Groundwater Model for the Central and Northern Parts of the Lower Platte River and Missouri River Tributary Basins

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HDR

THE FLATWATER GROUP INC.

TBirdie Consulting inc

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1.0 Introduction

The Nebraska Department of Natural Resources (NDNR) performs an annual evaluation of the expected long-term availability of surface water supplies and hydrologically connected groundwater supplies in all basins that have not been designated as fully appropriated or over appropriated. This includes the Lower Platte River and Missouri River Tributary (LPMT) basins (study area) (Figure 1-1). NDNR currently uses analytical methods to assess the impacts of groundwater pumping on streams in the study area. Numerical groundwater modeling techniques are generally preferred for calculating the groundwater depletion component of the NDNR's annual basin status evaluations because they are recognized as the best available science and methodology to do so. As a result, NDNR is working to develop numerical groundwater models in all basins across the state.

The approach to the development of groundwater modeling tools for the LPMT basins is to develop one model for the central and northern part of the study area and a second model for the southern part. The central and northern model is the subject of this report. The development of the southern model is to follow the completion of the central and northern model.

To date, no numerical groundwater model is available that encompasses the entirety of the LPMT study area. Therefore, NDNR has contracted with HDR to assess the data available and the data needed to develop a groundwater model that can be used to support NDNR's annual evaluation of the study area, outlined by NDNR in request for proposal (RFP) Number 3818Z1.

This report presents a single groundwater flow model for the central and northern parts of the study area. The foundation for the development of the groundwater flow model includes three earlier HDR reports, including *Analysis of Available Hydrogeologic Data and Conceptual Model of the Hydrogeology within the Lower Platte River and Missouri River Tributary Basins* (HDR 2012), *Hydrogeologic Assessment for Potential Development of Groundwater Modeling Tools in the Lower Platte River and Missouri River Tributary Basins* (HDR 2013a), and *Groundwater Model Development Plan for the Lower Platte and Missouri River Tributary Basins* (HDR 2014).

A draft version of this groundwater model and report was peer reviewed by Olsson Associates in late 2016. The key findings of that review were discussed with HDR and incorporated into a work plan to be addressed in the final model (Appendix A). This final model report describes the model after the tasks outlined in that work plan were completed.

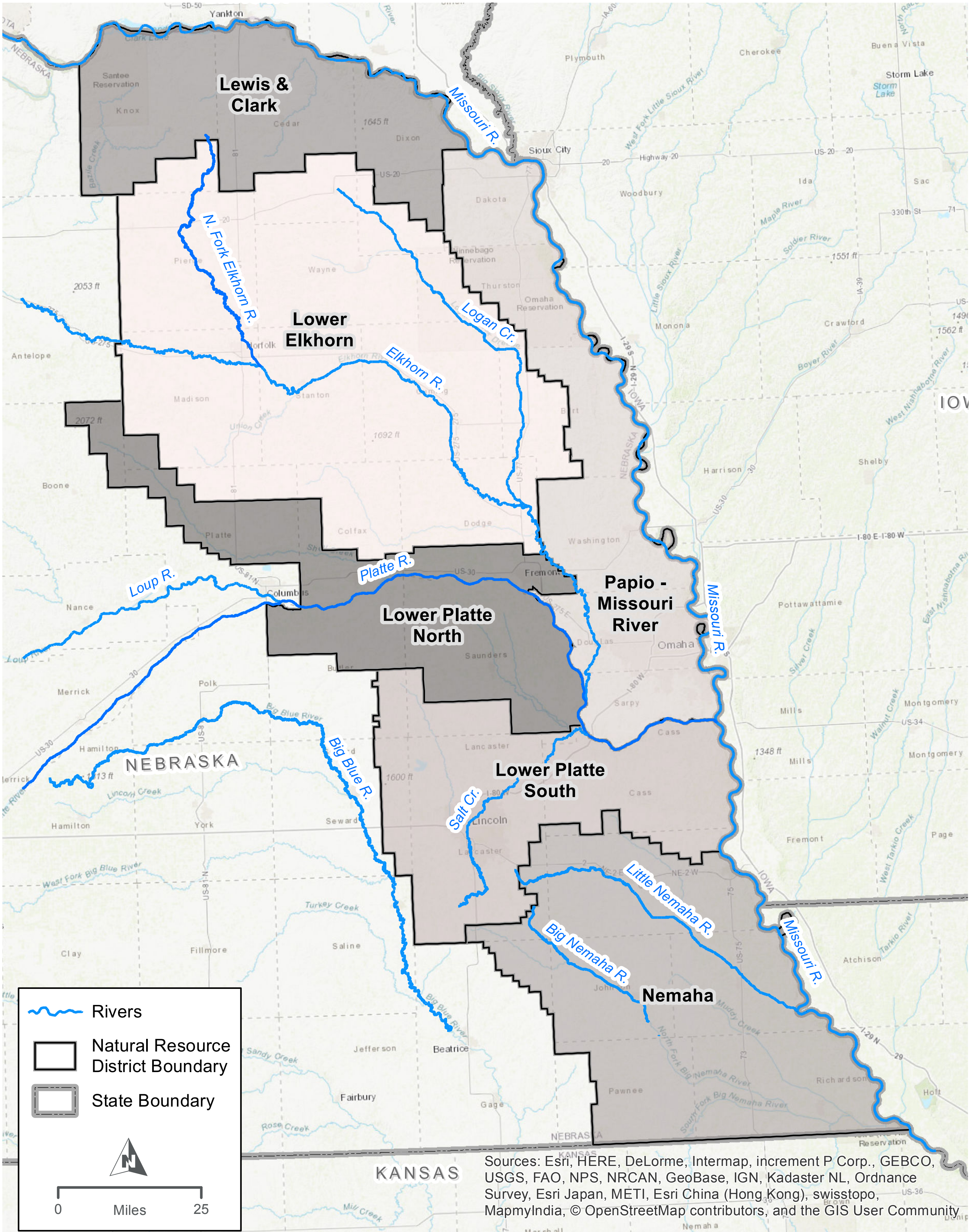
1.1 Purpose and Scope

The purpose of this study was to develop a groundwater flow model that can be used by NDNR to evaluate the appropriation status in the LPMT basins. This report presents the construction and calibration of the specific groundwater flow model that was developed as a tool that can be used to evaluate the effect of well pumping on stream baseflow in the central and northern parts of the LPMT basins. It consists of a large part of eastern Nebraska (Figure 1-1) and includes the areas covered by the following Natural Resources Districts (NRDs):

- Lewis and Clark NRD (LCNRD)
- Lower Elkhorn NRD (LENRD)
- Lower Platte North NRD (LPNNRD)
- Lower Platte South NRD (LPSNRD)
- Papio-Missouri River (PMRNRD)

The model domain includes the northern part of the Nemaha NRD, and covers the central and northern parts of the LPMT basins and the northern part of the Nemaha River Basin (Figure 1-2). The southern part of the study area, including all of the Nemaha NRD and Nemaha River Basin, will be the subject of a separate groundwater modeling project, which will be completed in the future.

To achieve the project objective, the groundwater flow model must be able to reproduce the transient baseflow conditions measured on the major streams, while also reproducing the transient groundwater level changes as measured in wells, located throughout the study area. The scope of this modeling study was not to reproduce every detail of the hydrogeologic system, but rather to develop a tool that can be used to evaluate groundwater-management scenarios over a regional spatial scale, and a time periods of multiple years with yearly and monthly temporal resolution. Development of the regional model focused on generalized hydrogeologic characteristics within the study area and did not attempt to describe local-scale variations that can affect groundwater flow at the local scale. Due to the regional scale of the study, the model is not intended for, and may not be well-suited for, analysis of local-scale problems, where the desired detail requires simulation of local aquifer heterogeneity or local aquifer stresses at spatial and temporal scales that are smaller/shorter than those represented by the model documented in this report. Further assessment of local-scale or shorter-period hydrologic processes and impacts generally requires additional study and/or development of a new groundwater modeling tool and associated simulations.



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CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 1-1 - STUDY AREA

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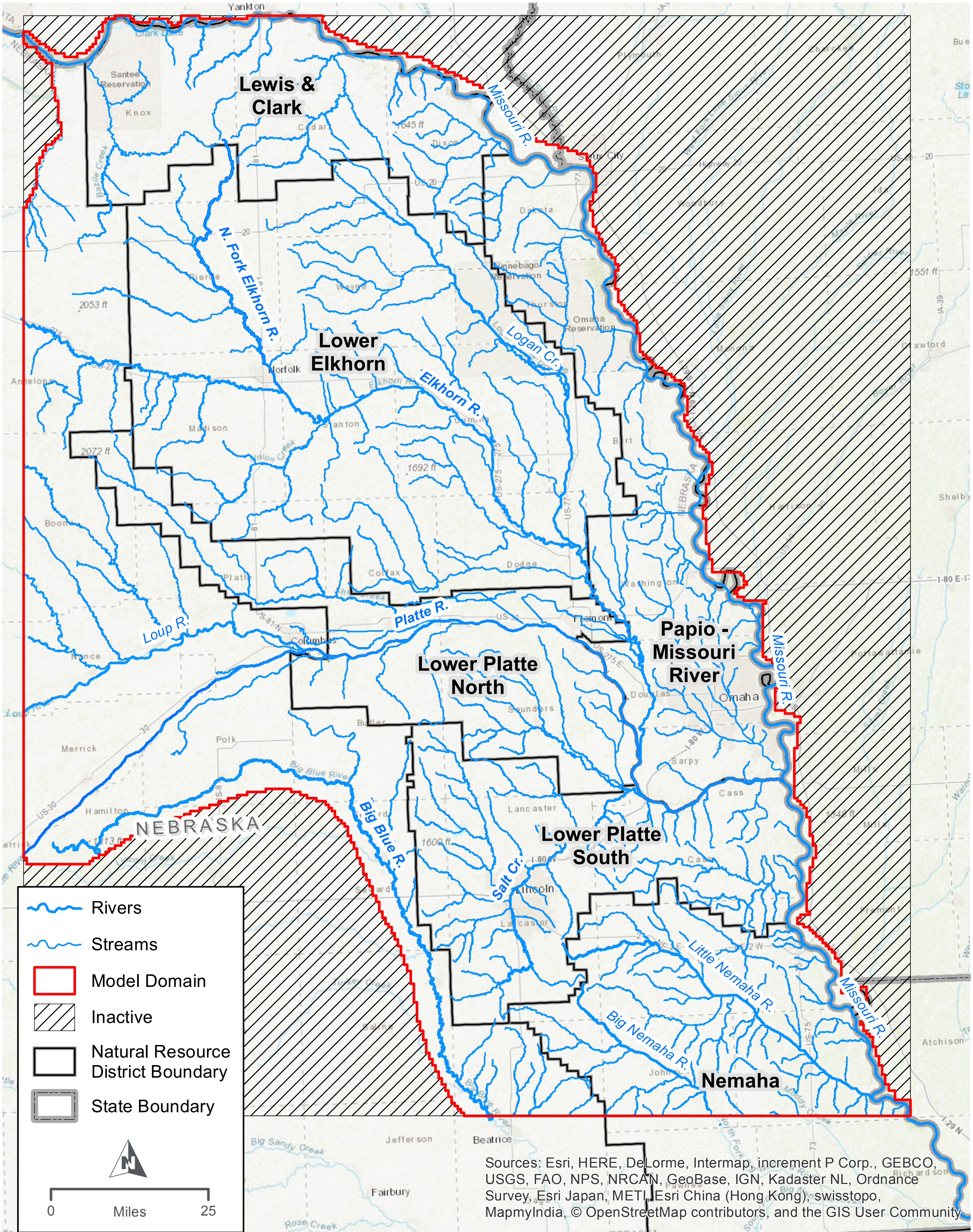

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FIGURE 1-2 - MODEL DOMAIN

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1.2 Report Organization

This report is organized as follows:

- Section 1.0 Introduction
- Section 2.0 Geology
- Section 3.0 Hydrogeology
- Section 4.0 Groundwater Pumping and Recharge
- Section 5.0 Model Construction
- Section 6.0 Model Calibration
- Section 7.0 Sensitivity Analysis
- Section 8.0 Discussion
- Section 9.0 Model Application and Limitations
- Section 10.0 Summary
- Section 11.0 References

The development of key modeling datasets is not repeated in this report, but many of the concluding maps and charts are included. Figures and tables have been included in the body of this report following the reference of each figure and table.

2.0 Geology

This section presents the results of geologic and hydrogeologic reviews and studies for the construction of a groundwater flow model within the LPMT basins study area.

The hydrogeology of the LPMT basins is complex due to the glacial origin of the youngest sediments; the entire study area has been glaciated except for the western edge. Figure 2-1 illustrates the approximate thickness of the glacial till deposits. The geologic materials in eastern Nebraska generally consist of alluvium, loess, or glacial till overlying bedrock. This region is characterized primarily by low-permeability glacial till containing localized perched or semi-perched aquifers. The geologic and hydrostratigraphic units within the basin and their water-bearing properties are listed in Table 2-1.

The topographic setting of the LPMT basins is dominated by rolling hills with major valleys along major rivers and creeks. To the west, the area includes plains and dissected plains. Figure 2-2 illustrates the land surface topographic configuration.

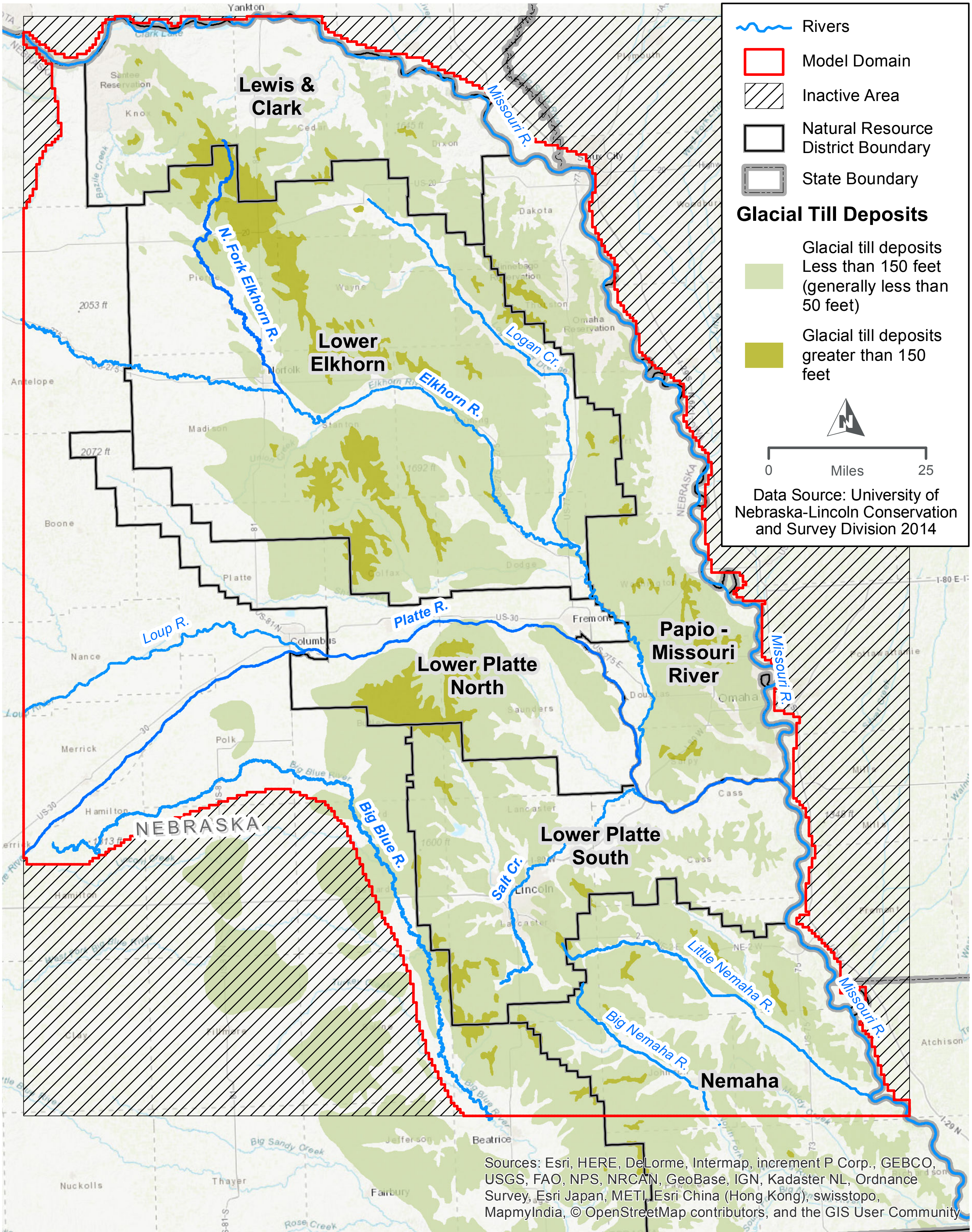

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FIGURE 2-1 - GLACIAL TILL DEPOSITS

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Table 2-1. Geology and Hydrostratigraphy of the Study Basin (after NDNR 2006)

System	Hydrogeologic Unit	Material Characteristics	Maximum Thickness (feet)	Hydrogeologic Characteristics
Principal Aquifer				
Quaternary	Platte River Aquifer	Alluvial gravel, sand, silt, and clay deposited within the incised bedrock valley of the Platte River.	100	Unconfined and hydraulically connected with the Platte River. Yields 900 gallons per minute (gal/min) to 2,000 gal/min of water to wells.
	Elkhorn River Aquifer	Alluvial gravel and sand deposited within the incised bedrock valley of the Elkhorn River.	90	Unconfined aquifer with wells yielding 700 gal/min to 1,200 gal/min.
	Missouri River Aquifer	Alluvial gravel, sand, and silt deposited within the incised bedrock valley of the Missouri River.	100	Unconfined to semi-confined and hydraulically connected with the Missouri River. Wells generally yield 300 to 700 gal/min, and locally yield as much as 1,500 gal/min.
	Paleovalley alluvial aquifers	Fluvial gravel, sand, silt, and clay deposited within bedrock valleys. Commonly underlying thick, fine-grained deposits of glacial till and loess.	275	Semi-confined to confined alluvial aquifers. Well may yield 400 gal/min to 1,200 gal/min.
	Loess	Silt with a little very fine sand and clay deposited as wind-blown dust.	unknown	May provide small amounts of water to shallow stock or domestic wells.
	Till	Glacier deposited silty, sandy clay with some gravel, pebble, and cobbles.	unknown	Relatively impermeable but may contain small perched groundwater or sand deposits that yield water to small capacity wells.

System	Hydrogeologic Unit	Material Characteristics	Maximum Thickness (feet)	Hydrogeologic Characteristics
Bedrock Aquifers				
Tertiary	Ogallala Group	Gravel, sand, silt, clay, with some lime-cemented beds.	0–200	Widespread aquifer in Nebraska, but not an important source of water in the study area.
Cretaceous	Dakota Group	Massive to cross-bedded friable sandstone interbedded with clayey to slightly sandy shale.	<140	Unconfined or semiconfined aquifer. Wells can yield 50 gal/min to 750 gal/min of water. Water is of variable quality. Used as a primary water source only when other sources are not available.
Confining Bedrock				
Permian and Pennsylvanian	Undifferentiated shale, limestone and sandstone	Shale interbedded with limestone and sandstone. Sandstone is generally thin-bedded and may contain coal.	<1,000	Not a major aquifer. Fractured limestone may yield 20 gal/min to 50 gal/min of water to wells.

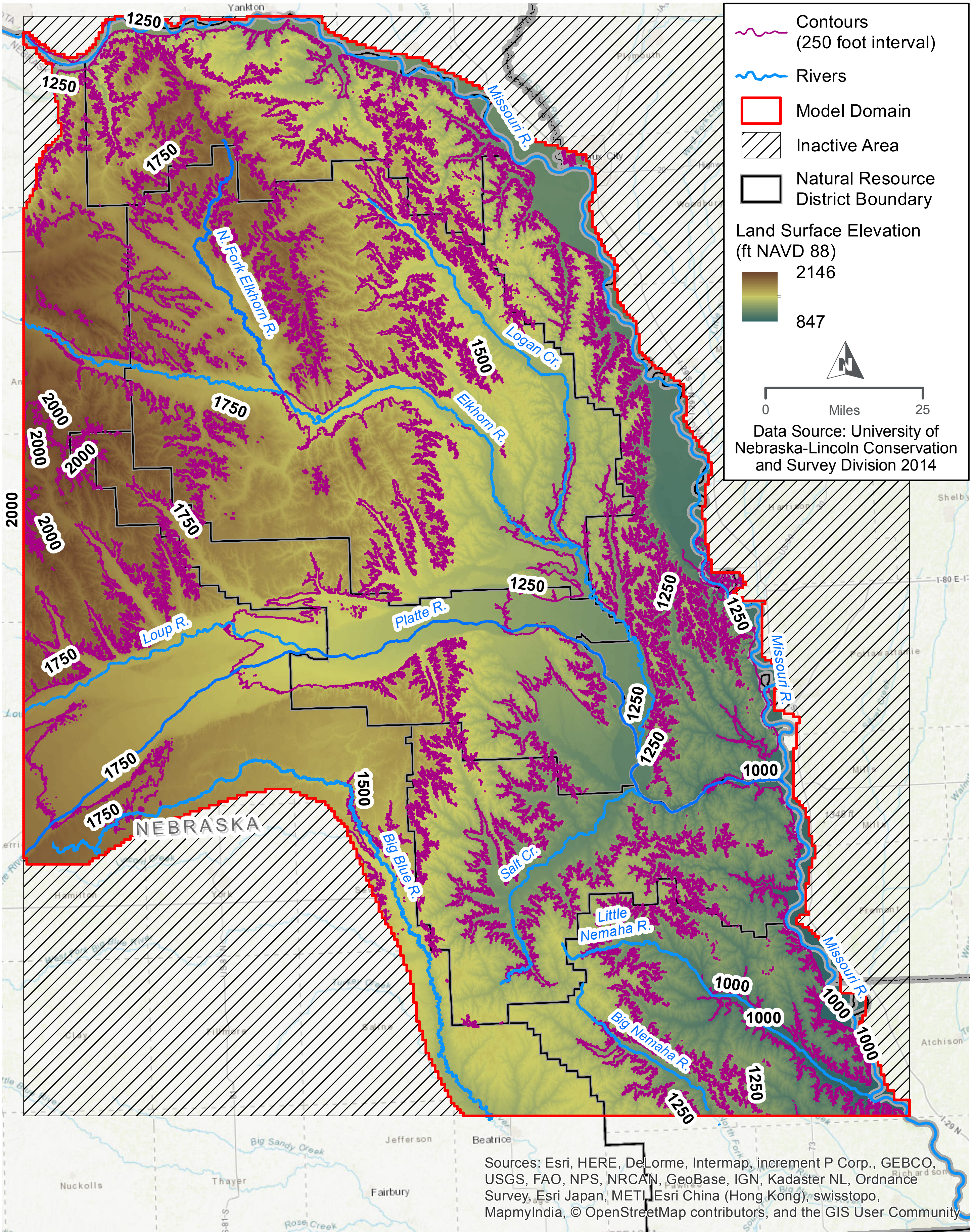

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FIGURE 2-2 - LAND SURFACE ELEVATION

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The principal aquifer in the study area comprises unconsolidated sediments of Quaternary age that overlie bedrock. Two types of unconsolidated geologic deposits commonly have been developed as aquifers: alluvium and glacio-fluvial paleovalleys. Alluvium occurs within the valleys of modern streams (for example, the Big Nemaha, Platte, Loup, and Elkhorn Rivers, and Logan Creek) and typically contains sand and gravel with excellent storage and water-transmitting properties. In the context of this study, a paleovalley refers to a valley incised into bedrock by eastward-draining streams across eastern Nebraska. Large expanses of glacial till are present throughout most of the basins. These materials are generally of low permeability, but have been cut in several areas by present-day rivers forming alluvial valleys, and by ancient rivers forming buried paleovalleys. The valleys are filled with permeable sand and gravel, which serve as conduits to flow in an otherwise low-permeability surrounding material. Overlying the principal aquifer is a mantle of loess that either does not supply a significant amount of groundwater, or is not saturated and occurs at elevations above the water table.

Secondary aquifers in the study area include several bedrock units. The most widespread water-bearing hydrogeologic unit of the bedrock aquifers is the Dakota Group. Water development in the Dakota Group may be limited by sufficient supply from the shallow principal aquifer, and by well yield and water quality limitations. The Ogallala Group is an aquifer in the northwest part of the study area, but does not generally yield large quantities of water in the study area. In extreme southeast Nebraska, the Tertiary and Cretaceous geologic units, along with other bedrock units, have been eroded away and the remaining bedrock unit (Permian and Pennsylvanian Undifferentiated) is not generally considered an aquifer, but rather an aquitard, or confining unit where local water-bearing strata are found underlying this low-permeability unit. These bedrock aquifers supply a small amount of water compared to the principal aquifer but can be an important local source of water (Summerside et al. 2005). However, they generally are not in direct hydrologic connection with the streams in the LPMT basins (NDNR 2006).

3.0 Hydrogeology

As discussed in Section 2.0, there are two significant aquifers within the study area, the unconsolidated principal aquifer and the secondary bedrock Dakota Aquifer. Streams include the Lower Platte River, Missouri River, Nemaha River, and their tributaries.

3.1 Principal Aquifer

The principal aquifer in eastern Nebraska generally is defined as the unconsolidated Quaternary age alluvial and glacio-fluvial deposits, and does not include the Tertiary Ogallala Group or older bedrock units. We note that conceptualization of the regional flow system causes an extrapolation of this connected aquifer to the southeastern portion of the study area, but the reader should be cautioned that the principal aquifer and the Dakota Aquifer are absent in parts of southeastern Nebraska. Generally this area is comprised of much lower permeability materials than the rest of the study area, except where alluvial, or paleovalley, aquifers are present. The reader is cautioned to consider this when viewing subsequent figures of the principal aquifer and Dakota Aquifer in this report.

3.1.1 Structure

The groundwater model conceptualization defines the principal aquifer as consisting of unconsolidated Quaternary deposits that overlie bedrock. Figure 3-1 depicts the elevation of the base of the principal aquifer. This dataset is assigned to be the base of the uppermost model layer.

3.1.2 Water Table Conditions

3.1.2.1 Predevelopment

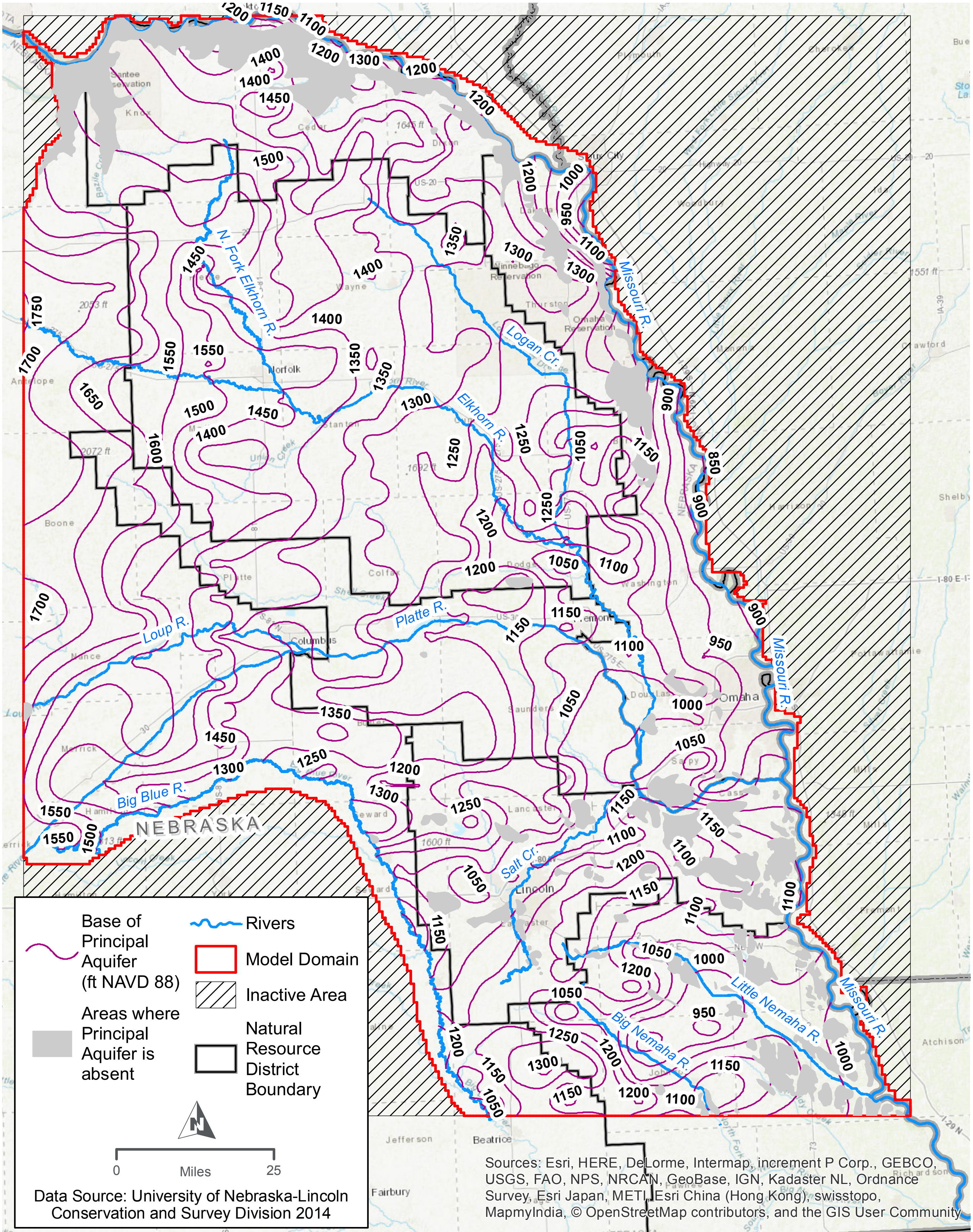
In 1979, the University of Nebraska–Lincoln Conservation and Survey Division (UNLCSD) developed a statewide groundwater contour map using its database of well water levels. The map represents the elevation of the top of the saturated zone of the principal aquifer. The interpreted groundwater contours are presented in Figure 3-2. A review of groundwater level hydrographs prior to 1979 in the study area suggests that there were little to no long-term trends. Thus, the 1979 water table is considered to be a suitable approximation of predevelopment conditions.

3.1.2.2 Spring 2010

Another valuable dataset for the development of a groundwater flow model is the establishment of a groundwater flow map that is reflective of recent conditions, which is shown in Figure 3-3. The 2010 water level elevation map is based on approximately 1,076 wells located in the six NRDs within the study area. The location and distribution of these groundwater-level monitoring points is very consistent across the study area, with only the extreme southern part of the study area having a noticeably lower well density.

3.1.2.3 Change from Predevelopment to Spring 2010

The calculated total change in groundwater elevation from predevelopment to spring 2010 is shown in Figure 3-4. This map shows areas where modest groundwater declines have been observed, but there are also areas where significant groundwater rises have occurred. The areas of groundwater rise are more widespread in the study area and are primarily located within the LENRD, but also portions of the LCNRD and LPNNRD.



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-1 - BASE OF THE PRINCIPAL AQUIFER

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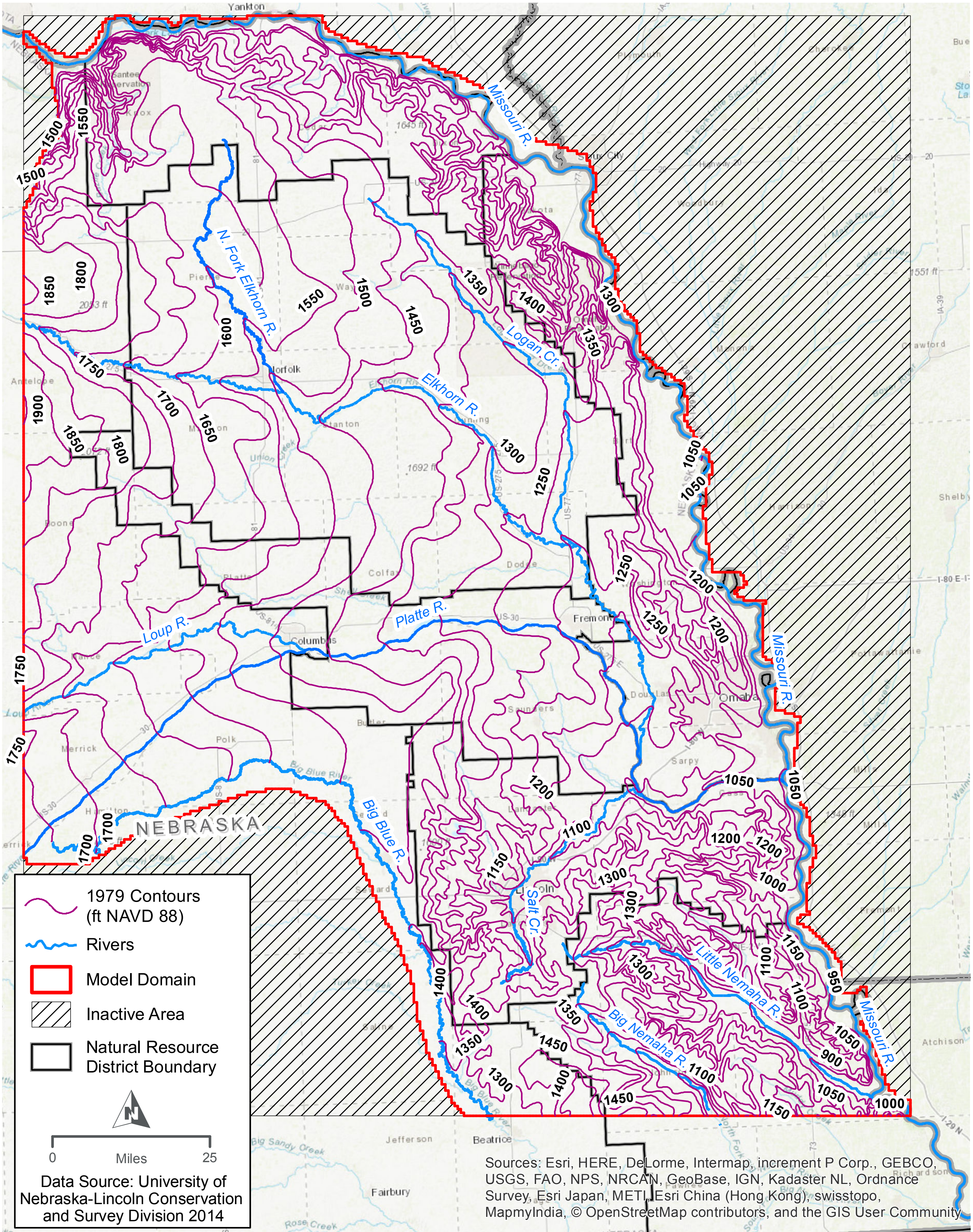

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-2 - WATER TABLE FOR THE PRINCIPAL AQUIFER, PREDEVELOPMENT

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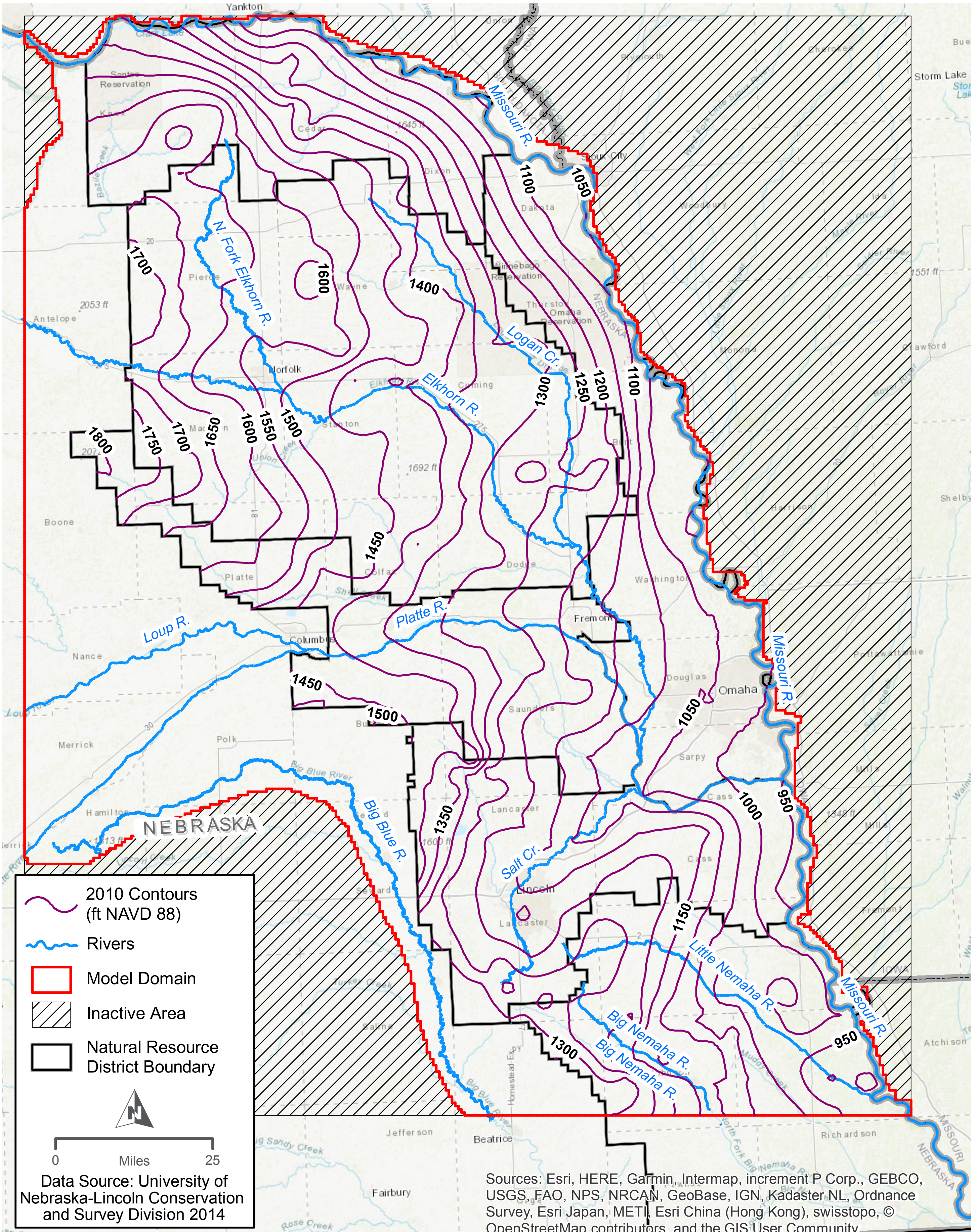

