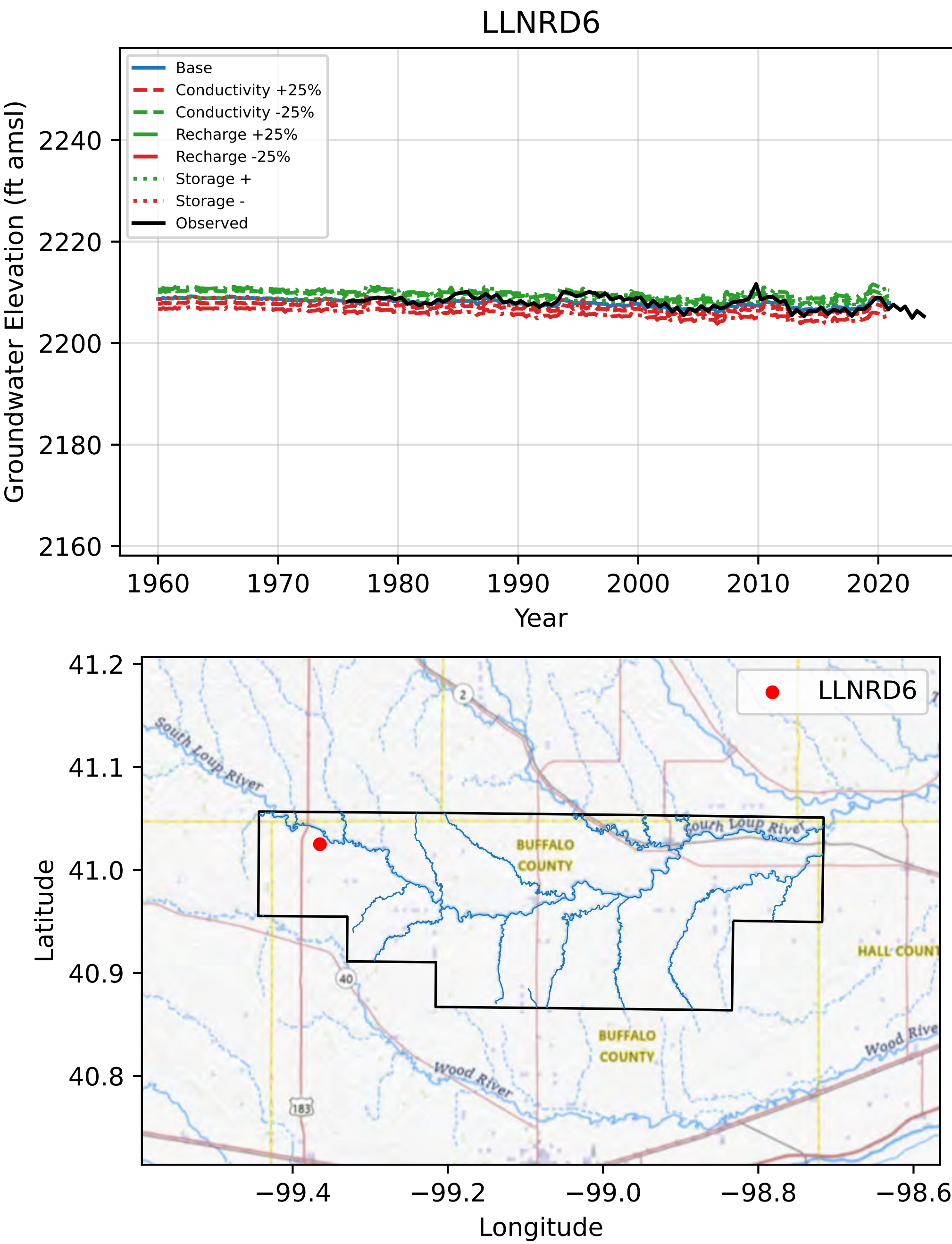


USGS16
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

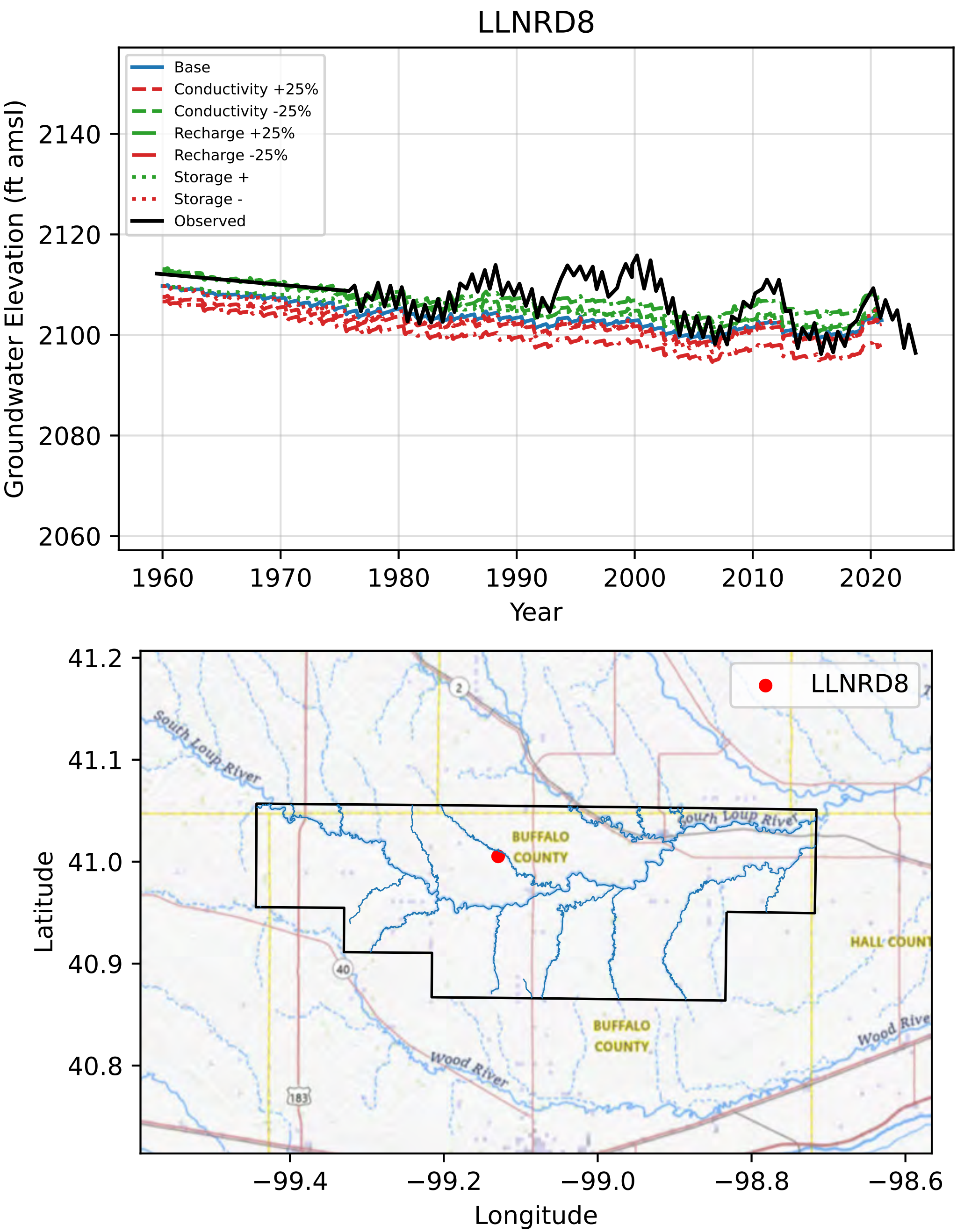
Appendix D
Hydrographs for Sensitivity Analysis

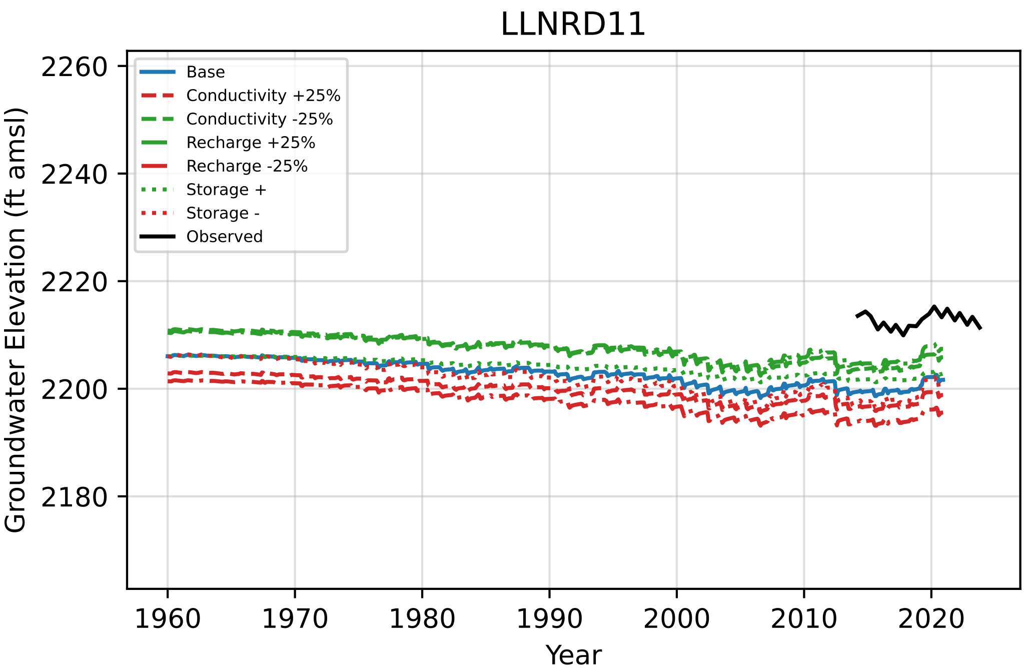

LLNRD1
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
Year
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020

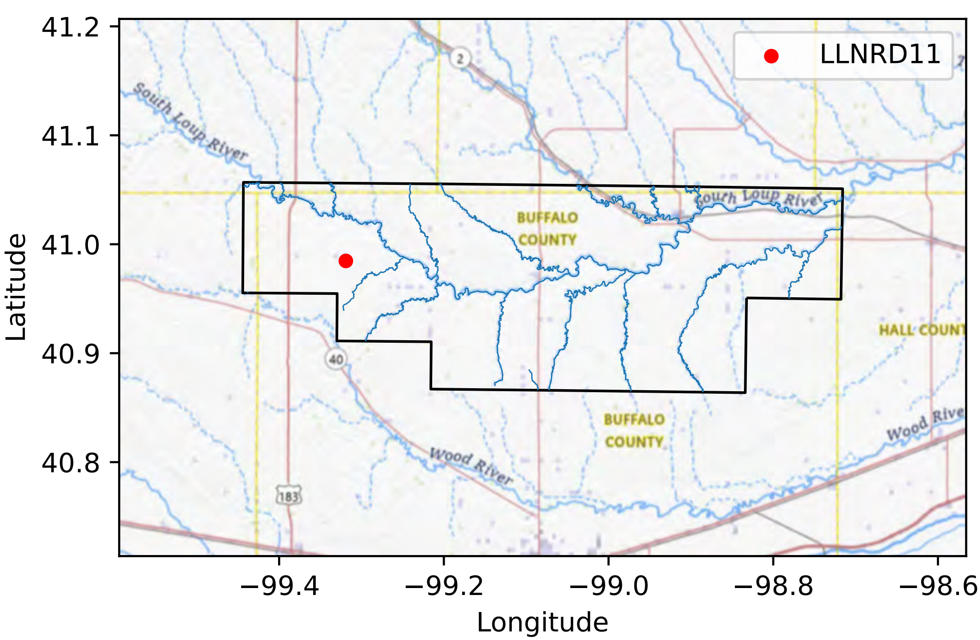

LLNRD1
Latitude
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6

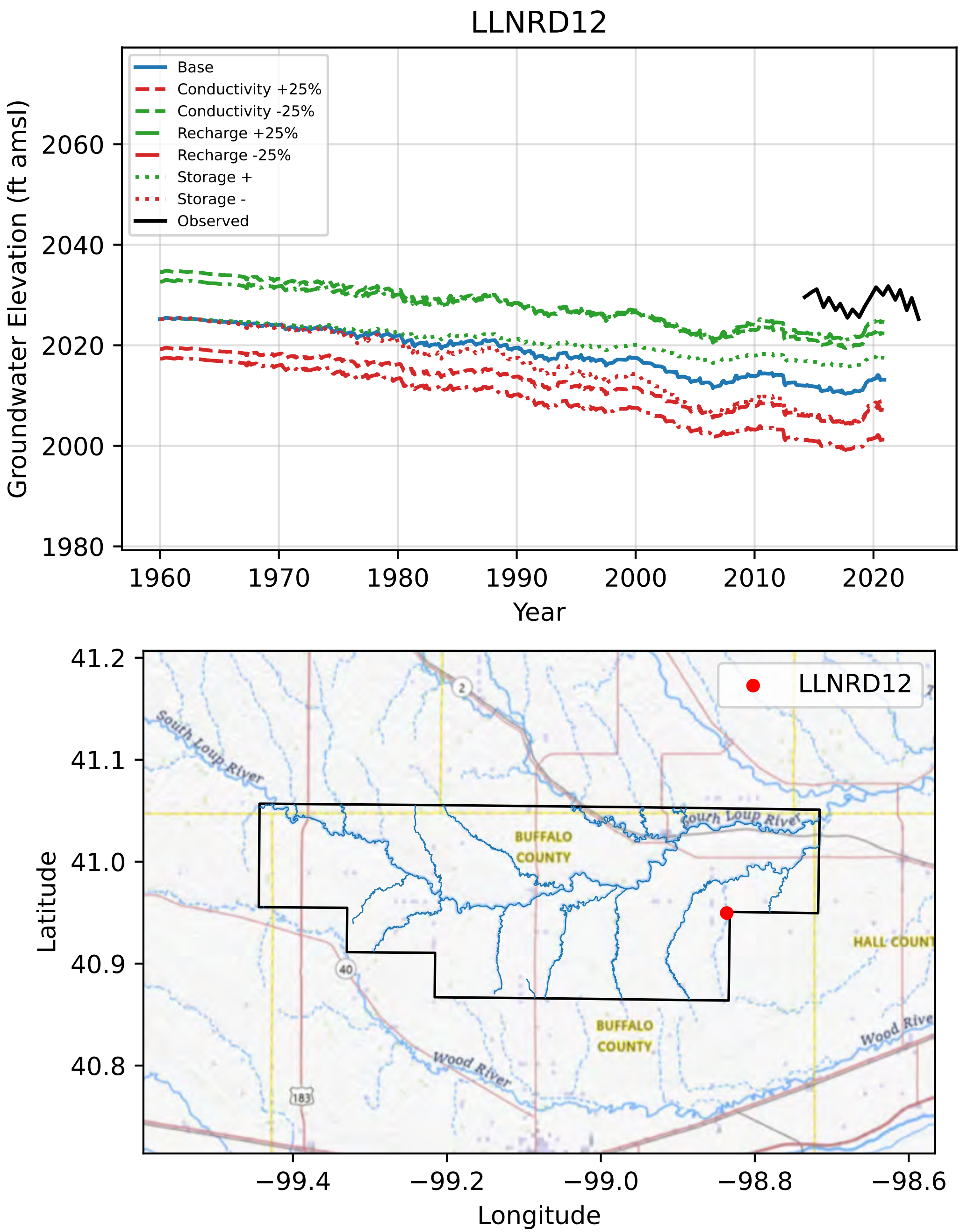


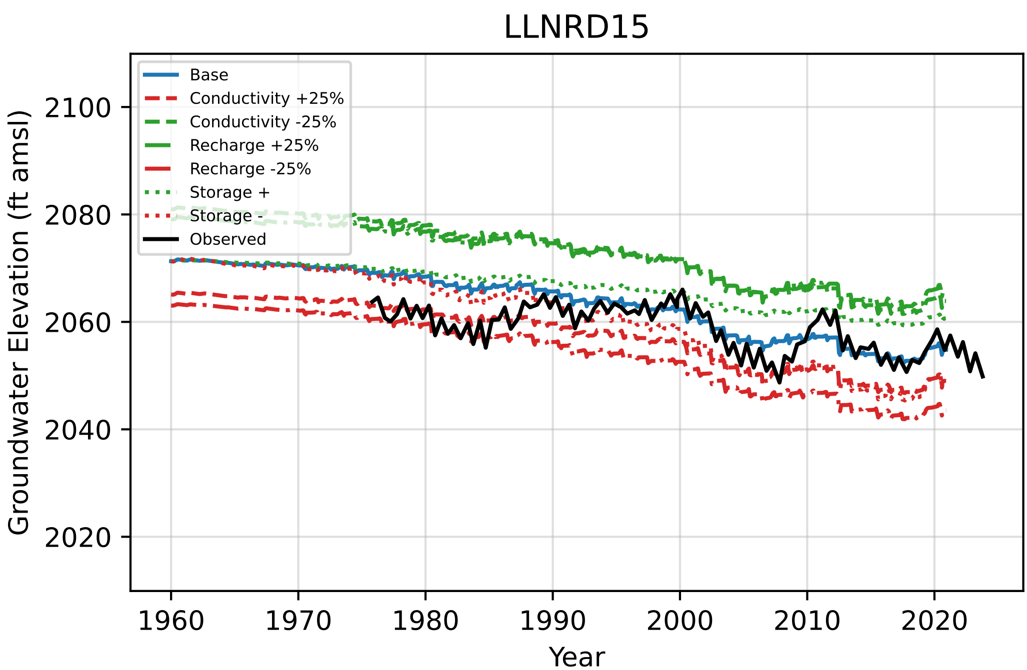
LLNRD6
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2240
2220
2200
2180
2160
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD6
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River