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-3 - WATER TABLE FOR THE PRINCIPAL AQUIFER, SPRING 2010

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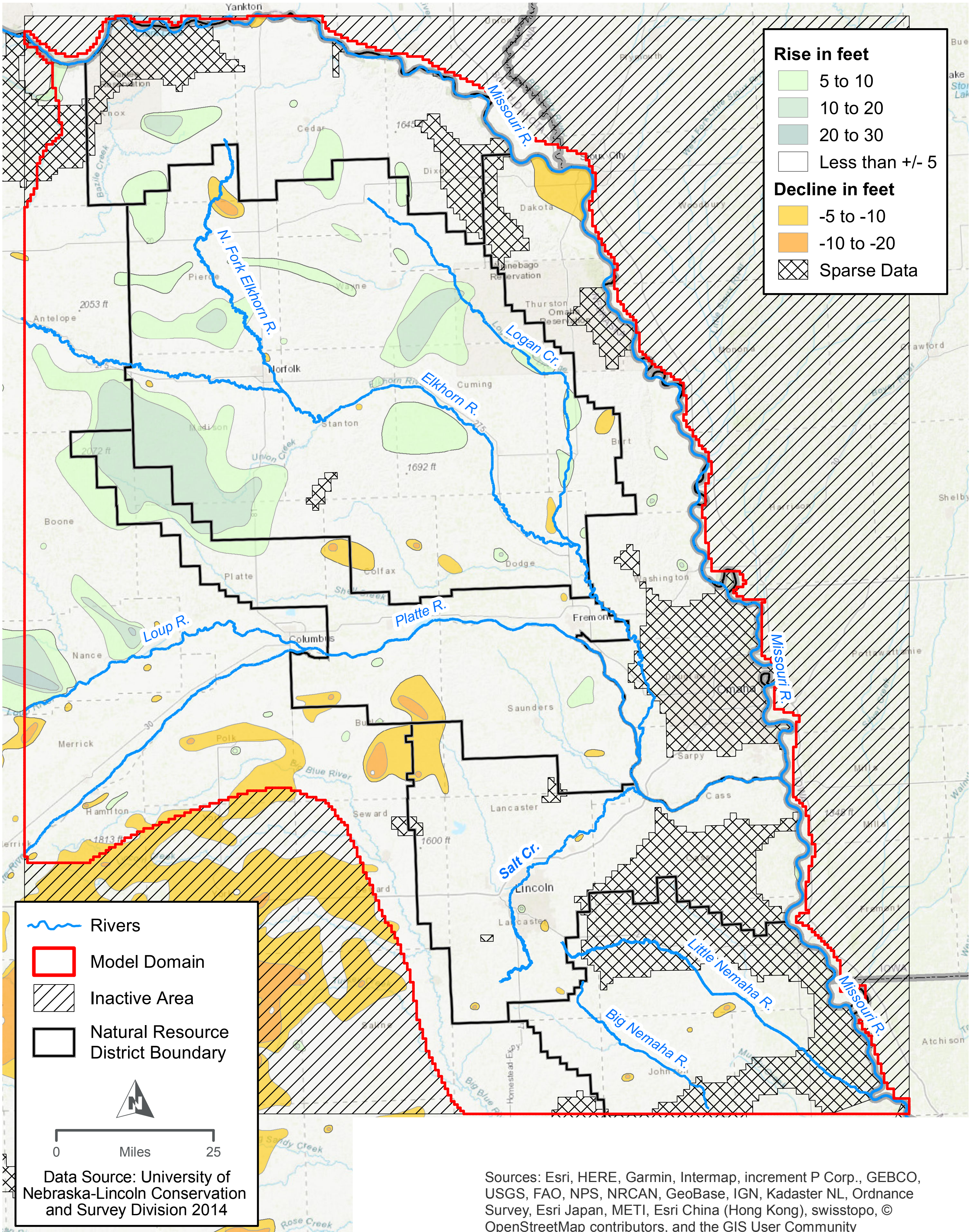

Data Source: University of Nebraska-Lincoln Conservation and Survey Division 2014

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

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FIGURE 3-4 - GROUNDWATER LEVEL CHANGE - PREDEVELOPMENT TO SPRING 2010

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3.1.3 Hydraulic Properties

An estimate of the thickness-weighted average horizontal hydraulic conductivity (K_H) distribution of the unconsolidated deposits, including the principal aquifer, was developed using available data from the UNLCSD Test Hole database.[1] This distribution is presented in Figure 3-5. Horizontal conductivity values were estimated from grain size, degree of sorting, and silt content of the saturated aquifer sediments using bore logs from the UNLCSD Test Hole database (HDR 2013a). The distribution and range of K_H values shown in Figure 3-5 provided a guide and initial estimates as inputs during model construction, later altered during calibration, of the LPMT basins groundwater flow model.

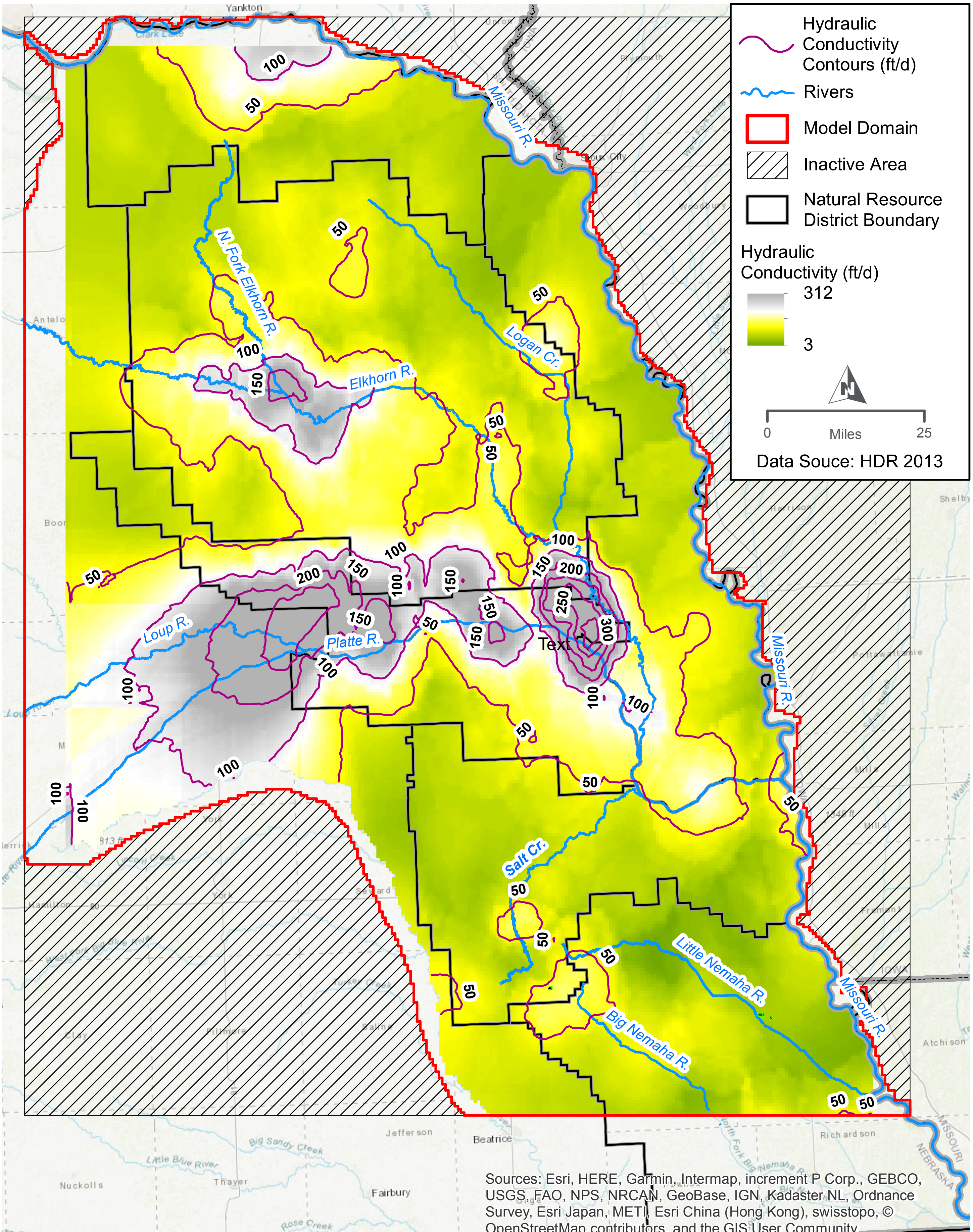
The saturated thickness of the principal aquifer at each test hole location was calculated using 2010 groundwater level elevations in the Nebraska Statewide Groundwater Level Program database[2] and the elevation of the base of the principal aquifer. The saturated thickness map is presented in Figure 3-6.

Transmissivity values were calculated to reflect the total aquifer saturated thickness for each test hole. The calculations were made for each individual lithologic unit by multiplying the assigned hydraulic conductivity by the saturated thickness of each individual unit. The aquifer transmissivity is the sum of the transmissivity values of the individual lithologic units. The transmissivity map is presented in Figure 3-7.

3.2 Bedrock Aquifer

The bedrock is a secondary aquifer in the study area and primarily consists of the Ogallala and Dakota Groups. The Ogallala Group primarily consists of sands and gravels and some lime cemented beds. This unit occurs at the land surface in much of central and western Nebraska, but has been eroded away in the study area, except in the northwest portion of the study area. The Dakota Group consists of sandstone and shale units that occur in the stratigraphic interval between the base of the Cretaceous system and the top of the first major sandstone bed below the Cretaceous Greenhorn Limestone (Ellis 1986). The Dakota Group occurs at the land surface in eastern Nebraska and lies at depths of more than 7,000 feet in the southwestern part of the Nebraska panhandle. The Dakota Group is present in the majority of the study area, however it is absent in the southeastern part of the study area, due to post-Cretaceous erosion.

[1] http://snr.unl.edu/csd-esic/StateTHDatabase/Metadata/Testholes_lithology.html
[2] http://water.unl.edu/mapsdbgis



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CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-5 - TEST HOLE DERIVED HYDARULIC CONDUCTIVITY OF THE PRINCIPAL AQUIFER

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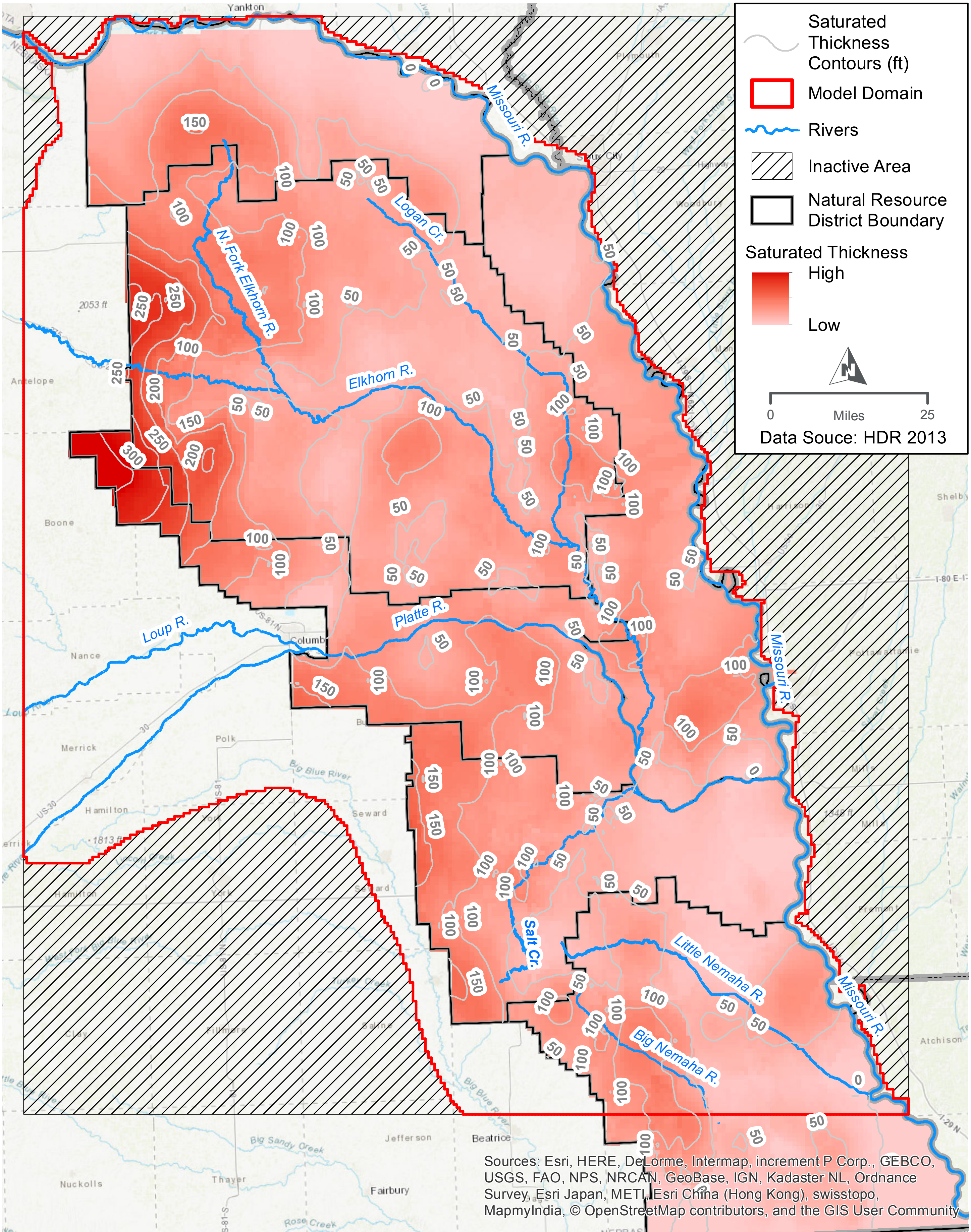

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-6 - TEST HOLE-DERIVED SATURATED THICKNESS OF THE PRINCIPAL AQUIFER, SPRING 2010

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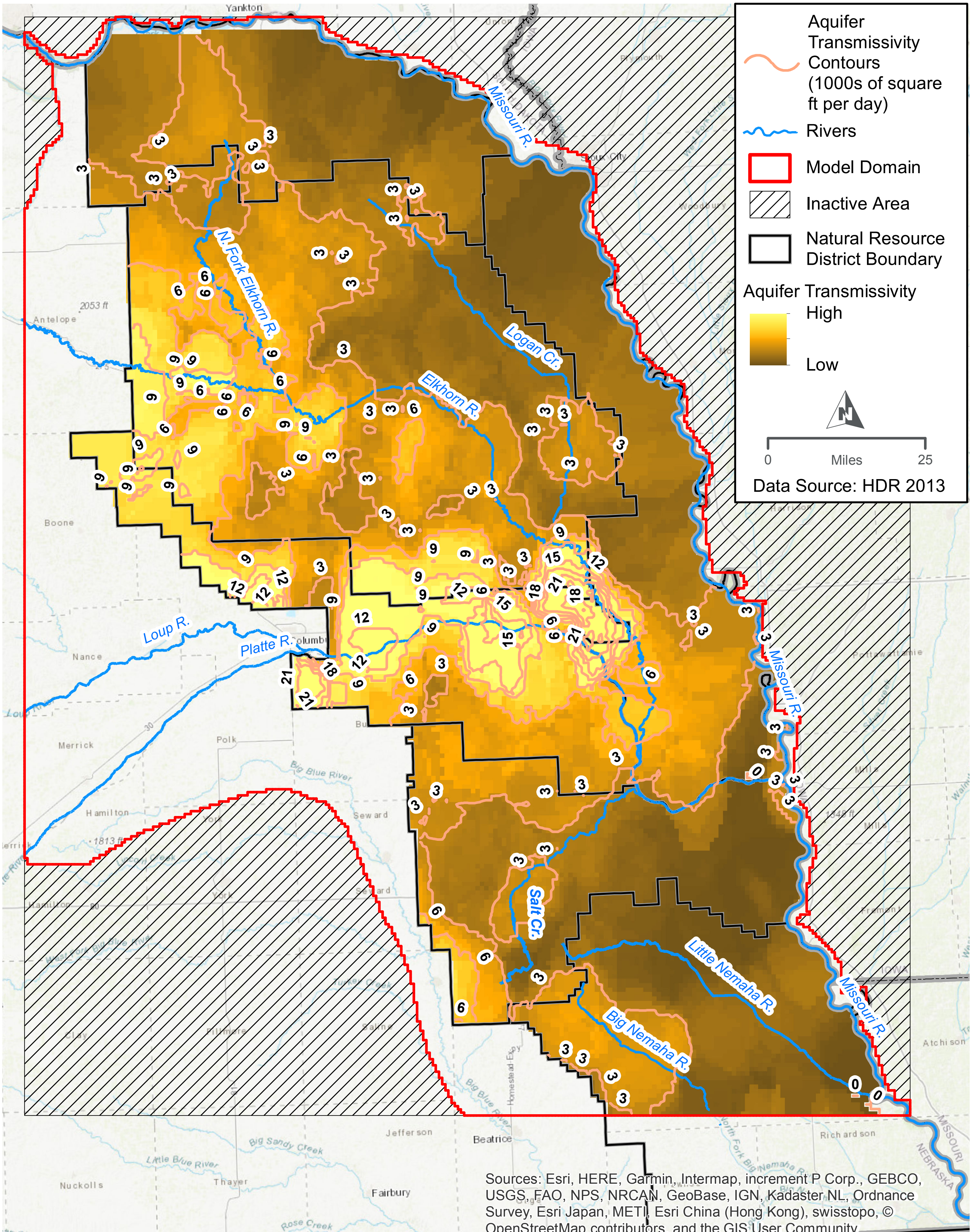

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-7 - TEST HOLE DERIVED TRANSMISSIVITY OF THE PRINCIPAL AQUIFER

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3.2.1 Structure

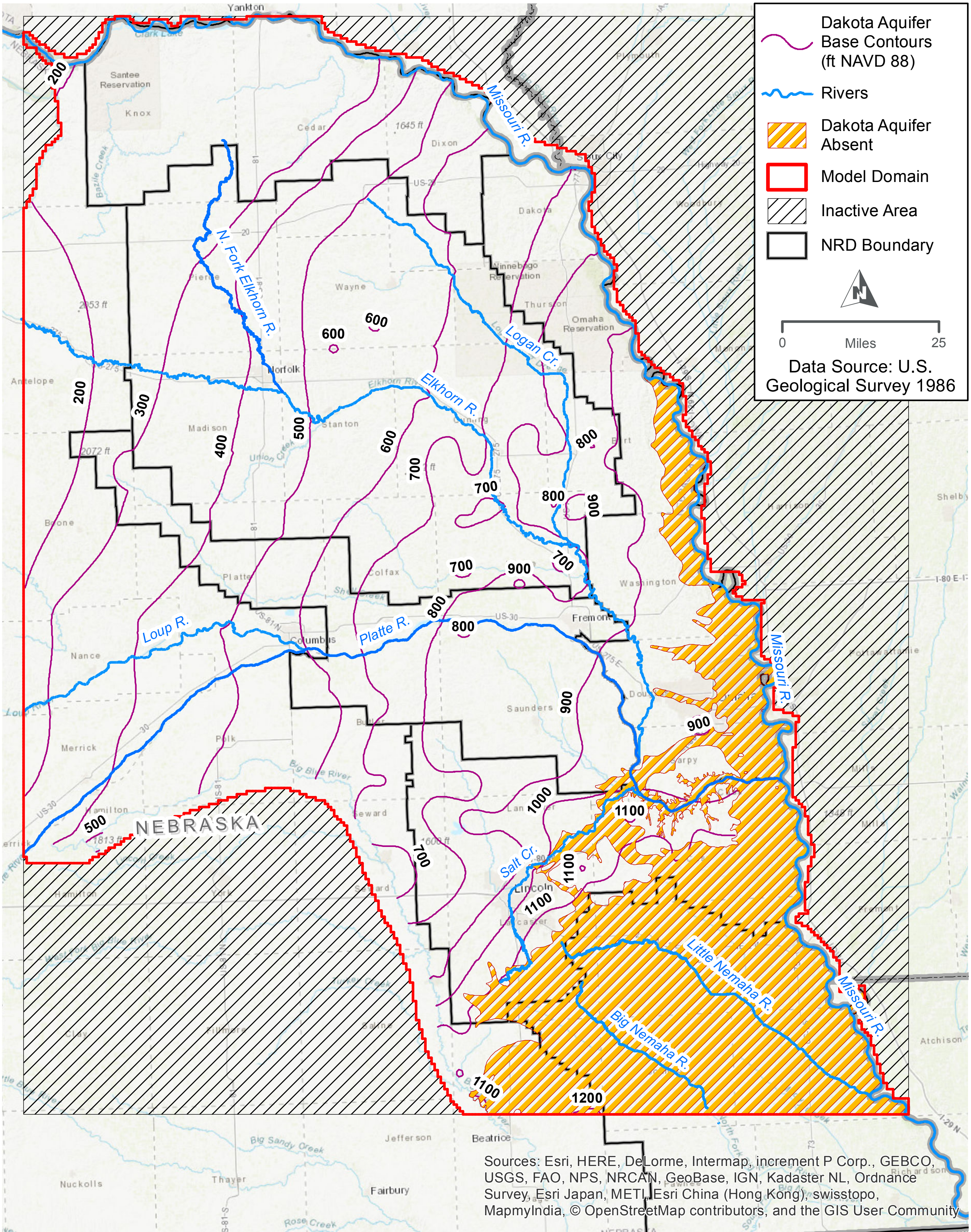
The top of the bedrock aquifer is the base of the overlying principal aquifer, which was shown previously in Figure 3-1. The base of the bedrock aquifer is considered to be the bottom of the Dakota Aquifer, which was interpolated from data presented in the U.S. Geological Survey (USGS) Open-File Report 86-526, *Hydrogeologic Data for The Dakota Aquifer System in Nebraska* (Ellis 1986). The depth to the bottom of the Dakota Aquifer, as presented by Ellis (1986), was used to develop the elevation of the base of the bedrock aquifer map (Figure 3-8). The elevations were determined by taking the depths presented in the document and subtracting that value from the land elevation at the same location.

The elevation contours presented in Figure 3-8 illustrate that the bedrock aquifer is buried deeper in the northern part of the study area, which is consistent with the presence of the Great Plains confining unit in this part of the study area. It also shows that the bedrock aquifer is absent in the southeastern part of the study area.

3.2.2 Potentiometric Surface

The regional potentiometric surface contours of the bedrock aquifer are assumed representative of the Dakota Aquifer, which are illustrated in Figure 3-9. In areas where the Dakota Aquifer occurs as an unconfined aquifer, it is possible that it is in hydraulic connection with streams. This unconfined region generally coincides with the area of the Dakota Aquifer where it is directly overlain by the unconsolidated Quaternary deposits. Where the Dakota Aquifer underlies the Great Plains confining unit, it is unlikely that the Dakota Aquifer is hydraulically connected to streams.

Because of limited data and groundwater use from the bedrock aquifer, groundwater levels are believed to have undergone little change during recent times. This can also deduced from one well in the USGS NWIS water level data base (ID: 41054209609350) that was identified as a Dakota Aquifer monitoring well, as found in the Nebraska Statewide Groundwater Level Program database.



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-8 - BASE OF THE DAKOTA AQUIFER

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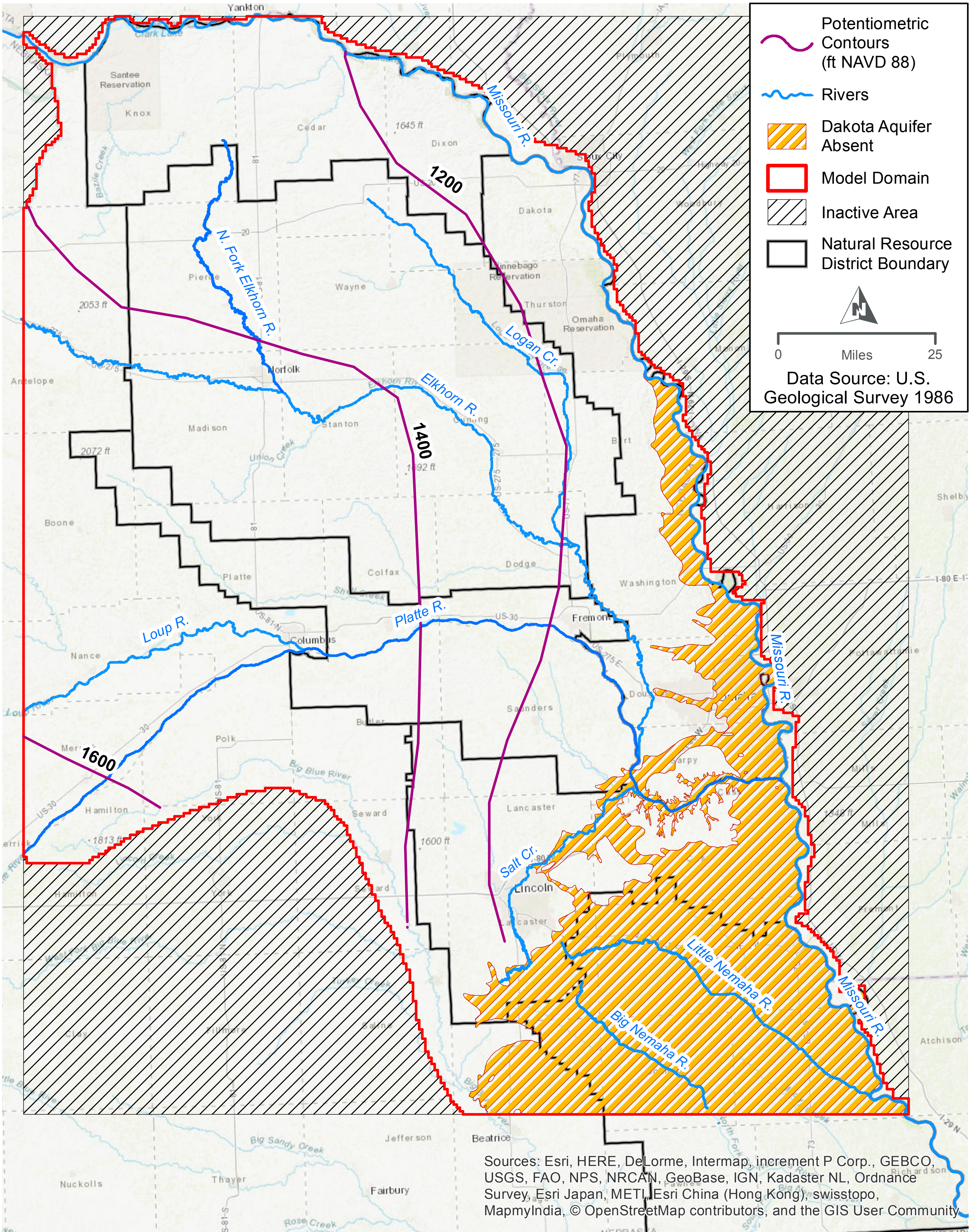

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 3-9 - REGIONAL POTENTIOMETRIC SURFACE OF THE DAKOTA AQUIFER

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3.3 Surface Water Hydrology

By NDNR definition, the Lower Platte River Basin includes all areas that drain into the Lower Platte River, with the exception of the Loup River Basin and the Upper Elkhorn River Basin. Major streams in the Platte River Basin include Shell Creek, Salt Creek, and Wahoo Creek. The Missouri River Tributary basins include the areas of Nebraska that drain into the Missouri River between its confluence with the Niobrara River and its confluence with the Platte River. Major streams in this basin include Bazile, Bow, Aowa, Elk, Omaha, Blackbird, and Papillion Creeks.

The Nemaha River Basin in Nebraska is defined as the areas of Nebraska south of the Platte River Basin that drain directly into the Missouri River and includes the Missouri River below its confluence with the Platte River. Major streams in the Nemaha River Basin include Weeping Water Creek, the Little Nemaha River, and the Big Nemaha River.

USGS maintains several streamflow gages within the study area. The records start and end at various dates, but several of the gages have records during the predevelopment period. In addition to these gages, NDNR maintains stream gages throughout Nebraska. A summary of available streamflow data was provided in the *Analysis of Available Hydrogeologic Data and Conceptual Model of the Hydrogeology within the Lower Platte River and Missouri River Tributary Basins* (HDR 2012). In all, approximately 50 stream gages have suitable records to support model calibration.

Stream baseflow data are used to calibrate a groundwater flow model and to establish observational aquifer water budgets. These values are determined from the streamflow statistics that were developed from gaged stream sites. The study team identified 16 stream gages with continuous periods of record that include a historical record that extends back to 1950, and 40 gages with extensive historical records that are suitable for estimation of baseflow and use as calibration targets (figure shown in Section 6).

The methods used in the analysis to estimate baseflow targets for model calibration are summarized as follows. The approach was to calculate three streamflow statistics, including:

- the baseflow index (BFI), defined as the ratio of mean annual baseflow to mean annual streamflow;
- the 7Q10, defined as the lowest 7-day average flow that occurs (on average) once every 10 years; and
- the 50th percentile exceedance discharge.

These low-flow stream statistics are used to bracket the baseflow calculated by the model while assessing the level of calibration. For model calibration purposes, the range of baseflow calibration targets over time at a gage are considered approximately equal to the baseflow value as developed using the BFI, and no lower than the calculated 7Q10. The 50th percentile exceedance discharge was used to aid in bracketing the estimated baseflow on the high side.

3.4 Water Budget

An overview of the study area volumetric water budget, exclusive of runoff, for steady-state (predevelopment) conditions consists of the following:

- Flows In = Groundwater flows entering the Lower Platte Basin from the western edge of the model plus total net recharge to the aquifers
- Flows Out = Flows exiting the Lower Platte Basin through Platte River baseflow at Louisville plus groundwater flows exiting the Missouri River Tributary Basins through the Missouri River

Estimates of groundwater flow entering and exiting the study area within the principal aquifer were based on two existing datasets. Previous HDR studies of the LPMT basins presented several datasets in the eastern part of the study area. However, the study area for this water budget evaluation is larger than the domain of those HDR studies, extending farther to the west. In the western areas, the evaluation of boundary flows relied on data downloaded from the datasets for the Central Nebraska Groundwater Flow Model (CENEB; Brown and Caldwell 2013).

In general, the approach to calculating an estimate of boundary flows for the principal aquifer was to divide the eastern and western boundaries into subareas. For each subarea, the regional hydraulic gradient was calculated from a 2010 potentiometric surface map, and the regional transmissivity was calculated from representative hydraulic conductivity and saturated thickness values. The study team calculated the widths of flow through the area represented by the subarea boundaries. The product of the transmissivity, hydraulic gradient, and width of flow (length of boundary) is the estimated boundary flow, in units of volume per time. The study team used the same approach to calculate the boundary flows for the bedrock aquifer.

The study team estimated the baseflow of the Platte River at the Louisville streamflow gage (USGS ID: 06805500) through analysis of low flow statistics. The annual baseflow is based on the annual minimum 7-day observed streamflow for the period of record (1954 through 2013). The long-term baseflow is an average of the annual values. The average net groundwater recharge, from 2000 to 2009, has been previously calculated and mapped in *MODIS-Aided Statewide Net Groundwater-Recharge Estimation in Nebraska* (Szilagyi and Jozsa 2013).

Table 3-1 summarizes the conceptual volumetric water budget within the model domain during steady-state, predevelopment conditions. As shown in Table 3-1, when checked against the baseflow of the Platte River at Louisville, the other components of the conceptual model water budget appear to correlate reasonably well. The location of the Louisville gage, at the downstream segment of the Basin, provides an excellent point to perform the check of water budget components.

A detailed description of the conceptual water budget for steady-state (predevelopment) conditions is presented in *Groundwater Model Development Plan for the Lower Platte and Missouri River Tributary Basins* (HDR 2014).

Table 3-1. Summary of Conceptual Predevelopment Water Balance during Steady-State Conditions

Water Budget Components	Flows (Acre-feet per year)
Flows In	
Groundwater Entering the Lower Platte Basin from the Western General Head Boundary	94,059
Total Net Recharge	1,267,623
Total Flows In	1,361,682
Flows Out	
Groundwater Flows Exiting the Missouri River Tributary Basins through the Missouri River	65,581
Baseflow of the Lower Platte Basin at Louisville	1,222,854
Total Flows Out	1,288,435
Balance	
Percent Error	5.4%

Note: Percent error calculated by dividing the difference between the flows in and flows out by the largest flow component.

4.0 Groundwater Pumping and Recharge

This section describes the process of developing pumping and recharge values for application in the groundwater model. A detailed discussion on the development of pumping and recharge for the LPMT Groundwater Model is provided in *Final: The Lower Platte Missouri Tributaries Northern and Central Model: Regionalized Soil Water Balance Model* (The Flatwater Group, Inc. 2018), which is included in this report as Appendix B.

Pumping and recharge in the groundwater model are developed with a watershed model incorporating land use information to estimate agricultural pumping volumes and to place the pumping within model grid cells.[3] The watershed model used a virtual well technique in which pumping was assumed to take place in the model grid cell in which it was applied.[4] The watershed model is discussed in detail in Section 4.2.

[3] Model grid cell is defined herein as the intersection of a model row and column, and a model cell is the intersection of a model row, column, and layer.

[4] The virtual well technique overcomes the lack of defined relationship between the well that pumps the irrigation water and the field where the water is applied.

Pumping for the groundwater model was developed in three steps. The first step was to categorize the pumping distribution from either the principal or bedrock aquifers (model layers 1 and 2). The second step involved defining the geographic extent where pumping from each layer can occur and specifying how any pumped volume was to be proportioned between the two aquifer layers. The third step was to quantify the volume of agricultural pumping in each model grid cell for each stress period and to assign the pumping volumes from step two to the appropriate aquifer (principal or bedrock) using the distribution defined in step one. Unlike the virtual well approach used in the watershed model, municipal and industrial pumping estimates were assigned to model grid cells containing the location of the specific wells and originate from the NDNR well registration data.

Recharge was developed within the watershed model. The watershed model incorporated land use information, precipitation, and applied irrigation to estimate recharge in each model grid cell for each stress period.

4.1 Development of the Pumping Distribution between Model Layers

This section summarizes groundwater development in the study area, delineating areas where well pumping occurs, and assigns pumping to either the principal or bedrock aquifers. For this study, wells are divided into three categories: high capacity, low capacity, and expected wells. Registered wells are assigned to either the principal or the bedrock aquifer. Categorizing wells into high and low capacities is determined from NDNR well registration data; a high capacity well is considered one with a reported yield of 50 gallons per minute (gpm) or more at the time of construction. Otherwise, the well is considered a low capacity well. The term “expected well” is used where land use data suggests that groundwater pumping occurs but there are no registered wells within the model grid cell. High capacity wells are typically used for irrigation, industrial, and municipal purposes. Low capacity wells are typically shallow wells and used for domestic and livestock purposes. The designation of an aquifer associated with a given registered well is based on the location of the pumping elevation reported in the well registration. If the pumping elevation is below the top of the bedrock aquifer, the well is assigned to the bedrock aquifer. All other wells are assigned to the overlying principal aquifer.

Figure 4-1 illustrates a timeline for the cumulative development of high capacity wells in the principal and bedrock aquifers. Figure 4-2 depicts a histogram of new wells constructed by decade. As illustrated, the drilling of high capacity wells was greatest during the 1970s and 2000s. By 2012, approximately 77 percent of the high capacity wells were in the principal aquifer, and the remaining wells were in the bedrock aquifer. Figure 4-3 shows the locations of principal aquifer high capacity wells as of September 2012. A band of relatively high-density high capacity wells is an indication of the presence of paleovalley aquifers surrounded by regions of lower permeability materials, such as glacial till or poorly producing Dakota Group. Figure 4-4 shows the locations of bedrock aquifer high capacity wells as of September 2012. As shown on this map, wells in the northwest part of the study area pump water from the Ogallala Group, which has been defined in this study to be a bedrock aquifer unit. The other bedrock wells pump from the Dakota Group and are more common where this aquifer is not deeply buried.

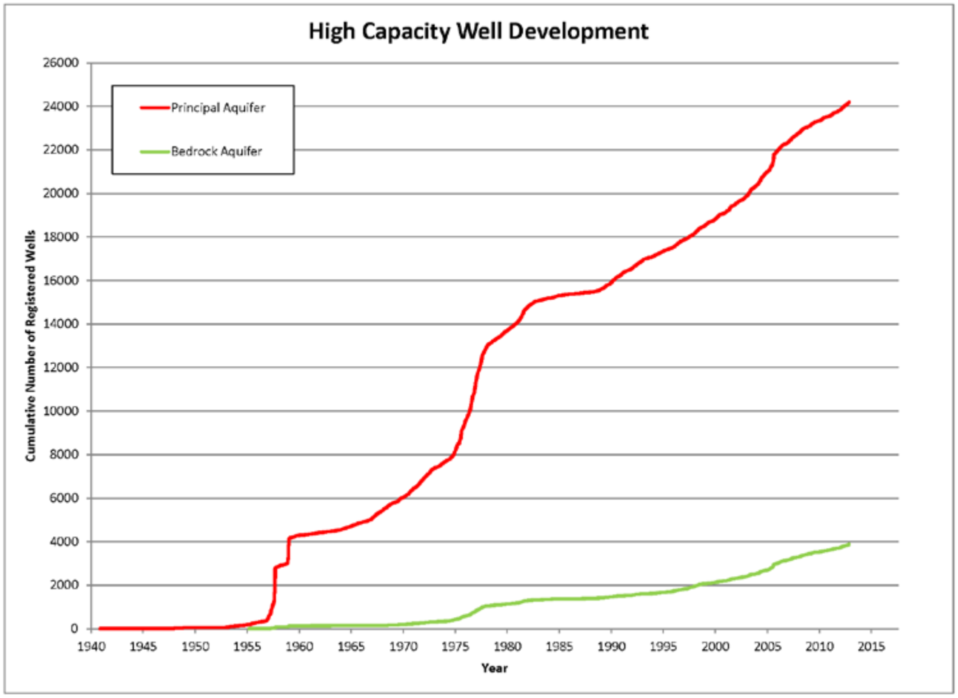

Figure 4-1. Cumulative Registration of High Capacity Wells in Principal and Bedrock Aquifers

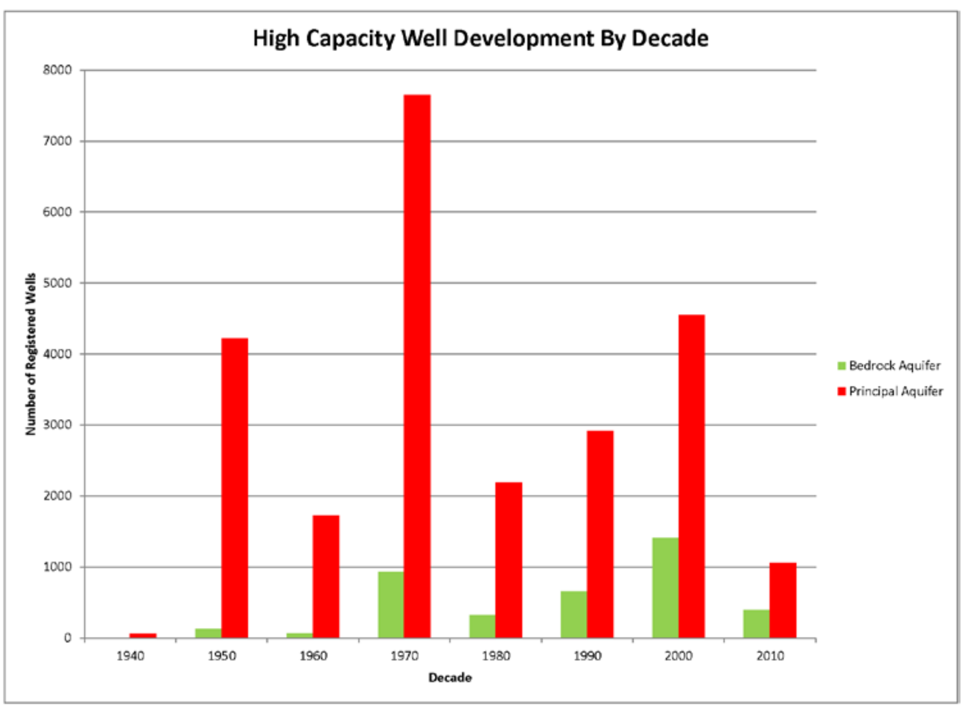

Figure 4-2. Development of High Capacity Wells in Principal and Bedrock Aquifers

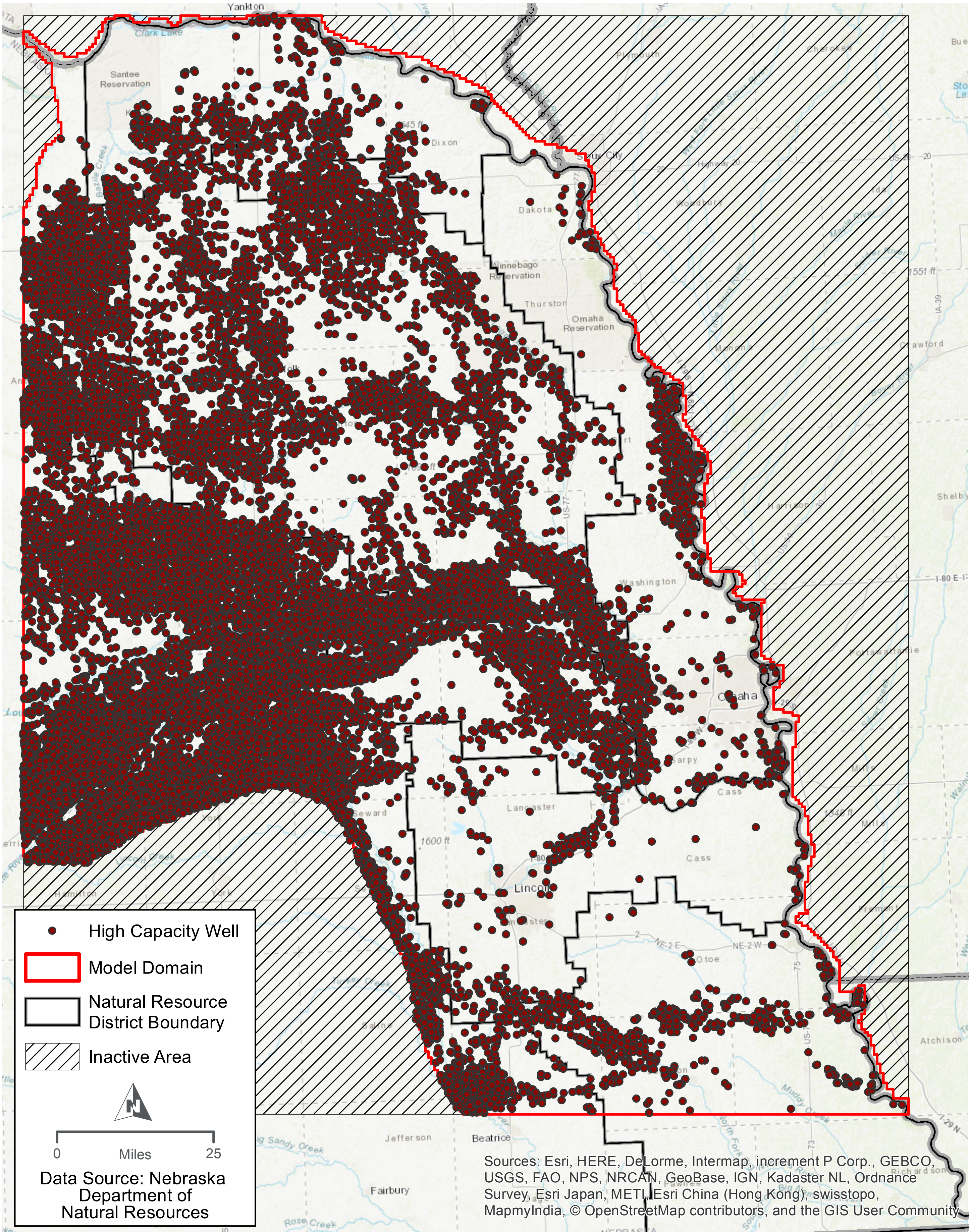

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FIGURE 4-3 - HIGH CAPACITY WELLS IN THE PRINCIPAL AQUIFER, 2012

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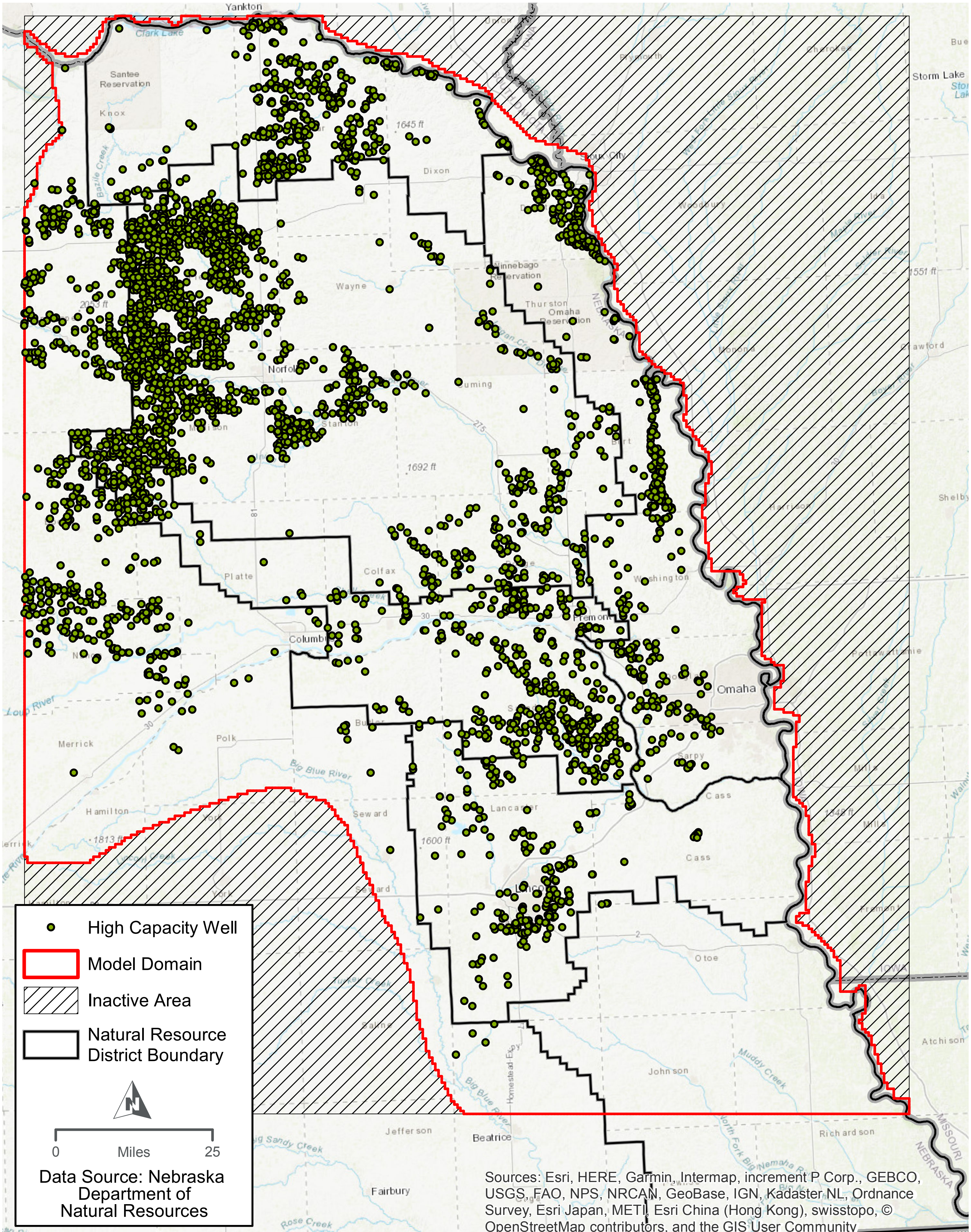

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FIGURE 4-4 - HIGH CAPACITY WELLS IN THE BEDROCK AQUIFER, 2012

The assignment of high capacity wells to the principal or bedrock aquifer is based on the location of the pumping elevation that is provided on the well registration form. This assignment was performed with geographic information systems (GIS) procedures for the entire model domain. To assist in the assignment of low capacity and expected wells to an aquifer, the study area is divided into two groundwater zones (Figure 4-5). Zone 1A delineates areas where the principal aquifer overlies a relatively deep bedrock aquifer (deep in comparison to the Ogallala bedrock aquifer—represented as Zone 1B). In Zone 1B, all of the low capacity and expected wells are assumed to be screened in the principal aquifer. Although the Ogallala Aquifer is a significant water source, model cells with low capacity wells or expected wells had the pumping assigned to the overlying principal aquifer. As shown in Figure 4-5, Zones 1A and 1B are in the northwest and southeast parts of the study area. Zone 2 delineates an area where the Dakota Aquifer is the bedrock unit. In this zone, sediments overlying the Dakota Group bedrock unit provide an opportunity in some areas for high and low capacity wells to be constructed in either the principal or the bedrock aquifers. In this zone, the assignment of registered low capacity wells to the principal or bedrock aquifer is based on the elevation of the well pump. For wells without data on the pump elevation, and where there are no registered wells, 75 percent of the estimated pumping is assumed to be from the principal aquifer and 25 percent from the bedrock aquifer.

A flowchart that illustrates the process for assigning pumping distribution to model layers within model grid cells is presented in Figure 4-6. The flowchart is applied for each model grid cell, thus, completing the pumping assignment for the entire model. If a model grid cell contains more than one registered well, part of the process is repeated for each well. In these cases, the assigned pumping to the model cell is based on the percentage of the well capacities on the well registration forms. The model grid cell pumping distribution was provided to, and implemented in, the watershed model to spilt pumping volumes between the aquifer layers.

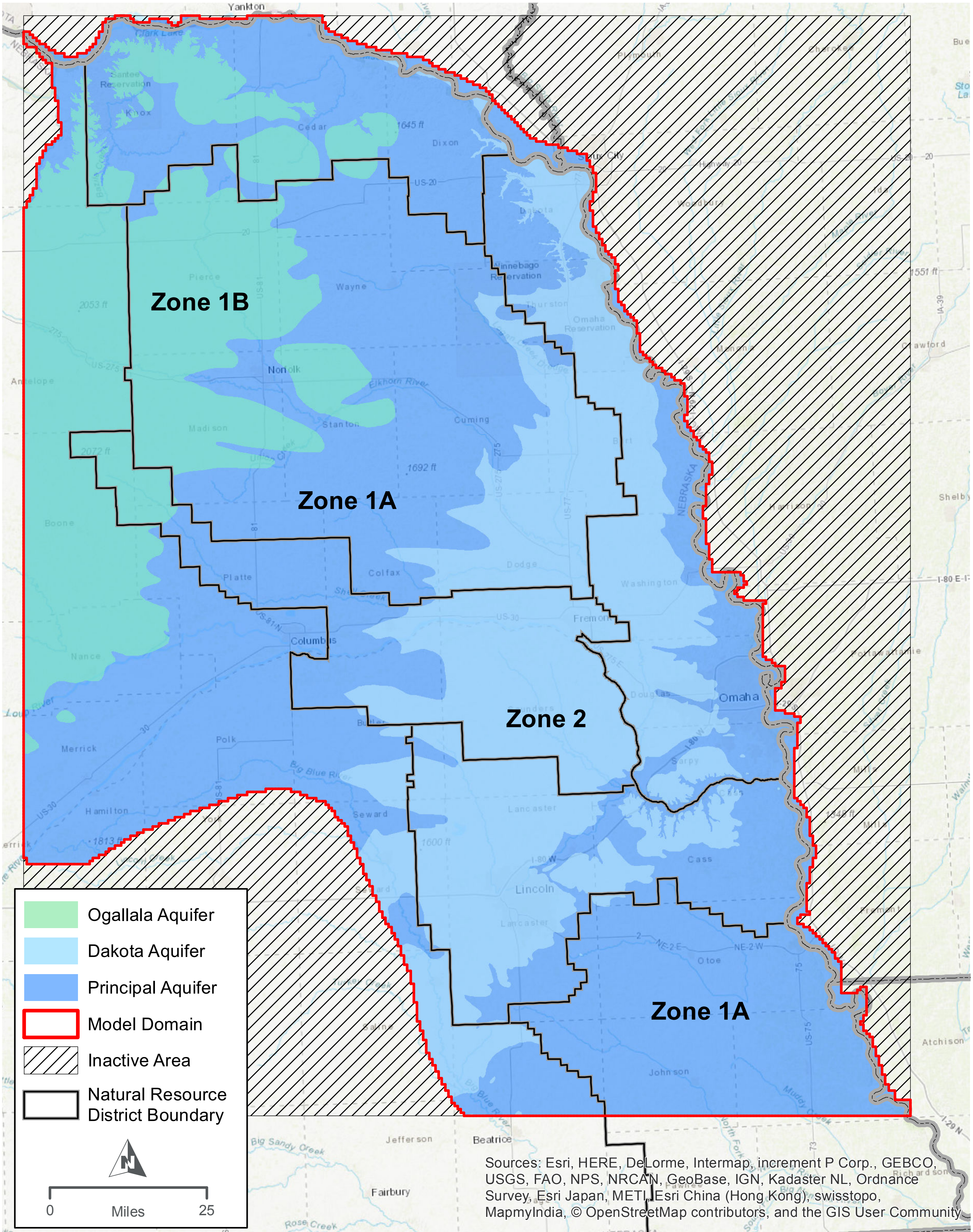

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FIGURE 4-5 - GROUNDWATER ZONES FOR PUMPING WELL ASSIGNMENT

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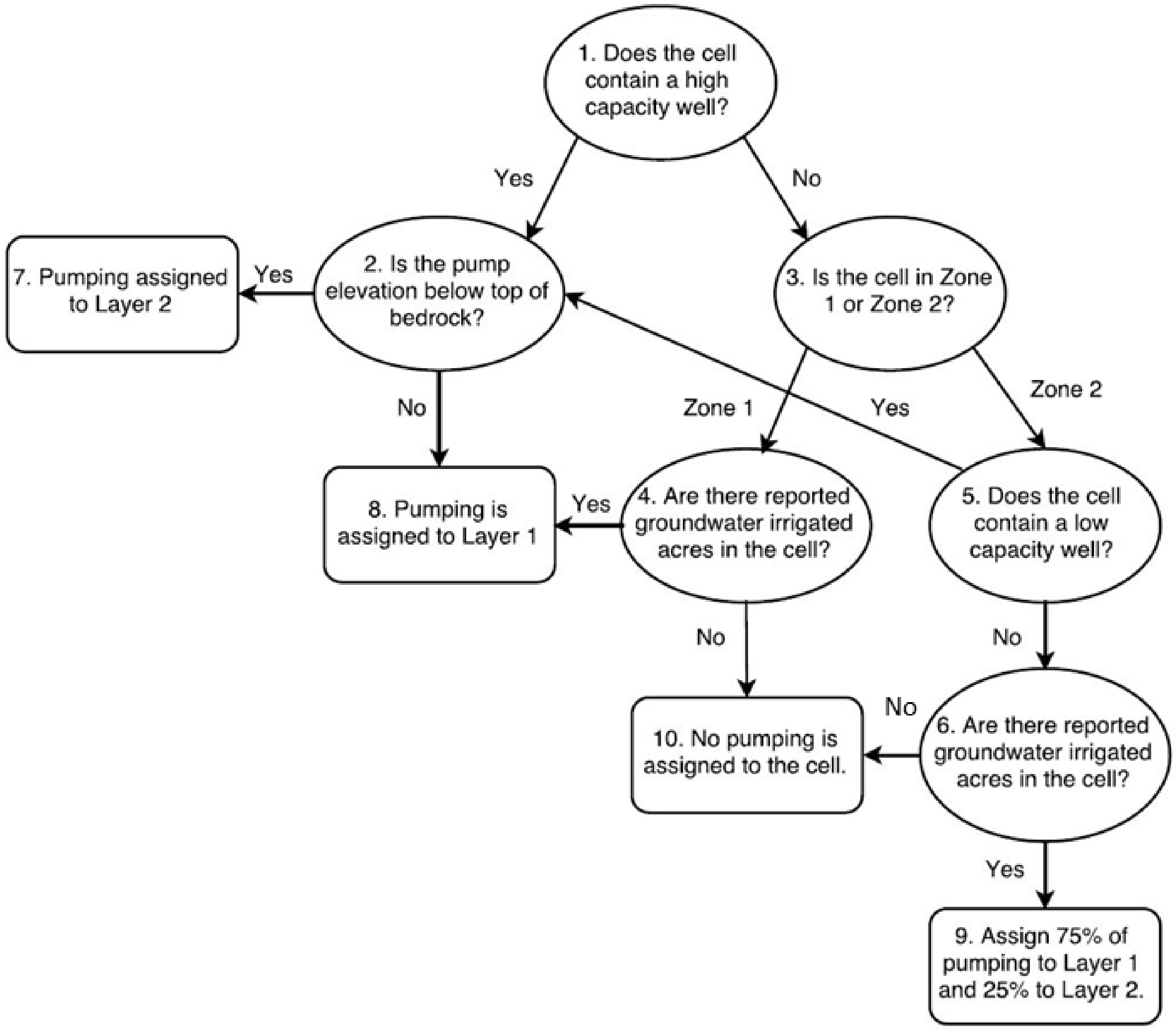

Figure 4-6. Flowchart Illustrating Process for Assignment of Pumping to Model Cells

4.2 Watershed Model

Agricultural pumping and recharge estimates were developed using the LPMT watershed model. The watershed model was designed to ensure that supplies and uses of water are accurately accounted for within a balanced water budget. The watershed model consists of four traditional components, which estimate the weather conditions, develop field-level estimates of the soil water balance, and scale these estimates regionally to develop recharge and pumping input files for the groundwater model. These four components include:

1. Climate model
2. Soil water balance model – CROPSIM
3. Spatial and temporal distribution model of the CROPSIM results
4. Regionalized soil water balance (RSWB) model

4.2.1 Climate Model

Weather represents the primary input into the watershed model, while the remaining parts of the model define the system and reflect how it reacts to the weather conditions. Precipitation, temperature, and reference evapotranspiration (ET) are the necessary climate inputs for the RSWB model. Precipitation and temperature are readily available from a system of weather stations located throughout the model domain. Reference ET is a calculated product of other available weather data. Limited by the breadth of historically available weather variables, the climate model employs a modified Hargreaves-Samani approach calibrated to the ASCE Standardized Penman-Montieth reference ET. Weather data were collected from 50 weather stations (Figure 4-7) in and around the LPMT model domain. Further information on the climate model can be found in *CROPSIM Net Irrigation Requirement* (The Flatwater Group, Inc. 2014).

4.2.2 Soil Water Balance Model – CROPSIM

Soil characteristics influence how crops respond to climate and management conditions. Soils can be thought of as acting like miniature reservoirs that store and release water for vegetative growth (ET), allow the water to drain as recharge, or restrict infiltration, which results in overland flow, generating surface runoff. Each model grid cell was assigned a soil class based on the predominant CROPSIM soil class. Starting with the STATSGO2 soils database (U.S. Department of Agriculture, Natural Resources Conservation Service, Web Soil Survey[5]) each soil association unit was assigned a CROPSIM soil class based on three soil properties: water-holding capacity, hydrologic soil group, and distance to groundwater. The soil class covering the largest area of each model grid cell was assigned to the cell. This process reduced the number of soils in the model to 22 soil classes. Figure 4-8 shows the assignment of the CROPSIM soil class to each model grid cell.

[5] http://websoilsurvey.nrcs.usda.gov/

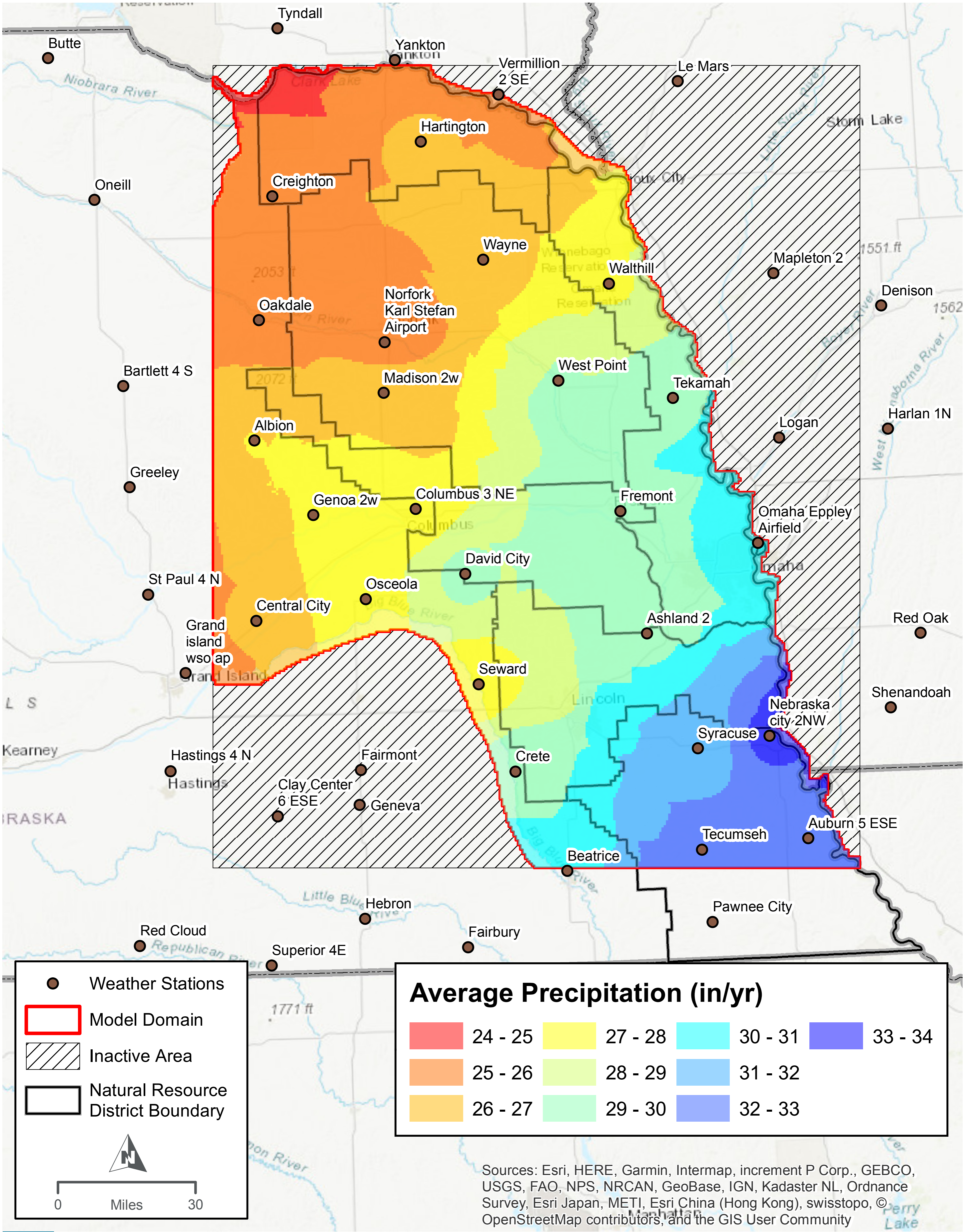

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FIGURE 4-7 - WEATHER STATIONS AND AVERAGE PRECIPITATION

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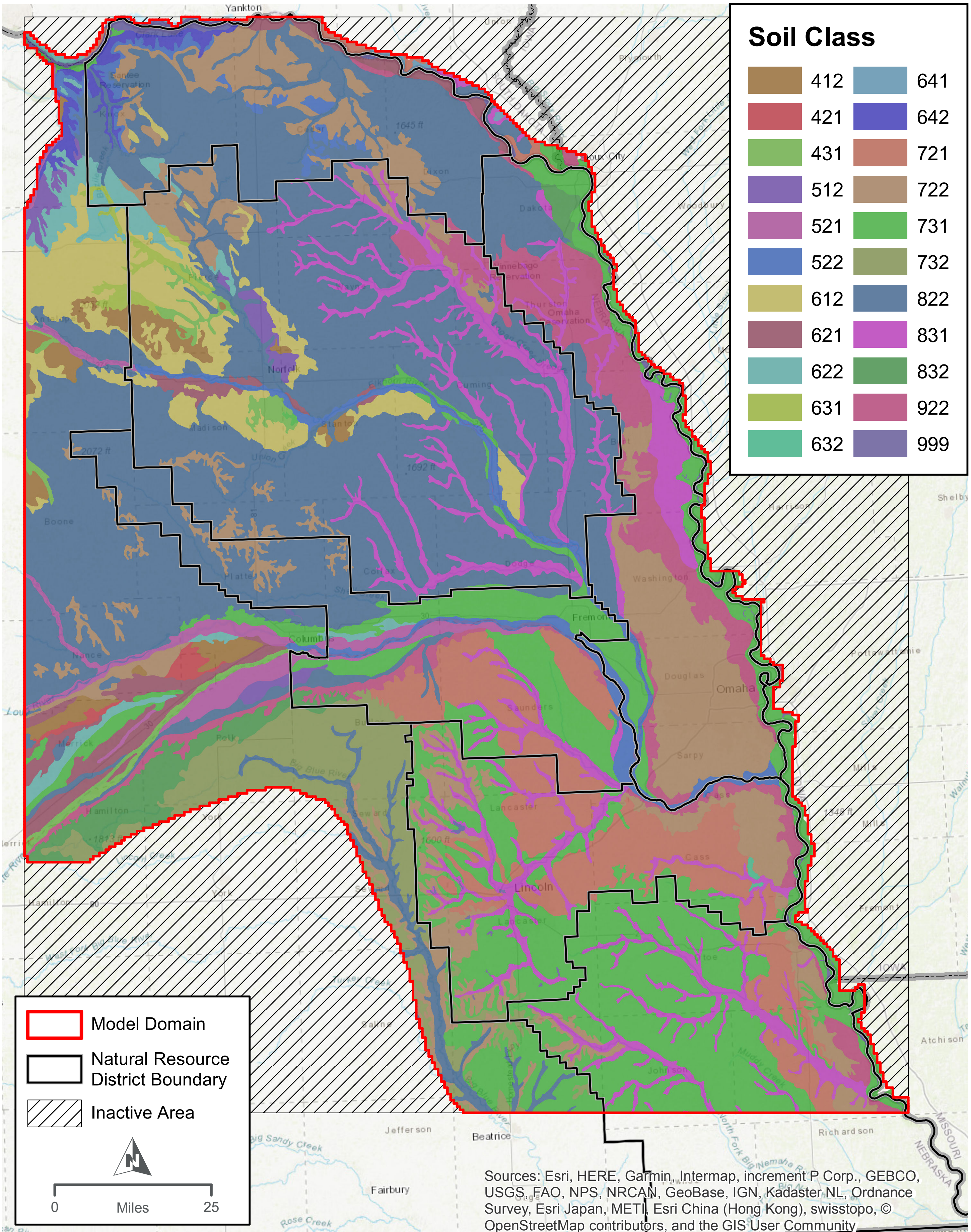

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FIGURE 4-8 - ASSIGNMENT OF THE CROPSIM SOIL CLASSES

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The weather data from the climate model is entered into the soil water balance model, CROPSIM, developed by Dr. Derrel Martin at the University of Nebraska–Lincoln (UNL) and described in more detail by Martin et al. (1984). CROPSIM is a water-driven point source model that combines the weather data with representative system characteristics (crop phenology, soils, management, and irrigation) to estimate the inflows and outflows of the daily soil water balance (Equation 1).

Equation 1

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

where:

SWC_i = Soil water content at time step i
P = Precipitation
I_{net} = Net irrigation
RO = Runoff
ET = Evapotranspiration
DP = Deep percolation

The daily calculations are compiled and written to monthly summaries.

Starting with a known volume of water in the soil profile, precipitation is applied. Precipitation is split between the water that infiltrates into the soil profile and overland flow (runoff) leaving the edge of the field. The infiltration fills the soil profile from the top downward. ET removes water from the root zone with CROPSIM. In the event that the amount of water in the soil profile exceeds the water-holding capacity of the soil, the excess water drains into the subsurface below as deep percolation. The remaining volume equates to the ending moisture content in the soil profile.

Vegetative growth is simulated from a specified planting date, progressing through its phenological development tracked by growing degree days. The development of the plant extends the root system deeper into the soils, 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. The next step is to determine if there is sufficient water in the root zone. If adequate water exists, it is transpired; otherwise, the crop is stressed and a reduced rate of transpiration is determined. ET is the combination of this transpiration and evaporation from the soil surface.

For irrigated simulations, the watershed model employs a management-allowed depletions technique for irrigation scheduling. If the soil moisture content drops below a management-specified level of depletion, an irrigation event is triggered. A net irrigation volume is added to the soil profile. Net irrigation represents the portion of the applied gross or total irrigation that infiltrates into the soil profile. This technique ensures that a sufficient amount of water is available to the crop to meet its full transpiration demand; that is, the net irrigation requirement (NIR). A series of long-term simulations was made, subjecting a variety of vegetation types to the climatic conditions measured at the weather station. This process was repeated for a selection of crops (5), soil (22), and irrigation methods (irrigated and non-irrigated) at each weather station. Furthermore, to capture the effect of improving technology and farming practices, three sets of simulations were created to represent the tillage practices common for periods beginning in 1949, 1973, and 1998.

4.2.3 Spatial and Temporal Distribution Model of the CROPSIM Results

The next part of the watershed model interpolates between the points where CROPSIM was modeled, both temporally and spatially. First, the CROPSIM results were time trended between each of the three tillage practice periods. Next, these results were interpolated spatially using an inverse weighted distance technique, dominant soil class, and the three nearest weather stations. The results are sets of water balance parameters (P, NIR, DP, RO, and ET) covering the LPMT model domain for each crop under irrigated and non-irrigated conditions. An example of average annual corn NIR is shown in Figure 4-9.

4.2.4 Regional Soil Water Balance (RSWB) Model

The final component of the watershed model is the RSWB model. Its primary purpose is to develop estimates of pumping and recharge, and to create the appropriate MODFLOW WEL and RCH files (well and recharge files, respectively) for importing into the groundwater model. To accomplish this, the RSWB model incorporates the watershed characteristics and the soil and climate water balance parameter datasets to determine precipitation, estimate irrigation demand, apply irrigation, and partition the applied water sources to recharge, runoff, and ET while accounting for non-idealized conditions.[5] Additionally, the RSWB model is used to further partition the direct field runoff between streamflow contribution and transmission losses to recharge and ET. Finally, the RSWB model is capable of incorporating miscellaneous sources of recharge and pumping into the WEL and RCH files deemed significant but not readily determined within the constructs of the RSWB model.

4.2.4.1 Land Use

Land use is used to define the types of vegetation being grown in each model grid cell, as well as if the crops are being irrigated and from which source (precipitation only [dryland], groundwater only, surface water only, or groundwater and surface water [comingled]). The land use coverage was developed by NDNR. The land use in the model domain has seen an expansion of groundwater irrigated lands over the simulation period from approximately 250,000 acres to roughly 2.1 million acres (Figure 4-10).

[5] Idealized conditions refer to an environment in which water is the only limiting factor. In reality, there are a number of potential variables that influence crop water consumption that are not necessarily reflected in the soil water balance developed in the regional soil water balance (RSWB) model.