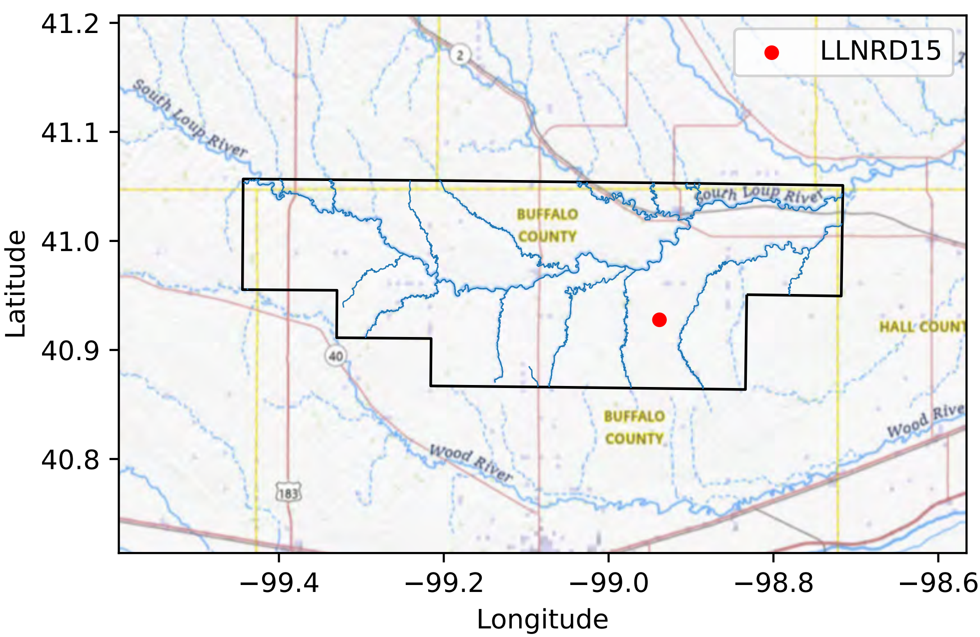

LLNRD8
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2060
2080
2100
2120
2140
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD8
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River

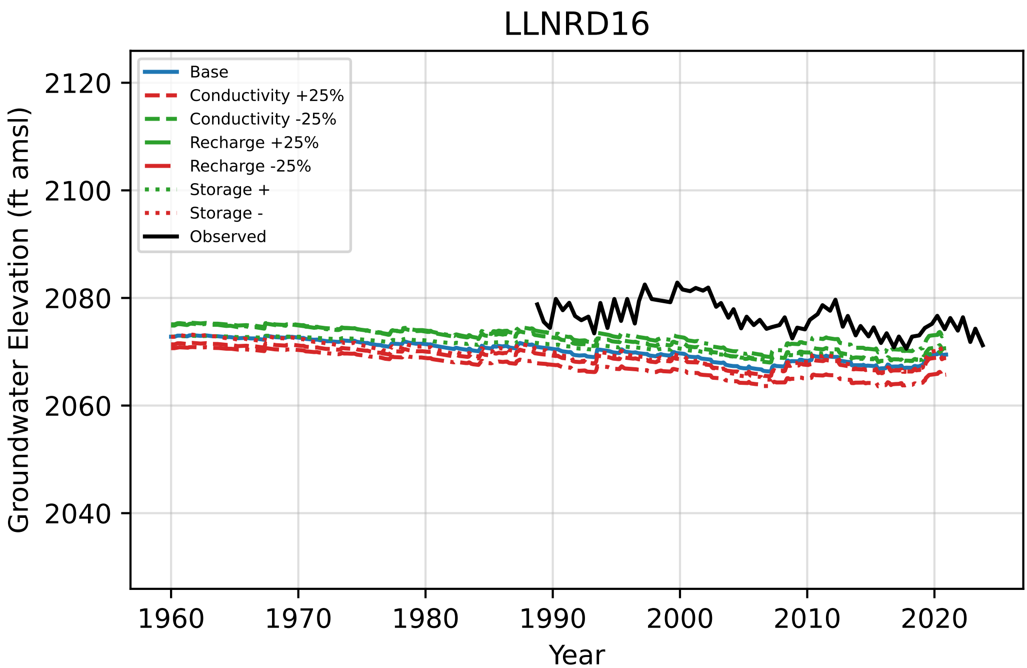

LLNRD11
Groundwater Elevation (ft amsl)
Year
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
2260
2240
2220
2200
2180
1960
1970
1980
1990
2000
2010
2020


LLNRD11
Latitude
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6

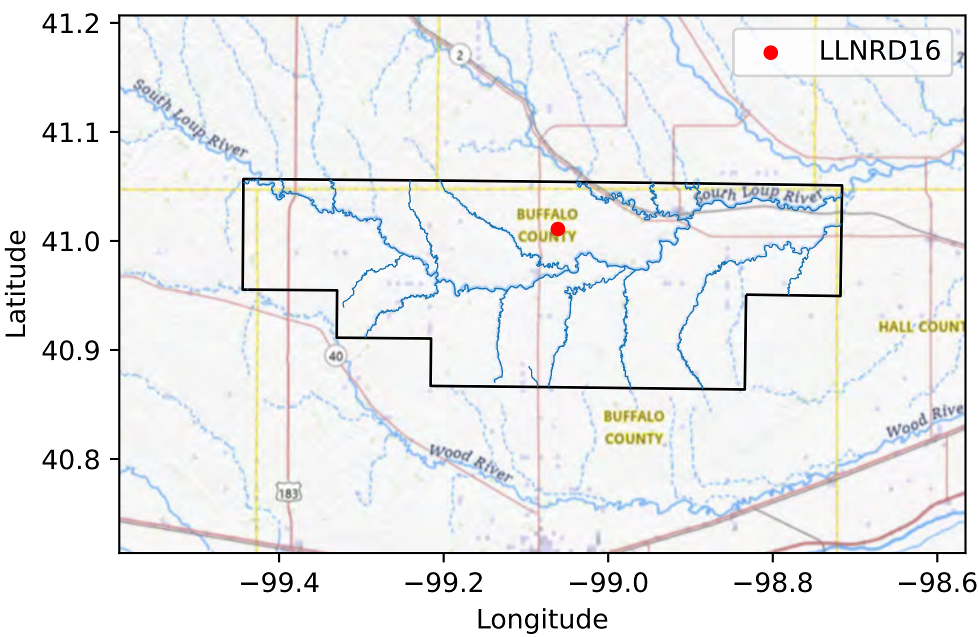

LLNRD12
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2060
2040
2020
2000
1980
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD12
South Loup River
BUFFALO
COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD15
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2100
2080
2060
2040
2020
1960
1970
1980
1990
2000
2010
2020
Year

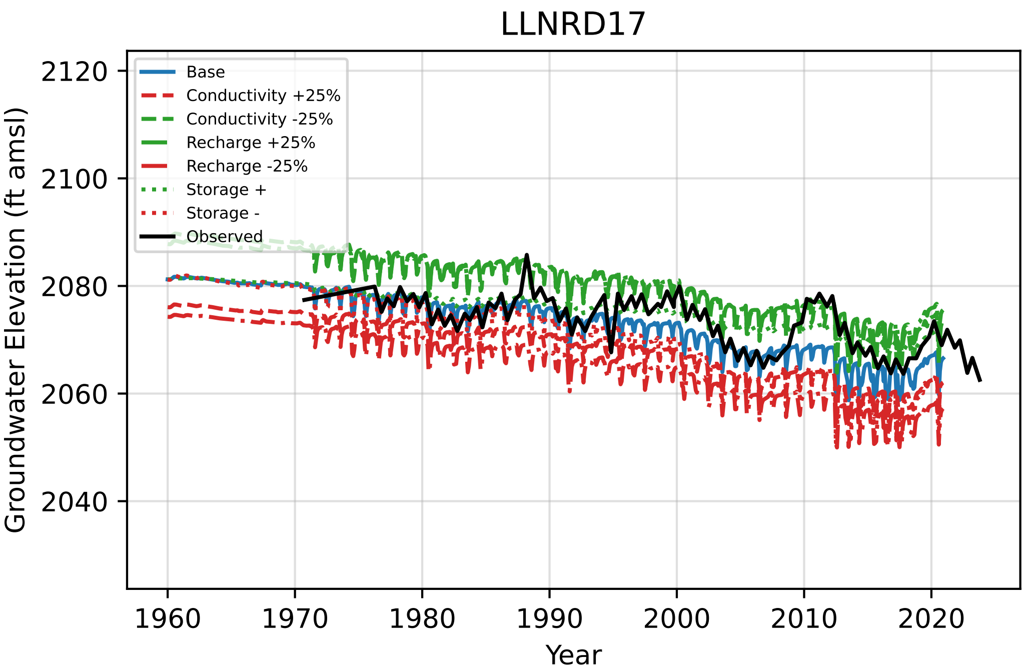

LLNRD15
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



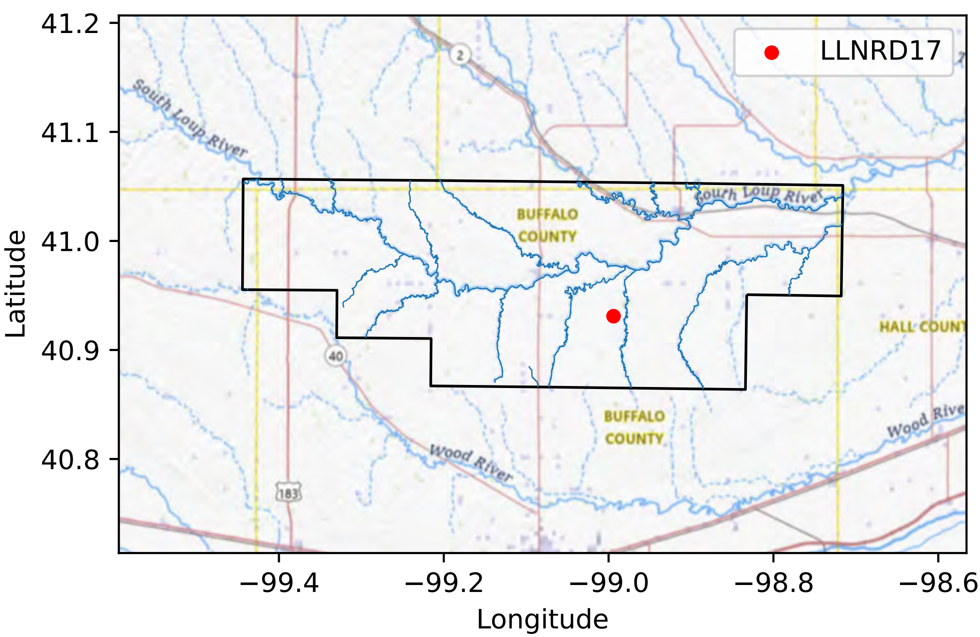
LLNRD16
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2040
2060
2080
2100
2120
1960
1970
1980
1990
2000
2010
2020
Year



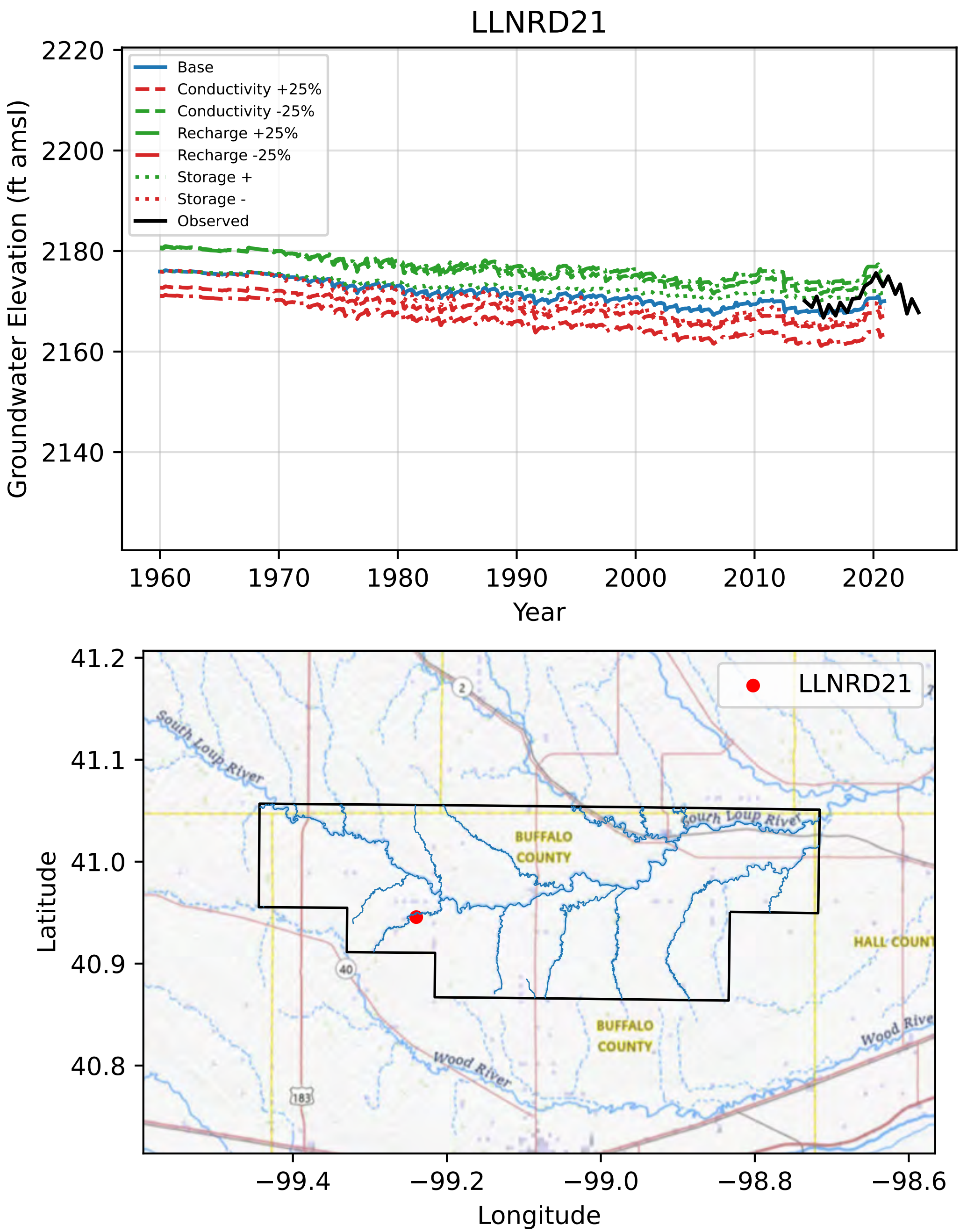
LLNRD16
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood River

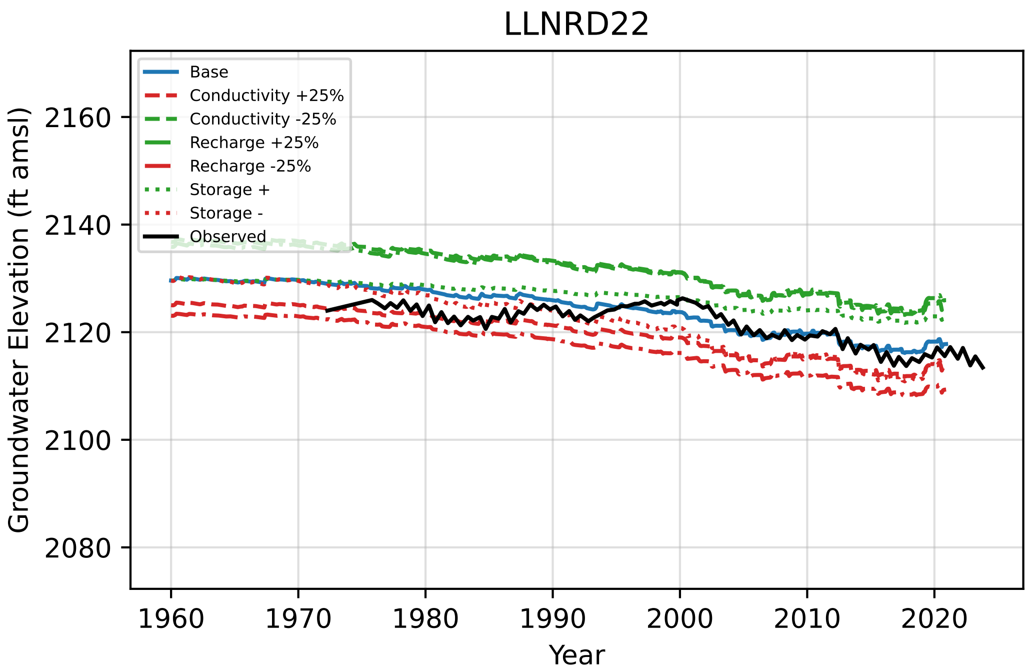


LLNRD17
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2120
2100
2080
2060
2040
1960
1970
1980
1990
2000
2010
2020
Year