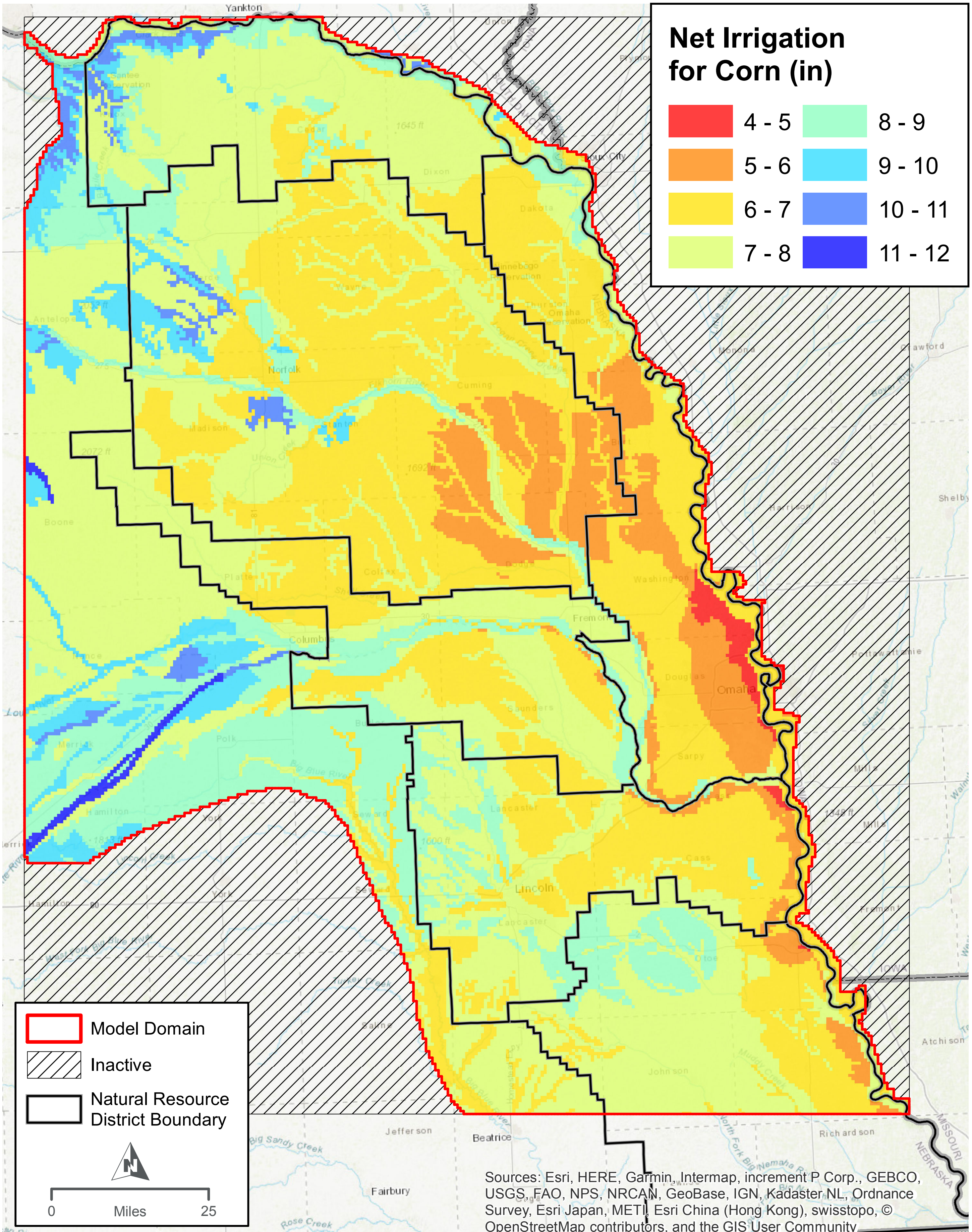

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FIGURE 4-9 - AVERAGE ANNUAL NET IRRIGATION REQUIREMENT FOR CORN

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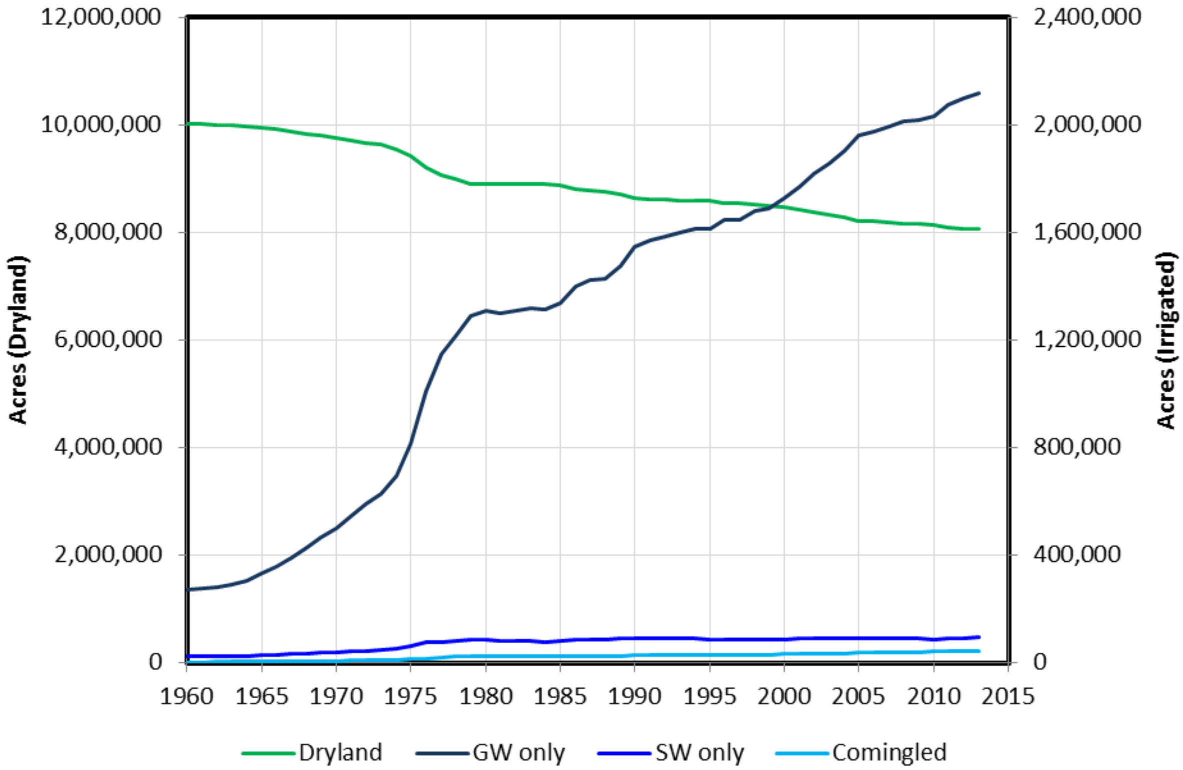

Figure 4-10. Development of Irrigated Acres in the LPMT Model Domain

4.2.4.2 RSWB Model Regions

The RSWB model employs two types of input regions to aid in spatial calibration of recharge: runoff zones and coefficient zones. The runoff zones (Figure 4-11) represent delineation of the model domain following select watershed boundaries, usually designated by a stream gage collection point, and are used to assist in calibrating the watershed model to the overland runoff component of the gaged streamflow. The design consists of 74 runoff zones, with zones 1 through 62 representing drainage areas terminating at a point along a stream, and zones 63 through 74 consisting of the boundary area along the model perimeter. Coefficient zones represent geographical groups, which exhibit similar water budget responses. Each zone and soil combination controls a set of the RSWB model coefficients, which act as adjustment factors that are used to calibrate the RSWB model. The design includes 14 coefficient zones (Figure 4-12), with each zone subdivided by CROPSIM soil class.

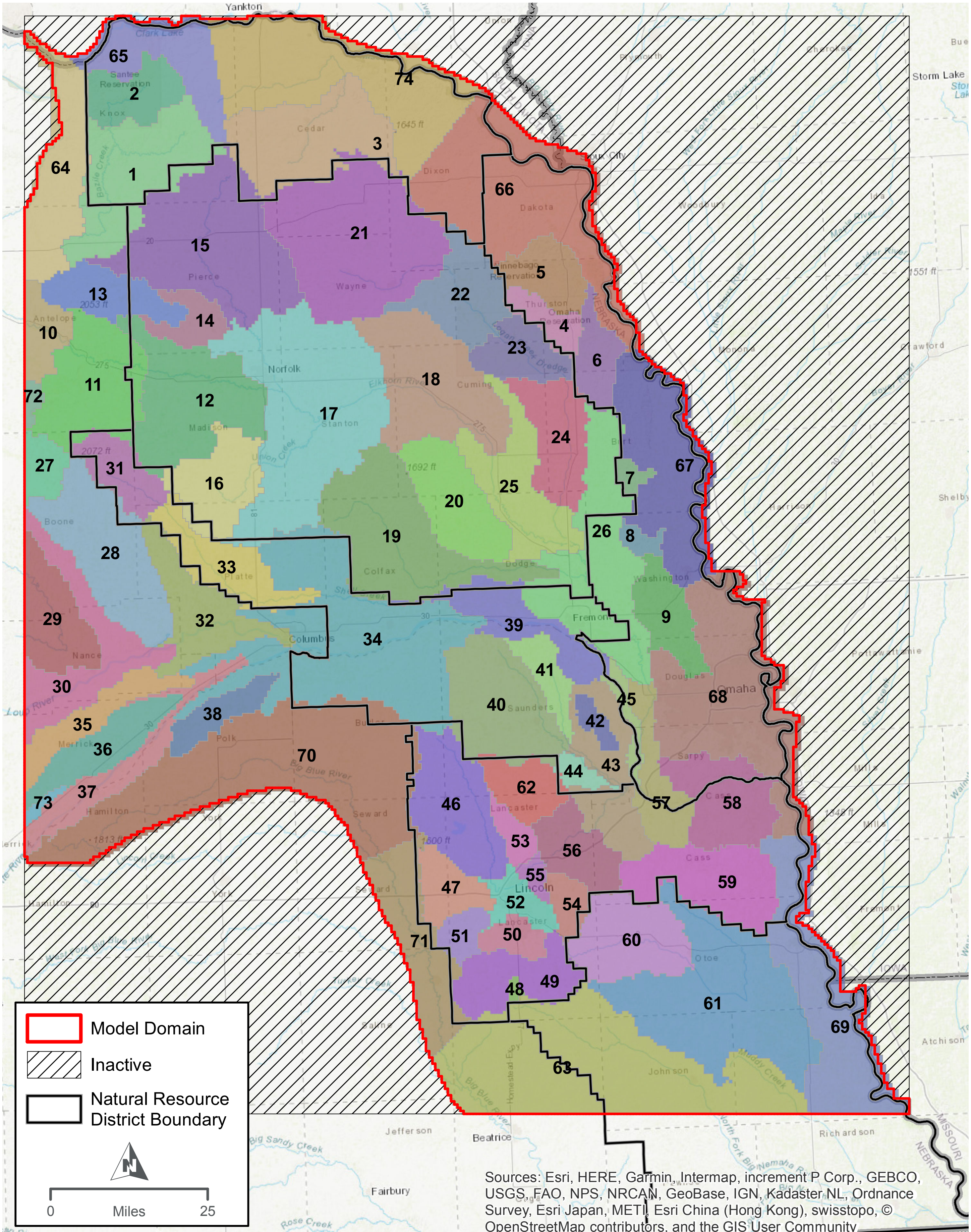

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FIGURE 4-11 - WATERSHED MODEL RUNOFF ZONES

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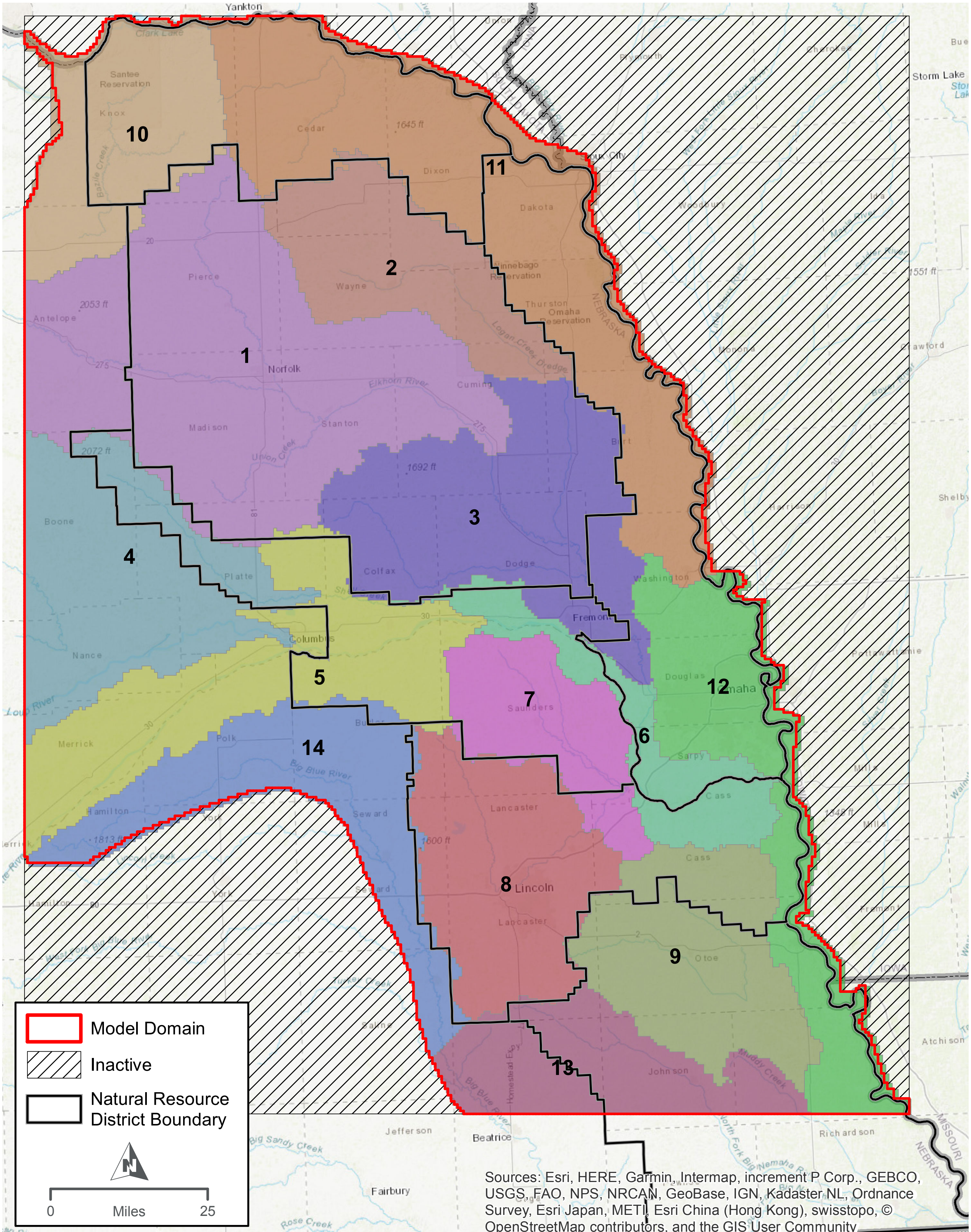

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FIGURE 4-12 - WATERSHED MODEL COEFFICIENT ZONES

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4.2.4.3 Groundwater Model Pumping (WEL File)

The WEL file is a formatted input file for the groundwater model. The file includes the aquifer layer the pumping is extracted from, the row and column index of the cell the pumping occurs within, and the rate at which the pumping is extracted for each stress period. The WEL file was built using the stress periods defined for the LPMT groundwater model, with annual stress periods from 1960 through 1985 and monthly stress periods from 1986 through 2013, including one stress period at the beginning representing steady-state predevelopment conditions (Table 4-1). Pumping values in the WEL file are the sum of agricultural, municipal, and industrial pumping.

Table 4-1. Model Stress Periods

Simulation Period	Number of Stress Periods	Length of Stress Period (days)	Times Steps Per Stress Period
Average predevelopment	1	n/a	1
1960 – 1985 (annual)	26	365.25	1
1986 – 2013 (monthly)	336	30.43	1

4.2.4.3.1 Agricultural Pumping

Due to limited information relating wells to fields, the RSWB model incorporates a virtual pumping technique for agricultural pumping. The pumped water is assigned to the cell in which it is applied as opposed to the cell that contains the well. The pumping is assigned to a layer designation based on the characterization defined in Section 4.1. The final step before populating the WEL file with the pumping values was to remove pumping from the river cells. Restrictions within the groundwater model limit the number of inputs a cell can manage. Therefore, any pumping located in a designated river cell was moved to an adjacent non-river cell.

Agricultural pumping represents the volume of irrigation water applied to lands receiving groundwater irrigation. Using the land use dataset, the NIR datasets, the irrigation system information, and assumptions about irrigation management, an estimate of pumping can be established (Equation 2). Within the land use dataset, the number of groundwater irrigated acres of each crop is defined for each active cell. These acres are further subdivided by crop type. The NIR is available from the NIR datasets for each crop simulated. The NIR is converted to gross pumping by applying an application efficiency. Finally, irrigators are assumed to be rational, applying only the volume of irrigation that is needed to meet the irrigation demand of their crops.

Equation 2

$$Pumping_{cell} = \sum \left(NIR_{crop} * \frac{Target_{NIR}}{AE_{GW}} * Ac_{crop} \right)$$

where:

$Pumping_{cell}$ = Total volume of agricultural pumping within the cell
NIR_{crop} = Net irrigation requirement of the crop
$Target_{NIR}$ = Target indicating the portion of the full demand needed to meet crop demand
AE_{GW}= Application efficiency for groundwater irrigated crops
Ac_{crop}= Area of the groundwater irrigated crop within the cell

During the period from 1960 through 2013, the average precipitation on groundwater irrigated acres was approximately 27.5 inches (in) and ranged from 16.5 in to 38 in, while the average pumping was roughly 8.25 in and ranged from 1 in to 15 in (Figure 4-13). The resultant volume of water pumped is shown in Figure 4-14.

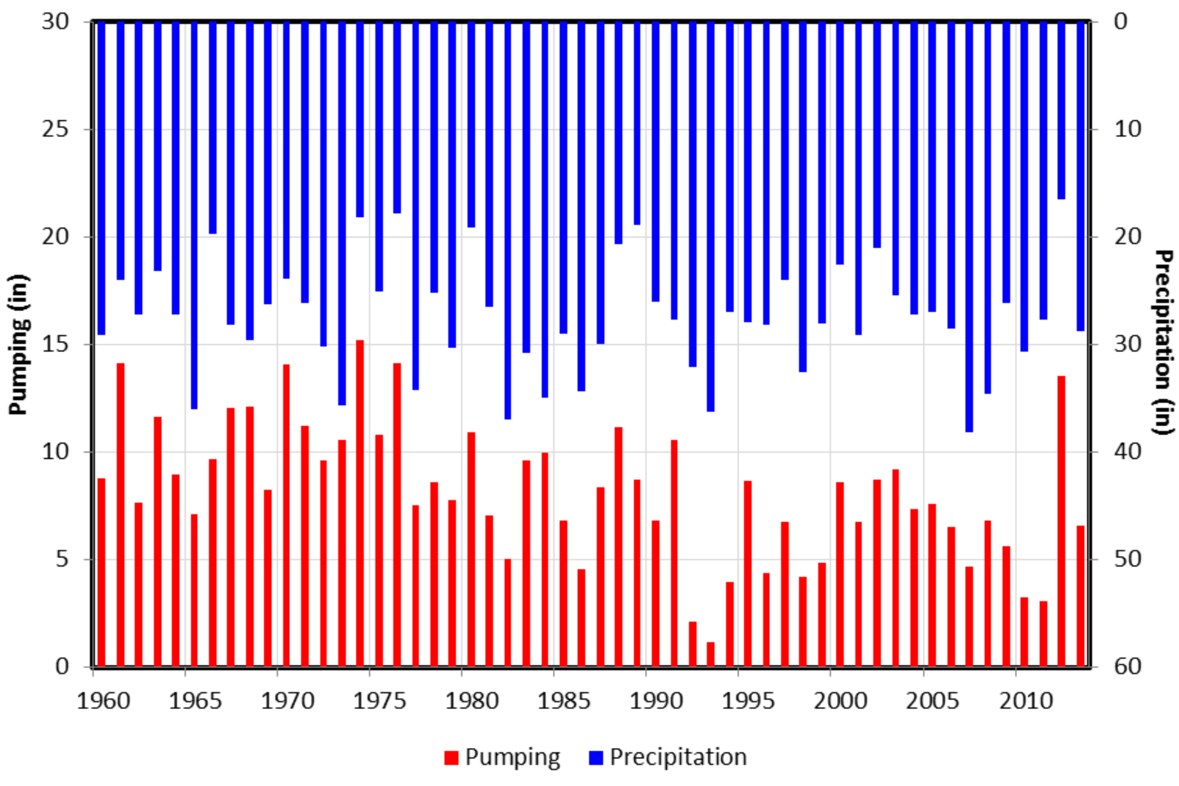


Figure 4-13. Annual Depth of Pumping in Agriculture Areas and Precipitation

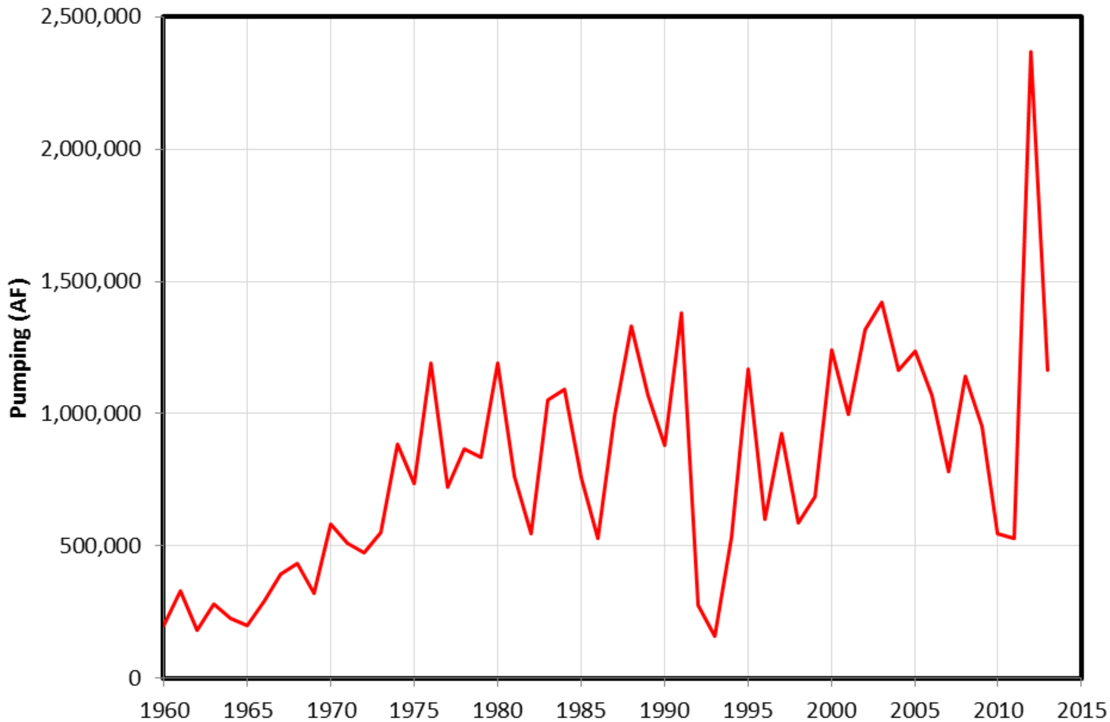


Figure 4-14. Annual Agriculture Pumping

4.2.4.3.2 Municipal and Industrial Pumping

The LPMT model includes the municipal and industrial (M&I) pumping within the WEL file. M&I pumping estimates were developed across Nebraska as part of the statewide M&I project. The LPMT incorporates the estimates that fall within the model domain.

Furthermore, the LPMT model expanded on the M&I database to include estimates of municipal pumping for the cities of Lincoln and Omaha, Nebraska. Municipal pumping estimates were a function of population and the per capita pumping estimates developed for the statewide M&I project, while being limited in total volume by the capacity of the developed municipal wells. The total pumping was then divided among the active registered wells weighted by the well capacity. The amount of annual municipal and industrial pumping is illustrated in Figure 4-15.

4.2.4.3.3 Pumping By Model Layer

The division of the pumping by layer was discussed earlier in Section 4.1. The agricultural, municipal, and industrial pumping is combined by layer for each stress period. Figure 4-16 illustrates the annual average total pumping for each layer. These pumping rates are consistent with the cumulative registration of high capacity irrigation wells, as shown in Figure 4-1. The spatial distribution of groundwater pumping is shown in Figure 4-17 for 1960, and in Figure 4-18 for 2013.

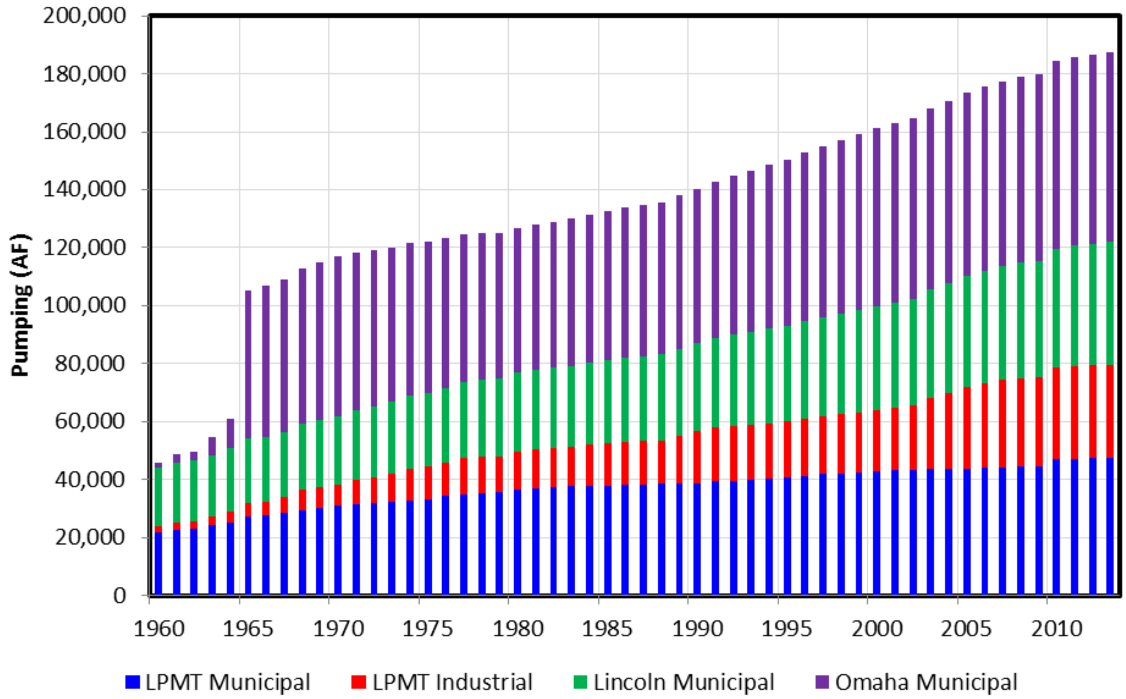


Figure 4-15. Annual Municipal and Industrial Pumping

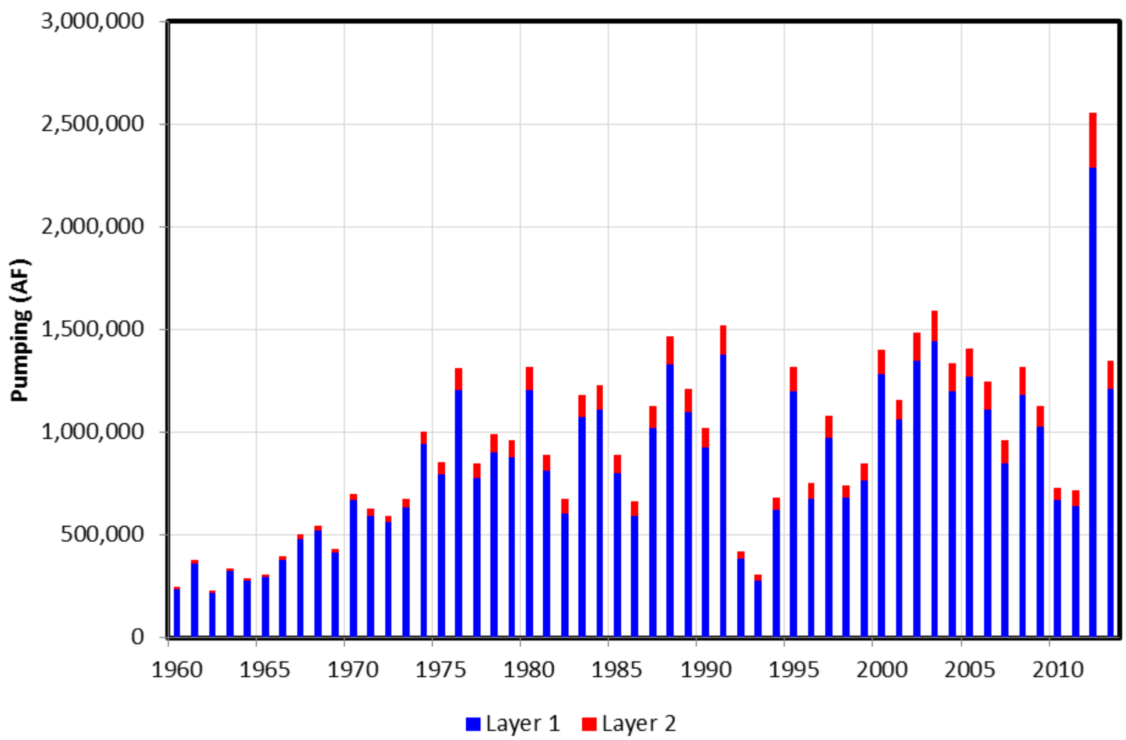
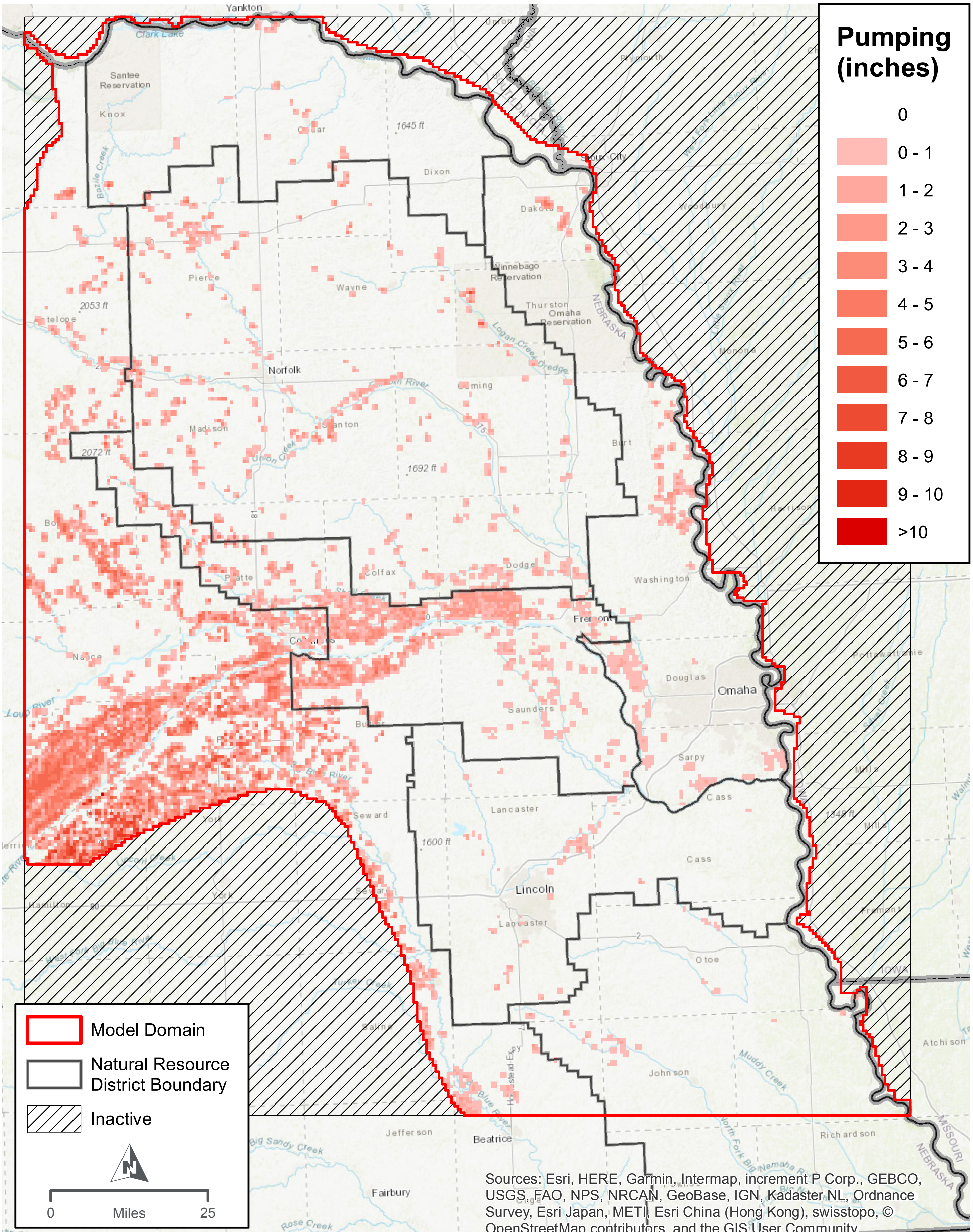


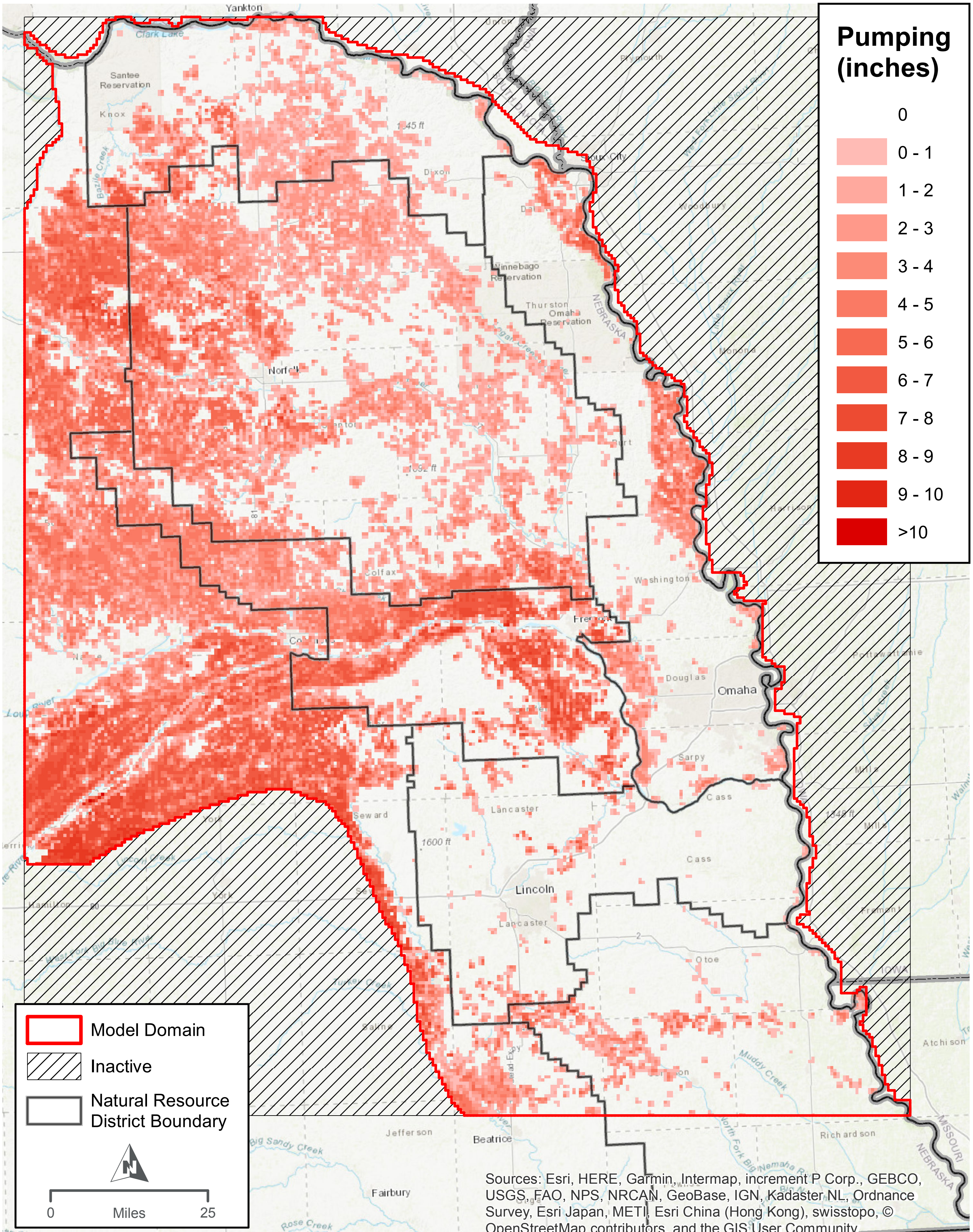
Figure 4-16. Average Annual Pumping Rates by Layer



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 4-17 - GROUNDWATER PUMPING IN 1960

PATH: Z:\PROJECTS\NDNR\236592_LWRPLATTERVRTRIBBASINWTR\MAP_DOCS\FINAL\2018_LPMT_REPORT_FIGURES\LPMT_FIG4_17_EXTENTGWPUMPING1960.MXD - USER: NROSSMAN - DATE: 11/9/2018



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 4-18 - GROUNDWATER PUMPING IN 2013

PATH: Z:\PROJECTS\NDNR\236592_LWRPLATTERVRTRIBBASINWTR\MAP_DOCS\FINAL\2018_LPMT_REPORT_FIGURES\LPMT_FIG4_18_EXTENTGWPUMPING2013.MXD - USER: NROSSMAN - DATE: 11/9/2018

4.2.4.4 Groundwater Model Recharge (RCH File)

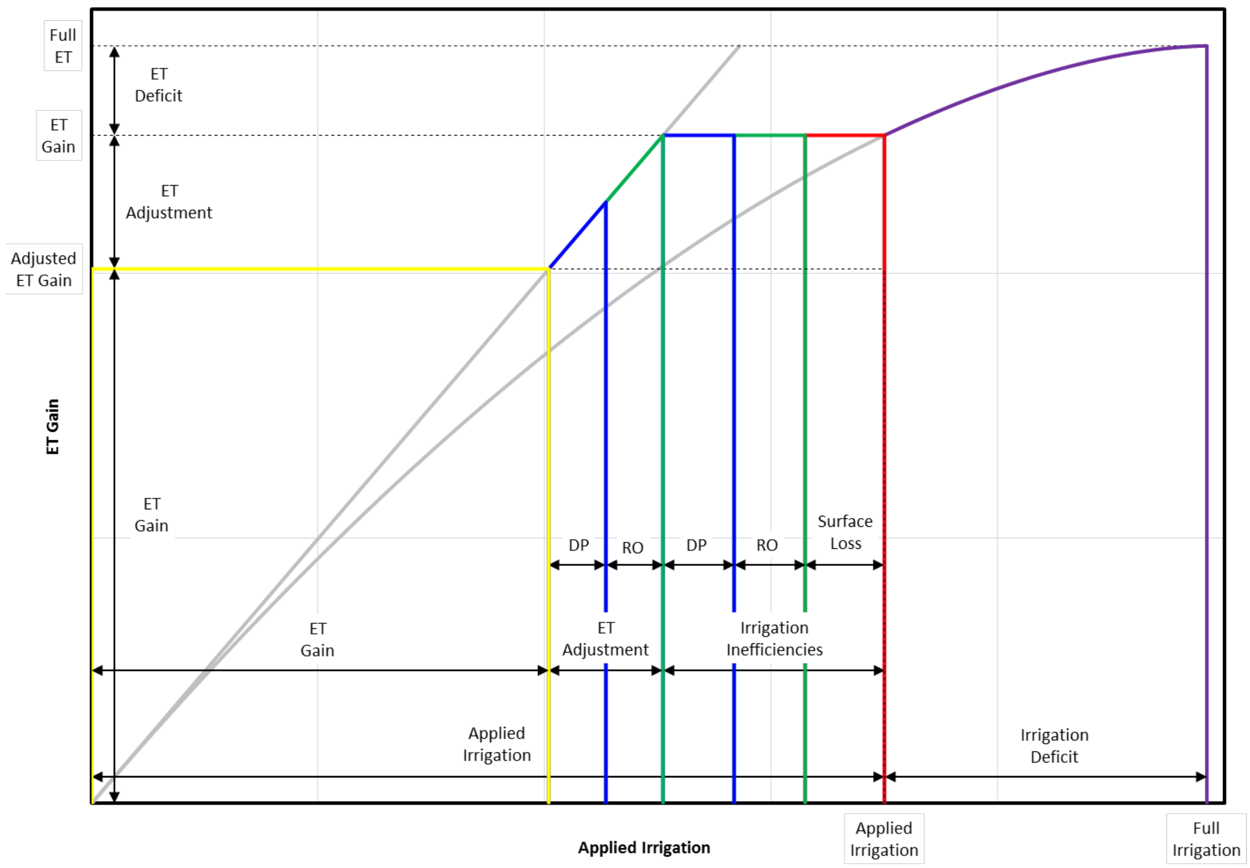
The RCH file is a formatted input file for the groundwater model. The RCH file includes recharge rates for each model grid cell for each stress period and is assigned to the top active model layer. The RCH file was built using the stress periods defined for the LPMT model, as listed in Table 4-1.

Recharge represents the portion of the water budget that drains past the root zone and percolates to the aquifer below. The watershed model uses deep percolation as an estimate of recharge, understanding there is a difference between what drains below the soil profile and what reaches the aquifer. The total recharge estimate is composed of four components: (1) the estimate from the soil water balance model; (2) adjustments to ET for non-idealized conditions; (3) irrigation inefficiencies; and (4) runoff transmission losses. The soil water balance model develops an initial estimate of deep percolation for a crop growing under the given weather conditions.

The recharge occurring from the application of irrigation water is a result of irrigation systems not being fully efficient. This inefficiency requires irrigation systems to apply water in addition to that required volume to meet specified crop transpiration needs. This additional water representing the application inefficiencies is divided among runoff, deep percolation, and surface losses.[6] Additionally, adjustments are made to ET to account for non-idealized conditions. These elements reduce the water use of the crops. This water is then converted to either runoff or recharge. The general concept is illustrated in Figure 4-19. The final source of recharge comes from the partitioning of field runoff. Only a portion of the runoff contributes to flow at the stream. The remaining portion represents transmission losses and is divided between ET and recharge. The later portion of recharge is referred to as indirect recharge, and is a function of direct agricultural runoff from a cell, a loss per mile variable, soil type, and the distance from the cell to the point along the stream at the end of the runoff zone.

Over the entire model period, from 1960 through 2013, on average, there was approximately 3.80 in of recharge in the LPMT model domain. Of this recharge, 3.34 in can be attributable to direct recharge and 0.46 in to indirect recharge. The average annual recharge rates for the LPMT model are shown in Figure 4-20, which illustrates the spatial variability. The annual temporal variability for the simulation period can be seen in Figure 4-21, and the average monthly recharge volumes since 2001 are shown in Figure 4-22. These results reflect the effects that soils, precipitation, irrigation, soil water content, and timing have on recharge rates. Table 4-2 summarizes annual recharge, pumping, and net recharge (recharge minus pumping) volumes over the 14 coefficient zones generated from the RSWB model.

[6] In this context, surface losses represent the evaporative losses experienced during the application of irrigation water.



*the terms in this figure are exaggerated to assist in visualizing the concept

Figure 4-19. Partitioning the Depth of Applied Irrigation between Evapotranspiration, Runoff, Deep Percolation, and Surface Losses

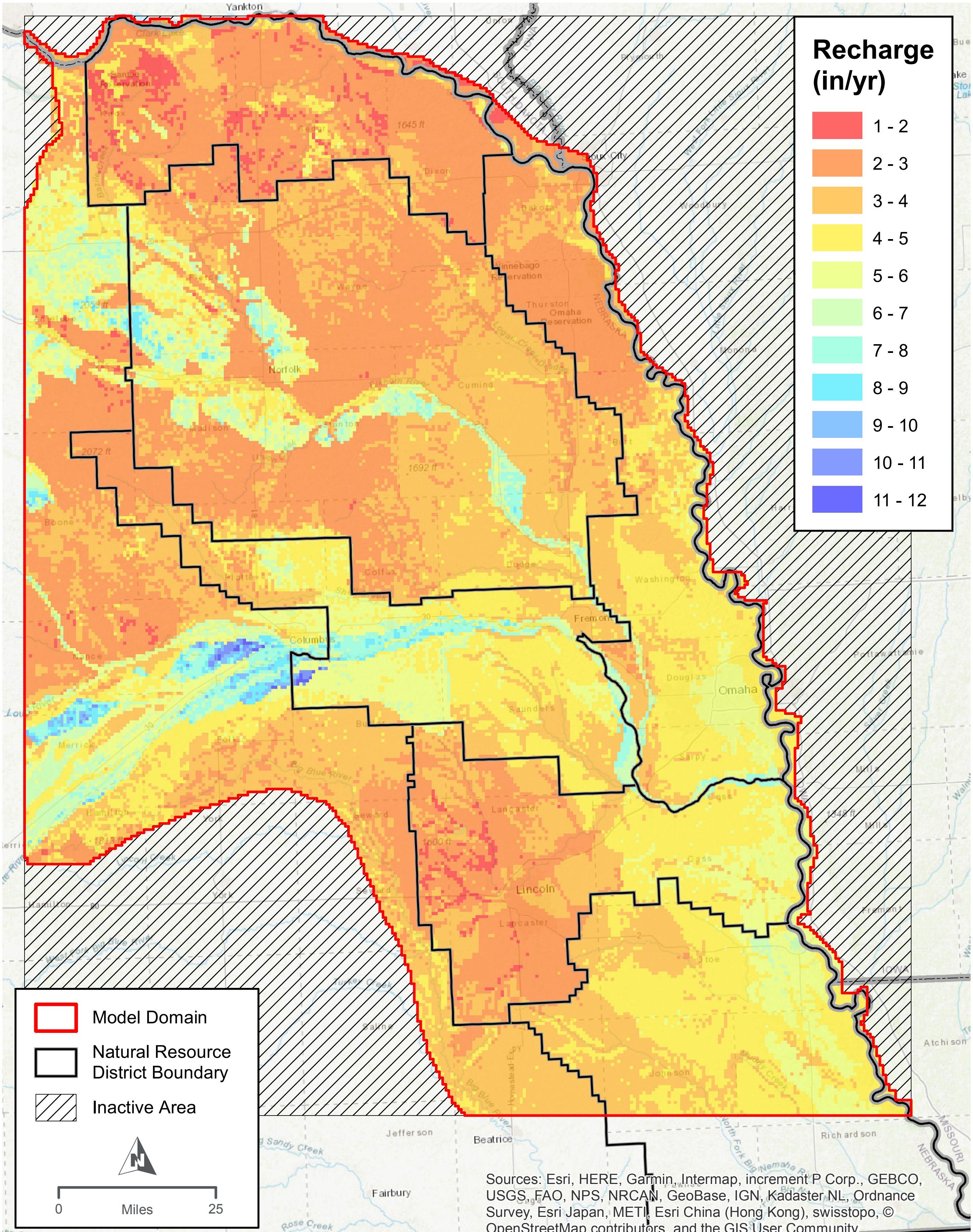


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FIGURE 4-20 - AVERAGE ANNUAL RECHARGE RATES FROM THE WATERSHED MODEL: 1960-2013

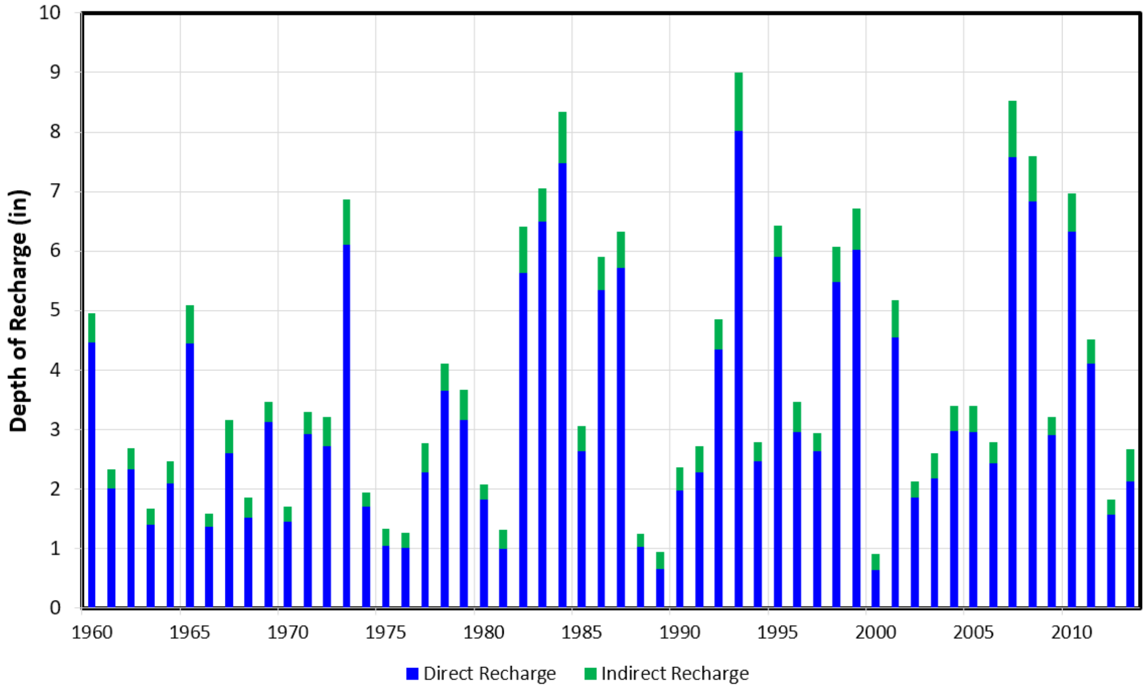

Figure 4-21. Spatially Averaged Annual Recharge Rates from the Watershed Model

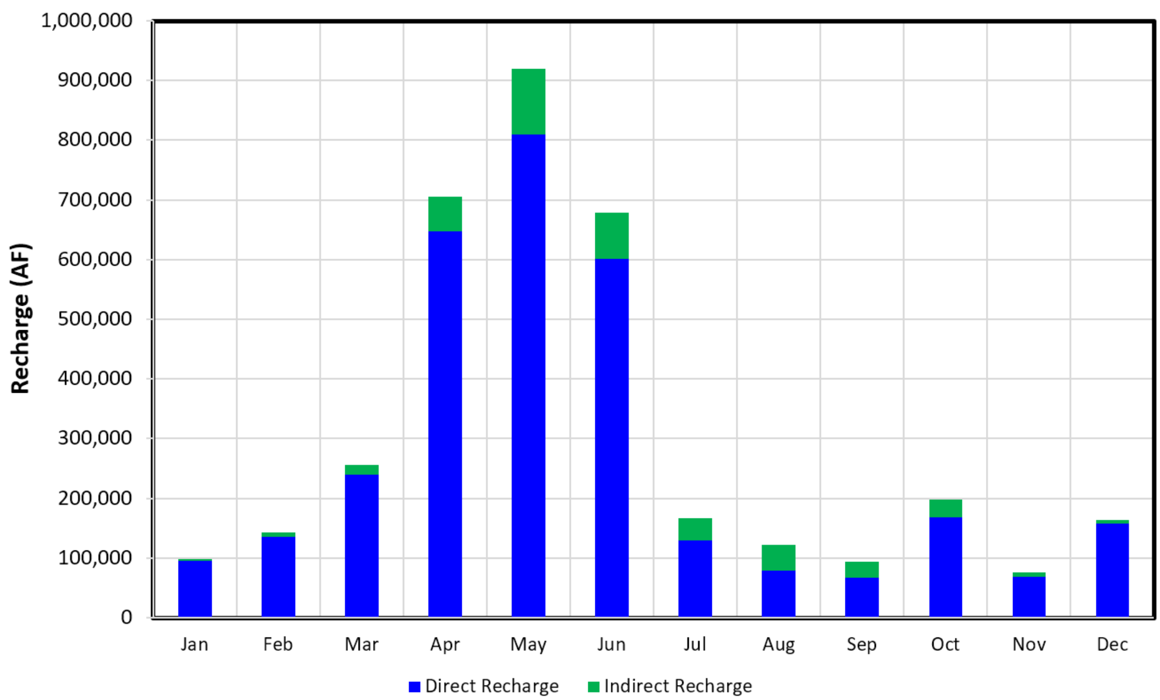

Figure 4-22. Averaged Monthly Recharge from the Watershed Model: 2001-2013

Table 4-2. Breakdown of the Average Recharge and Pumping from the RSWB Model (1960-2013)

Lower Platte Missouri Tributaries Central and Northern Model - Run009e					
Watershed Model					
Coefficient Zone (A)	Acres (B)	Pumping (AF) (C)	Direct Recharge (AF) (D)	Indirect Recharge (AF) (E)	Net Recharge (AF) (F) = (D) + (E) - (C)
1	1,611,200	162,419	452,848	46,039	336,469
2	518,400	27,266	117,864	16,386	106,984
3	890,240	35,262	247,140	22,716	234,593
4	791,520	113,892	205,603	21,929	113,640
5	787,680	170,431	321,731	61,628	212,929
6	340,640	24,350	127,036	6,842	109,529
7	385,280	25,170	129,299	13,393	117,522
8	650,400	4,389	143,319	3,544	142,474
9	626,400	1,989	199,843	38,500	236,355
10	576,640	35,280	144,681	23,309	132,709
11	1,329,600	42,065	278,871	45,762	282,567
12	673,920	2,234	238,690	27,931	264,387
13	482,560	15,378	123,992	23,048	131,662
14	645,600	135,310	139,180	43,026	46,896

4.3 Watershed Model Results

This section presents an overview of the results from the last component of the watershed model, specifically the RSWB model.

4.3.1 Water Budget

Table 4-3 summarizes the key water budget terms represented in the RSWB model. Parameter values are shown both in terms of depth per acre and percent of total applied water (TAW). Depth values shown in the table represent the average volumes (from 1960 through 2013) divided by the total area of the model domain; thus depths of applied groundwater (GW) and surface water (SW) are smaller than might be expected because irrigated acres cover a portion of the model domain (averaging 15.37 percent). Several terms include the same water at different stages of the modeling process—the bold terms indicate the water budget components that balance (as percentages of overall water budget flows, they sum to 100, and as depths, they equal the depth of TAW). For example, the indirect ET and indirect recharge values reflect the portion of the direct runoff that does not contribute to streamflow.

Long-term averages fell within a range of results from other projects in the model area. Estimated long-term average recharge of 3.8 in reflect the results shown in *Regional Estimation of Total Recharge to Ground Water in Nebraska* (Szilagyi et al. 2005), which estimated that the mean long-term annual recharge varies from 2 in to 6.5 in across the model domain. Furthermore, recharge as percentage of applied water (average 12.93 percent) was within the range of 9 to 17 percent seen across most of the region, with isolated pockets reaching greater than 20 percent.

4.3.2 Net Recharge (Recharge minus Pumping) Calculated by the RSWB Model

Net recharge is a measure of the impact of the external stresses applied to the aquifer from the basis of the watershed model, defined as recharge minus pumping. The map of average net recharge (Figure 4-23) shows areas that are primarily contributing and extracting water to the aquifer. On average, over the period from 1960 through 2013, there was roughly 2.87 in of net recharge in the LPMT model domain.

Table 4-3. Long Term Average Water Budget for Components of the RSWB Model

Parameter	Depth (in)	Total Applied Water (%)
Total Applied Water (TAW)	29.37	100.00
Precipitation	28.36	96.56
Groundwater Irrigation Application	0.93	3.15
Surface Water Irrigation Application	0.08	0.29
Total ET	**23.34**	**79.45**
Direct Evapotranspiration	22.85	77.78
Indirect Evapotranspiration	0.49	1.67
Total Recharge	**3.80**	**12.93**
Direct Recharge	3.34	11.37
Indirect Recharge	0.46	1.56
Direct Runoff	3.19	10.86
Runoff Contributions to Streamflow	**2.24**	**7.63**
Change in Soil Water Content	0.00	-0.01

Notes:
- Totals may not sum to 100 percent due to rounding.
- Groundwater and surface water depths applied (as irrigation) are calculated by dividing the volume of water applied by the total area of the model domain, causing these depths to be much smaller than those applied at individual fields. Total irrigated area ranged from 2.98 percent in 1960 to 28.0 percent in 2013, and averaged 15.37 percent from 1960 through 2013. The average depths of water applied only to irrigated areas was 7.47 in/acre for groundwater, and 9.13 in/acre for surface water.
- Indirect ET and recharge indicate those portions of overland flow that are partitioned during transmission, causing some water to not reach streams.

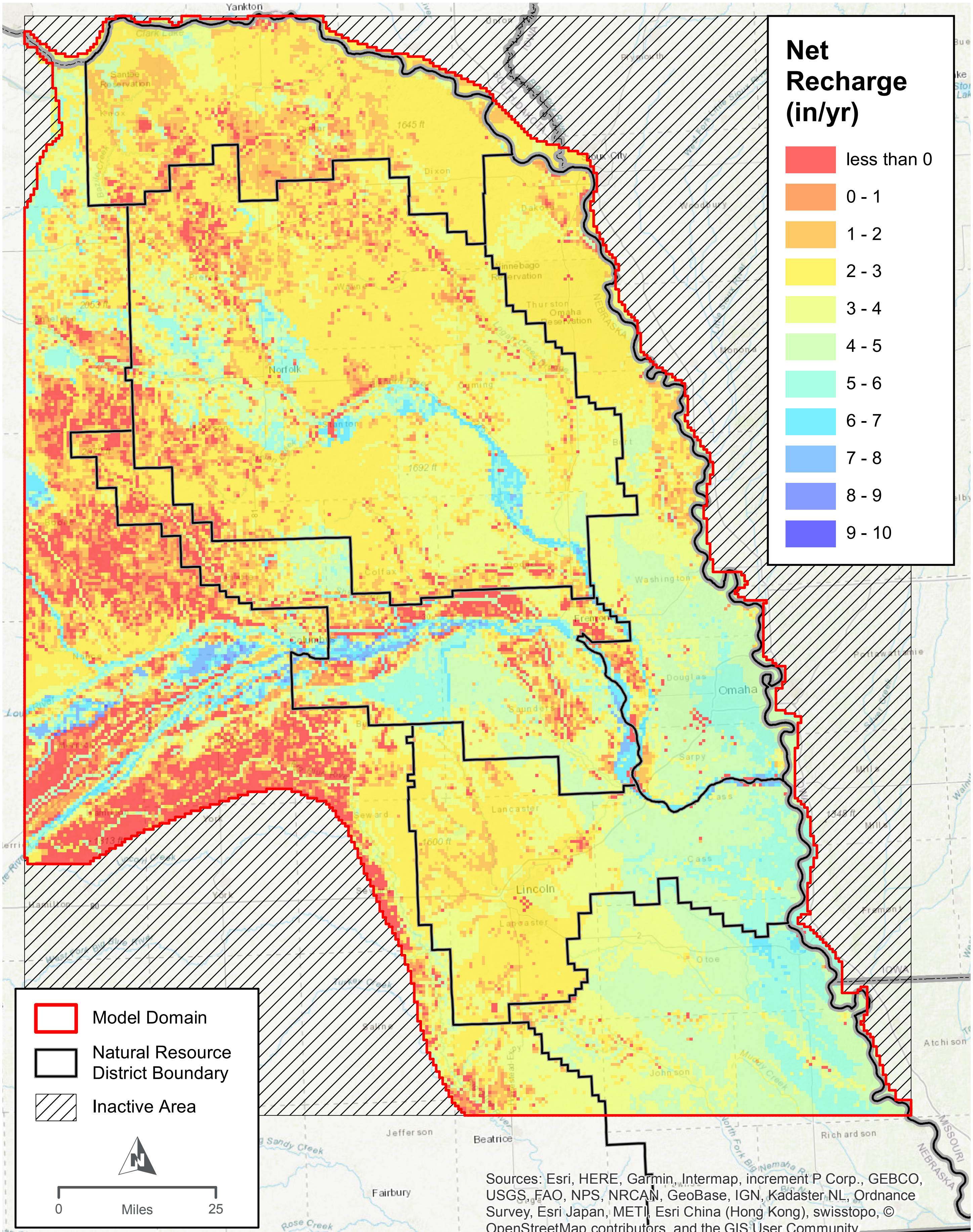

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FIGURE 4-23 - AVERAGE ANNUAL NET RECHARGE RATES (RECHARGE MINUS PUMPING) FROM THE WATERSHED MODEL, 1960-2013

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5.0 Model Construction

This section describes model construction details that were developed to simulate groundwater flow and stream-aquifer interactions within the principal and bedrock aquifers in response to groundwater pumping and recharge.

5.1 Model Code and Processing Software

Numerical groundwater models require large amounts of data from numerous sources to define the aquifer characteristics and properties and hydrologic stresses. These data were assembled as spatially referenced data layers using GIS software ArcGIS for Desktop,[7] and then assigned to the groundwater model at discrete intervals in space and time.

The groundwater flow modeling code used was MODFLOW-2005 (Harbaugh 2005), with the layer property flow (LPF) package and Strongly Implicit Procedure (SIP) solver. The model was assembled, and runs were initiated using Groundwater Vistas, Version 6.85, Build 11 (Environmental Simulations, Inc., 2011).[8] Pre- and post-processing used Microsoft Office programs, Groundwater Vistas, and ArcGIS.

The coordinate system used for the study is the Nebraska State Plane Coordinate System of 1983. It is based on a network of geodetic control points referred to as the North American Datum of 1983 (NAD 83) State Plane Nebraska Federal Information Processing Standards (FIPS) 2600 Feet. The vertical datum used for the study is the North American Vertical Datum of 1988 (NAVD 88). The model coordinate system is False Easting at 1640416.66666667, False Northing at 0.00000000, and no rotation.

5.2 Model Domain

The model domain, as shown in Figure 1-2, focuses on the central and northern part of the six NRDs that are in the study area. Locally, this includes the lower basins of the Platte, Loup, and Elkhorn Rivers as well as tributaries to the Missouri River and the northern tributaries of the Little Nemaha and Big Nemaha Rivers. The Missouri River comprises the northern and eastern boundary of the model domain. The western boundary, oriented north to south, is located approximately 7 miles west of the Lewis and Clark and Lower Platte North NRDs, thereby providing sufficient buffer between the NRDs of interest and the western boundary. The southwest boundary is aligned just west of the Big Blue River. The southern boundary is oriented east to west and is located immediately south of the mouth of the Little Nemaha River. The domain for the southern part of the LPMT model would include all of the Nemaha River Basin, resulting in some overlap of the central and northern model and the southern model.

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[7] http://www.esri.com/software/arcgis
[8] http://groundwatermodels.com/ESI_Software.php

5.3 Model Grid and Layering

The model is discretized by 350 rows and 282 columns in the x and y directions using 0.5-mile by 0.5-mile cells; Figure 5-1 illustrates the grid spacing in the model domain for a local area. The model consists of two vertical layers. The top layer represents the principal aquifer and the bottom layer represents the bedrock aquifers, as previously described. Of the 197,400 total cells in the model, there are 64,347 active cells in layer 1 and 69,168 active cells in layer 2. The model grid is spatially consistent with the grid system used on other groundwater models developed by and for NDNR.

Layer 1 simulates groundwater flow in the principal aquifer. The top of this layer represents land surface (Figure 2-2), which was derived from the Digital Elevation Model (DEM). The base of layer 1 (Figure 3-1) was specified from data compiled by UNL and presented in the LPMT modeling report plan (HDR 2014). Layer 2 is an amalgamation of various bedrock units. The top of this layer was set 10 feet below the bottom of layer 1 to provide hydraulic impedance between the principal and bedrock units by specifying a leakance value in MODFLOW. The bottom of layer 2 (Figure 3-8) was established from the data compiled by USGS (Ellis 1986).

5.4 Perimeter Boundaries

Perimeter model boundaries are based on a conceptualization of the groundwater flow conditions within the model domain and are shown for principal and bedrock aquifers in Figures 5-2 and 5-3. For the principal aquifer, the Missouri River comprises the northern and eastern boundaries of the model and is represented by the MODFLOW River boundary (River) package that permits head-dependent fluxes of water into and out of the model. The western side of the model domain is an area of significant underflow into the study area from the Ogallala Aquifer and younger High Plains Aquifer units, and are represented as a MODFLOW General Head boundary (GHB) package. The southwestern boundary coincides with the Big Blue River and was also assigned as a River boundary. The southern boundary, which crosses the Nemaha River Basin, is represented as a GHB. The model design makes the Big and Little Nemaha Rivers unsuitable for streamflow depletion calculations due to the proximity of these rivers to the model boundaries. Streamflow depletion analyses in these rivers will be conducted using the southern model, which is to be developed and documented in the near future.

In the bedrock aquifers (layer 2), groundwater flows primarily eastward toward the Missouri River. Groundwater in this unit in Iowa, where the Dakota Group is used for water supply, flows westward toward the Missouri River. Therefore, the Missouri River is a natural hydrologic boundary, and accordingly, a no-flow boundary underneath the Missouri River was specified in layer 2, which forces groundwater in layer 2 to discharge into the overlying Missouri River. The southern boundary is located approximately along the edge of the southern extent of the Dakota Aquifer, as shown in Figure 3-8; therefore, no-flow conditions are prescribed for this boundary. In the north, groundwater moves approximately parallel to the model boundary; therefore, a no-flow boundary was prescribed in the north. The bedrock extends westward underneath the principal aquifer along the western boundary; consequently, a GHB was prescribed along this boundary.

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FIGURE 5-1 - MODEL GRID DISCRETIZATION

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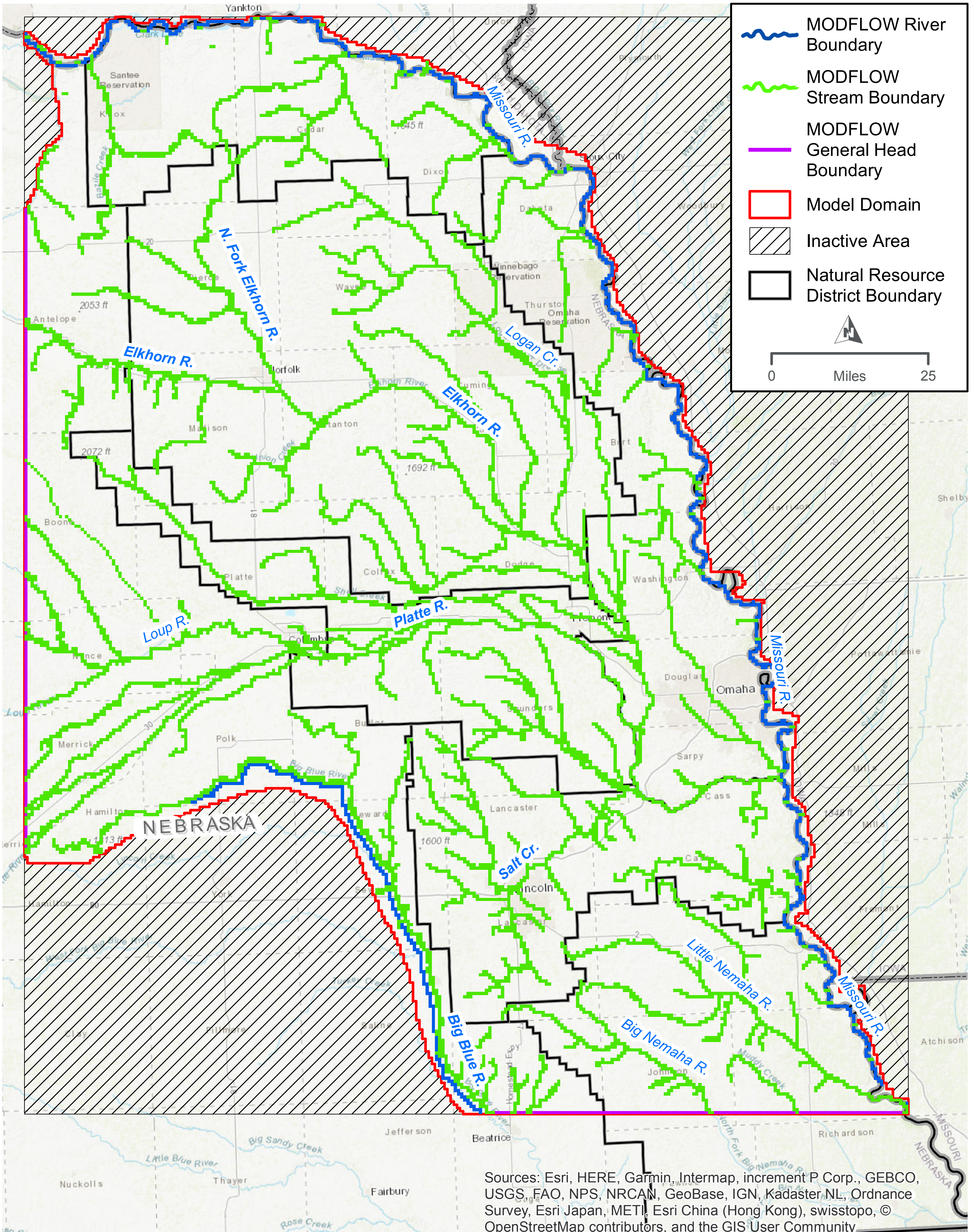

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 5-2 - PRINCIPAL AQUIFER BOUNDARY DEFINITIONS

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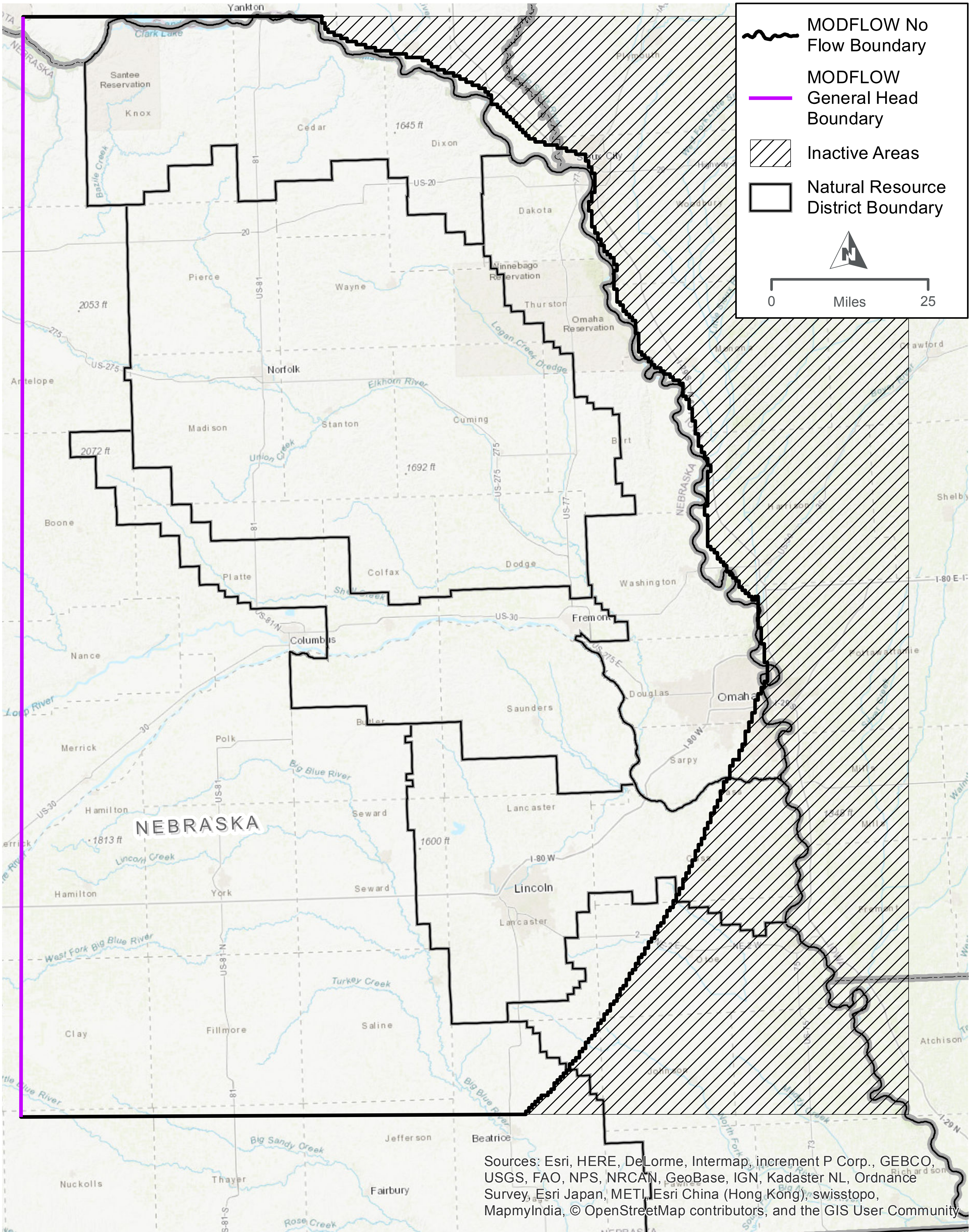

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FIGURE 5-3 - BEDROCK AQUIFER BOUNDARY DEFINITIONS

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Both, the River and the GHB boundaries are used to simulate flows into and out of the model using the following equation:

Equation 3

$$Q = C\ (H_b - H_{gw})$$

The flow (Q) into and out of the model is controlled by the difference between the heads of the boundaries (H_b) and the aquifer (H_{gw}) and the conductance (C) across the model boundary given by:

Equation 4

$$C = K * L * W / M$$

where:

C = boundary conductance (L^2/T)
K = conductivity of the boundary (L/T)
L = length of the boundary in the model cell (L)
W = width of the boundary in the model cell (L)
M = thickness of the streambed sediments (L)

The heads (H_b) in the River boundaries were specified using the USGS land surface DEM. The heads in the western and southern GHB boundaries within the principal aquifer were specified using the potentiometric surface presented in Figure 3-3. The heads along the western GHB boundary in layer 2 were specified using the potentiometric surface in the bedrock units presented in Figure 3-9. The boundary heads in both layers were held constant throughout the calibration period. The long-term stability of the groundwater levels along the western edge of the model is illustrated by hydrographs presented later in this section. The hydraulic conductance at the GHB boundaries is set to a high value to simulate nearly constant head conditions. For the Missouri River boundary cells, the aquifer hydraulic conductivity, river bed hydraulic conductivity, and riverbed thickness were set to 100 feet per day (ft/d), 3 ft/d, and 1 foot, respectively. Sensitivity simulations documented in Section 7.0 indicate that the simulation results are relatively insensitive to the stream and river bed conductance.

5.5 Internal Boundaries

Internal boundary conditions include streams and recharge. ET from the groundwater system was accounted for using the MODFLOW Evapotranspiration (EVT) package when the water table was less than 7 feet from the land surface. Similar to the rivers, streams allow for exchange of water between surface water and groundwater systems as a function of the hydraulic head and conductance between these two bodies of water (Equations 5 and 6). The major differences between the river and stream package are that the stage in the river package is independent of streamflows, while in the stream package, the stage varies as a function of the streamflows and stream geometry, and there is a flow accounting procedure in the stream package that prevents streamflow losses (recharge of the aquifer) when the model simulates a dry steam condition.

Recharge represents the amount of infiltration into the aquifer or net outflow if ET dominates. Each of these boundary types is discussed in the following subsections.

5.5.1 Streams

The Stream package for MODFLOW was used to simulate stream-aquifer interaction at internal streams within the study area. Not all streams within the LPMT basins are perennial, but the Stream package allows the portions of streams to go dry if there are not flows from upstream or not any inflows from groundwater. The selection process for the delineation of streams was presented in *Groundwater Model Development Plan for the Lower Platte and Missouri River Tributary Basins* (HDR 2014). The stream network segment and reach numbers were assigned by a combination of automated and manual methods, and are consistent with documentation for the MODFLOW SFR1 package (Prudic et al. 2004).

The stream network within the model domain, consisting of 527 segments, is shown in Figure 5-2. Flow along the stream channels is simulated using Manning's equation, which relates stream depth and stream hydraulic head to flow by the following equation:

Equation 5

$$Q = \left(\frac{1.486}{n}\right) AR^{2/3} S_o^{1/2}$$

where:

Q = stream discharge, in units of volume per time
n = Manning's roughness coefficient, dimensionless
A = cross-sectional area of the stream, in units of square feet
R = hydraulic radius, in units of feet
S_o = slope of the stream bed, dimensionless

A Manning's roughness coefficient of 0.03 was specified based on the CENEB model and was assumed to be reasonable for this model. The streambed slopes were derived from the streambed elevation estimated using the DEM.

The amount of water exchanged between the stream and aquifer is governed by Darcy's Law as formulated in Equations 3 and 4.