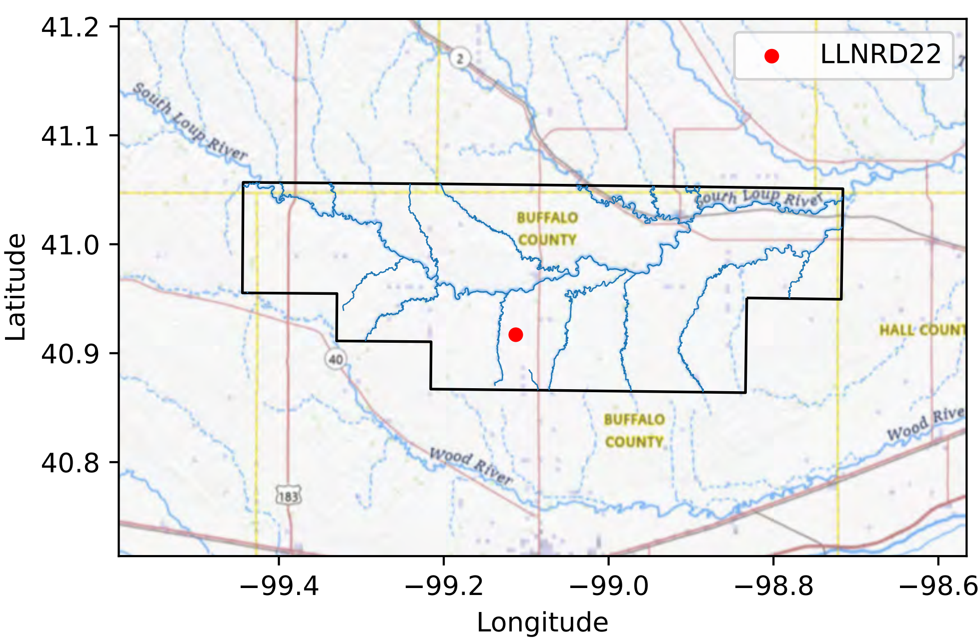


LLNRD17
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River

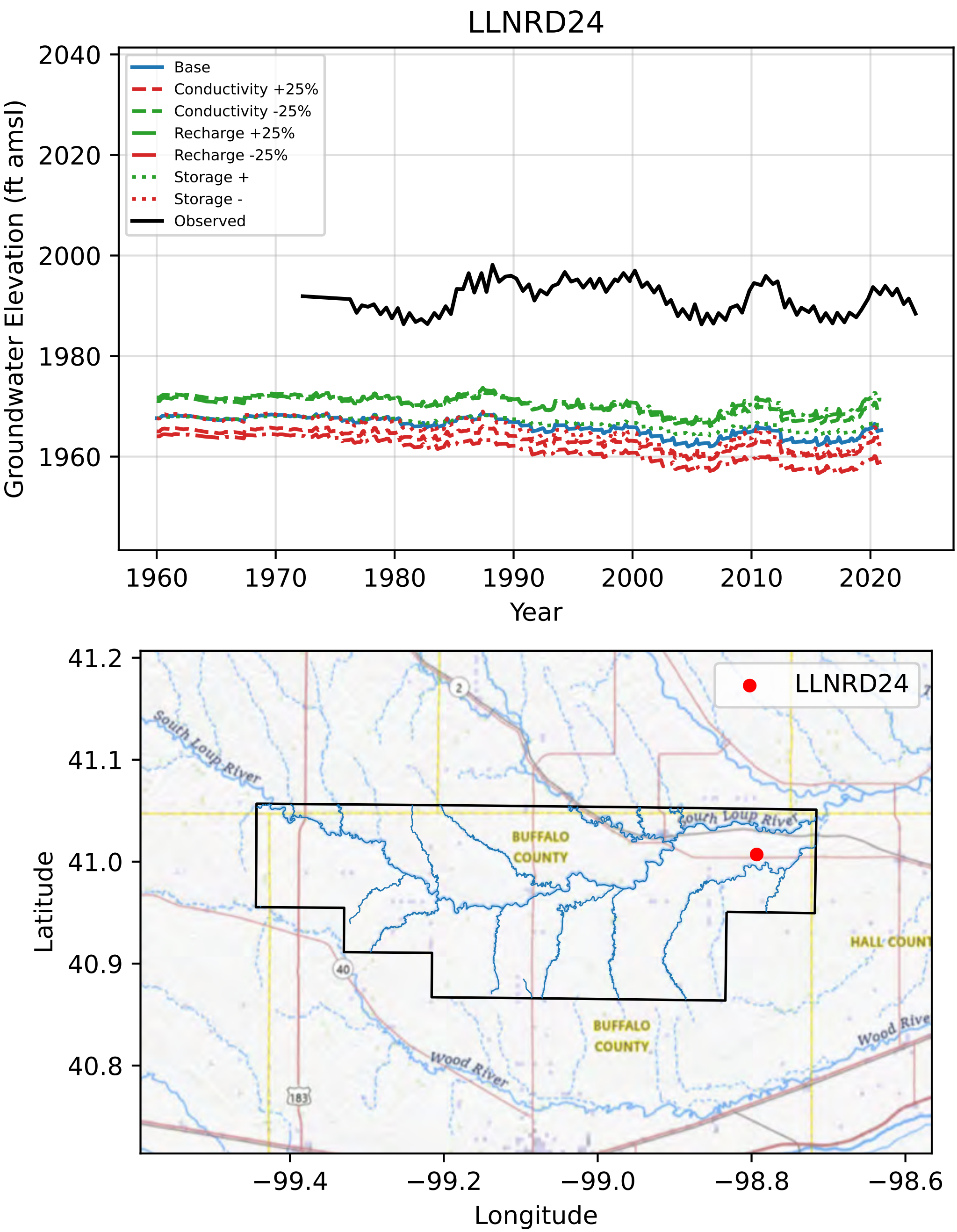

LLNRD21
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD21
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



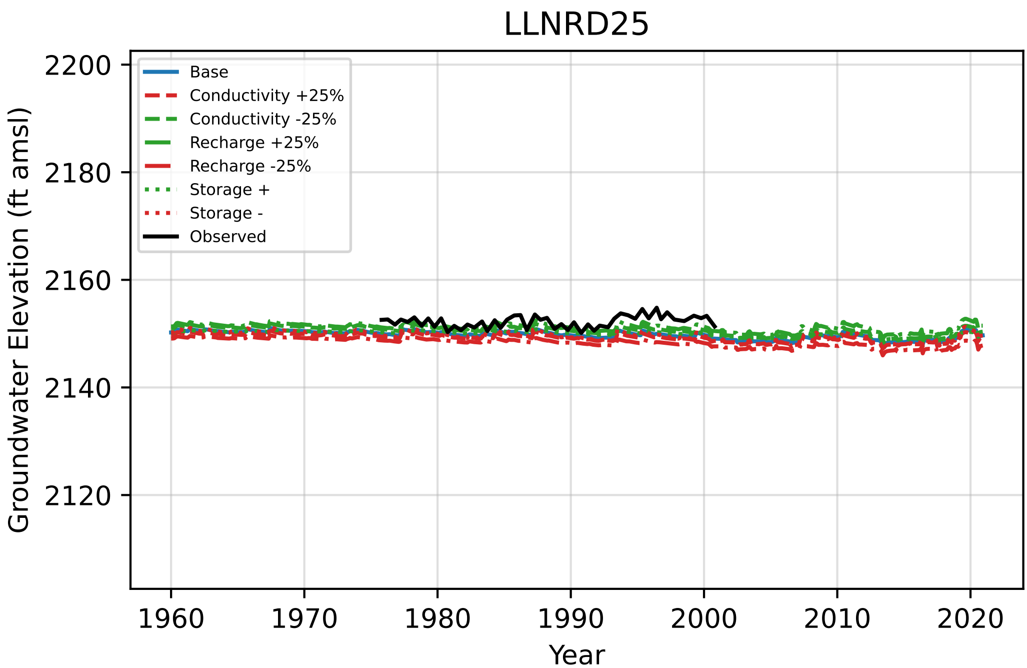
LLNRD22
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year

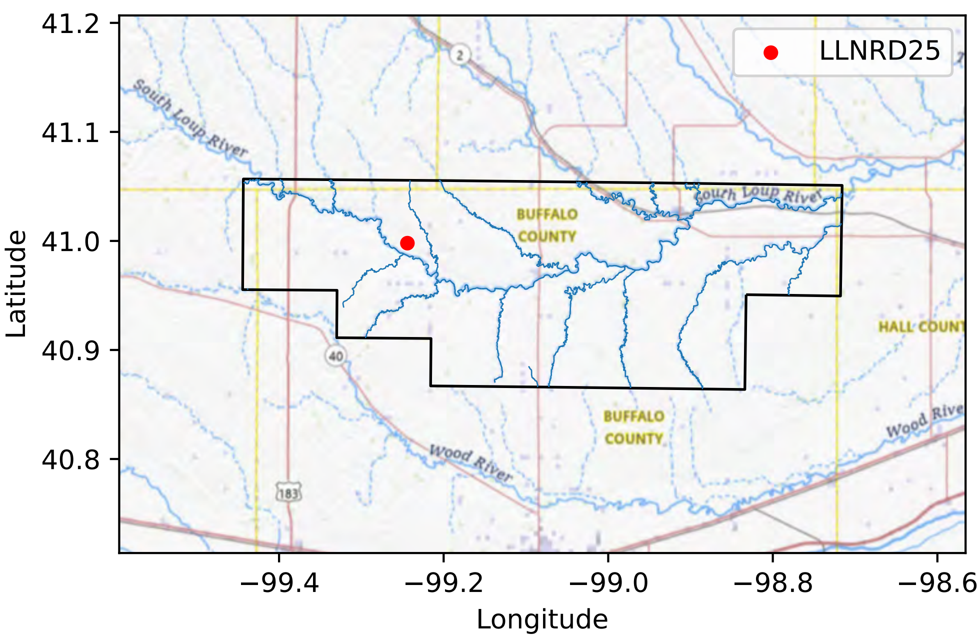


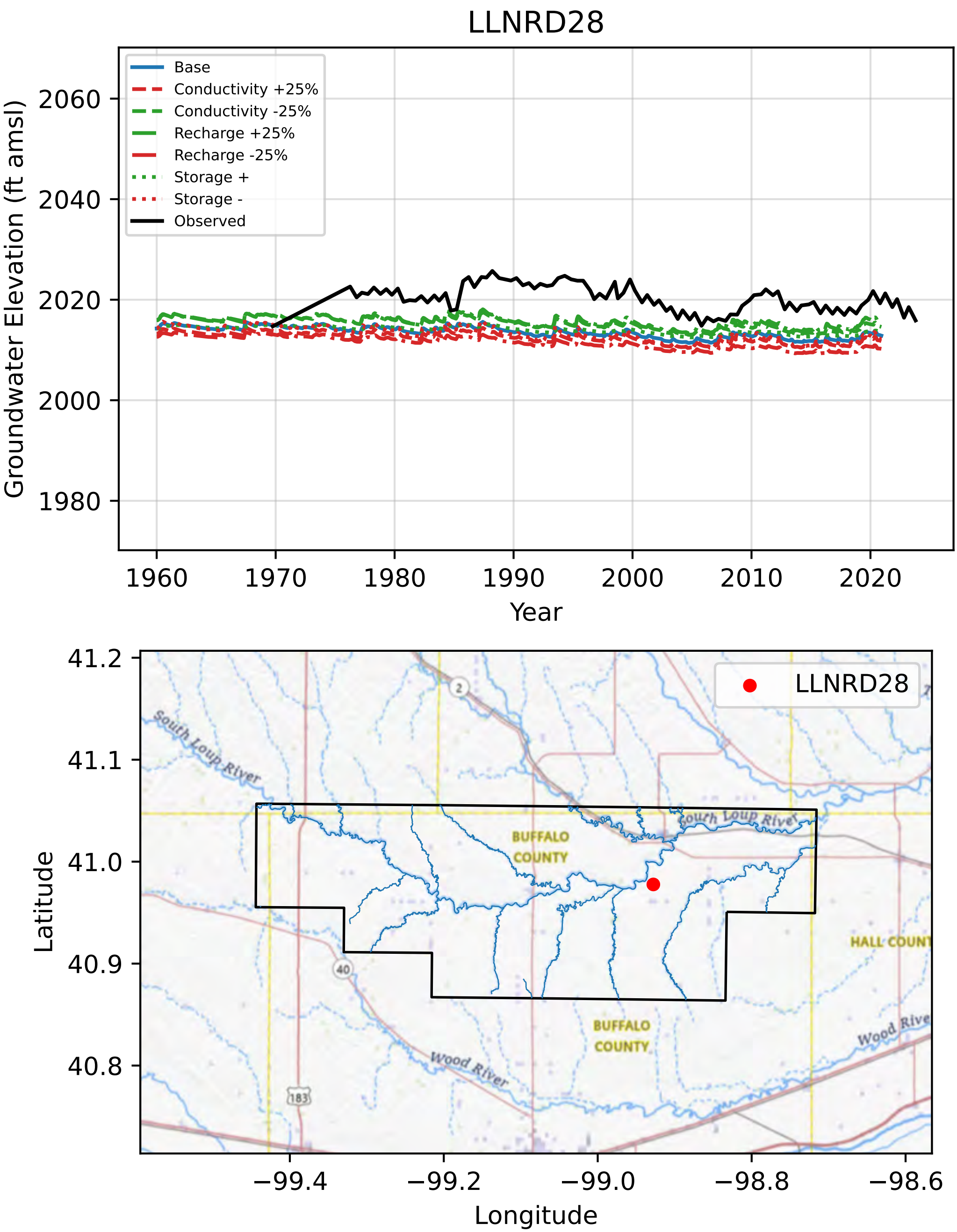
LLNRD22
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



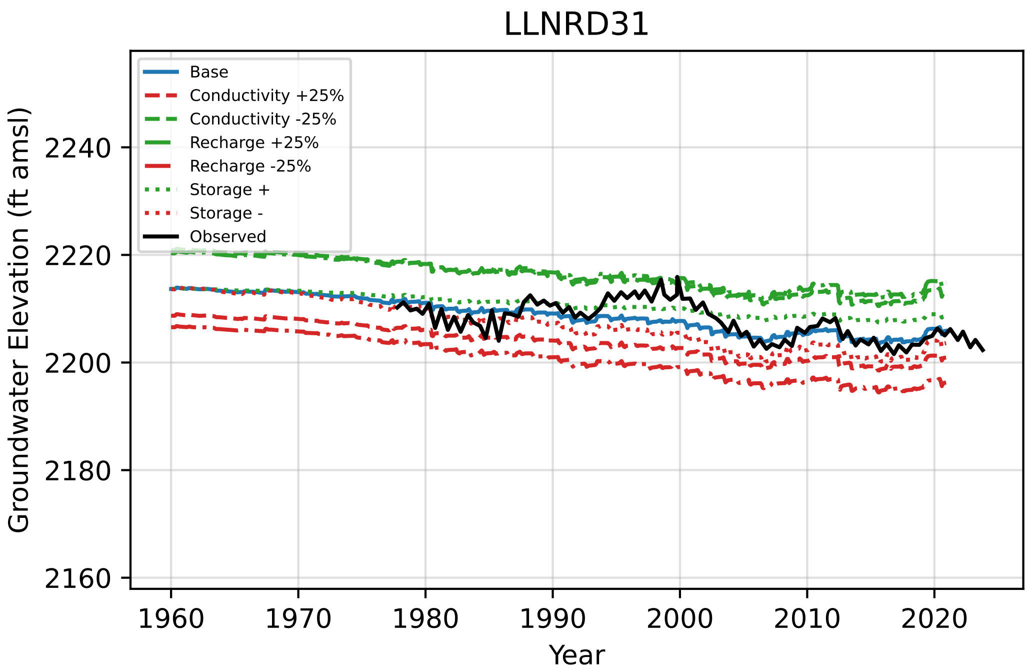
LLNRD24
Groundwater Elevation (ft amsl)
Year
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
2040
2020
2000
1980
1960
1960
1970
1980
1990
2000
2010
2020
Latitude
Longitude
LLNRD24
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6


LLNRD25
Groundwater Elevation (ft amsl)
2200
2180
2160
2140
2120
1960
1970
1980
1990
2000
2010
2020
Year
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed

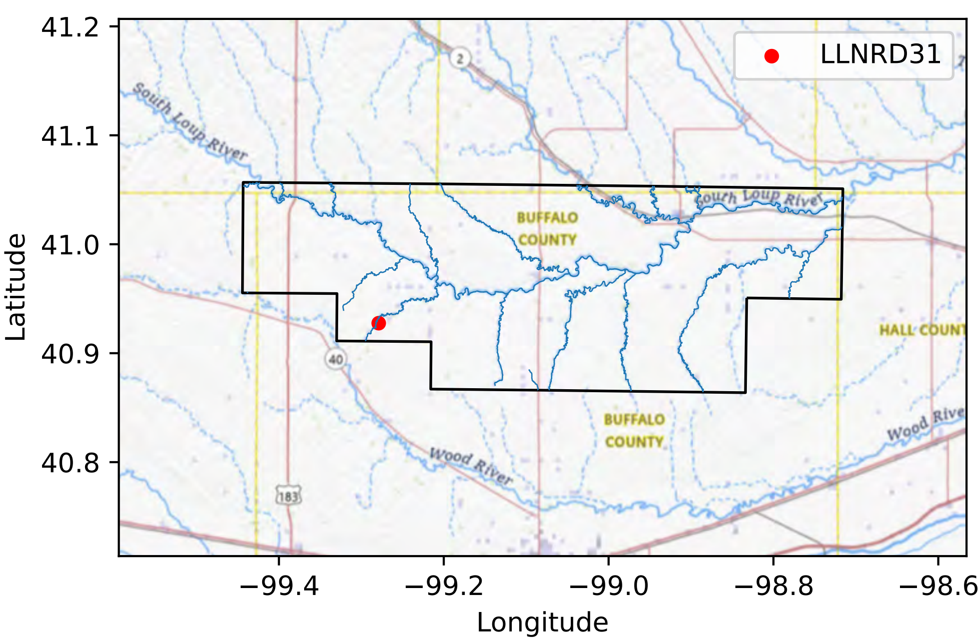

LLNRD25
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive



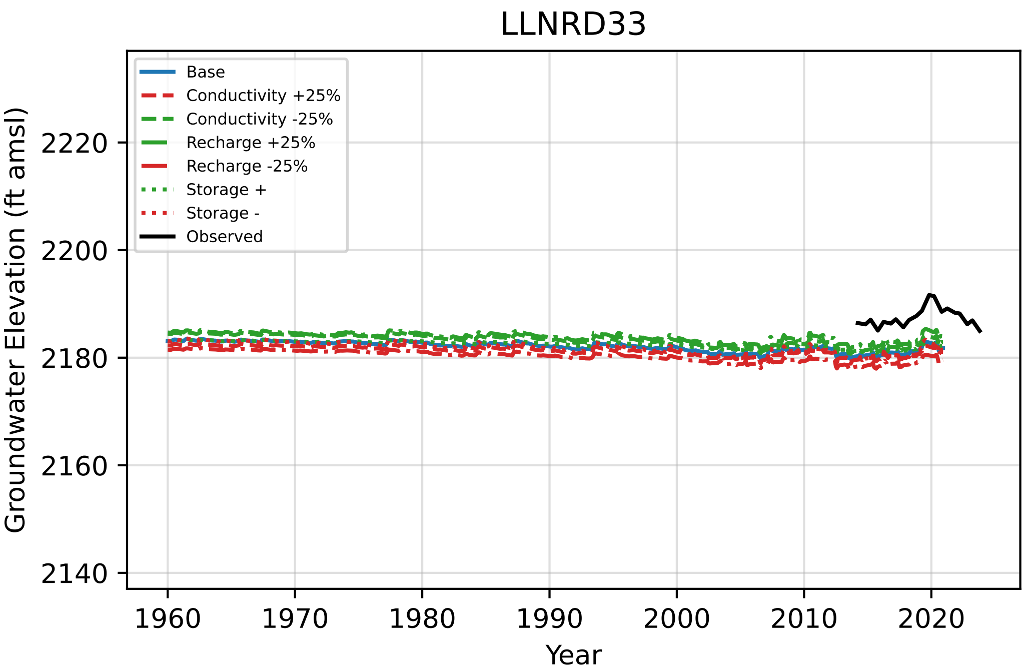
LLNRD28
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
1980
2000
2020
2040
2060
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD28
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River

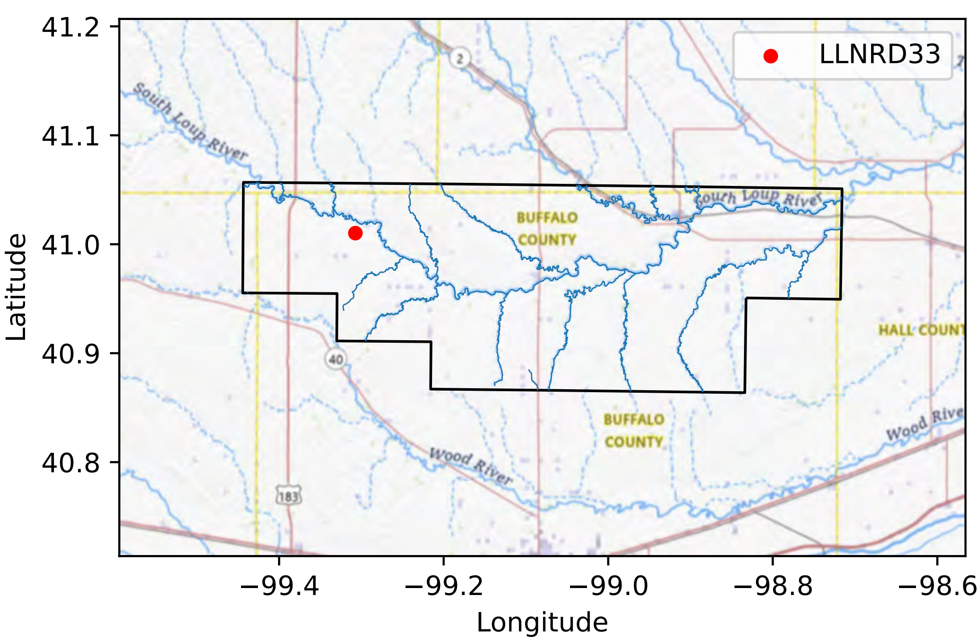


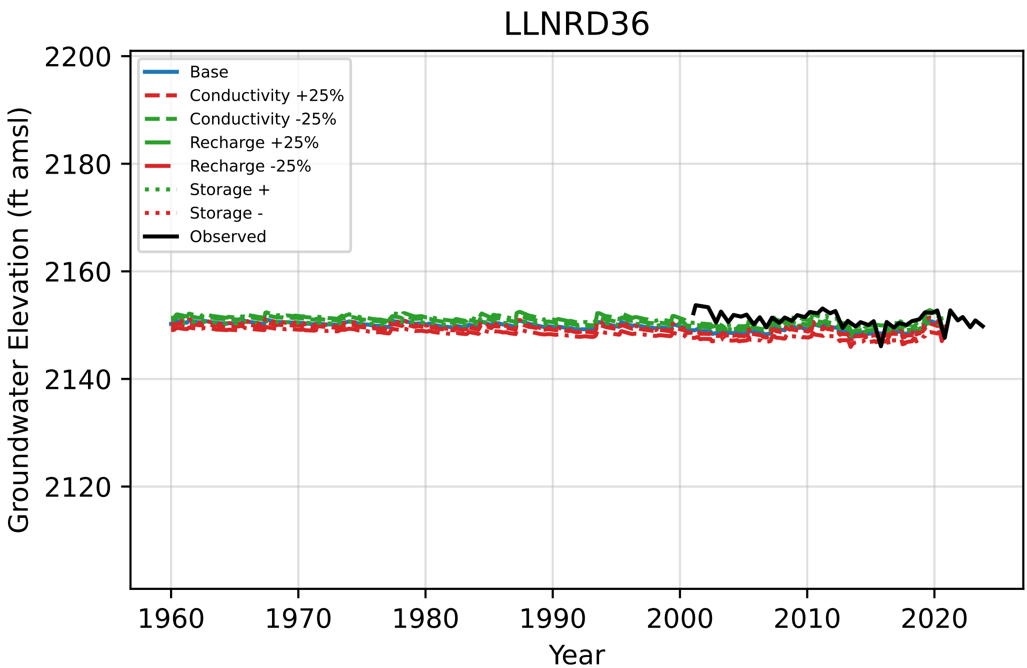
LLNRD31
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2160
2180
2200
2220
2240
1960
1970
1980
1990
2000
2010
2020
Year

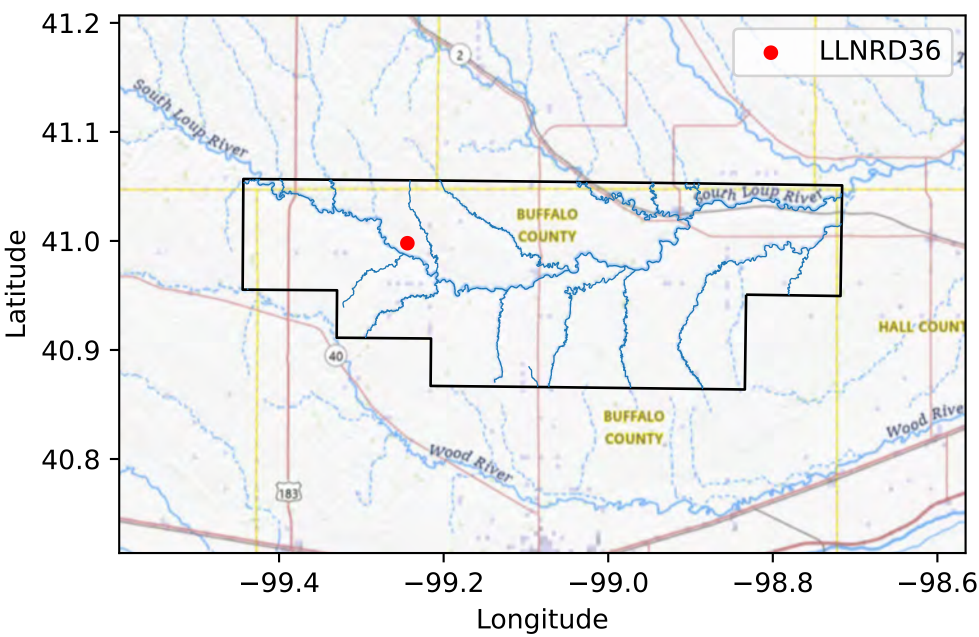


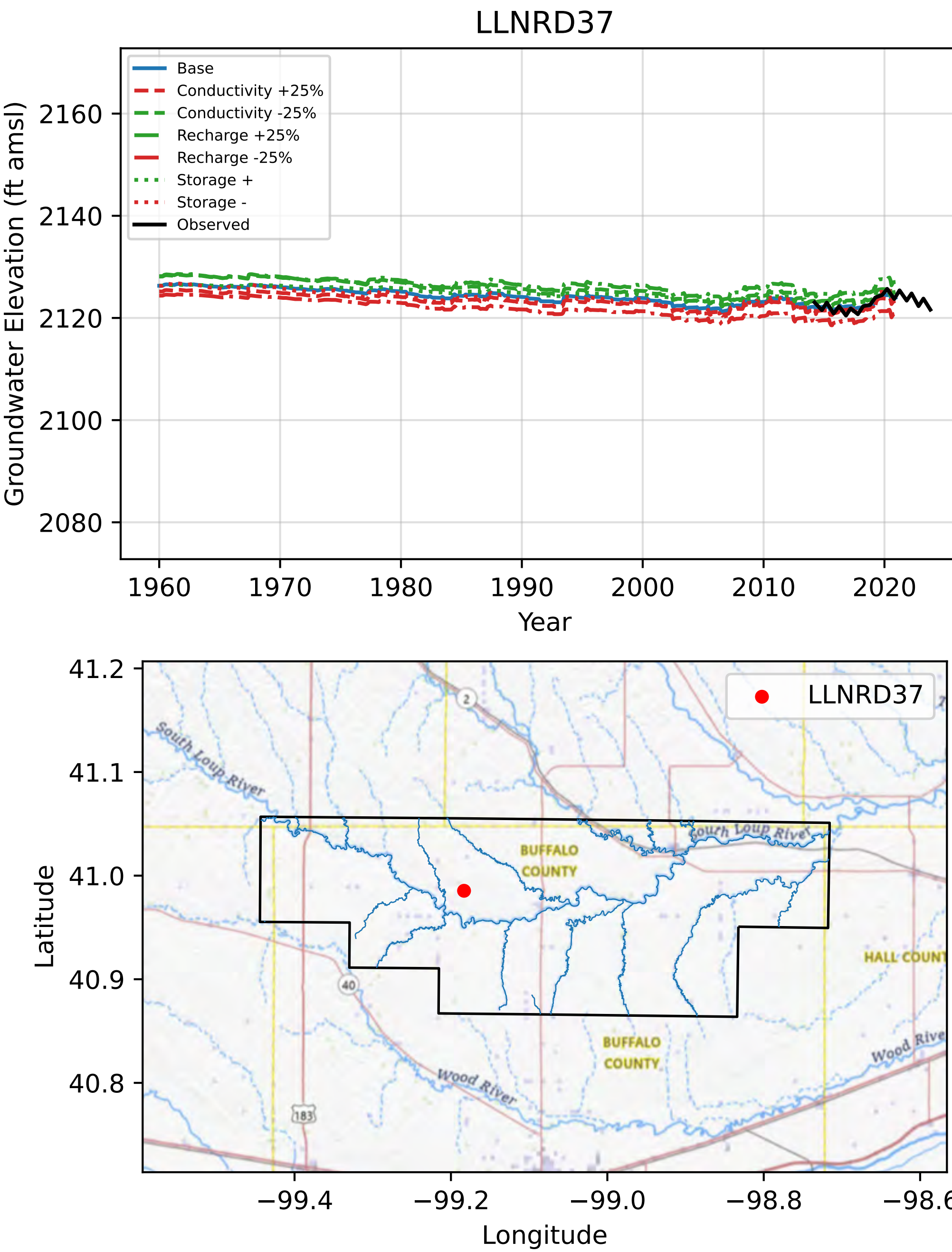
LLNRD31
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

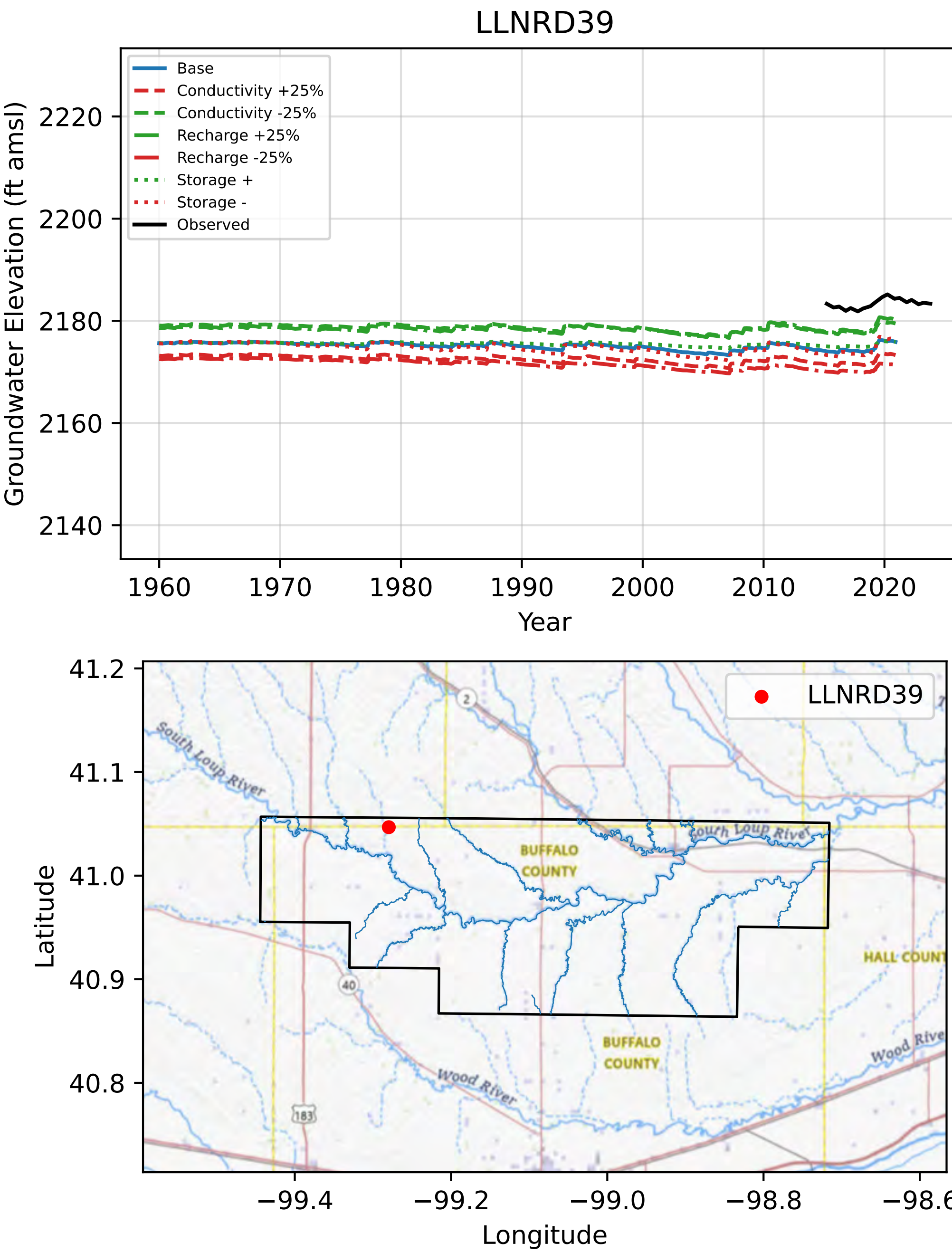

LLNRD33
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year

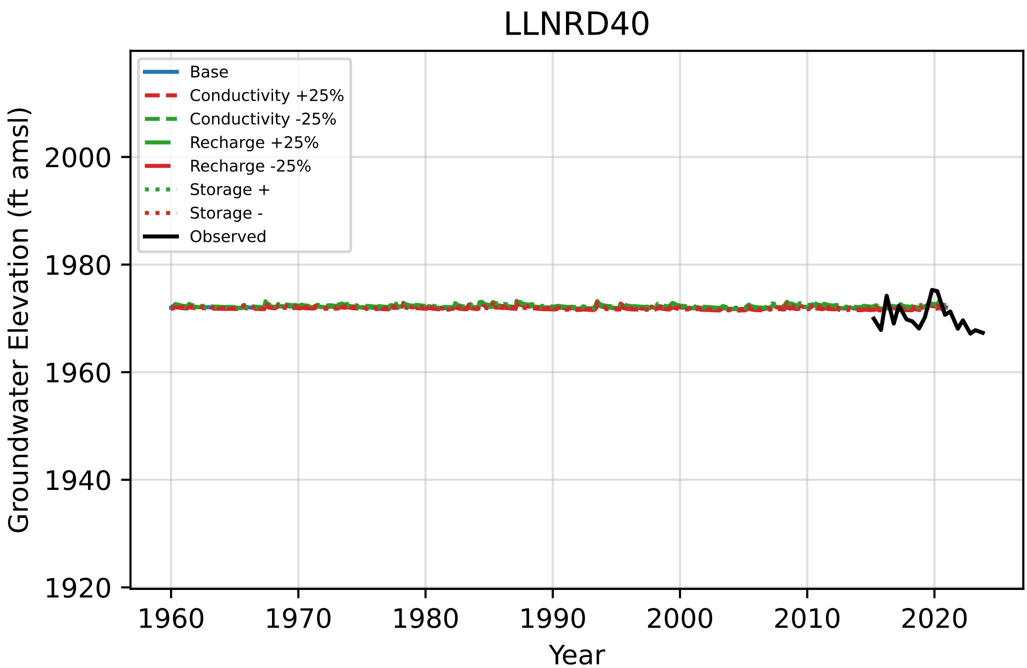

LLNRD33
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD36
Groundwater Elevation (ft amsl)
Year
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
2200
2180
2160
2140
2120
1960
1970
1980
1990
2000
2010
2020