The vertical conductivity and thickness were set to 3 feet per day and 2 feet, respectively. This results in a streambed resistance (thickness/conductivity) of 0.66 day, which is in accordance with the estimate of less than 1.0 day for this ratio proposed by Anderson (2007) for streams with a sandy bottom. Length of streams was set according to the length of NHD polylines[9] within each grid cell, and the width of streams was set equal to 50 feet.

[9] 1:100,000 resolution National Hydrography Dataset (https://www.usgs.gov/core-science-systems/ngp/national-hydrography)

A large amount of streamflow in the Platte, Loup, and Elkhorn Rivers enters the model domain along the western boundary because these rivers extend further west. Additionally, inflow also occurs along two minor streams: Cedar River and Beaver Creek. Therefore, it was necessary to estimate the baseflow entering the model domain at the western model boundary in these rivers/creeks to account for the conservation of water in the model. The historical baseflow information at gaging stations along the rivers in the proximity of the western boundary was used to estimate the baseflow influx of the Platte, Loup, and Elkhorn Rivers. Average annual baseflows were estimated along these rivers along the western boundary of the model domain for 1960 through 1985, and average monthly baseflows were estimated from 1986 through 2013 in accordance with the model stress periods. The median baseflow beginning in 1960, from values used in the CENEB model (Brown and Caldwell 2013), was applied as inflows for the Cedar River and Beaver Creek. Locations of these rivers/creeks and gaging stations are shown in Figure 5-4. The annual baseflow hydrograph at the three gaging stations along the Platte River near the western boundary are shown in the inset in Figure 5-4, which suggests very similar flow rates at all three stations. Therefore, the average baseflow at the upstream gaging station (Odessa #06770000) was used to specify inflow in the Platte River at the western boundary. Figure 5-5 shows the baseflow hydrographs at the western boundary applied as inflows to the model in the Platte, Loup, and Elkhorn Rivers. The median baseflow applied to the western boundary for the entire period of simulation for the Platte, Loup, Elkhorn, and Cedar Rivers, and Beaver Creek are listed in Table 5-1.

Table 5-1. Baseflow Specified at Western Boundary for Major Rivers and Creeks Entering the Model

River/Creek	Median Inflow at Western Boundary (cfs)
Loup River	1,550.4
Platte River	821.9
Cedar River	192.4
Elkhorn River	104.6
Beaver Creek	53.6

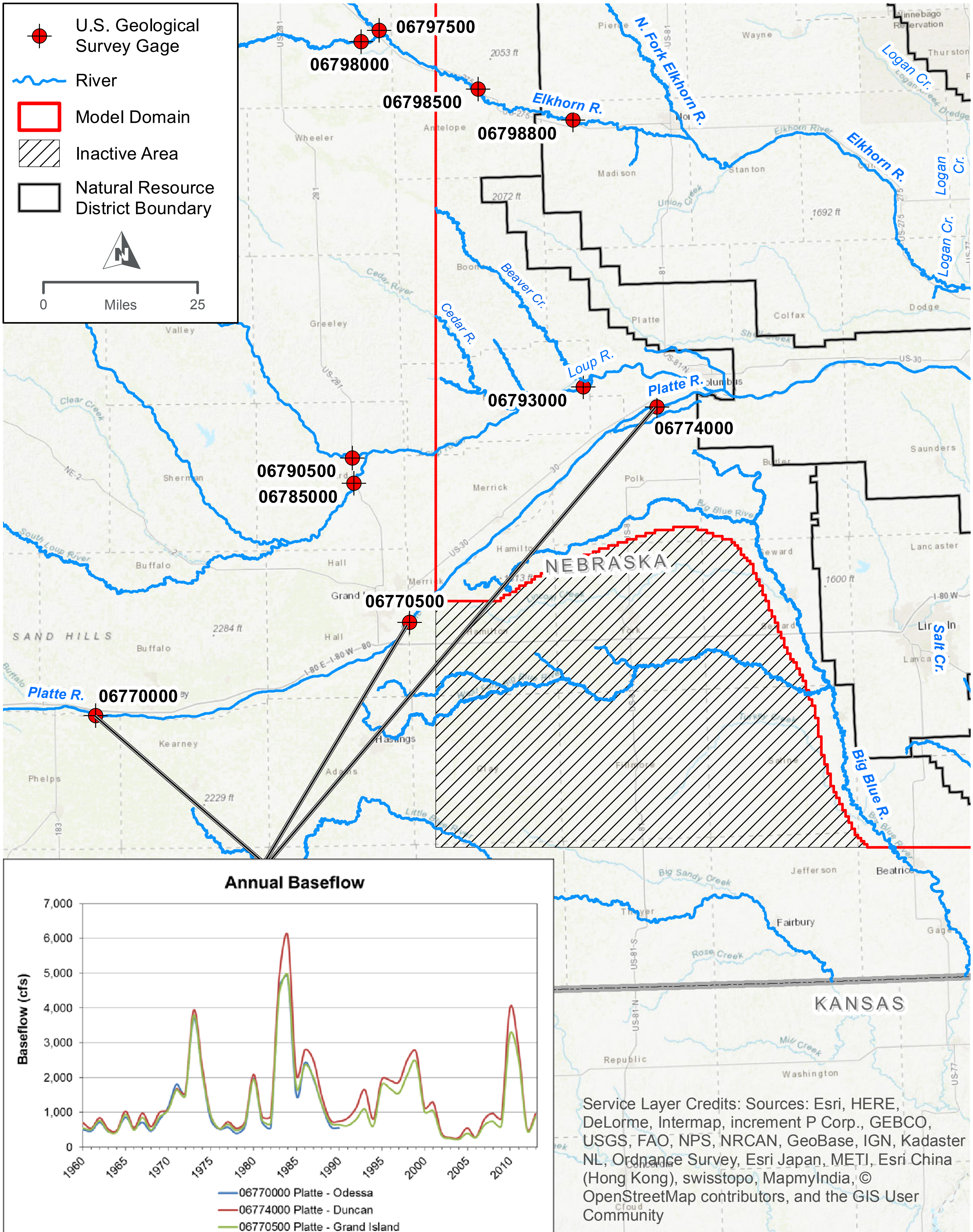

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FIGURE 5-4 - GAGING STATIONS ON THE PLATTE, LOUP AND ELKHORN RIVERS

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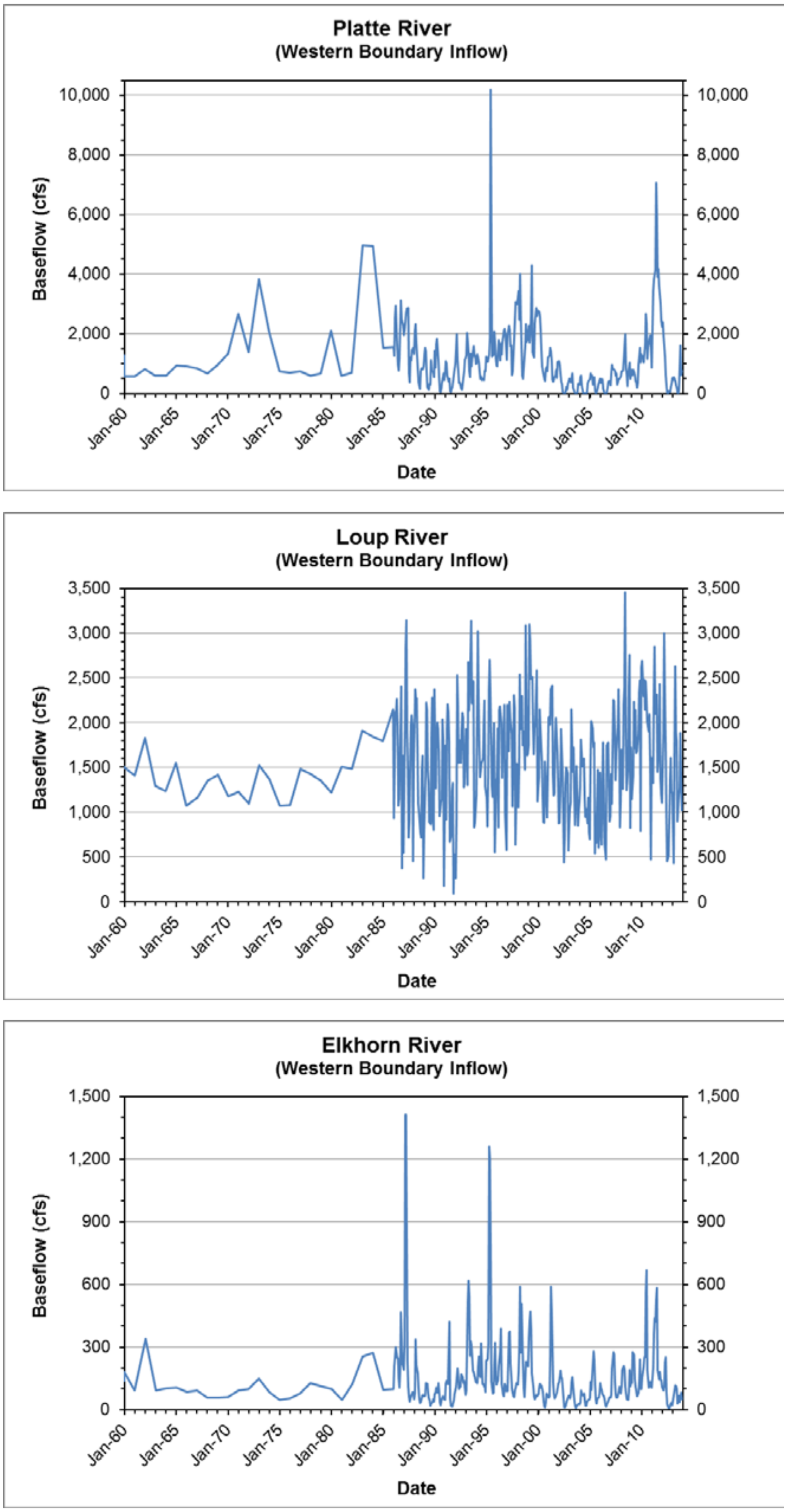


Figure 5-5. Baseflow for Major Streams along the Model Western Boundary

5.5.2 Recharge and Pumping

The development of recharge values is discussed in detail in Section 4. The RSWB model calculates the recharge rates applied to each model grid cell for each stress period by accounting for precipitation, runoff, and ET from crops. The initial average RSWB model recharge distribution for the transient simulation period (1960 through 2013) resulted in an average recharge over the entire model domain of 4.7 in per year.

Although not initially planned, recharge was established as a calibration parameter in the use of the Parameter Estimation software (PEST) to implement a more rigorous groundwater model calibration. Initial recharge rates were adjusted with PEST, providing a series of recharge targets to be achieved with the watershed model. The watershed model was then adjusted in certain portions of the model domain where the RSWB calibration parameters were tuned to achieve the target recharge rates, ultimately resulting in improved match between observed well groundwater levels and stream baseflow. This was conducted in a way that maintained an accurate water budget output from the RSWB model to ensure that appropriate distributions of flows occurred throughout the calibration period while keeping the calibration parameters with a reasonable range.

Groundwater pumping for domestic, irrigation, industrial, and municipal purposes in the principal and bedrock aquifers is documented in Section 4.1. Detailed explanation is provided in this section regarding quantification of pumping and the technical approach implemented to assign withdrawals in each model layer. Pumping was assumed to be reliably calculated and therefore was not adjusted during calibration.

5.5.3 Groundwater Evapotranspiration

Model evapotranspiration from groundwater was simulated in areas where the water table was close to land surface (that is, wetlands and riparian areas; Figure 5-6). These areas were identified from the National Wetlands Inventory developed by the U.S. Fish & Wildlife Service,[10] and from soil series hydrology information from the STATSGO2 dataset, within which model cells were assigned to the MODFLOW EVT package, which simulates discharge from the groundwater system via transpiration and evaporation, based on the following equation:

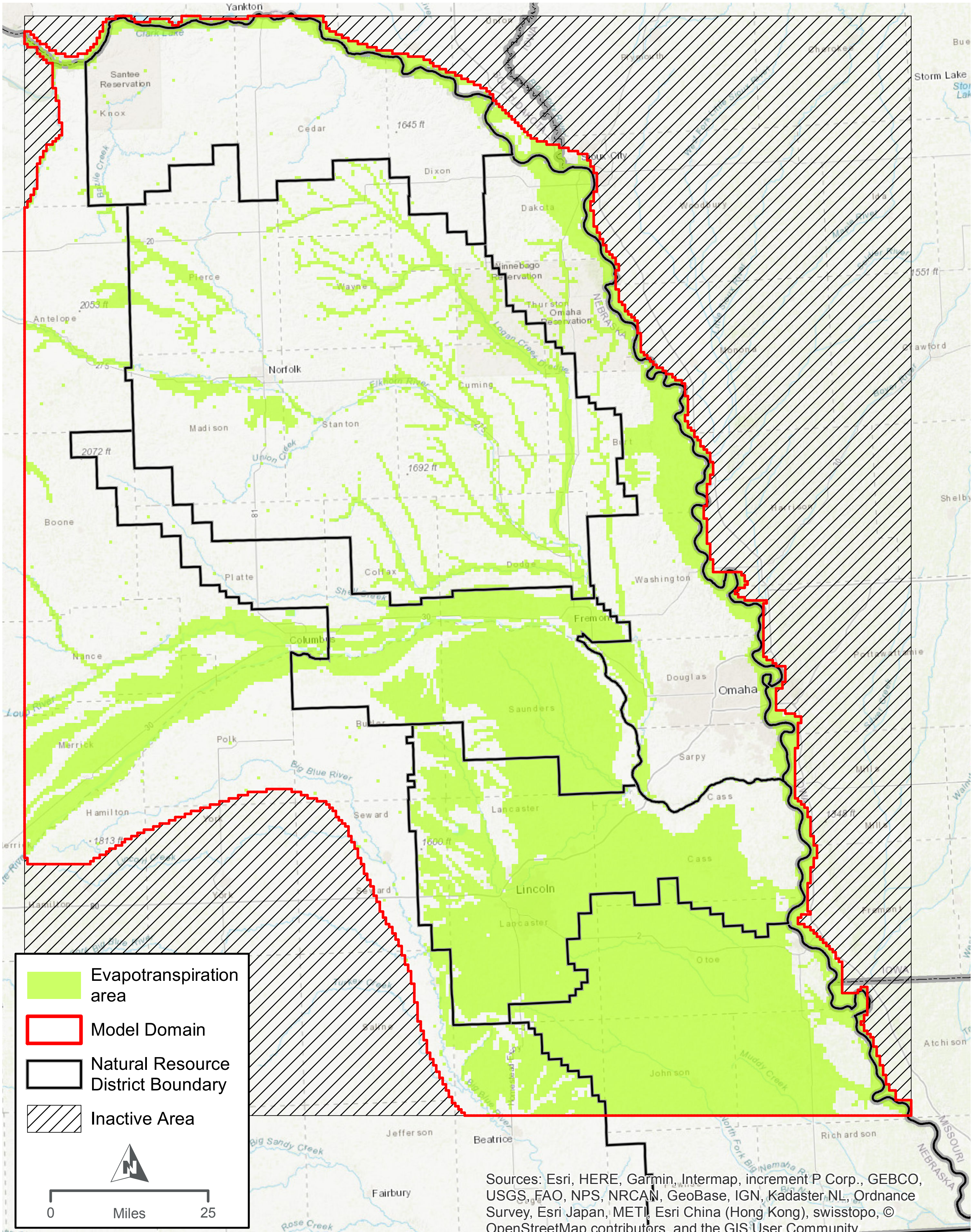
Equation 6

$$Q_{ET} = Q_{ETM}\left(\frac{h-(h_s-d)}{d}\right)$$

where:

Q_{ET} = evapotranspiration rate, in units of volume per time
Q_{ETM} = maximum evapotranspiration rate, in units of volume per time
h = head in the cell, in units of length
h_s = head at which the maximum ET rate occurs (land surface), in units of length
d = extinction depth, in units of length

[10] https://www.fws.gov/wetlands/Data/Data-Download.html



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 5-6 - GROUNDWATER EVAPOTRANSPIRATION AREAS

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The maximum ET rate occurs when the simulated water table is at or above the ET surface (h_s) and decreases to zero in a linear manner as the simulated head approaches the extinction depth (Figure 5-7). The maximum ET was assumed to occur when the water table is at land surface.

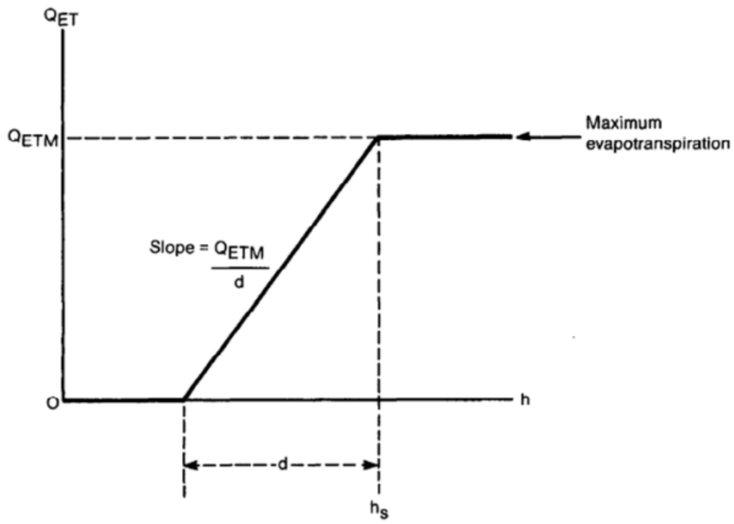

Figure 5-7. Conceptualization of Flow Dynamics in the MODFLOW EVT Package (after Harbaugh 2005)

The wetland coverage for the LPMT model domain was 261,000 acres, which represents approximately 2.5 percent of the total area. The wetlands were divided into groups based on the types of vegetation prevalent and their relative rates of water use. An area is defined as having a high water table if the depth to groundwater is less than 6 feet in the STATSGO2 soil database and coverage map. Approximately 4.7 million acres within the model domain, mostly in the southern part of the model, have a depth to groundwater of less than 6 feet.

A uniform extinction depth of 7 feet was specified based on literature review, and has the same value as used in the Northern High Plains Groundwater Flow Model (Peterson et al. 2016), and is near the average value determined by Szilagyi et al. (2013) for the Central Platte River Valley. The EVT package used a maximum ET rate of 40 in. To account for ET already considered in the watershed model, the maximum ET rate in each cell was reduced by the average dryland pasture ET in the model grid cell to arrive at the annual ET rate for the EVT package. For the period 1960 through 1985 (during which an annual stress period was implemented), the annual ET rate was applied directly to each EVT package cell. For the simulation period from 1986 through 2013, in which monthly stress periods were implemented, the annual ET was proportioned to monthly values as defined in Table 5-2. This distribution was developed using the average monthly distribution, from 1985 through 2010, of irrigated alfalfa ET for the active EVT package cells.[11]

[11] Irrigated Alfalfa was chosen as the reference distribution due to the relative water-intensive nature of growing alfalfa, a trait common among wetland vegetation. Additionally, the irrigated scenario did not limit the amount of

Table 5-2. EVT Package Monthly Distribution of Annual Maximum Evapotranspiration Rate

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
% Annual ET Rate	2.0	2.0	4.0	11.0	15.0	16.0	16.0	14.0	11.0	5.0	2.0	2.0

5.6 Hydrogeologic Parameters

5.6.1 Hydraulic Conductivity

The study team considered two sources of horizontal hydraulic conductivity (K_H) in the principal aquifer. The first source considered was the K_H estimates from aquifer (pump) tests conducted at 12 sites (Figure 5-8) during previous studies. The K_H from these 12 sites ranges from 5 to 678 ft/d, and averages 232 ft/d. These data cover only a small part of the study area and are not sufficiently widespread to establish hydraulic conductivity (K) zones throughout the model domain. The second source considered was estimates from interpolation based on estimates from the test hole drilling program that were discussed in Section 3.1.3 and shown in Figure 3-5. As shown in Figure 3-5, these K_H estimates resulted in nearly all of the area outside of the vicinity of the Elkhorn River and Platte River valleys to be less than 50 ft/d. This underlying data source used in estimating initial K_H shown in Figure 3-5 was also used during the Cooperative Hydrology Study (COHYST), but found to provide only a limited value in achieving a calibrated K_H distribution (personal communication, Mahesh Pun, 2015).

Given the lack of independent information to establish the distribution of K_H, it is preferable to let the inverse parameter estimation process guide the determination of K_H throughout the model domain. Therefore, it was decided to populate the K_H field using the Pilot Point methodology (Doherty et al. 2010). The method uses a kriging interpolation scheme to assign the K_H distribution in the model domain with the pilot points serving as anchors where the parameter values are first assigned. This results in a smooth variation of K_H over the model domain. Pilot points have been increasingly used over the past two decades in groundwater model calibration (de Marsily et al. 1984; RamRao et al. 1995; LaVenue and de Marsily 2001). The assignment of number and location of pilot points was based on guidelines specified in the literature (Doherty et al. 2010; Anderson et al. 2015), which takes into consideration the location of the groundwater level calibration targets, a sufficient spatial distribution, model boundaries, observed hydraulic gradient (spring 2010 contour map), as well as boundaries of K zones (defined based on geologic information). The 26 K zones and 309 pilot points used during model calibration within the LPMT model area are shown in Figure 5-9.

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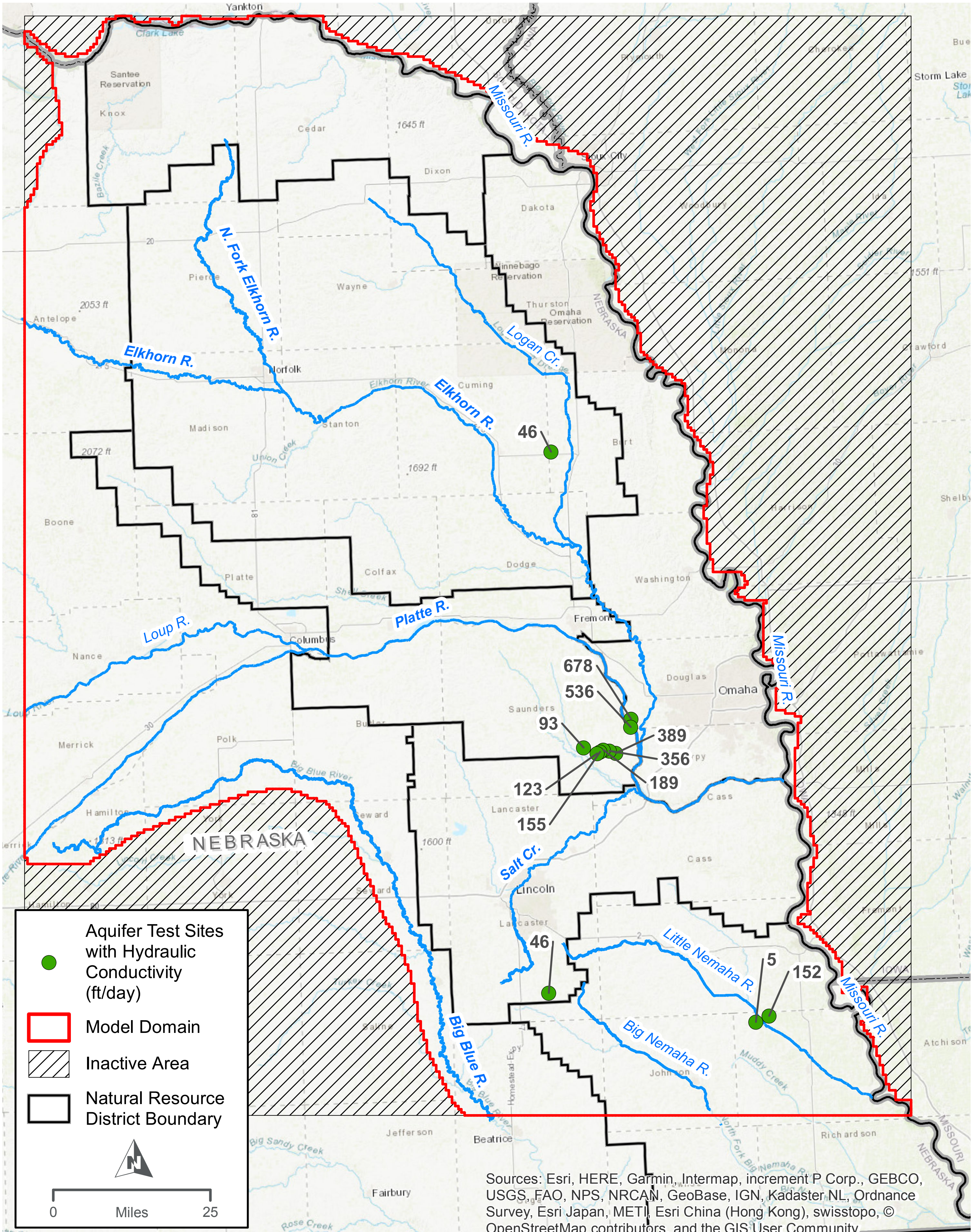
water available to the alfalfa crop for transpiration; this translates to a distribution where the vegetation uses water when it needs it.



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 5-8 - AQUIFER TEST SITES AND RESULTING HYDRAULIC CONDUCTIVITY

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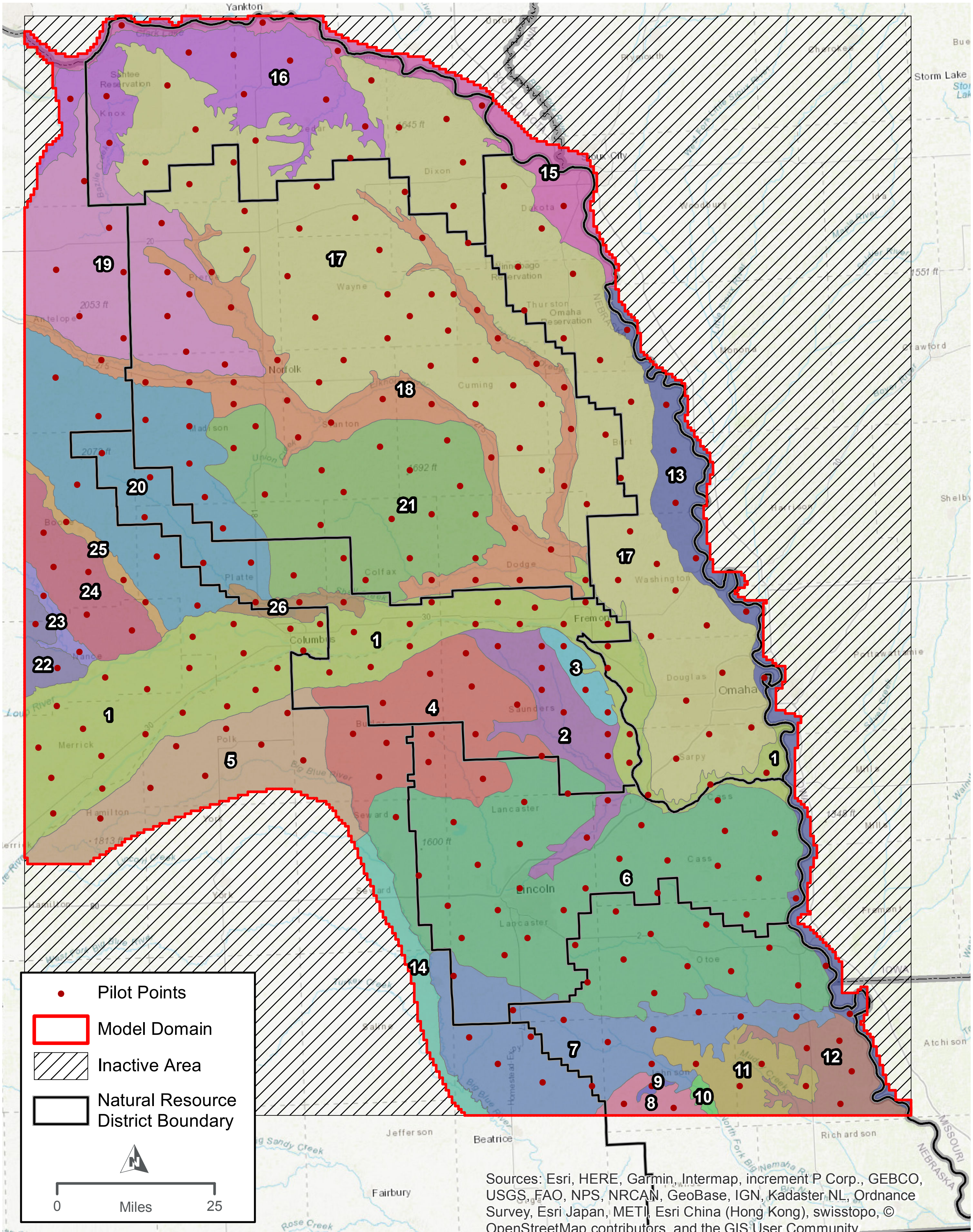

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CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 5-9 - PILOT POINTS AND HYDRAULIC CONDUCTIVITY ZONES FOR PEST ESTIMATION

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Establishment of K zone boundaries was conducted by overlaying several data sources within a single GIS project map and creating a new layer upon review. Drawing was generally done at a scale of 1 in equals 4 miles (1:253,400) and adjusted to make sure boundaries were appropriately matched in areas where more than one dataset overlaps. The tracing option in ArcMap was used as much as possible to trace the edges of the source files. The data sources used in the creation of the K zones include (1) generalized hydrogeologic areas (shapefile obtained from NDNR), (2) hydraulic conductivity of the principal aquifer based on interpolation of test-hole attributes (HDR 2013a; Figure 3-5), (3) transmissivity of the principal aquifer based on test-hole attributes (HDR 2013a; Figure 3-7), (4) high capacity wells in the principal aquifer (Figure 4-3), (5) areas where the principal aquifer is absent (Figure 3-1), (6) glacial till (UNLCSD Geology Related GIS Data[12]), and (7) land surface topography from a 30-m DEM (USGS National Elevation Dataset).

The minimum, maximum, and average hydraulic conductivity in each zone is presented in Figure 5-10. For model calibration purposes, the upper and lower limit of K values within each zone were allowed to vary no more than 25 percent of the range determined from the UNLCSD Test Hole database within each K zone (Figure 5-10). This ensured that the magnitude of the calibrated K_H is closely bounded by estimated values.

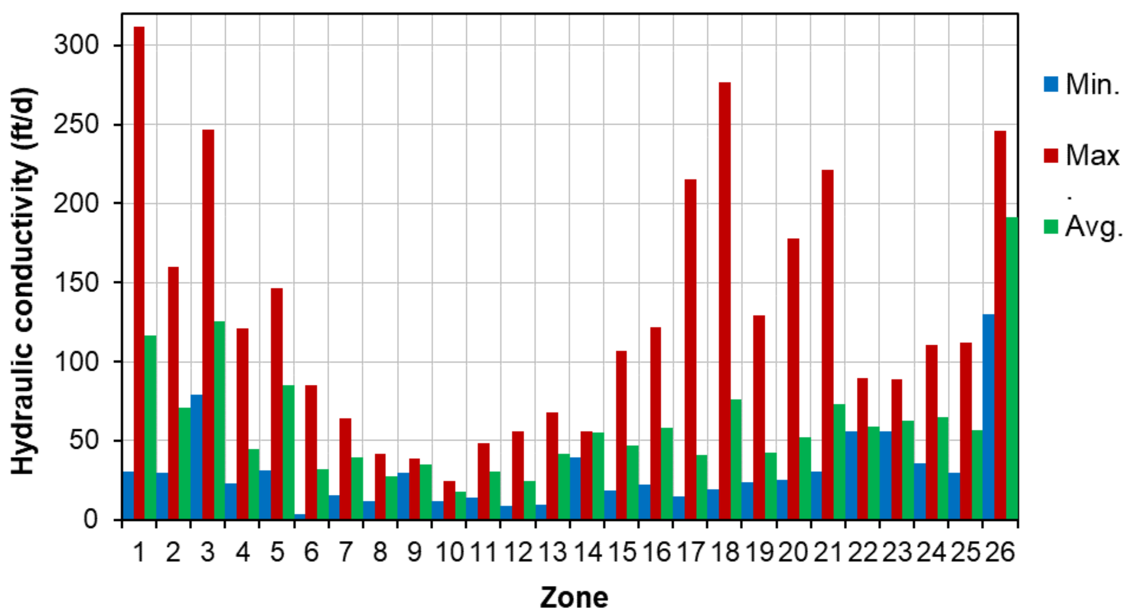


Figure 5-10. Range and Average Hydraulic Conductivity in each Zone based on Kriging Interpolation of Data in the UNLCSD Test Hole Database (data after HDR 2013a)

[12] http://snr.unl.edu/data/geographygis/geology.aspx

The hydraulic conductivity distribution was optimized during the calibration process to minimize the discrepancies between observed and simulated groundwater level and baseflow targets, and to achieve a reasonable global water budget. The final calibrated hydraulic conductivity distribution is presented and discussed in Section 6.8. In the bedrock units (layer 2), a single uniform hydraulic conductivity value was specified in the model cells. This was deemed appropriate given the lack of hydrogeologic data in the bedrock units. In both layers, the hydraulic conductivity was assumed to be laterally isotropic; that is, $K_x = K_y$. The vertical hydraulic conductivity (K_z) is not a modeling parameter because the exchange of water between the layers in the model is controlled by the magnitude of leakance between layers 1 and 2.

5.6.2 Storage

The conceptual model defines layer 1 as unconfined and layer 2 as confined. Accordingly, a specific yield is assigned in layer 1, and specific storage is assigned in layer 2. The specific yield and specific storage values are assumed to be uniform and are model calibration parameters. Calibrated values are presented and discussed in Section 6.8.

5.6.3 Leakance

Leakance is calculated as the effective vertical hydraulic conductivity of the material between model layers divided by a distance term representing the thickness of the hypothetical unit impeding flow between the model layers. The amount of groundwater exchange (Q) between layers 1 and 2 is governed by the following equation:

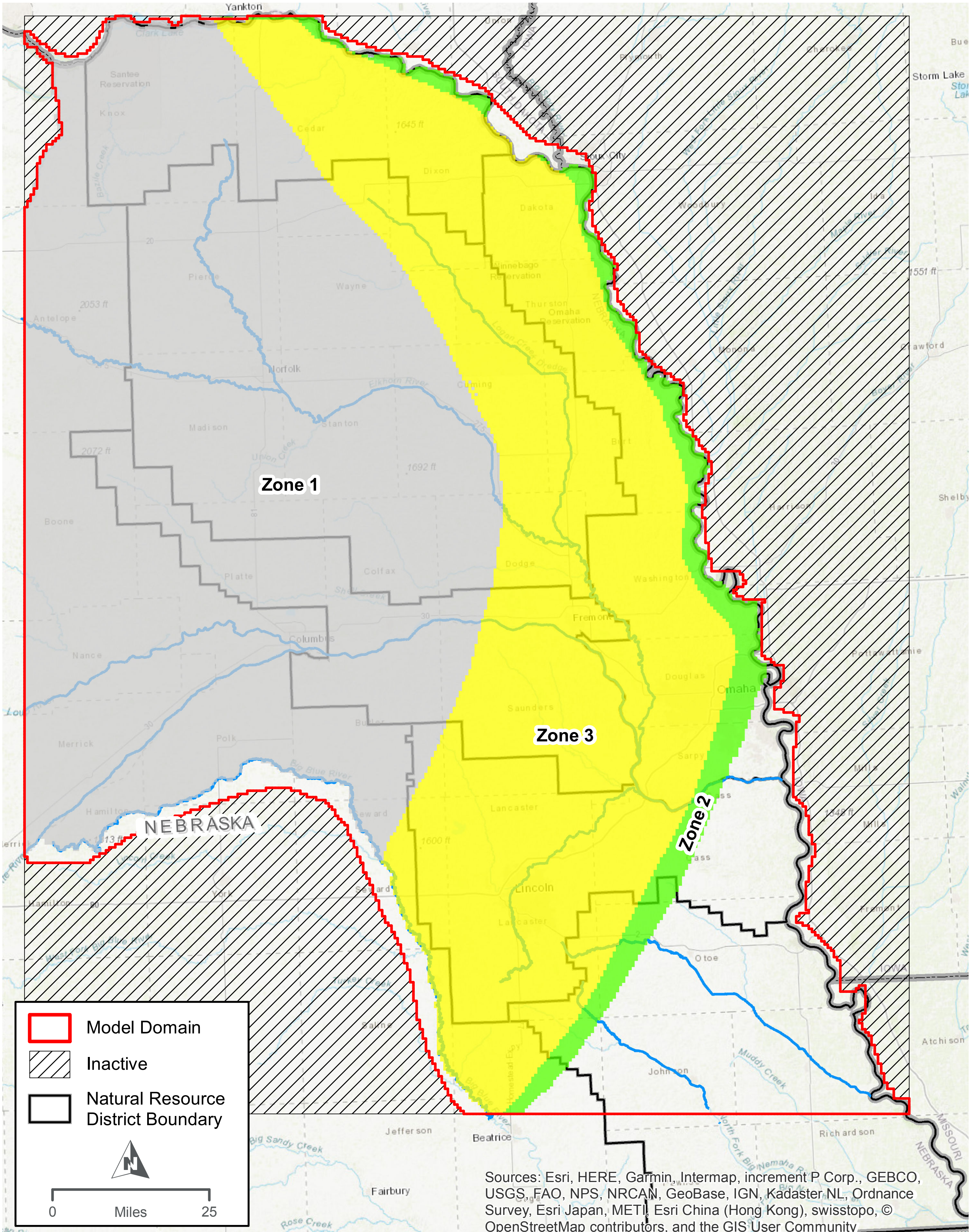
Equation 7

$$Q = L_k\,(H_{l1} - H_{l2}) * L * W$$

where:

L_k = hydraulic leakance (T^{-1}) between layers 1 and 2
H_{l1} and H_{l2} = heads (L) in the layers 1 and 2, respectively
L = length of the model cell (L)
W = width of the model cell (L)

The leakance is a model calibration parameter and is allowed to vary independently in each model cell. Leakance zones were established for PEST calibration purposes. These zones are shown in Figure 5-11. The final calibrated values for this parameter are discussed in Section 6.8.