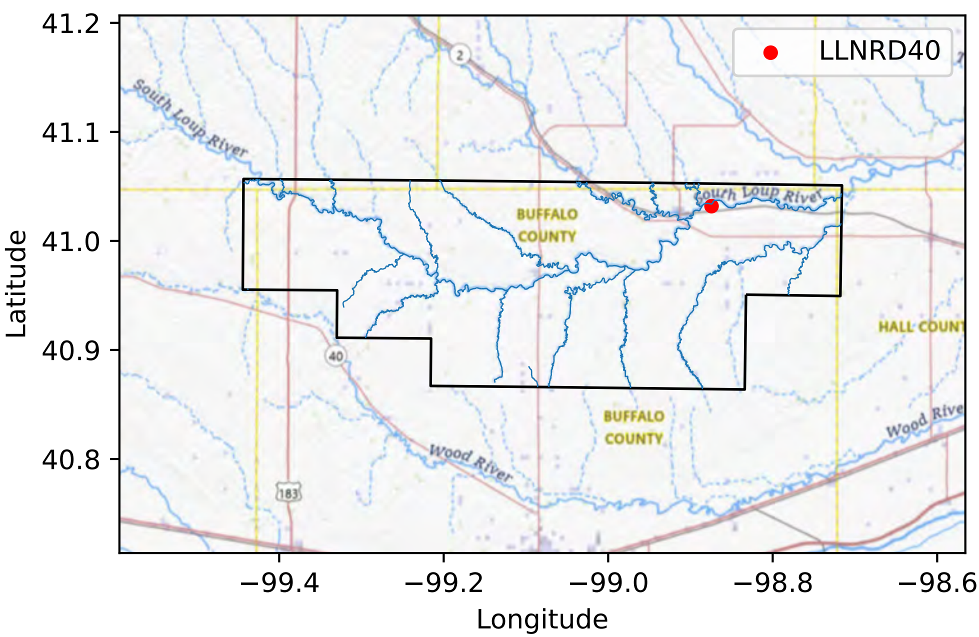

LLNRD36
Latitude
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6


LLNRD37
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD37
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

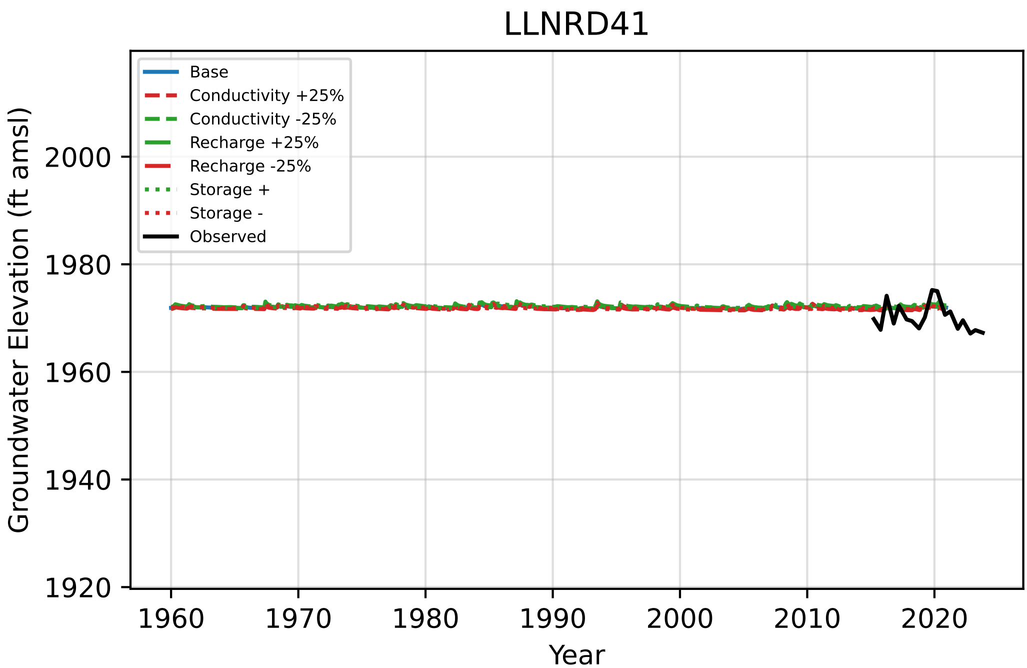

LLNRD39
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD39
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

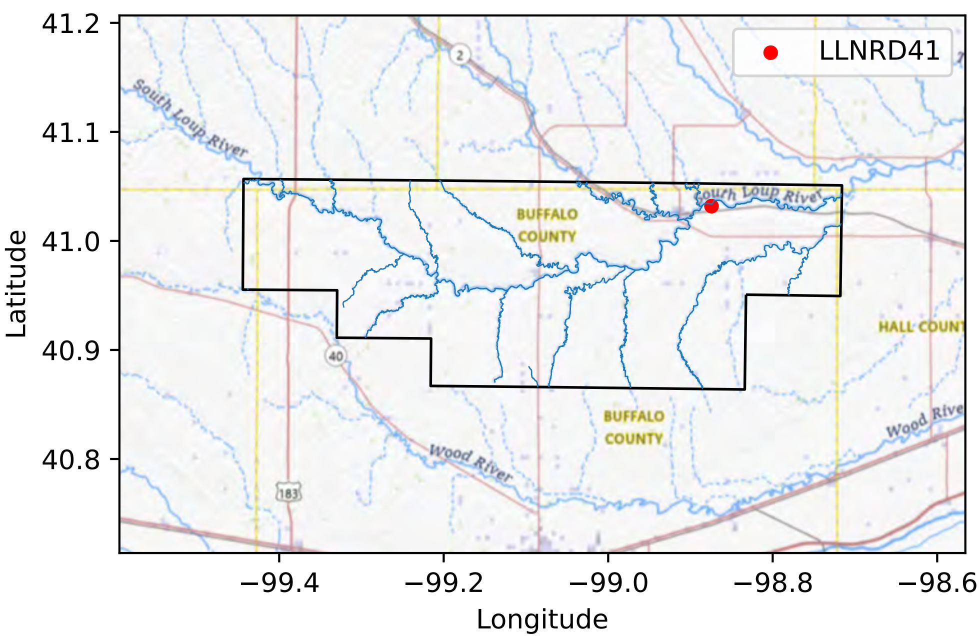


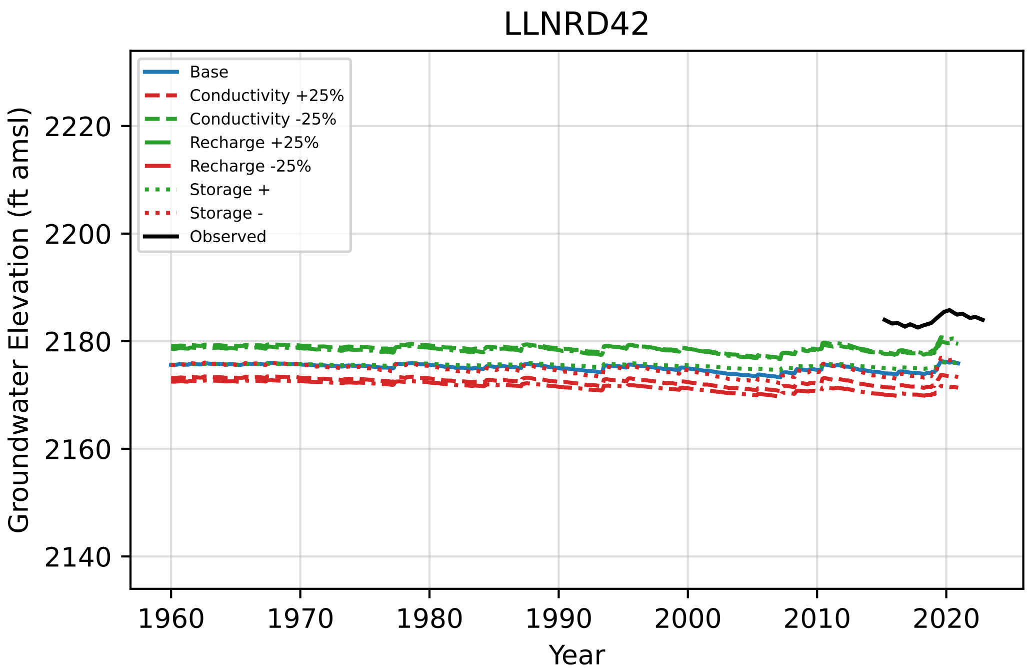
LLNRD40
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2000
1980
1960
1940
1920
1960
1970
1980
1990
2000
2010
2020
Year



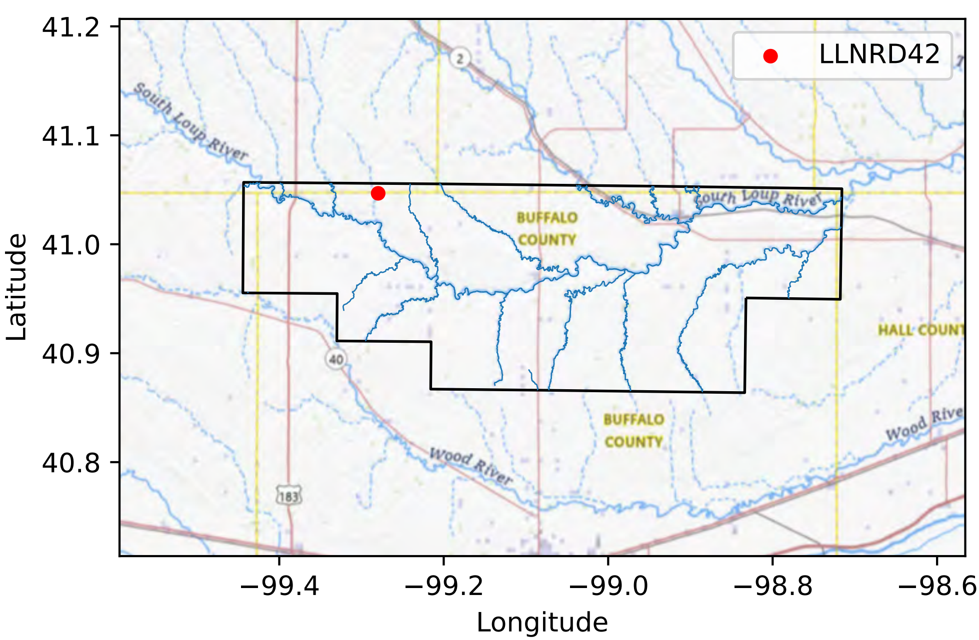
LLNRD40
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
41.2
41.1
41.0
40.9
40.8
Latitude
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD41
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2000
1980
1960
1940
1920
1960
1970
1980
1990
2000
2010
2020
Year

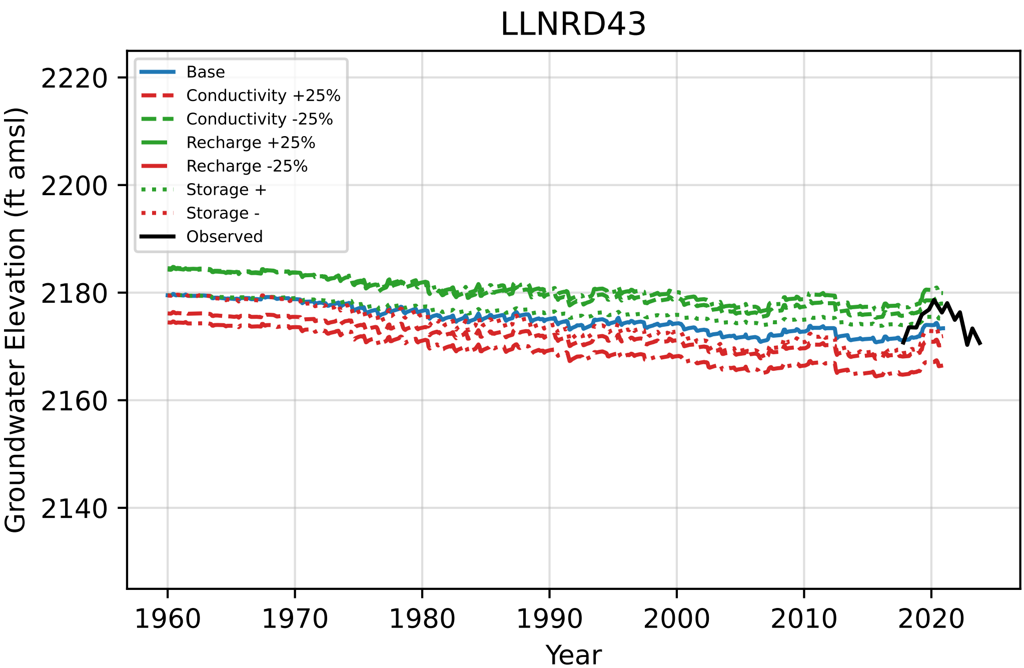

LLNRD41
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



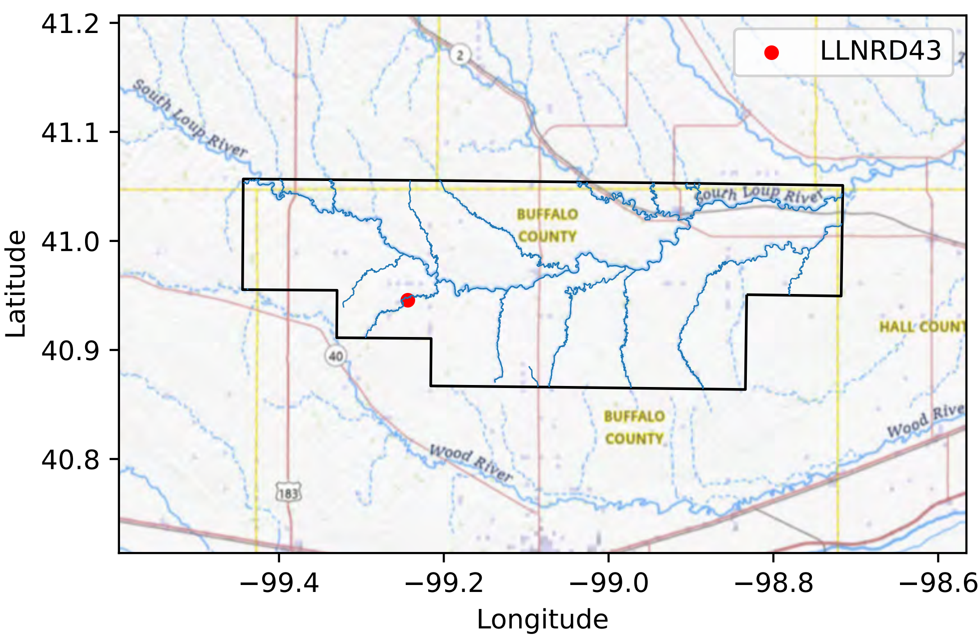
LLNRD42
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year



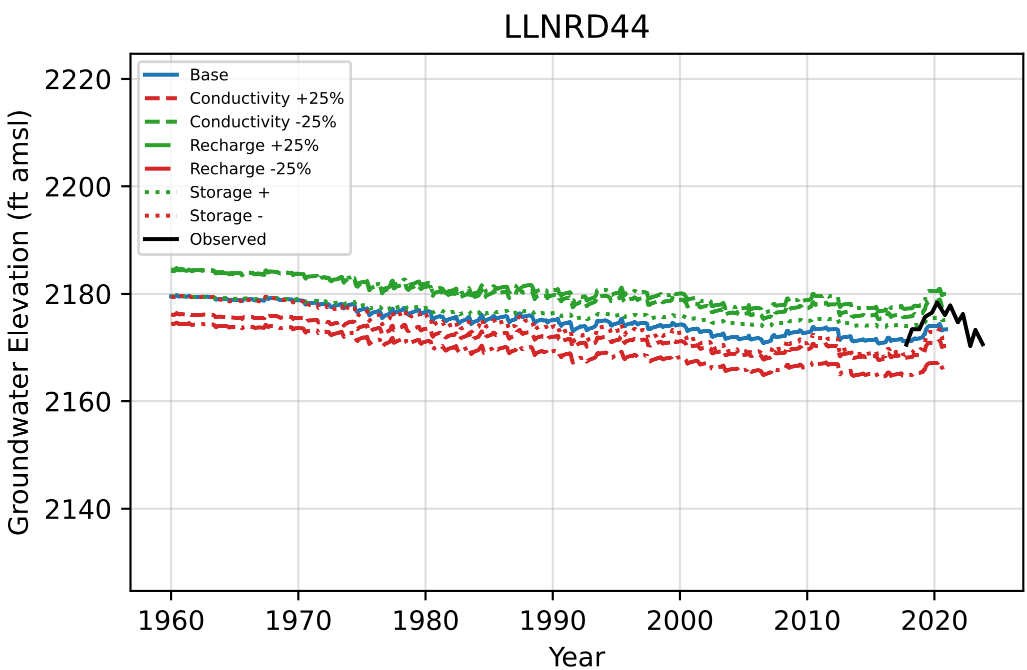
LLNRD42
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
Wood Rive
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