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 5-11 - LEAKANCE ZONES

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6.0 Model Calibration

6.1 Calibration Period

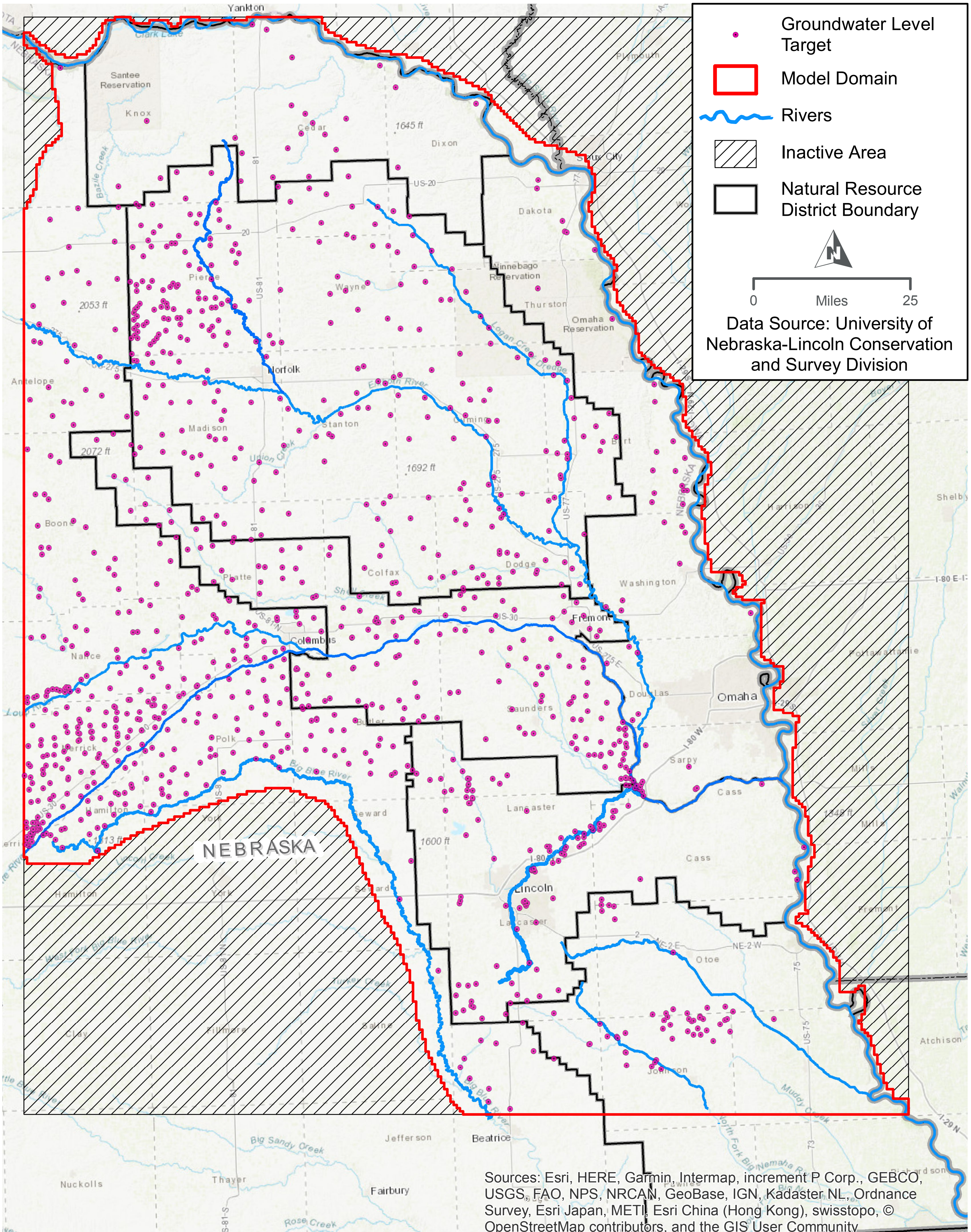
The calibration period spanned from January 1960 through December 2013. An annual temporal discretization (stress period) was implemented from 1960 through 1985, and was followed by monthly stress periods from 1986 through 2013. The hydrologic stresses (recharge, pumping, and stream inflows along the western boundary) varied during the stress periods, with the exception of the Cedar River and Beaver Creek. As noted in Table 4-1, the first stress period in the model was assigned as steady state to reflect the assumption that prior to 1960, there was minimal development in the study area. The groundwater levels and streamflows during the first stress period were assumed to be in a state of dynamic equilibrium. The implementation of an initial steady-state stress period provided a starting condition that was hydrologically consistent with the transient simulations that followed. See the watershed model documentation (Appendix B) for a description of how recharge was developed for first (steady state) stress period.

6.2 Calibration Targets

6.2.1 Groundwater Levels

All available historical groundwater level data in the study area were obtained via the most up-to-date version of a statewide database, maintained by UNLCSD. The UNLCSD and USGS evaluate the adequacy and accuracy of the water-level data contained in the statewide database (Young et al. 2016). Following a review of the data for quality control and consistency with the 2010 water table map and land surface elevations, a set of 1,080 wells, with 83,575 individual measurements, was selected for model calibration purposes. This set includes only wells with records spanning at least 10 years and having at least 10 measurements during the calibration period. Measurements from the months of June, July, and August were removed to reduce impacts on the simulation from localized pumping. Additionally, in model cells with multiple monitoring wells, records from wells containing the most measurements were retained to limit spatial bias during calibration. In a few instances, the water-level records appeared to be from the same well but at a different location, and only the well with the most records was retained in these cases. The location of the observation wells is presented in Figure 6-1. Review of the groundwater-level hydrographs, and the map of groundwater-level change (Figure 3-4), reveals relatively steady levels and fluctuations generally within a narrow range. This is primarily due to relatively low pumping, a moderately high recharge rate and hydraulic conductivity and storage capacity, as well as substantial underflow into the model domain from the west. Because the water levels have remained relatively stable, the 2010 potentiometric surface (Figure 3-3) was selected as a qualitative calibration target to demonstrate reproducibility of the regional groundwater flow pattern.

From the groundwater level datasets, only one (USGS 410542096093501) could be identified to represent groundwater level in the bedrock units. Therefore, there is a paucity of data in the bedrock units, and consequently, the generalized potentiometric surface in the bedrock aquifer (Figure 3-9) is used to demonstrate reproducibility of the potentiometric surface configuration in layer 2.



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 6-1 - GROUNDWATER MONITORING WELLS USED FOR CALIBRATION

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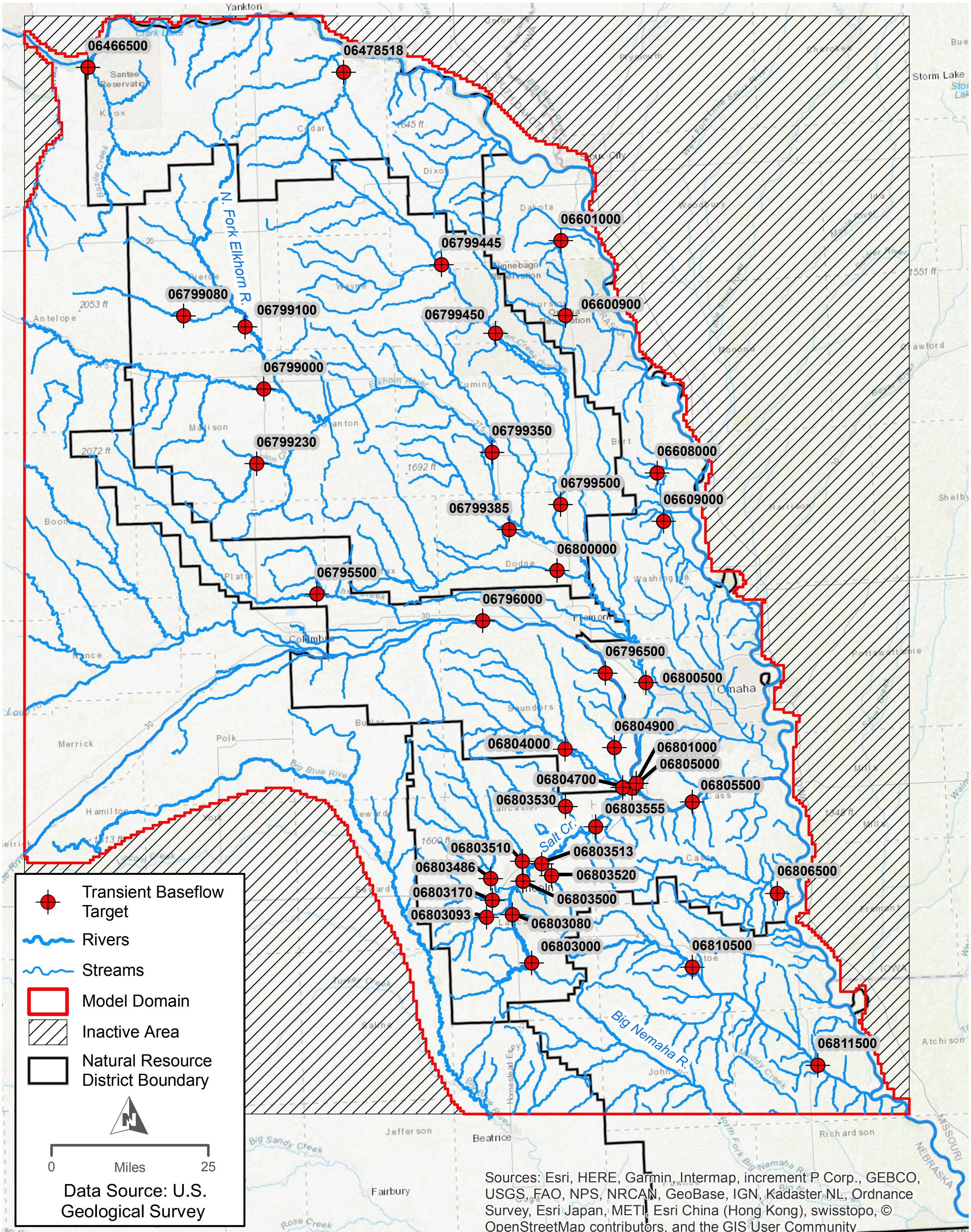
6.2.2 Stream Baseflow

The study team selected 40 USGS streamflow gaging stations within the model domain for calibration targets. These stations have recorded continuously over most of the calibration period. There are many sites at which recording of the streamflow commenced prior to 1960. The baseflow at these sites was used to aid in calibration of the predevelopment and transient periods. Figure 6-2 shows the location of the gaging stations used as baseflow calibration targets. Because the groundwater model simulates only baseflow in the streams, baseflow was estimated from records of daily total streamflow via hydrograph separation. A key calibration target is the baseflow in the Platte River at the gaging station near Louisville, Nebraska (USGS ID: 06805500), prior to discharging into the Missouri River. It represents the summation of baseflow in not only all three major rivers in the study area (Elkhorn, Loup, and Platte) that merge upstream of this gaging station, but also the streamflow in all tributaries to these three rivers. Likewise, reach gains (of baseflows) between the upstream gages of these major streams and the downstream Louisville gage were assessed to gain an understanding of the baseflow generated within the interior of the model domain, irrespective of inflows into the domain where the major streams cross the western boundary. Upstream gages capturing the inflows include the gaging station on the Elkhorn River at Norfolk, Nebraska (USGS ID: 06799000), and the gaging station on the Platte River at North Bend, Nebraska (USGS ID: 06796000).

6.2.3 Synoptic Seepage Runs

The transient model included a comparison of simulated stream baseflow to spot synoptic streamflow observations and measurements at 90 known or suspected perennial headwater stream reaches, collected by NDNR staff during a low-flow period in late October 2014. The survey was performed to evaluate the level of reproducibility of the baseflow at locations other than the streamflow gaging stations. From 63 reaches, semi-quantitative observations about the channel characteristics and flow (or wetness) were recorded as one of three options: wet, ponding, or dry. Stream baseflow was measured at 27 reaches within the model domain during the synoptic survey. The locations of the two sets of seepage run sites compared to the location of simulated streams are presented in Figure 6-3.

The primary objective of the comparison was to ensure that the model qualitatively simulated the existence of baseflow when streamflow was observed, and vice versa. The data were reviewed to ensure representativeness of the groundwater system because there was a precipitation event prior to the field visit, and several sites have elevations above the mapped regional water table (based on 2010 potentiometric surface), which could indicate local perched aquifer conditions in some cases, potentially indicating that observed flows were not caused by discharge of groundwater from a regional aquifer. Furthermore, due to the recent rainfall event, the measured streamflow could actually have been derived from overland flow into the streams and/or ponded rainwater rather than baseflow discharging from the groundwater system. Despite there being a number of sites in which representativeness were questioned, the comparison was made using all available data.



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 6-2 - SELECTED STREAMFLOW GAGES USED FOR MODEL CALIBRATION

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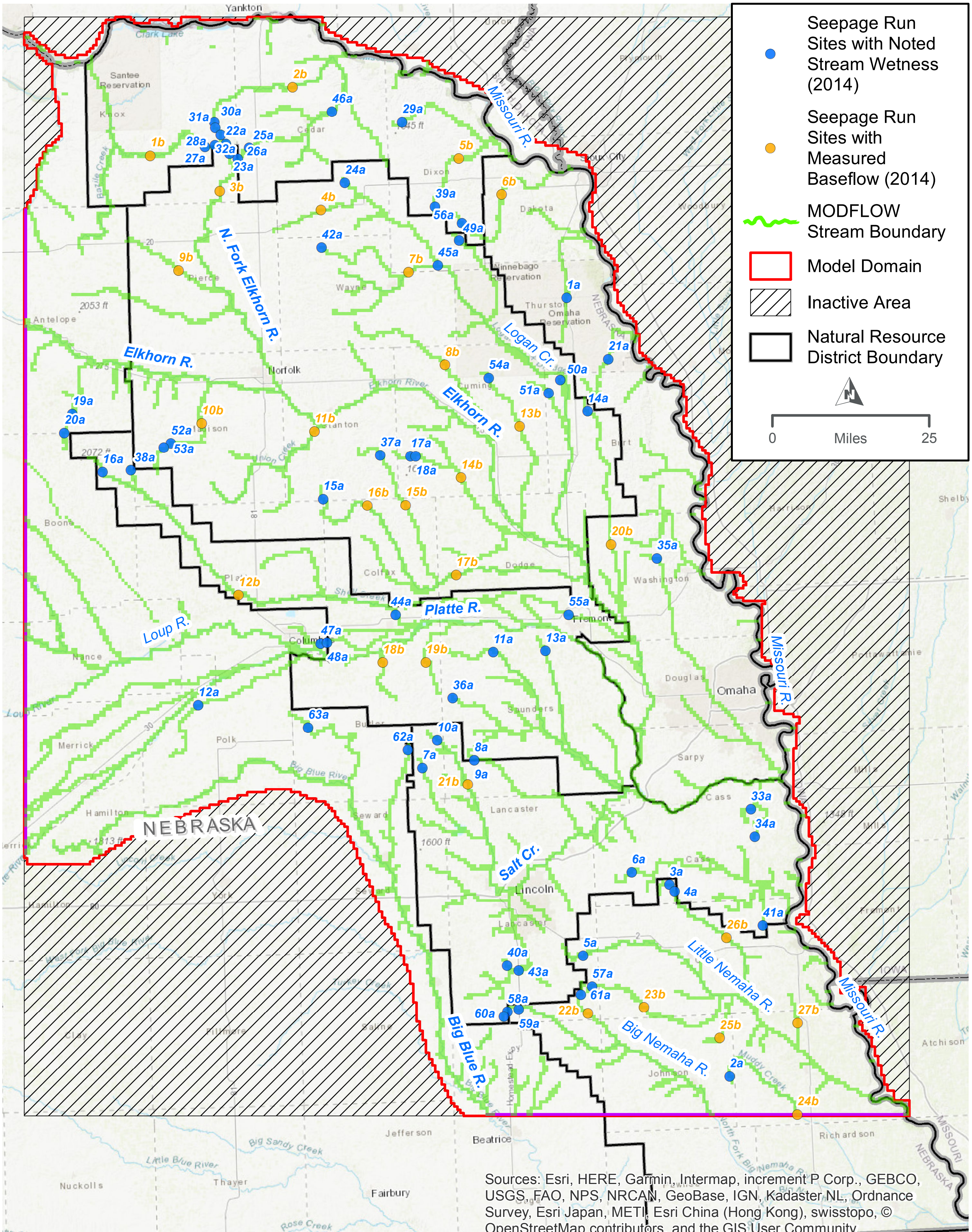

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FIGURE 6-3 - LOCATION OF SYNOPTIC SEEPAGE RUN SITES

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6.3 Calibration Criteria and Goals

The following criteria were established as the model calibration goals:

1) The model should have a volumetric water budget error that is less than 1 percent (Anderson et al. 2015). The water budget error is defined as the total inflow minus the total outflow, divided by either the inflow or outflow, whichever yields the highest error.
2) The model simulated water budget should be reasonably consistent with the conceptual water budget that was presented in Table 3-1.
3) The Normalized Root Mean Squared Error (NRMSE) should be less than 10 percent, with a goal of achieving less than 5 percent. An NRMSE of less than 10 percent is generally considered appropriate for a calibrated groundwater flow model. A lower NRMSE indicates a better statistical model calibration. The NRMSE is described as the standard deviation of the groundwater level residuals divided by the range of measured groundwater levels. Residuals are simply the differences between each simulated and measured variable of interest.
4) The model should have a random (spatial) error distribution. A plot of the Mean Error (ME; residual versus observed values) should indicate no obvious trends. The ME is a measure of overall model bias between simulated and measured groundwater levels and should be attempted to be reduced to a value as close to zero as possible.
5) There should be a reasonable visual match between the model simulated and measured potentiometric surfaces. When calibrated, the model should be able to reproduce the direction and magnitude of the hydraulic gradient observed within the study area.
6) The model should simulate stream baseflows approximately equal to the baseflows derived from observed streamflow hydrographs. This analysis was extended to include a comparison between baseflow gains in a large interior reach, but no calibration criteria were established.
7) The model should generally (qualitatively) simulate the existence or absence of baseflow at sites where a synoptic survey was performed of the low-flow streamflow conditions.

6.4 Calibration Parameters and Initial Values

The horizontal hydraulic conductivity, recharge, streambed conductance, leakance between model layers 1 and 2, and the specific yield/storage were varied during model calibration.

The following sections summarize the selected approach implemented for the initial parameterization of the calibration parameters. The final calibrated parameter values are presented in Section 6.8.

6.4.1 Recharge

Sensitivity simulations indicated that water levels and baseflows simulated are sensitive to groundwater recharge. As previously discussed, recharge varies in each MODFLOW model cell and in each stress period in accordance with the accounting of precipitation, surface runoff, irrigation, ET from the unsaturated zone, and soil water content in the watershed model. Therefore, to vary recharge in the groundwater model, it must be the result of adjustment of input parameters and general model improvements to the watershed model. This approach to the development of groundwater recharge rates ensures that all flows accounted for in the watershed model satisfied the conservation of mass principle.

It was not practical or technically defensible to adjust recharge in each model cell during calibration; therefore, 14 recharge zones were established by aggregating cells to reduce the number of calibration parameters to a manageable level. These recharge groups are related to the coefficient zones in the watershed model (Figure 4-12). During calibration of the groundwater model, the recharge in each of these zones was varied by a multiplier so as to reduce the calibration residuals. These multipliers were then considered in the watershed model to derive an improved estimate of recharge, matching those more closely required for the groundwater model, by varying key RSWB parameters related to precipitation and irrigation partitioning. Adjustment of the RSWB model parameters remained within a reasonable uncertainty range to derive new recharge estimates and simultaneously satisfied the surficial conservation of mass principle. Several such back-and-forth iterations were conducted during the calibration process. The final run of the watershed model provided the recharge rates applied on a cell-by-cell basis used directly in the final groundwater model run.

6.4.2 Hydraulic Conductivity

The selected calibration procedure allows horizontal hydraulic conductivity in the principal aquifer to vary in each cell. As previously discussed, the hydraulic conductivity field in the principal aquifer was populated using the PEST Pilot Point methodology (Doherty et al. 2010). A total of 309 PEST pilot points were used at the locations shown in Figure 5-10, and each of these pilot points is a calibration parameter. Initially, each pilot point was provided a value of hydraulic conductivity equal to the average value of the K zone the pilot point falls inside, as described in Section 5.6.1. Within the bedrock units (layer 2), a single uniform hydraulic conductivity zone was established for all model cells with an initial value of 10 ft/d specified, and then varied manually during the calibration process. In both layers, the horizontal hydraulic conductivity is assumed to be laterally isotropic; that is, $K_x = K_y = K_H$. The vertical exchange of water between the layers is based on the leakance parameter.

6.4.3 Storage

A uniform specific yield value of 0.1 was initially assigned for layer 1. A constant value of 0.05 for specific storage was specified in layer 2. These parameters were varied manually during the calibration process.

6.4.4 Leakance

Based on initial sensitivity studies during the calibration process, three leakance zones were established as shown in Figure 5-12. Leakance governs the amount of groundwater exchanged between the principal and bedrock aquifers. An initial leakance value of 1.0E-05 day^{-1} was specified for all three leakance zones.

6.5 Approach

The calibration process combines a manual trial-and-error approach with automated iterative parameter estimation using PEST (Welther et al. 2015). The groundwater levels and baseflow hydrographs presented in Appendices C and D, constrained by reasonable bounds of recharge, were the calibration targets. The pilot points and recharge multipliers were the calibration parameters along with a single uniform value for the specific yield in the principal aquifer. The calibration methodology involved the following iterative approach:

- PEST optimization runs were first conducted, which resulted in a set of recharge and hydraulic conductivity values.
- The recharge rates achieved became targets during readjustment of key parameters in the watershed model.
- In an iterative process, the updated recharge distribution for the 54-year calibration period was then used in a new set of MODFLOW runs that resulted in another updated set of recharge rates and hydraulic conductivity values at the pilot points.
- A final model run of PEST was made whereby the final recharge values from the watershed model were applied, and only hydraulic conductivity was adjusted using PEST.

Early in the calibration process, the specific yield in the principal aquifer, the specific storage in the bedrock units, and the leakance between layers 1 and 2 were manually adjusted.

6.6 Calibration Performance Results

This section presents an evaluation of the transient model output for the model run that included the final iteration of CROPSIM and the RSWB model (the watershed model), which provided the final recharge used to force the groundwater model, and subsequent adjustment of hydraulic conductivity that improved the level of calibration. The evaluation consists of a comparison between the model simulated and observed groundwater levels and stream baseflows through the study area.

6.6.1 Groundwater Levels

Calibration criteria numbers 3 through 5 specify the head calibration goals. Table 6-1 presents the calibration statistics for all groundwater level observations (that is, head residuals) for the transient calibration period. A total of 1,080 wells were used, containing 83,575 targets, with a range of 1,014 feet. The calibrated model achieves a Root Mean Squared Error (RMSE) of 13.5 feet and a 1.3 percent NRMSE, which exceeds the 10 percent calibration criteria. The ME is approximately 3.5 feet, indicating a slight overall under-estimation of groundwater levels. At all groundwater level observation wells, the absolute value of the time-averaged head residuals are less than 59 feet, and 62 percent (665 out of 1,080) are less than 10 feet. Figure 6-4 displays a histogram of the frequency of time-averaged head residuals, which again indicates a slight tendency toward under-estimation of the observed heads (positive residuals). Overall, these statistics indicate that the model is meeting the calibration goals. The location of all 1,080 groundwater level targets is presented in Figure 6-1, and the qualitative comparison of simulated and observed groundwater levels can be made by examining hydrographs in Appendix C. The simulated and observed groundwater level hydrographs at nine select wells are shown in Figure 6-5, providing a qualitative comparison of the overall pattern and trends in groundwater levels scattered around the model domain.

Table 6-1. Model Calibration Statistics for Groundwater Levels in the Principal Aquifer

Calibration Metric	Value
Root Mean Squared Error, RMSE (feet)	13.48
Normalized Root Mean Squared Error, NRMSE (%)	1.33
Range of Observed Groundwater Levels (feet)	1,014.01
Mean Absolute Error, MAE (feet)	9.86
Mean Error, ME (feet)	3.47
Minimum Head Residual (feet)	-118.60
Maximum Head Residual (feet)	150.86
Number of Observations	83,575
Number of Observation Wells	1,080

Notes:
Residuals calculated as observed minus simulated.

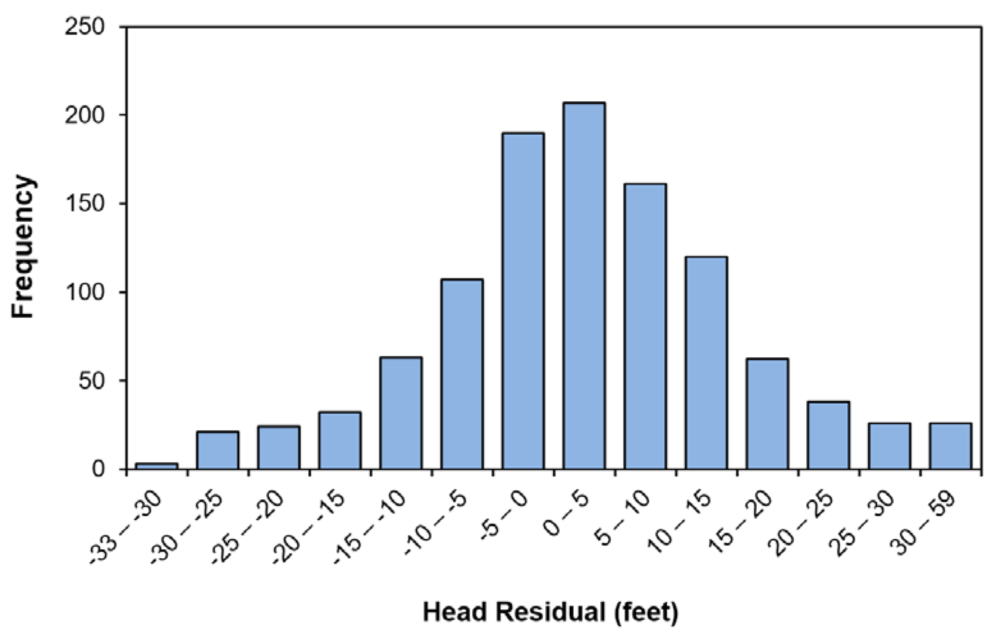
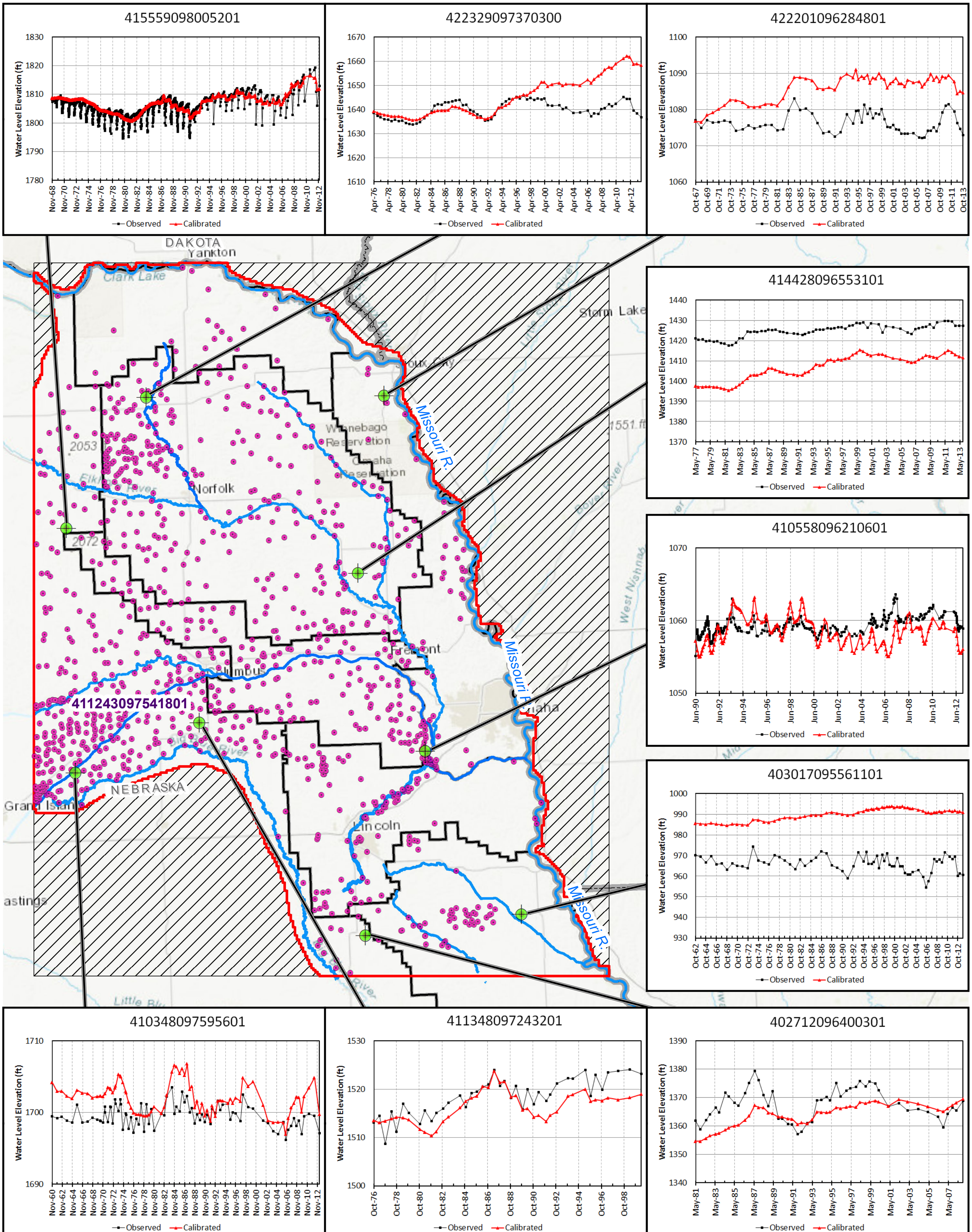


Figure 6-4. Histogram of Average Head Residuals



CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 6-5 - COMPARISON OF SELECT SIMULATED AND OBSERVED GROUNDWATER LEVEL HYDROGRAPHS

Examination of the groundwater level hydrographs indicates that, for the most part, the model reasonably approximates the absolute magnitude and dynamics of groundwater levels within the study area. Exceptions include an upward trend simulated in the northwestern portion of the LENRD that is not observed, as well as examples of over-estimation and under-estimation of absolute hydraulic heads sparsely scattered around the study area at sites where groundwater level trends are approximated reasonably well. A plot of the time-averaged simulated versus observed groundwater levels is presented as a scatterplot in Figure 6-6, and the time-averaged head residuals versus observed groundwater level are shown as a scatterplot in Figure 6-7. These plots indicate that the simulated groundwater levels follow closely those observed and that there are no apparent trends in simulated groundwater levels with change in elevation, with the exception where the model under-estimates heads at observed elevations above approximately 1,550 feet NAVD88. Figure 6-8 presents the areal distribution of the average head residuals. There are some areas in which the average residuals indicate a tendency of bias, including under-estimation of observed heads in the northwestern portion of the domain along the Elkhorn River. Conversely, Figure 6-8 indicates a slight tendency for the model to over-estimate heads in clusters of wells north of the Elkhorn River, north of the Loup River, in a region between the confluence of the Loup River with the Platte River and Salt Creek, and along the southern side of Salt Creek.

The simulated potentiometric surface of the principal aquifer for spring 2010 is shown in Figure 6-9, which in general compares favorably with the interpreted potentiometric surface map for 2010 (Figure 3-3). The magnitude and direction of the hydraulic gradient are reasonably reproduced by the model, indicating that calibration goal 5 has been met. The simulated and measured groundwater levels at this site are presented in Appendix C, from which a satisfactory match can be inferred. The average head residual at this site is -7.6 feet. The simulated potentiometric surface in the bedrock aquifers (layer 2) is presented in Figure 6-10 and generally compares favorably with the estimated potentiometric surface presented in Figure 3-9. In general, the simulated (west to east) groundwater flow gradients are reproduced reasonably well by the model.