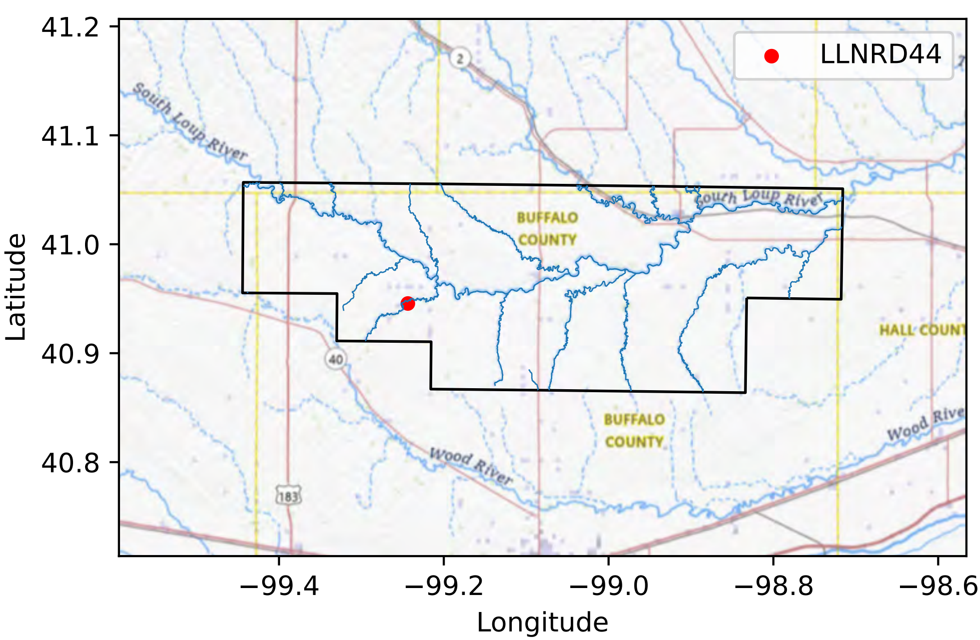
LLNRD43
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year



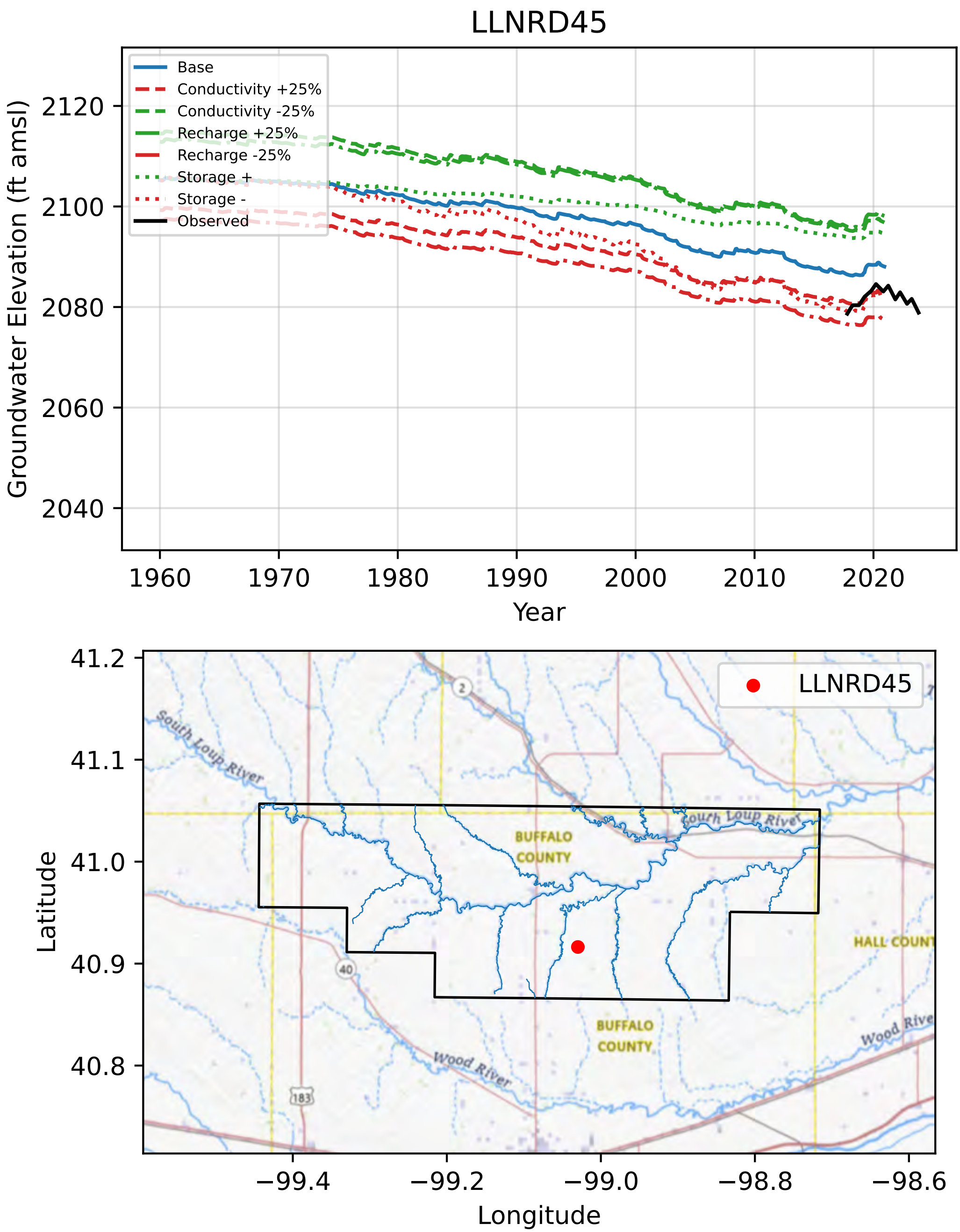
LLNRD43
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

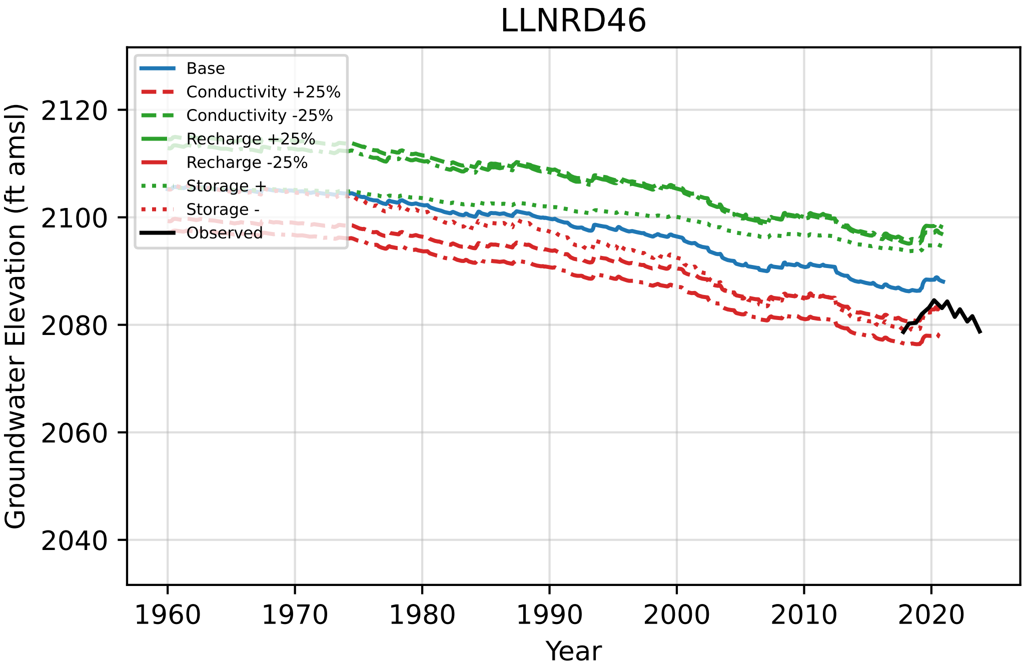


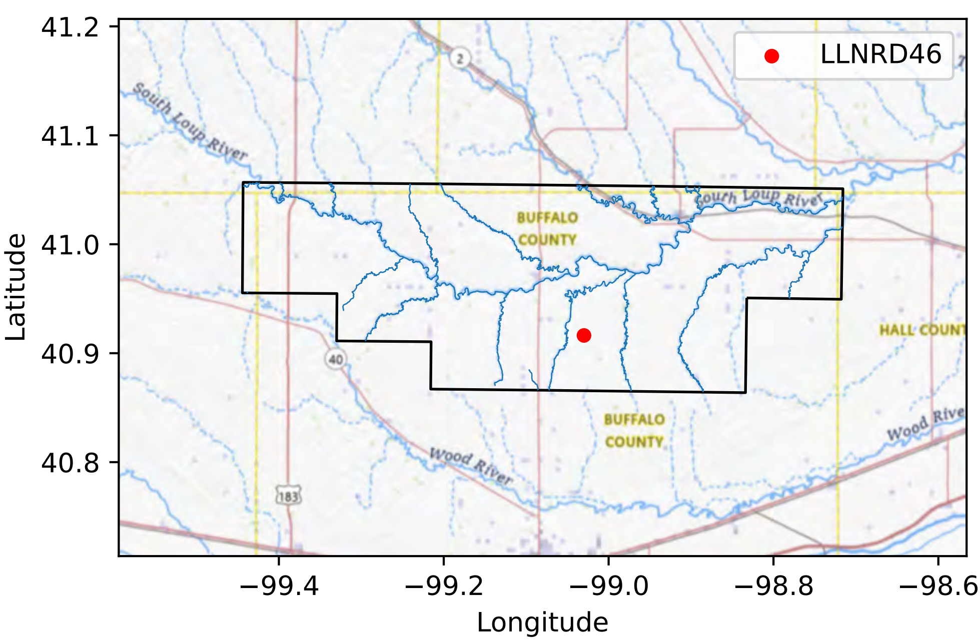
LLNRD44
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Year

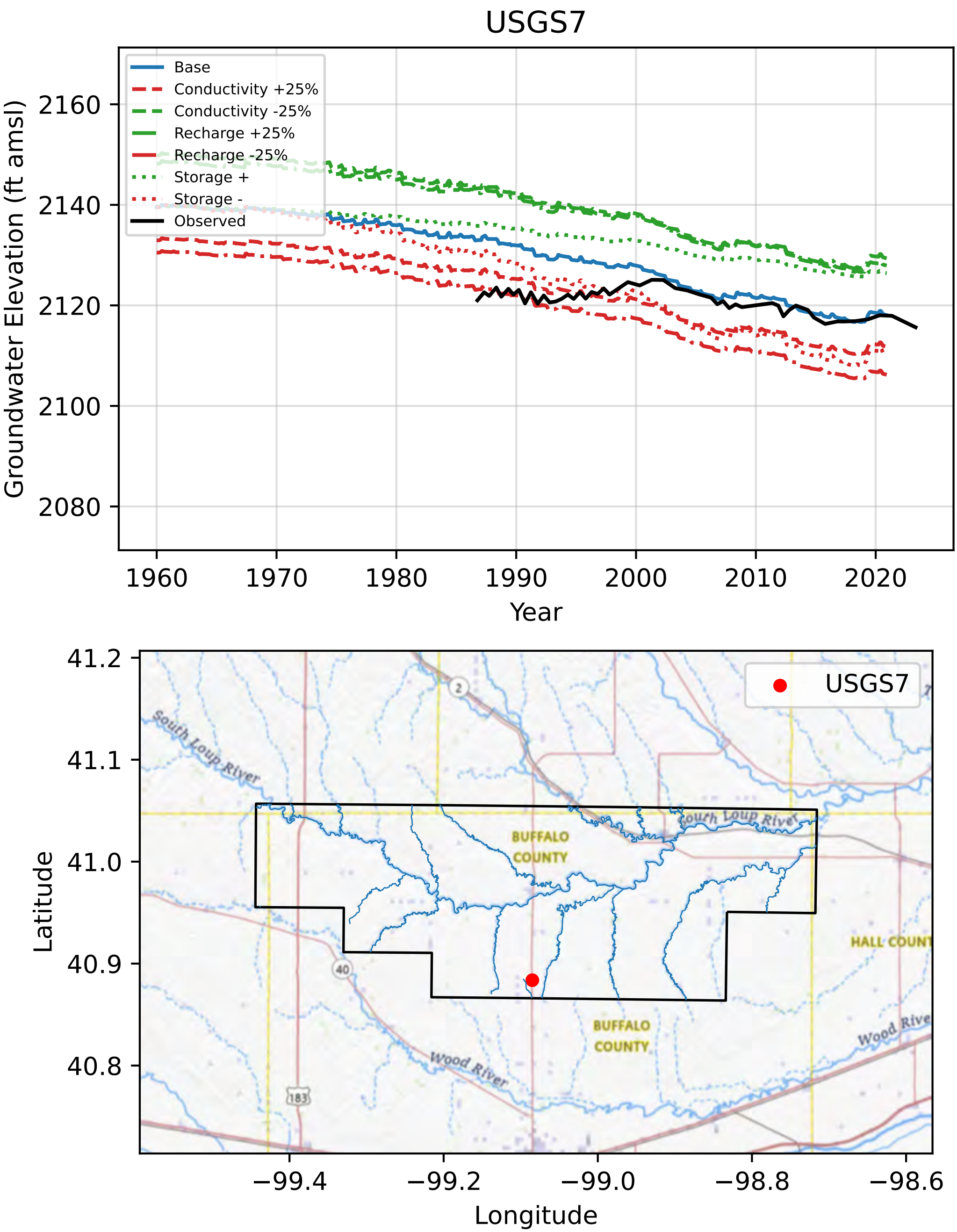


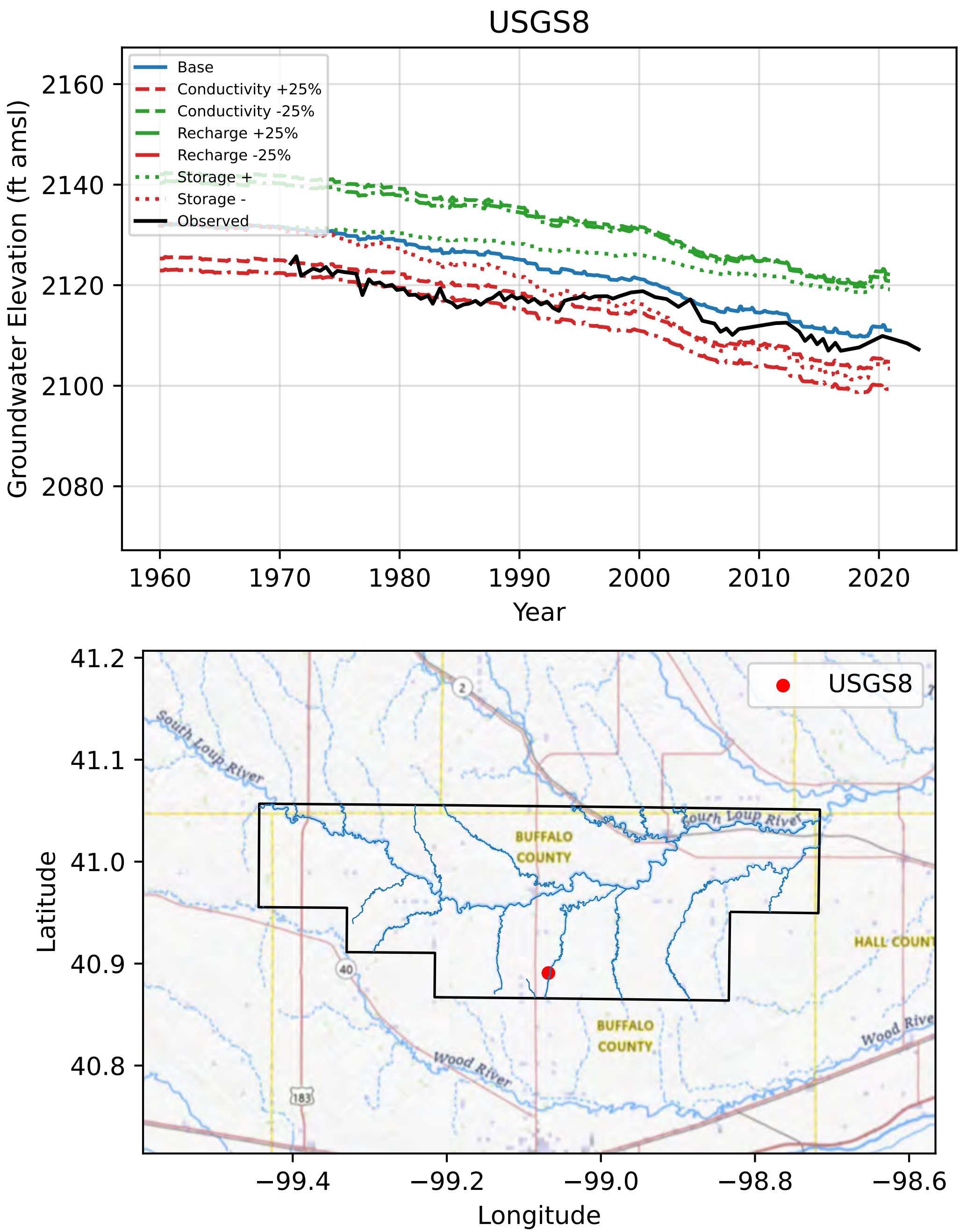
LLNRD44
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


LLNRD45
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2120
2100
2080
2060
2040
1960
1970
1980
1990
2000
2010
2020
Year
LLNRD45
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River
2
40
183

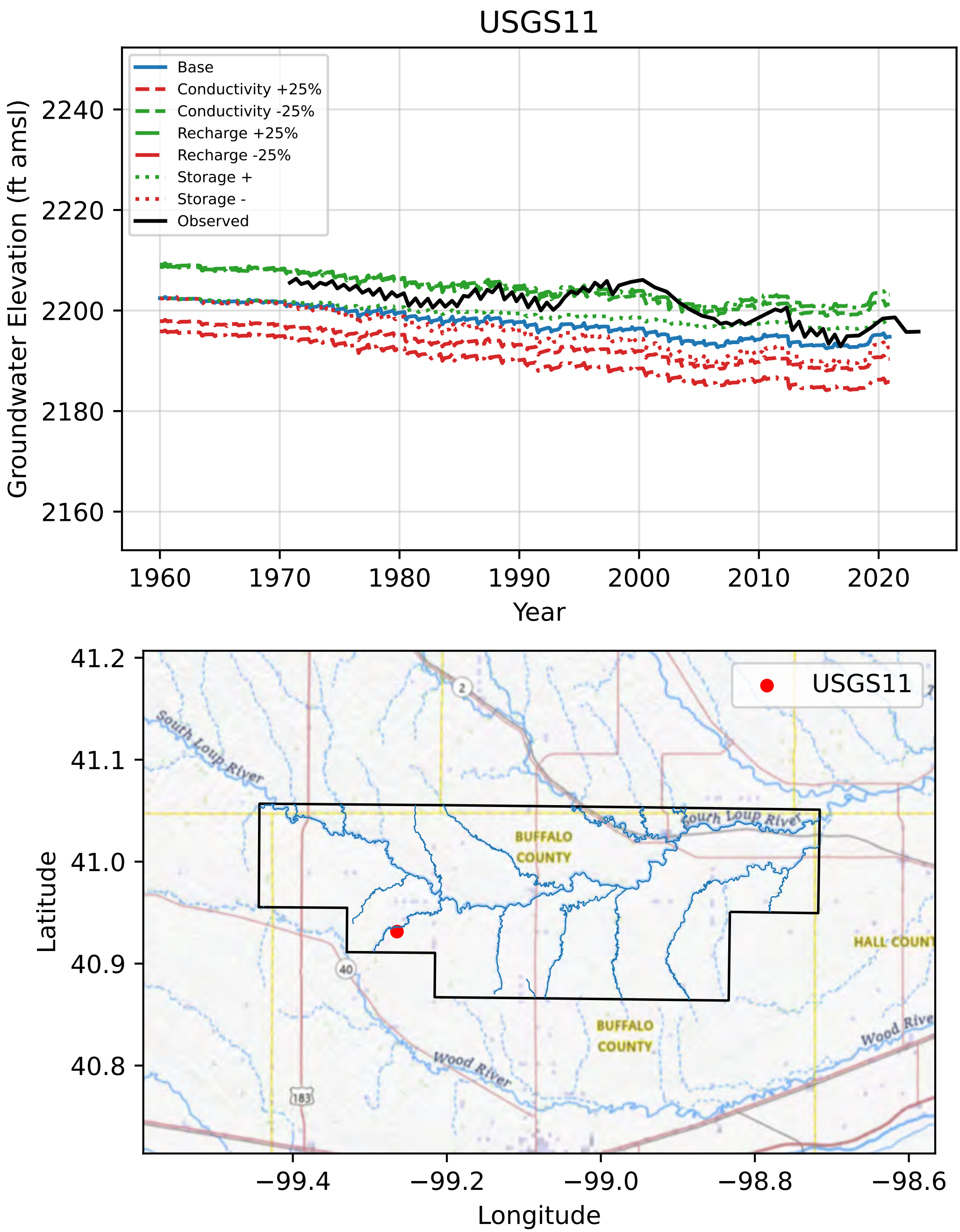

LLNRD46
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2120
2100
2080
2060
2040
1960
1970
1980
1990
2000
2010
2020
Year

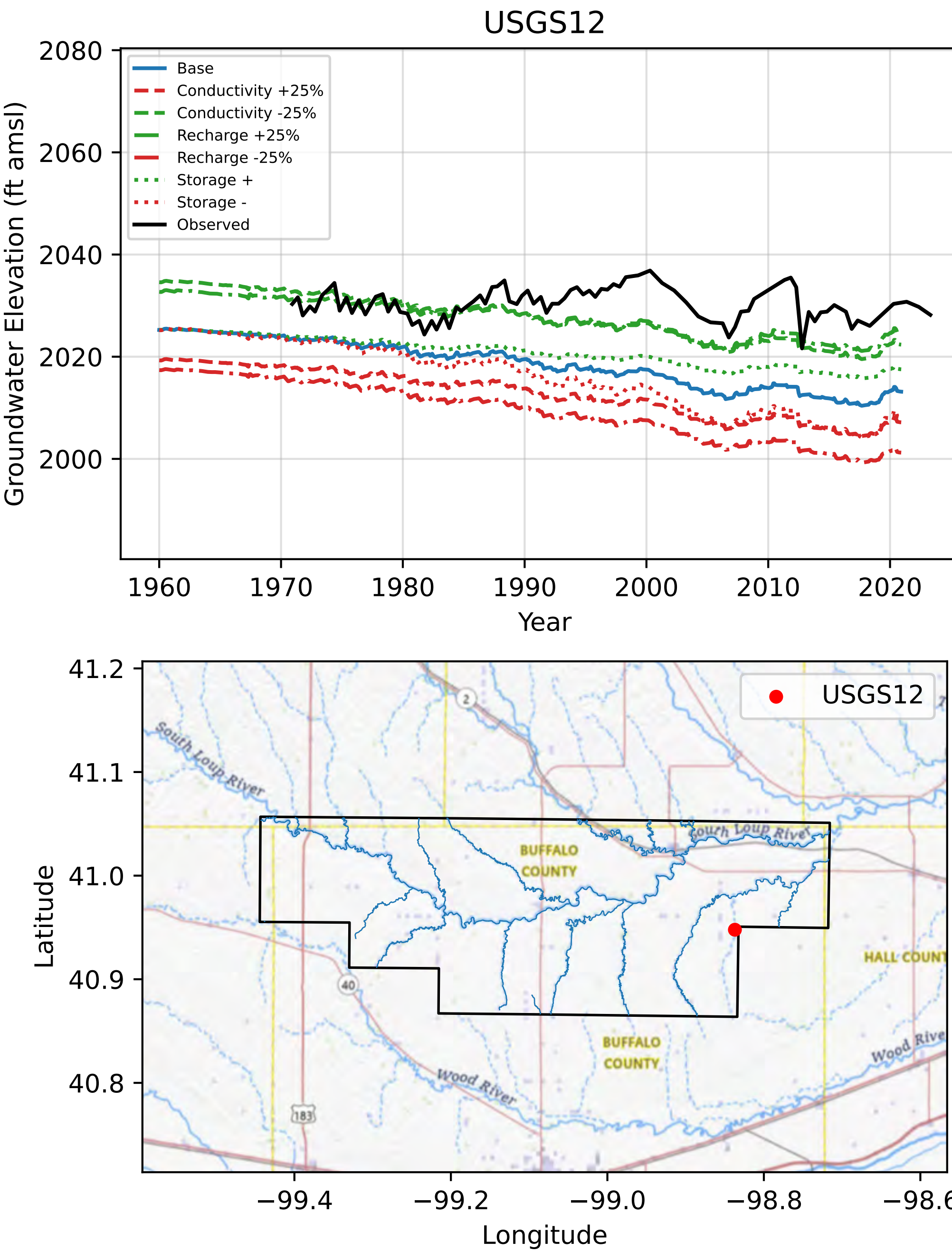

LLNRD46
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude

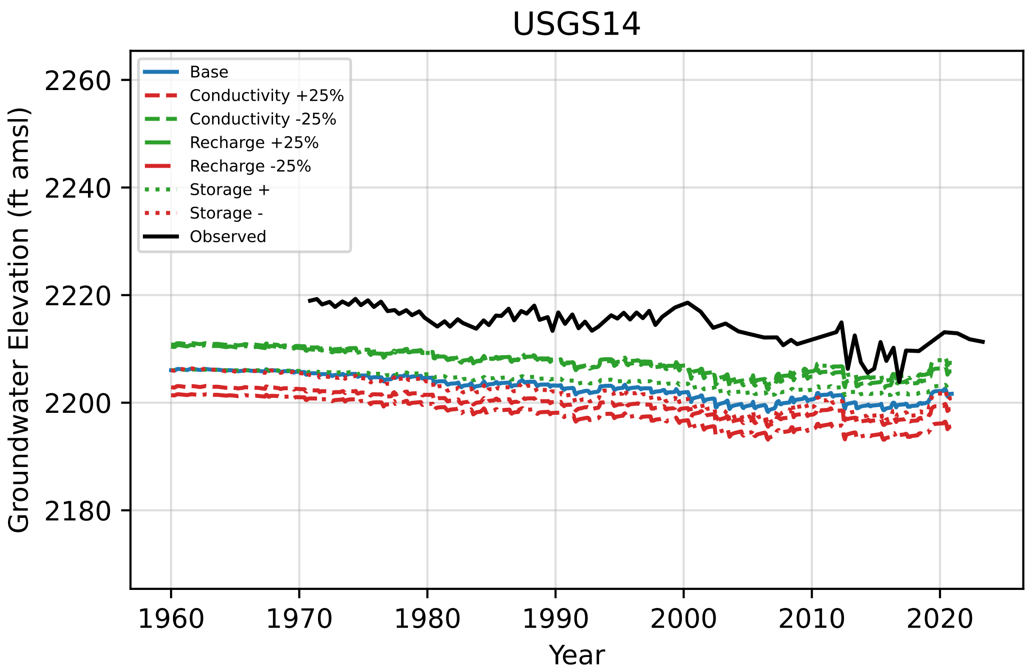

USGS7
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2080
2100
2120
2140
2160
1960
1970
1980
1990
2000
2010
2020
Year
USGS7
Latitude
40.8
40.9
41.0
41.1
41.2
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River

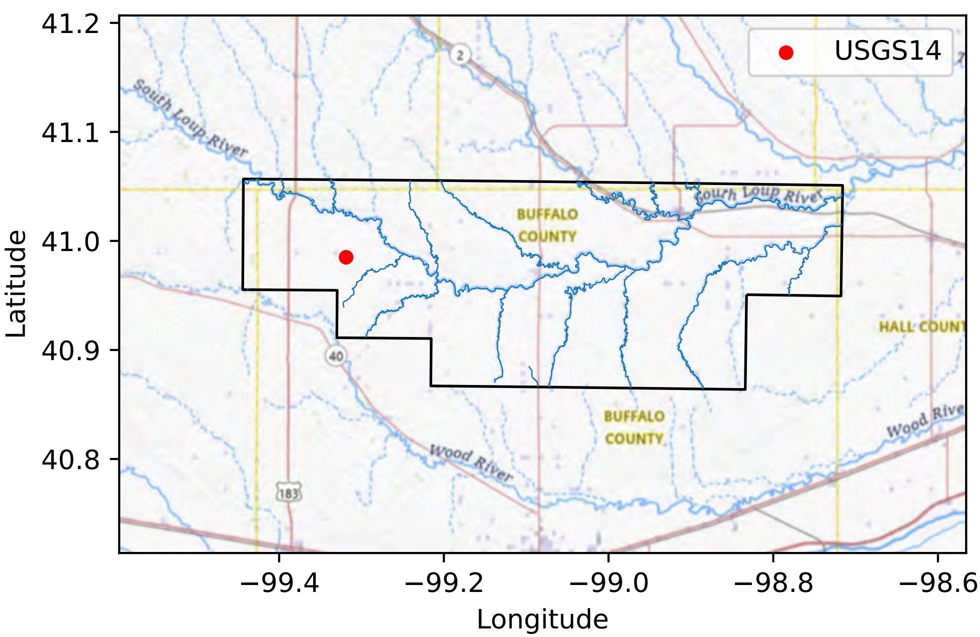


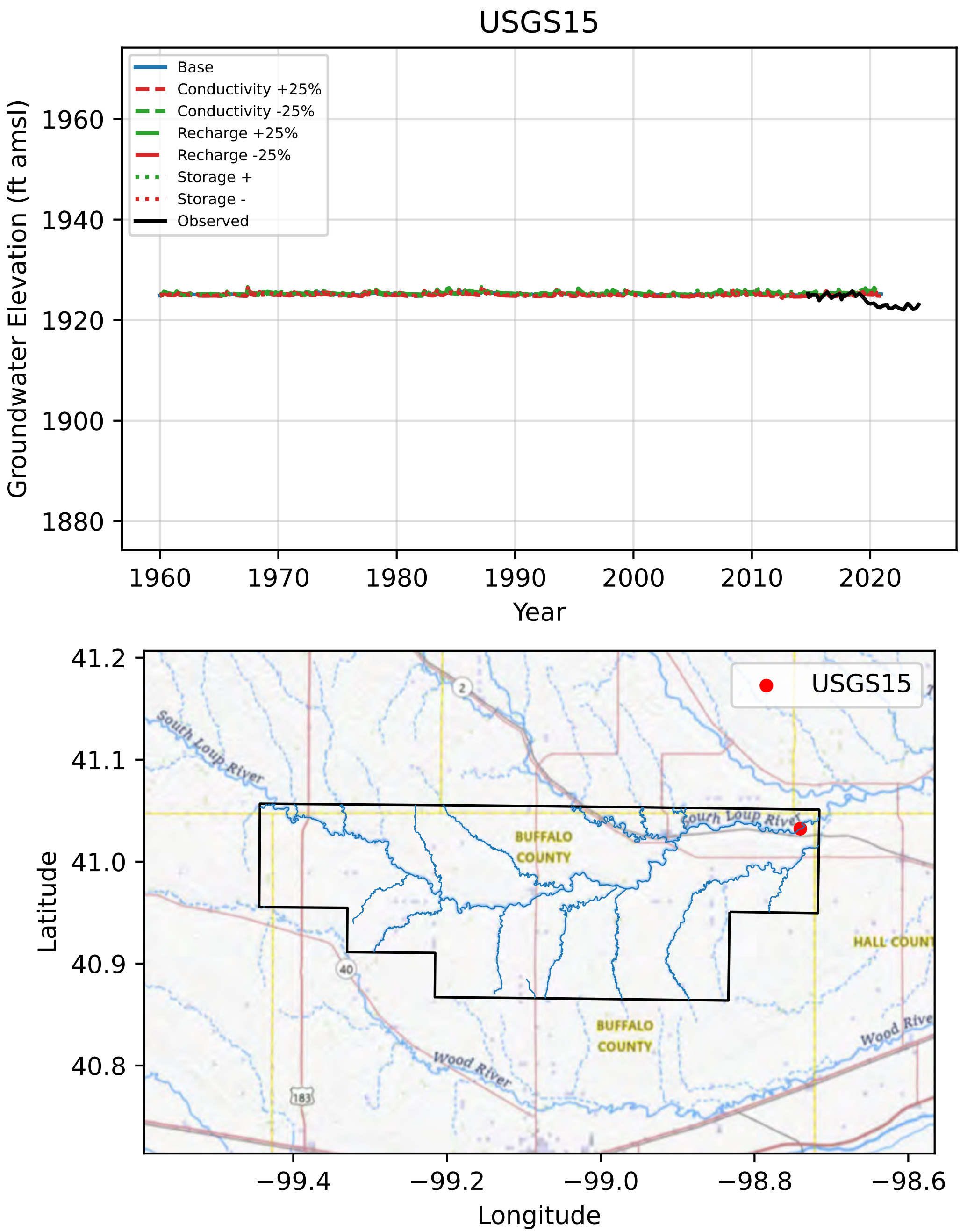
USGS8
Groundwater Elevation (ft amsl)
Year
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
2160
2140
2120
2100
2080
1960
1970
1980
1990
2000
2010
2020
Latitude
Longitude
USGS8
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River

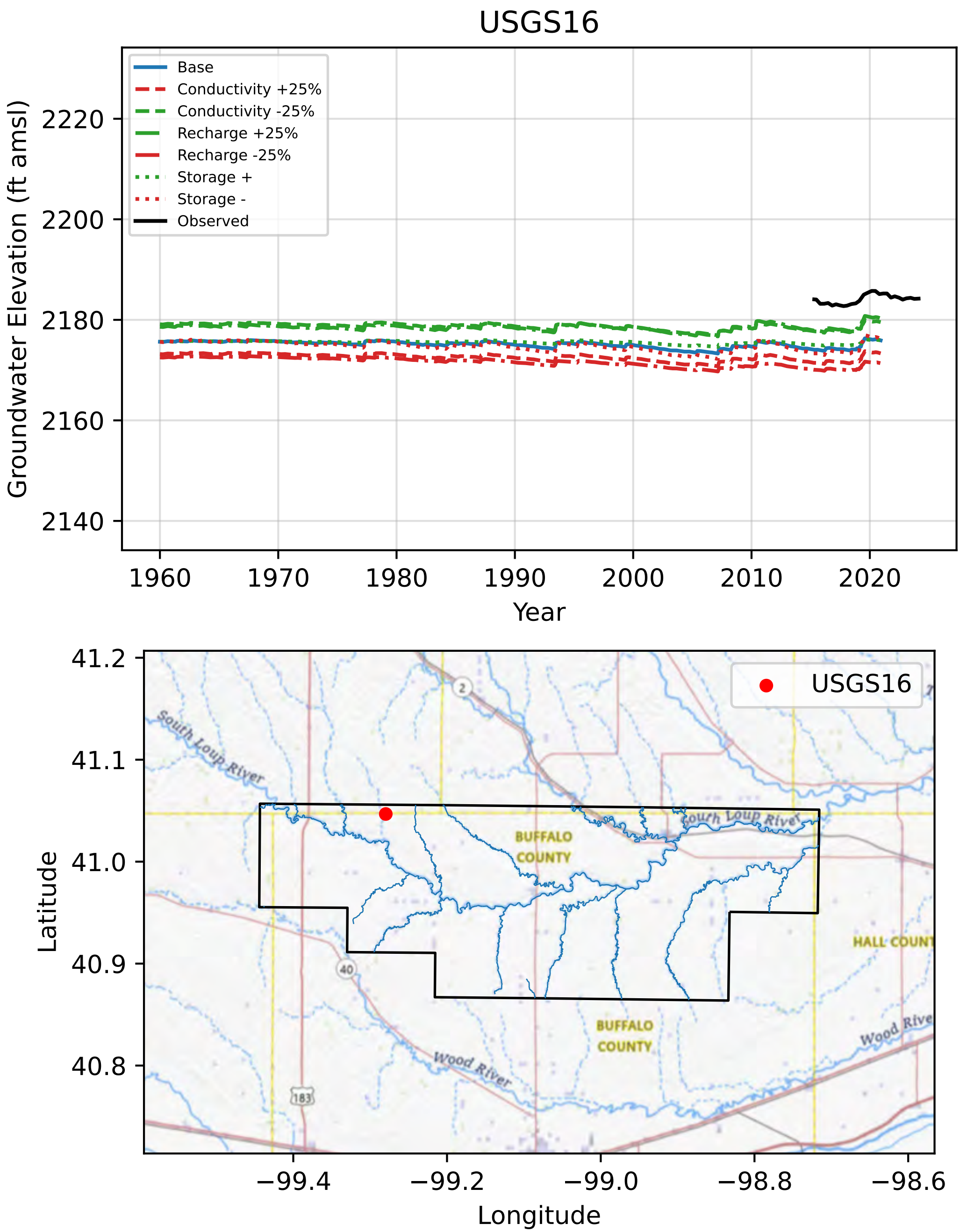

USGS11
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2240
2220
2200
2180
2160
1960
1970
1980
1990
2000
2010
2020
Year
USGS11
South Loup River
South Loup River
BUFFALO
COUNTY
BUFFALO
COUNTY
HALL COUNT
Wood River
Wood Rive
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude


USGS12
Groundwater Elevation (ft amsl)
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
2080
2060
2040
2020
2000
1960
1970
1980
1990
2000
2010
2020
Year
USGS12
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River


USGS14
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
2260
2240
2220
2200
2180
1960
1970
1980
1990
2000
2010
2020
Year


USGS14
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River


USGS15
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
Groundwater Elevation (ft amsl)
1960
1940
1920
1900
1880
1960
1970
1980
1990
2000
2010
2020
Year
USGS15
South Loup River
BUFFALO COUNTY
HALL COUNT
Wood River
Latitude
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
Longitude



USGS16
Groundwater Elevation (ft amsl)
Year
Base
Conductivity +25%
Conductivity -25%
Recharge +25%
Recharge -25%
Storage +
Storage -
Observed
2220
2200
2180
2160
2140
1960
1970
1980
1990
2000
2010
2020
Latitude
Longitude
USGS16
41.2
41.1
41.0
40.9
40.8
−99.4
−99.2
−99.0
−98.8
−98.6
South Loup River
BUFFALO COUNTY
BUFFALO COUNTY
HALL COUNT
Wood River

LRE WATER
CONNECTING WATER TO LIFE

Buffalo County Model README Document

To: Lower Loup Natural Resources District

From: LRE Water

Date: February 12, 2025

Project: 6002LLP02 – LLNRD Buffalo County Model

Subject: Running and Updating MODFLOW 6 Scenarios and Inputs

Summary

This document provides the Lower Loup Natural Resources District information on how to run the Buffalo County Model as well as how the three future scenarios described in the main report were developed, implemented, and analyzed. The following text assumes that the reader has a basic understanding of MODFLOW 6 inputs and outputs and access to pre- and post-processing routines in the form of either a Graphical User Interface (e.g. Groundwater Vistas or ModelMuse) or Python scripts.

1. Introduction

The Buffalo County Model (BC Model) is designed to be used by the Lower Loup Natural Resources District (LLNRD) to assess the impacts of proposed groundwater management scenarios on groundwater resources and guide management decisions. The final model is calibrated to thousands of historical groundwater level elevations. Three example scenarios simulated future changes in water levels and streamflow estimates are were provided along with the historical (a.k.a. the calibrated model) model files. To assist the LLNRD in updating and running the model in the future, LRE is providing this guidance document describing the basic process of running the model, scenario development, execution, and analysis.

The BC Model was developed using the Graphical User Interface (GUI) Groundwater Vistas (GWV) Version 8.3.0 Build 288. The model is run using MODFLOW Version 6.3.0. While GWV is propriety software, LRE has provided the LLNRD with all the necessary input files and executable codes to re-run or modify the scenarios described in the main report. Modification to existing or development of new scenarios requires some understanding of the development of MODFLOW 6 input and output files. Additionally, several inputs files are generated using python scripts that were developed specifically for the BC Model.

2. Historical Model Run and Model Calibration

The development of the calibrated model is described in detail in the main report. While the calibrated model generally should not be altered, there were several external processes that were used to create some of the model inputs that will need to be replicated when modifying the example future scenarios or when developing new future scenarios. This section documents the development of these model input files for the calibrated model. For a breakdown of the time discretization over the course of the full BC Model, see **Table 1**.

2.1 Recharge (RCH) and Well (WEL) Packages

The Flatwater Group (TFG) provided LRE Water with outputs from their Regionalized Soil-Water Balance Model that represent temporally and spatially distributed recharge and well pumping. Six recharge files and one "master" well file, which was subsequently divided into two files (one file for Alluvial Pumping, and one file for pumping from the Principal Aquifer), were used. These data are structured as 2D-arrays stored in .csv files that need to be reformatted to be compatible with MODFLOW 6. To achieve this reformatting, the provided Python scripts (RCH_Maker.py, WEL_Maker_Alluvial.py, and WEL_Maker_Other.py) should be used.

- RCH_Maker.py: This script apportions the recharge from TFG and creates a MODFLOW 6 Recharge package input file for the 6 types of recharge provided by TFG.
- WEL_Maker_Alluvial.py: This script apportions the pumping for wells within the lateral alluvial boundary to the top two layers of the model.
- WEL_Maker_Other.py: This script apportions the pumping for wells in Layers 2-5 (wells screened in the Principal Aquifer).

2.2 Streamflow Routing (SFR) Package

The flexibility of MODFLOW 6 allows for the application of time series data as inputs for differing stress packages, including the Streamflow Routing (SFR) package. For the BC Model, this allows for monthly flow rates to be applied to the starting stream segment (i.e. SFR Node) along the four major surface water bodies identified in the main report by linking the SFR Package to the provided external time series file (sfr_flow_rates.ts). This is advantageous as it allows for the efficient modification of flow rates without having to recreate the entire SFR package, which can be arduous.

Another feature that was added to MODFLOW 6 that was leveraged within the SFR Package is the ability to create an observation network in areas of interest. For the BC Model, SFR Nodes that correspond to the location of stream gages within the model Focus Area were identified and observations of cell inflow, cell outflow, and SFR flow were recorded for the duration of the model period. This observation file (BuffCo.sfr.usgs.obs) has been provided and further documentation of the observation package can be found in the MODFLOW 6 Document Description of Input and Output.

For both the time series inputs and observation features to be used, the SFR Node associated with either the inflow or observation location must be identified. The easiest way to do this is to view the provided shapefile of the SFR Package to identify the SFR Nodes interest.

2.3 Observation Utility for a Groundwater Flow Model

The use of Observation Packages is not a new utility within MODFLOW, but MODFLOW 6 has vastly expanded its capabilities. When creating the BC Model, this option was not available in GWV so it was created externally and incorporated manually. Thirty-two observation points that represent locations of collected groundwater elevation measurements within the Focus Area were identified and their corresponding model node numbers were recorded. The observation file (BuffCo.gwf.usgs.obs) has been provided and further documentation of the observation package can be found in the MODFLOW 6 Document Description of Input and Output.

3. Example Scenarios

As described in the main report, the BC Model was extended to simulate conditions through the year 2060. This extension assumed that conditions from 2008 to 2020 were representative of future conditions. The year 2008 was selected as the starting point because in 2008 the LLNRD began limiting applications for additional wells. All future conditions utilize the same model boundary conditions, geologic parameters, and discretization as the calibrated model to ensure continuity between scenarios. Four future runs are provided, a base case, where no changes were introduced to the model, and three scenarios where different management strategies were employed. These scenarios are intended to demonstrate the capability of the BC Model as an assessment tool and are not an endorsement or condemnation of any tested scenario. For full scenarios descriptions, see the main report. The following is intended to explain what was added or changed from the Base Case that allowed for the quick generation of possible management scenarios.

3.1 Base Case

The Base Case scenario provides a simulation of future conditions assuming that pumping, recharge, precipitation, streamflow, and other model inputs continues into the future. This was accomplished by amending the model input files to extend through the year 2060, increasing the stress period count, which consists of one month time steps, from 733 to 1213. Stress Periods 578 through 733, represents the years 2008 through 2020. These periods were repeated.

If the model is extended beyond 2060, increasing the number of stress periods can be achieved through multiple methods. LRE utilized the capabilities of GWV which allow for the number of stress periods to be increased while copying transient properties to create new input files. GWV is not required to accomplish this as input files can be extended using Excel or Python, or by manually copying data and pasting into the MODFLOW input text files.

For the Recharge and Well files provided by TFG, Python scripts that reformat and extend these data for the Base Case have been provided (RCH_Maker_Future.py, WEL_Maker_Alluvial_Future.py, and WEL_Maker_Other_Future.py). For a complete list of files needed for the Base Case, see **Table 2**.

3.2 Scenario 1: Stream Diversion

The implementation of an example stream diversion and subsequent redistribution to an area of high managed aquifer recharge (MAR) potential consisted of adding two additional MODFLOW 6 packages to the existing Base Case model file set. The two additional packages were a WEL file, which was added to simulate the removal of water from one model cell along the South Loup River, and an RCH file, which simulated the redistribution of water to a series of five model cells that correspond to the location of a potential MAR area within the Sand Creek Drainage.

The basic structure of the new WEL package is like that of the examples provided in the Base Case except for there being one well that is pumping every twelfth stress period from when it is first specified. In its current form, this corresponds to the well turning on for Stress Period 737 (May 2021), then turning off for Stress Periods 738 through 748 (June 2021 through April 2022), and turning on again in Stress Period 749 (May 2022). This cycle is repeated for the duration of the simulation. The same principle applies to the new RCH file, except there are five active cells that are receiving water for the same Stress Period that the WEL is active. See **Table 3** for more details on the additional files needed for Scenario 1.

It is important to note that the units differ between the WEL and RCH packages. The WEL package specifies pumping as a volume per time (L^3/T) while the RCH package specifies recharge as a flux (L/T). It is imperative that the volume of water that is extracted by the WEL package be distributed over the area of the number of cells specified in the RCH package or the water budget will be out of balance. See Figure 1 for a graphical representation of how this works for this example scenario. For a pumping rate of 1,500 gpm (255,750 ft^3/day), after converting units (cell size 1320' x 1320') and dividing by 5 cells the input rate is 0.33 ft/d.

3.3 Scenario 2: Theoretical Pumping Increase

Developing the example scenario in which future pumping was theoretically increased at the KAAPA Ethanol Plant at Ravenna was slightly more complex than the previous scenario as it took specific plant operations into account and necessitated modifying the SFR Package in addition to the creation of a new WEL Package. The creation of the WEL Package for this example scenario followed the same format as described above, except pumping began in January 2021 (Stress Period 734) and allowed to continue through the completion of the simulation (December 2060, Stress Period 1213). However, based on operations at the plant, one-third of total pumping is used in the byproduct of ethanol production, one-third is lost to evaporation, and one-third is returned to the South Loup. To facilitate this, the existing components of the Base Case SFR Package were modified. First, the time series file, sfr_flow_rates.ts, was modified using Excel to include an additional time series dataset representing the volume of water that would be returned to the South Loup River near the plant. Then, the actual SFR Package file was modified. After identifying the SFR Node by looking at the provided boundary condition shapefile, the inflow was specified to match that of the new time series column. This allowed the scenario to be representative of how the KAAPA Ethanol Plant at Ravenna would operate if a theoretical pumping increase were to come to fruition in the future. See **Table 4** for more details on the files that need to be modified for Scenario 2.

3.4 Scenario 3a-d: Pumping Allocations of 12", 7.5", 5", and 2.5"

The process for creating the four pumping allocations scenarios used a combination of GIS analysis, MS Excel calculations, and Python scripting. The steps are as follows:

1. The model cells (a.k.a nodes) within the Focus Area as this is where the allocations were identified. Using the Focus Area shapefile outline, model grid cells that fell within boundary were selected.

2. Scaling factors to limit pumping to the allocation rate were established. The Focus Area grid cells and Pumping values were exported into an Excel spreadsheet. Once the spreadsheet was populated, the current pumping volume per day for those cells for the period from 2008 to 2020 (Stress Periods 578 through 733) was brought into the spreadsheet. As allocations are an annual pumping restriction, the annual daily volumetric rate of pumping for each cell was quantified. Once these values were found, four daily volumetric thresholds were identified, as pumping in MODFLOW is specified as a volumetric rate. For each of these thresholds, a multiplier array of scaling factors was established. If the equivalent annual daily volumetric rate of pumping in a cell exceeded the allocation threshold, a the scaling factor was applied to reduce the daily volumetric rates for the entire year in question to limit the annual pumped volume to be equal to the allocation threshold.

3. CSV tables were created for model pumping. These were manually created by taking the existing TFG RCH and WEL .csv files and extending them through Stress Period 1213. This CSV has 1213 columns- one for each model month. Using a lookup function, if cells fell within the Focus Area, the allocation pumping rates were applied. If the cells fell outside the Focus Area, their existing pumping rates were applied.

4. Once these new .csv files were created, Python scripts were used to reformat the data to be compatible with MODFLOW 6. The Python Scripts "Wel_Maker_Alluvial_Allocations.py" and "WEL_Maker_Other_Allocations.py" convert the CSV files to MODFLOW 6 well package files.

5. See **Table 5** for more details on the files that need to be modified for Scenario 3.

Table 1. Stress Period Setup

Stress Period Type	Stress Period Number	Duration	Start Month	End Month	Model Period
Steady State	1	1 Year	01/1959	12/1959	Calibration
Transient	2 – 733	1 Month	01/1960	12/2020	Calibration
Transient	734 – 1213	1 Month	01/2021	12/2060	Future Examples (Repeat of Stress Periods 578 – 733)

Table 2. MODFLOW 6 files that are needed to run the Base Case Scenario that will be used to compare all example scenarios against.

Scenario	MODFLOW Package	Method of Creation
Base Case	BuffCo_BaseCase.disu	Groundwater Vistas
Base Case	BuffCo_BaseCase.drn	Groundwater Vistas
Base Case	BuffCo_BaseCase.evt	Groundwater Vistas
Base Case	BuffCo_BaseCase.ghb	Groundwater Vistas
Base Case	BuffCo_BaseCase.ic	Groundwater Vistas
Base Case	BuffCo_BaseCase.oc	Groundwater Vistas
Base Case	BuffCo_BaseCase.npf	Groundwater Vistas
Base Case	BuffCo_BaseCase.sto	Groundwater Vistas
Base Case	BuffCo_BaseCase_TS.sfr	Groundwater Vistas
Base Case	sfr_flow_rates.ts	Text Editor
Base Case	BuffCo_BaseCase.gwf.usgs.obs	Text Editor
Base Case	BuffCo_BaseCase.sfr.usgs.obs	Text Editor
Base Case	TFG_Farwell_CanalSeep_RCH.rch	Python Script
Base Case	TFG_COHYST_LatLoss_RCH.rch	Python Script
Base Case	TFG_RCH.rch	Python Script
Base Case	TFG_Platte_CanalSeep_RCH.rch	Python Script
Base Case	TFG_MLPPID_CanalSeep_RCH.rch	Python Script
Base Case	TFG_Farwell_LatLoss_RCH.rch	Python Script
Base Case	TFG_WEL_Other_Future.wel	Python Script
Base Case	TFG_WEL_Alluvial_Future.wel	Python Script

Table 3. Additional MODFLOW 6 files needed to run the Stream Diversion example scenario.

Scenario	MODFLOW Package	Method of Creation	Modification
Stream Diversion	BuffCo_Scen1_Diversion.wel	Text Editor	Additional Pumping Well to Divert Stream Water
Stream Diversion	DiversionRecharge.rch	Text Editor	Additional Recharge Zone to Redistribute Diverted Water

Note: For all files other than the .rch and .wel files in Table 1, the base naming convention will be BuffCo_Scen1_Diversion

Table 4. Modification to existing and additional MODFLOW 6 files needed to run the Pumping Increase example scenario.

Scenario	MODFLOW Package	Method of Creation	Modification
Pumping Increase	BuffCo_Scen2_Ethanol.wel	Text Editor	Additional pumping well at the location of the KAPPA Ethanol Plant
Pumping Increase	BuffCo_Scen2_Ethanol_TS.sfr	Text Editor	Modified existing SFR Package to include reference to a new inflow that is representative of the return flow from the Ethanol Plant to the South Loup River
Pumping Increase	sfr_flow_rates.ts	Text Editor	Modified existing time series file to include an additional column that specified the volume of return flow to the South Loup River

Note: For all files other than the .rch and .wel files in Table 1, the base naming convention will be BuffCo_Scen2_Ethanol

Table 5. Modification to existing and additional MODFLOW 6 files needed to run the Allocations example scenario. Four versions of these new files will need to be created.

Scenario: Data Type	MODFLOW Package	Creation Method	Modification
Allocation: Alluvial Well Pumping	TFG_WEL_Alluvial_Future12.wel (12″) TFG_WEL_Alluvial_Future75.wel (7.5″) TFG_WEL_Alluvial_Future5.wel (5″) TFG_WEL_Alluvial_Future25.wel (2.5″)	Python Script	Creation of WEL package that has allocations applied to the Focus Area. Requires the CSV file of the same name to create the new package.
Allocation: Principal Aquifer Well Pumping	TFG_WEL_Other_Future12.wel (12″) TFG_WEL_Other_Future75.wel (7.5″) TFG_WEL_Other_Future5.wel (5″) TFG_WEL_Other_Future25.wel (2.5″)	Python Script	Creation of WEL package that has allocations applied to the Focus Area. Requires the CSV file of the same name to create the new package.

Note: For all files other than the .rch and .wel files in Table 1, the base naming convention will follow the naming convention as the files listed in Table 4.