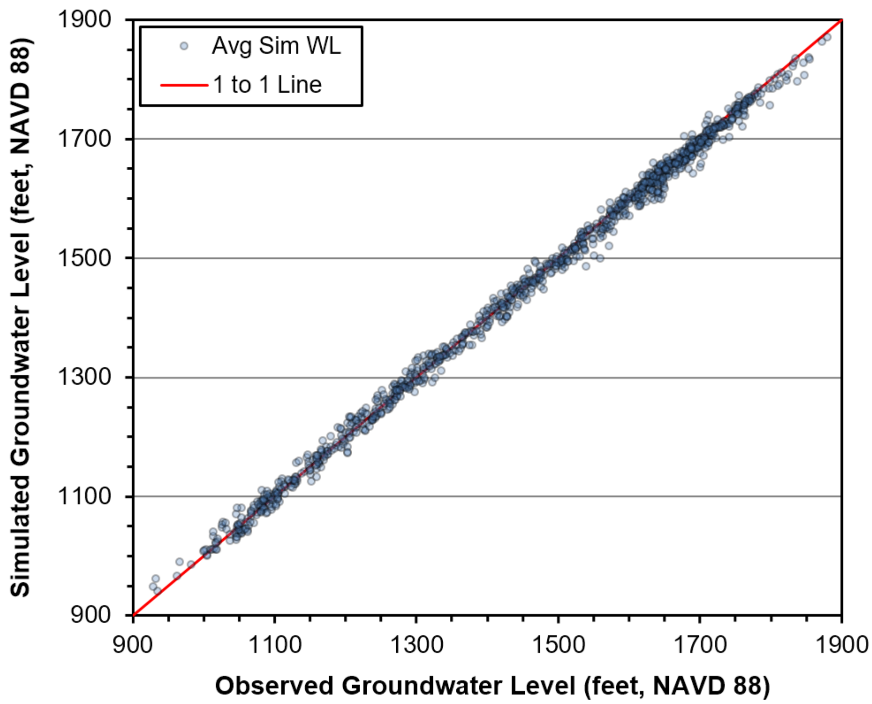


Figure 6-6. Time Averaged Simulated and Observed Groundwater Levels

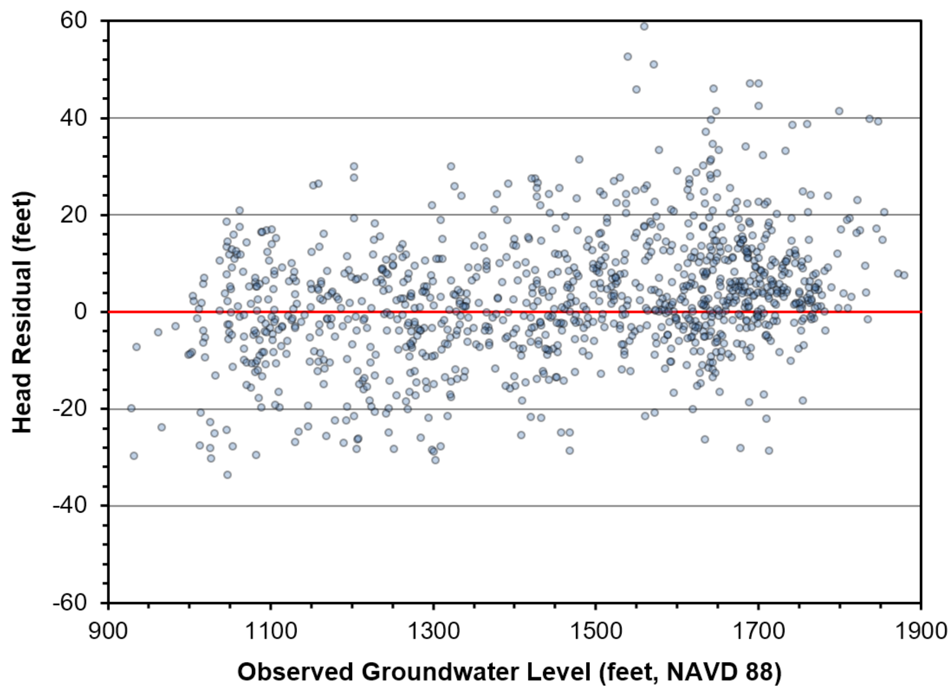


Figure 6-7. Time Averaged Head Residuals as a Function of Observed Groundwater Level

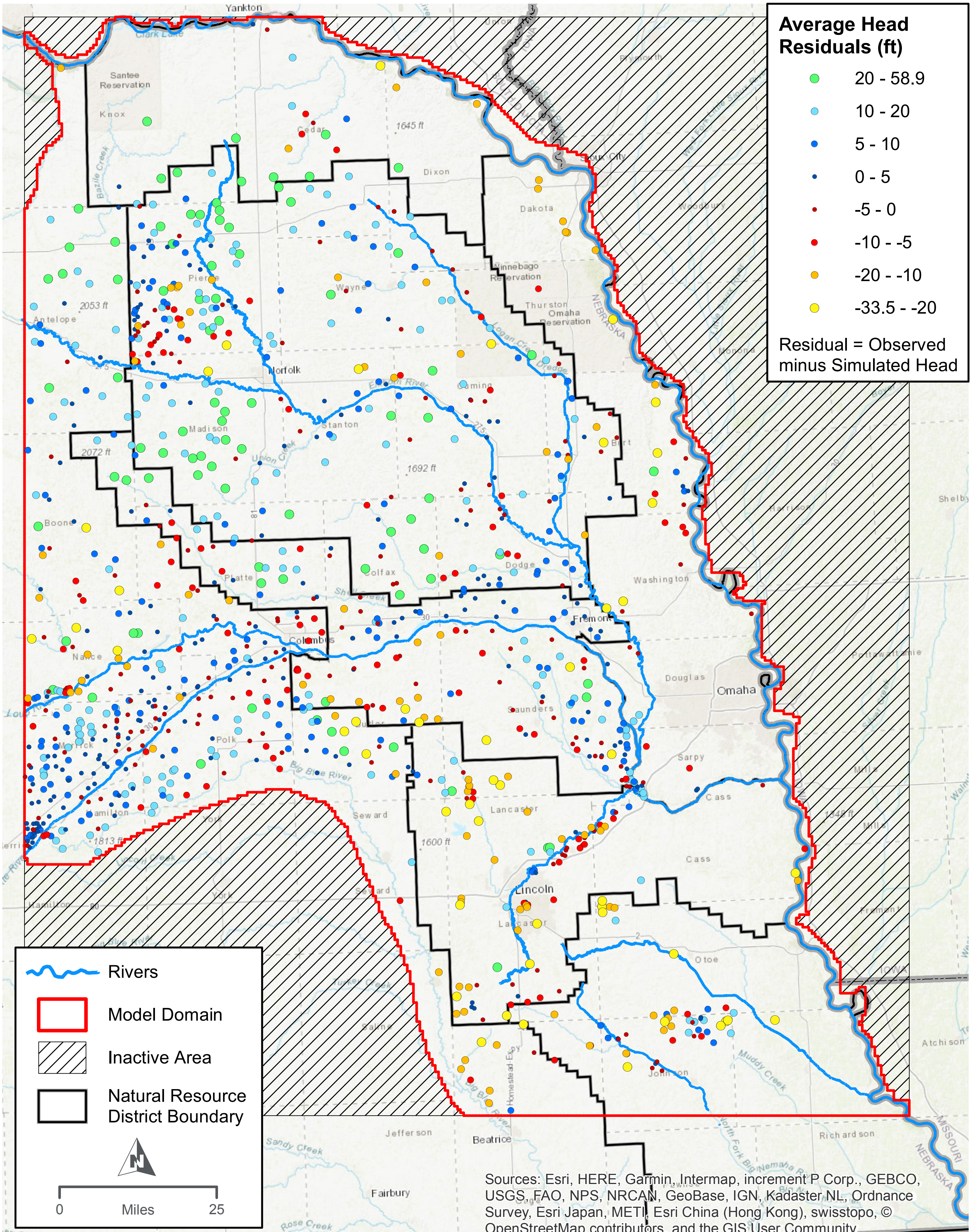


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FIGURE 6-8 - TIME AVERAGED HEAD RESIDUALS OF GROUNDWATER LEVEL TARGETS

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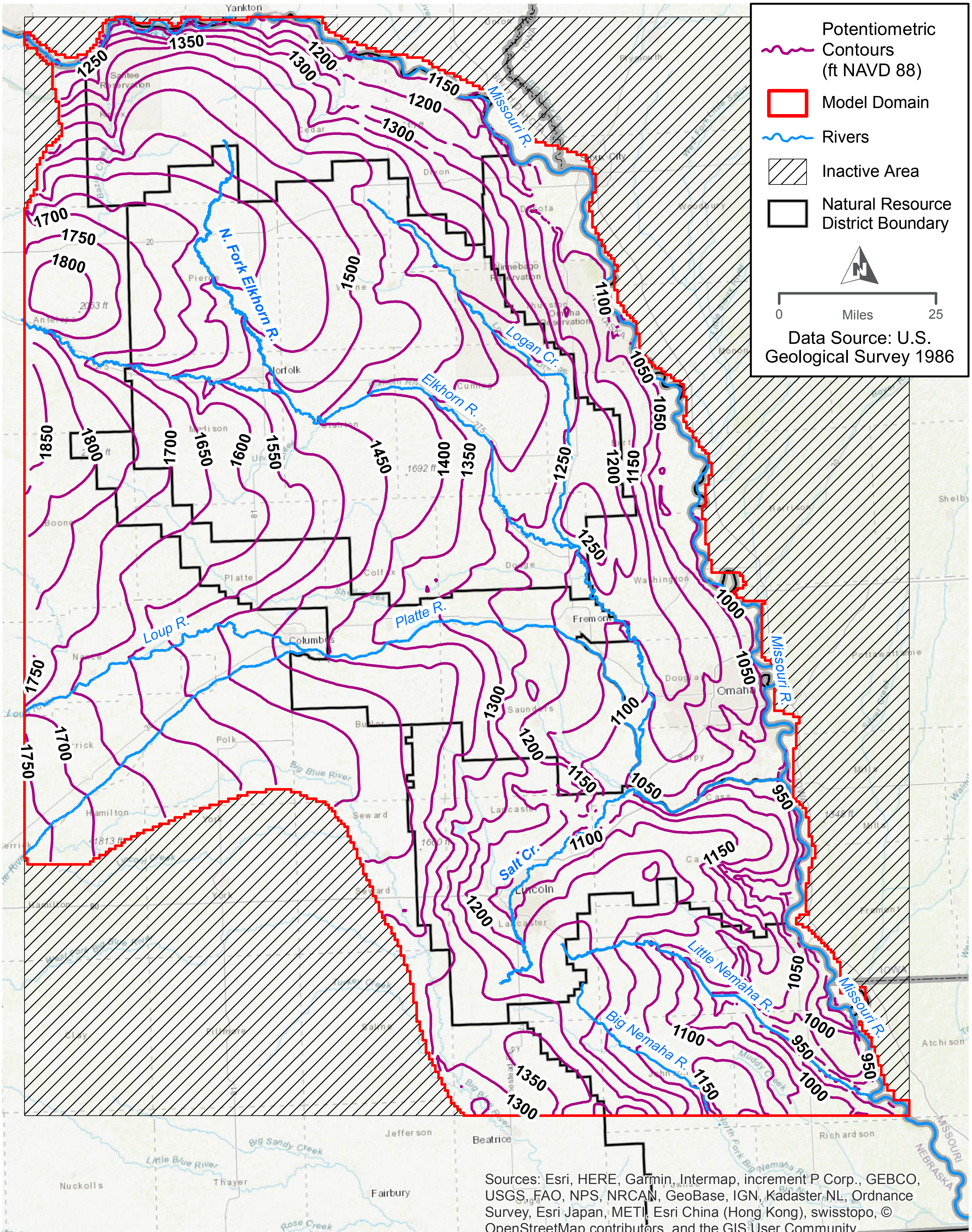

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

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FIGURE 6-9 - SIMULATED WATER TABLE OF THE PRINCIPAL AQUIFER, SPRING 2010

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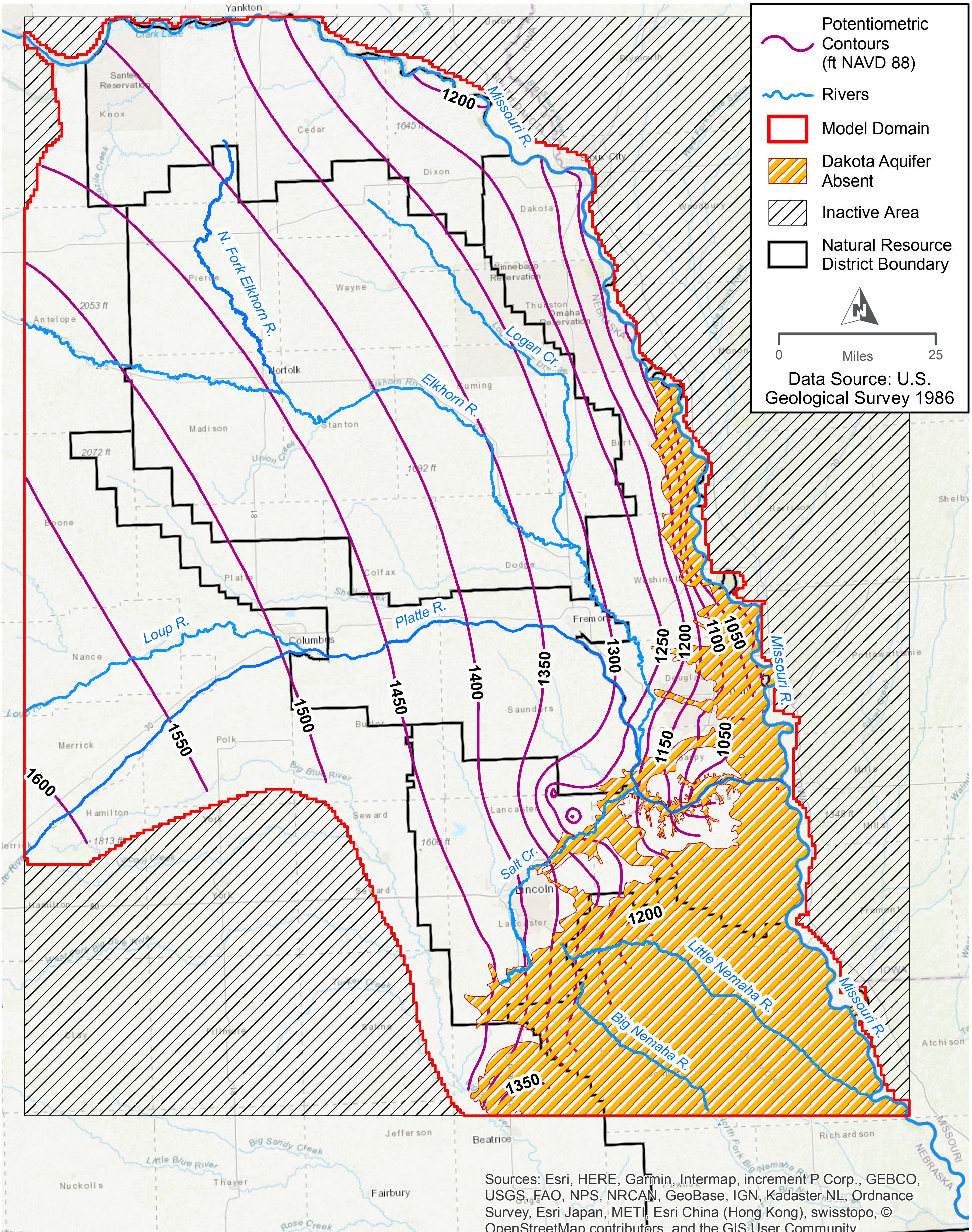

CENTRAL AND NORTHERN LOWER PLATTE & MISSOURI TRIBUTARY BASIN MODEL

FIGURE 6-10 - SIMULATED POTENTIOMETRIC SURFACE OF THE BEDROCK AQUIFER, SPRING 2010

6.6.2 Stream Baseflows

Calibration statistics for all baseflow residuals over the transient period are listed in Table 6-2. A total of 40 gaging stations were used, containing 9,787 baseflow targets, with a range in observed baseflows of 21,310.7 cubic feet per second (cfs). The calibrated model achieves an RMSE of approximately 550 cfs and a 2.6 percent NRMSE, as well as a 175 cfs Mean Absolute Error, indicating a reasonable quantitative match with the calibration targets. The ME is approximately 105 cfs, reflecting a relatively small under-estimation of baseflow relative to the large range in observed baseflow.

Table 6-2. Model Calibration Statistics for Stream Baseflows

Calibration Metric	Value
Root Mean Squared Error, RMSE (cfs)	553.5
Normalized Root Mean Squared Error, NRMSE (%)	2.60
Range of Observed Baseflows (cfs)	21,310.7
Mean Absolute Error, MAE (cfs)	175.1
Mean Error, ME (cfs)	104.8
Minimum Baseflow Residual (cfs)	-2,622.6
Maximum Baseflow Residual (cfs)	9,906.3
Number of Observations	9,787
Number of Observation Gages	40

Notes:
Residuals calculated as observed minus simulated.

The simulated and measured baseflow at nine select gaging stations are presented in Figure 6-11, and at all 40 gaging station are presented in Appendix D. In general, a suitable match can be inferred from the baseflow hydrographs, indicating that the model is capable of simulating the general observed trends as well as short-term (monthly) oscillations, and that calibration goal 6 has been satisfied. As discussed previously, the gaging station on the Platte River at Louisville (USGS ID: 06805500) reflects the accumulation of baseflow from most of the major streams in the model area prior to discharging into the Missouri River. The average percent error at this site is 21.8 percent, attributed primarily to an under-estimation of peak baseflows. This under-estimation of peak baseflows also occurs in the two adjacent NDNR models—the Central Nebraska (CENEB) model (Brown and Caldwell 2013) and the Blue River basins model (HDR 2013b)—and is thought to be caused by the necessary reliance on relatively coarse spatial and temporal discretization, and/or the difficulties inherent in deriving accurate baseflow from stream hydrograph separation techniques.

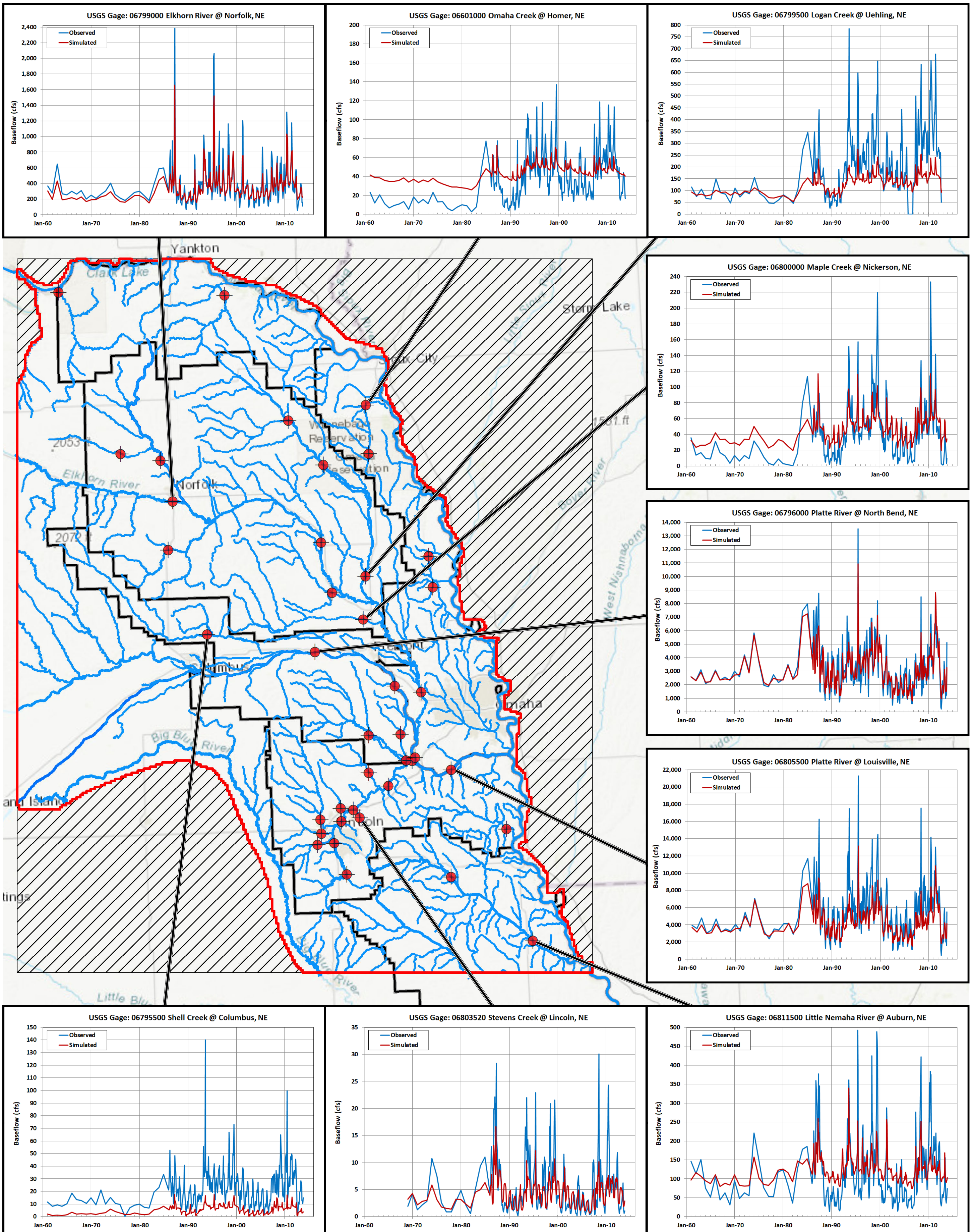

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FIGURE 6-11 - COMPARISON OF SELECT SIMULATED AND OBSERVED BASEFLOW HYDROGRAPHS

A slightly different comparison of the hydrologic functioning of the model compared to that estimated from observed streamflow data is that between reach baseflow gains, based on inflows and outflows from upstream gage(s) and a downstream gage, respectively. The comparison was made using the upstream gages on the Elkhorn River at Norfolk and on the Platte River at North Bend, and using the downstream gage on the Platte River at Louisville. Selection of these gages results in a reach represented accounting for baseflow gains along Salt Creek, Logan Creek, and portions of the Elkhorn and Platte Rivers, as wells as other contributing tributaries. Figure 6-12 depicts the location of the three selected gages and the observation-based estimated and simulated baseflow gains through the 54-year calibration period. While the comparison indicates that the simulated gains have a much smaller variability than estimated, in general the magnitude of the long-term averages are similar, and the model performs well in matching temporally the periods with higher, and lower, magnitude baseflow gains estimated from hydrograph separation.

6.6.3 Synoptic Seepage Runs

The primary objective of the comparison was to ensure that the model qualitatively simulated the existence of baseflow when stream baseflow was observed, and vice versa. The range, average, and October 2013 simulated baseflow and the observed streamflow or flow conditions at the 90 sites surveyed during the site visit in October 2014 are listed in Table 6-3. Out of the 67 sites where flow was either measured or noted as “wet,” the model was able to reproduce flow at 21 sites. Conversely, there were a total of 66 sites in which no flow was simulated, whereas 23 sites were observed with no flows “dry” or “ponding” conditions. Of the 27 sites with measured baseflow, the average flow residual between the observed rate and the average simulated rate is approximately 4.5 cfs, with a range of observed flow rates of 41.6 cfs. The ability of the model to capture the spatial variation and magnitude in seepage run flows at headwater streams is bolstered by the fact that only a fraction of the synoptic survey sites may be observations representative of groundwater discharge. These reasons have been discussed previously in Section 6.2.3.

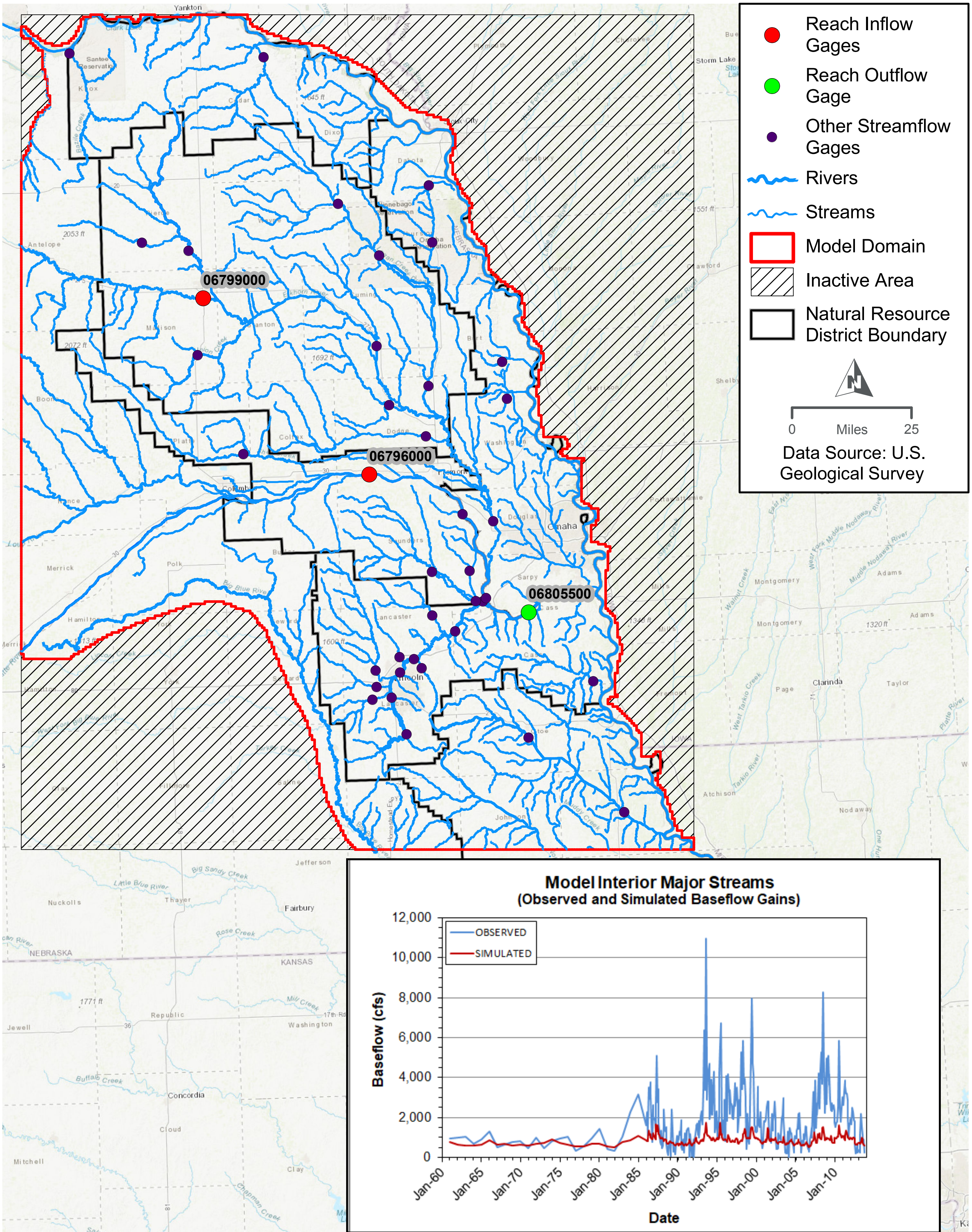

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FIGURE 6-12 - SIMULATED AND OBSERVED INTERIOR REACH BASEFLOW GAINS

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Table 6-3. Synoptic Seepage Run Flows Compared to Simulated Baseflows

Site ID[1]	Stream Name	Wetness / Measured Flow (cfs)	Simulated Baseflow (cfs)				Flow Residual as Obs - Sim (cfs)
			Minimum	Maximum	Average	October 2013	
1a	Omaha Creek	Wet	5.70	21.54	11.73	8.93	n/a
2a	Muddy Creek	Wet	0	0	0	0	n/a
3a	North Fork Little Nemaha River	Wet	0	0	0	0	n/a
4a	North Fork Little Nemaha River	Wet	0	0.40	0	0	n/a
5a	Little Nemaha River	Ponding	0	0	0	0	n/a
6a	Weeping Water Creek	Wet	0	0	0	0	n/a
7a	Oak Creek	Ponding	0	0	0	0	n/a
8a	Wahoo Creek	Dry	0	0	0	0	n/a
9a	Rock Creek	Wet	0	0	0	0	n/a
10a	North Oak Creek	Ponding	0	0	0	0	n/a
11a	Sand Creek	Wet	0	0	0	0	n/a
12a	Clear Creek	Dry	0	0	0	0	n/a
13a	Silver Creek	Wet	0	0	0	0	n/a
14a	Bell Creek	Wet	0	0	0	0	n/a
15a	West Fork Maple Creek	Wet	0	0	0	0	n/a
16a	Shell Creek	Wet	0	0	0	0	n/a
17a	Pebble Creek	Wet	0	0	0	0	n/a
18a	Pebble Creek	Ponding	0	0	0	0	n/a
19a	Cedar Creek	Ponding	0	0	0	0	n/a
20a	Cedar Creek	Ponding	0	0	0	0	n/a
21a	South Blackbird Creek	Wet	6.27	25.49	13.17	10.93	n/a

Site ID[1]	Stream Name	Wetness / Measured Flow (cfs)	Simulated Baseflow (cfs)				Flow Residual as Obs - Sim (cfs)
			Minimum	Maximum	Average	October 2013	
22a	North Fork Elkhorn	Ponding	0	0	0	0	n/a
23a	North Fork Elkhorn	Wet	0	0	0	0	n/a
24a	Perrin Creek	Wet	0	3.49	0.60	1.66	n/a
25a	Bow Creek	Wet	0	0	0	0	n/a
26a	Bow Creek	Wet	0	0	0	0	n/a
27a	Little Bazile Creek	Wet	0	0	0	0	n/a
28a	Little Bazile Creek	Wet	0	0	0	0	n/a
29a	Aowa Creek	Wet	0	0	0	0	n/a
30a	West Bow Creek	Wet	0	0	0	0	n/a
31a	West Bow Creek	Wet	0	0	0	0	n/a
32a	West Bow Creek	Wet	0	0	0	0	n/a
33a	Eightmile Creek	Wet	1.38	12.92	3.49	1.73	n/a
34a	Fourmile Creek	Wet	0	0.92	0.09	0	n/a
35a	Big Papillion Creek	Dry	0	0	0	0	n/a
36a	North Fork Wahoo Creek	Dry	0	0	0	0	n/a
37a	East Fork Maple Creek	Wet	0	0	0	0	n/a
38a	North Shell Creek	Ponding	0	3.54	1.03	1.69	n/a
39a	Rattlesnake Creek	Wet	0	0	0	0	n/a
40a	Wittstruck Creek	Ponding	0	0	0	0	n/a
41a	Big Slough	Wet	0.48	3.33	1.31	1.11	n/a
42a	Dog Creek	Wet	0	0	0	0	n/a
43a	Salt Creek?	Wet	13.52	42.10	21.12	16.54	n/a

Site ID[1]	Stream Name	Wetness / Measured Flow (cfs)	Simulated Baseflow (cfs)				Flow Residual as Obs - Sim (cfs)
			Minimum	Maximum	Average	October 2013	
44a	Shell Creek	Wet	0	84.66	28.06	21.33	n/a
45a	South Logan Creek	Wet	6.13	74.42	28.00	26.3	n/a
46a	Bow Creek	Wet	10.02	64.29	24.73	33.22	n/a
47a	Lost Creek	Ponding	5.75	46.13	17.33	14.88	n/a
48a	Lost Creek	Ponding	6.24	51.32	19.11	16.33	n/a
49a	Middle Creek	Wet	0	0	0	0	n/a
50a	Logan Creek Dredge	Ponding	54.97	244.76	114.60	102.07	n/a
51a	Little Logan Creek	Wet	0	0	0	0	n/a
52a	Battle Creek	Wet	0	0	0	0	n/a
53a	Battle Creek	Dry	0	0	0	0	n/a
54a	Cuming Creek	Ponding	0	0	0	0	n/a
55a	Rawhide Creek	Wet	2.10	25.97	7.21	3.39	n/a
56a	Elk Creek	Wet	0	0	0	0	n/a
57a	South Fork Little Nemaha River	Ponding	0	0	0	0	n/a
58a	Middle Branch Big Nemaha River	Ponding	0	0	0	0	n/a
59a	Middle Branch Big Nemaha River	Wet	0	0	0	0	n/a
60a	Middle Branch Big Nemaha River	Ponding	0	0	0	0	n/a
61a	North Fork Big Nemaha River	Ponding	0	0	0	0	n/a
62a	Plum Creek	Wet	0	0	0	0	n/a
63a	North Branch Big Blue	Ponding	0	0	0	0	n/a
1b	West Bow Creek	11.90	0.08	6.76	2.81	10.63	1.27
2b	Little Bazile Creek	11.70	0	0	0	0	11.70

Site ID[1]	Stream Name	Wetness / Measured Flow (cfs)	Simulated Baseflow (cfs)				Flow Residual as Obs - Sim (cfs)
			Minimum	Maximum	Average	October 2013	
3b	South Creek	38.00	1.43	27.81	11.91	13.04	24.96
4b	Elkhorn River, North Fork	6.73	0	0	0	0	6.73
5b	Elk Creek	36.10	0.52	10.25	3.95	3.51	32.59
6b	Middle Logan Creek	2.92	0	0	0	0	2.92
7b	Dry Creek	5.33	0	6.56	2.07	3.03	2.30
8b	South Logan Creek	42.60	15.03	74.82	29.90	29.11	13.49
9b	Plum Creek	14.60	0	4.36	1.32	1.14	13.46
10b	Battle Creek	1.82	0	0	0	0	1.82
11b	Cuming Creek	5.77	0	0	0	0	5.77
12b	Union Creek	17.40	4.36	133.92	36.72	35.45	-18.05
13b	Pebble Creek	6.88	0	16.07	5.30	6.47	0.41
14b	Maple Creek, West Fork	5.82	0	0	0	0	5.82
15b	Maple Creek, East Fork	9.76	0	0	0	0	9.76
16b	Bell Creek	38.80	0.49	3.65	1.25	1.13	37.67
17b	Maple Creek	32.40	9.07	78.53	33.33	30.31	2.09
18b	Shell Creek	10.60	0	56.52	5.32	1.40	9.20
19b	Bone Creek	3.26	0	0	0	0	3.26
20b	Skull Creek	3.47	0	21.11	12.55	15.34	-11.87
21b	North Oak Creek	10.68	12.31	45.21	28.38	31.18	-20.50
22b	Little Nemaha, North Fork	7.52	8.52	50.23	15.94	13.03	-5.51
23b	Little Nemaha, South Fork	1.44	2.02	32.43	7.40	4.27	-2.83
24b	Big Nemaha, North Fork	1.00	0	0.83	0.01	0	1.00

Site ID[1]	Stream Name	Wetness / Measured Flow (cfs)	Simulated Baseflow (cfs)				Flow Residual as Obs - Sim (cfs)
			Minimum	Maximum	Average	October 2013	
25b	Rock Creek	3.51	1.41	19.94	6.11	4.85	-1.34
26b	Spring Creek	1.52	0.54	3.95	1.82	1.44	0.08
27b	Muddy Creek	3.04	1.43	28.89	7.67	5.96	-2.92

Note:

1 Refer to Figure 6-3 for seepage run site locations. Stream surveys (for wetness) and streamflows were conducted by NDNR staff between October 22 and October 24, 2014. Two groups (a and b) are included in this table. Group a includes locations where the relative stream wetness was observed, whereas group b includes locations where streamflow was measured.

6.7 Water Budget

The volumetric water budget for the predevelopment simulation period is presented in Table 6-4. Approximately 2,360 cfs infiltrates into the system from precipitation and excess irrigation, and a net inflow of 460 cfs occurs as boundary flux (primarily from the west), for total net inflow of 2,820 cfs. Of this, 1,750 cfs exits the groundwater system through streams, and 410 cfs leaves the system primarily into the Missouri River along the eastern boundary.

Table 6-4. Model Volumetric Water Budget for Steady-State Predevelopment Conditions

Component	In		Out		Net	
	ac-ft/yr	cfs	ac-ft/yr	cfs	ac-ft/yr	cfs
Storage	0	0	0	0	0	0
Wells	0	0	0	0	0	0
River Leakage	266,168	368	561,448	776	-295,280	-408
Stream Leakage	487,706	674	1,753,792	2,422	-1,266,086	-1,749
ET	0	0	522,573	722	-522,573	-722
GHB	373,752	516	43,548	60	330,204	456
Recharge	1,711,653	2,364	0	0	1,711,653	2,364
Total	2,839,279	3,922	2,881,361	3,980	-42,081	-58

Notes:
ac-ft/yr = acre-feet per year, cfs = cubic feet per second, ET = evapotranspiration, GHB = General Head Boundary

The average water budget for the 54-year simulation in both model layers is presented in Table 6-5. Approximately 4,490 cfs of net recharge enters the system via precipitation infiltration and percolation, while 440 cfs enters the model through GHBs. A total of 1,260 cfs is withdrawn by pumping, and a net storage increase (rising water levels) of 240 cfs exists (sign convention is described in the MODFLOW documentation; Harbaugh 2005). Approximately 490 cfs exits the system via the Missouri River, and a net discharge of 2,130 cfs occurs to streams. The average volumetric water budget error for the calibration period is 0.07 percent.

Table 6-5. Average Model Volumetric Water Budget for the 54-year Calibration Period

Component	In		Out		Net	
	ac-ft/yr	cfs	ac-ft/yr	cfs	ac-ft/yr	cfs
Storage	1,477,268	2,041	1,653,910	2,285	-176,642	-244
Wells	0	0	909,663	1,256	-909,663	-1,256
River Leakage	270,323	373	621,823	859	-351,500	-486
Stream Leakage	571,671	790	2,113,926	2,920	-1,542,256	-2,130
ET	0	0	592,528	818	-592,528	-818
GHB	382,508	528	63,798	88	318,710	440
Recharge	3,249,745	4,489	0	0	3,249,745	4,489
Total	5,951,514	8,221	5,955,649	8,226	-4,135	-6

Notes:
ac-ft/yr = acre-feet per year, cfs = cubic feet per second, ET = evapotranspiration, GHB = General Head Boundary

To estimate the relative rates of groundwater flow in the principal and bedrock aquifers, the average water budget volumetric flow rates in each of these units for the 54-year calibration period is presented in Tables 6-6 and 6-7, respectively. In the principal aquifer, 4,450 cfs infiltrates into the system as recharge, 200 cfs enters the model domain along the boundaries, and a net of 260 cfs enters layer 1 from the underlying bedrock units. The total inflow into the principal aquifer is approximately 7,960 cfs. Of this, 1,140 cfs exits the system due to pumping, 490 cfs discharges into the Missouri River, and 2,130 cfs discharges into various streams in the study area.

In contrast to the principal aquifer, groundwater flow in the bedrock units is more sluggish, as indicated in Table 6-7. Approximately 40 cfs percolates from the principal aquifer, and 300 cfs returns to other areas of the bedrock aquifer. Approximately 240 cfs enters the bedrock through the boundaries, along with a net loss of storage of 170 cfs, resulting in a total net inflow of about 80 cfs. Of this, about 110 cfs is pumped out of the system. As expected, the overall rates of groundwater flow in the bedrock units are much smaller than in the principal aquifer.

Table 6-6. Average Model Volumetric Water Budget for the 54-year Calibration Period in Layer 1

Component	In (cfs)	Out (cfs)	Net (cfs)
Bottom	301	39	262
Storage	1,807	2,219	-412
Wells	0	1,144	-1,144
River Leakage	373	859	-486
Stream Leakage	790	2,920	-2,130
ET	0	818	-818
GHB	238	41	197
Recharge	4,450	0	4,450
Total	7,959	8,041	-82

Notes:
cfs = cubic feet per second, ET = evapotranspiration, GHB = General Head Boundary

Table 6-7. Average Model Volumetric Water Budget for the 54-year Calibration Period in Layer 2

Component	In (cfs)	Out (cfs)	Net (cfs)
Top	39	301	-262
Storage	233	65	168
Wells	0	112	-112
GHB	291	47	244
Recharge	39	0	39
Total	602	526	76

Notes:
cfs = cubic feet per second, GHB = General Head Boundary

6.8 Calibrated Parameters

6.8.1 Hydraulic Conductivity

The calibrated horizontal hydraulic conductivity (K_H) distribution in the principal aquifer is presented in Figure 6-13. In most of the model, K_H varies between about 5 and 360 ft/d. The average conductivity in layer 1 is 83.8 ft/d, which is lower than the average of 232 ft/d estimated from the pump test data (HDR 2013a) and discussed earlier in Section 5.6.1. This is as expected because a majority of the pump tests were performed in the alluvium of major river valleys or the Todd paleovalley. In the bedrock aquifer, a uniform conductivity of 5 ft/d provided a good match to the observed data during model calibration. There are no known firm estimates of hydraulic conductivity in the bedrock formations.

A generalized comparison for the principal aquifer can be made between the test hole estimated hydraulic conductivity presented in Figure 3-5, with the model calibrated hydraulic conductivity in Figure 6-13. Overall, the model-calibrated hydraulic conductivity values are generally somewhat greater. Although not evident in the color schemes of the two figures, the overall magnitudes are similar in many areas. Notably greater values are in the lower reach of Salt Creek and between the Little and Big Nemaha Rivers. The calibrated K_H pattern is influenced by the location of the pilot points and the edges of the K zones. Despite these differences, the regionalized hydraulic conductivity values produce calculated groundwater levels, baseflows, and overall water budget results that are reasonably well approximated and well within the calibration criteria.

6.8.2 Recharge

As previously discussed, recharge is variable in each model cell and also varies in each stress period. The average recharge over the 54-year calibration period was presented in Figure 4-20. The final average recharge rate averaged over the study area and over the entire 54-year calibration period is 3.8 in per year. The initial estimated recharge was 4.7 in per year, prior to adjustment to improve calibration of the groundwater model.

A key calibration target that provides credence to the final calibrated recharge magnitude and distribution for a large majority of the model area was the baseflow in the Platte River at Louisville gaging station. Approximately two-thirds of the inflows from recharge to the model domain discharges into streams that all merge into the Platte River upstream of this gage. The simulated and observed baseflows at this gaging station over the calibration period are in close agreement, as discussed in Section 6.6.2.

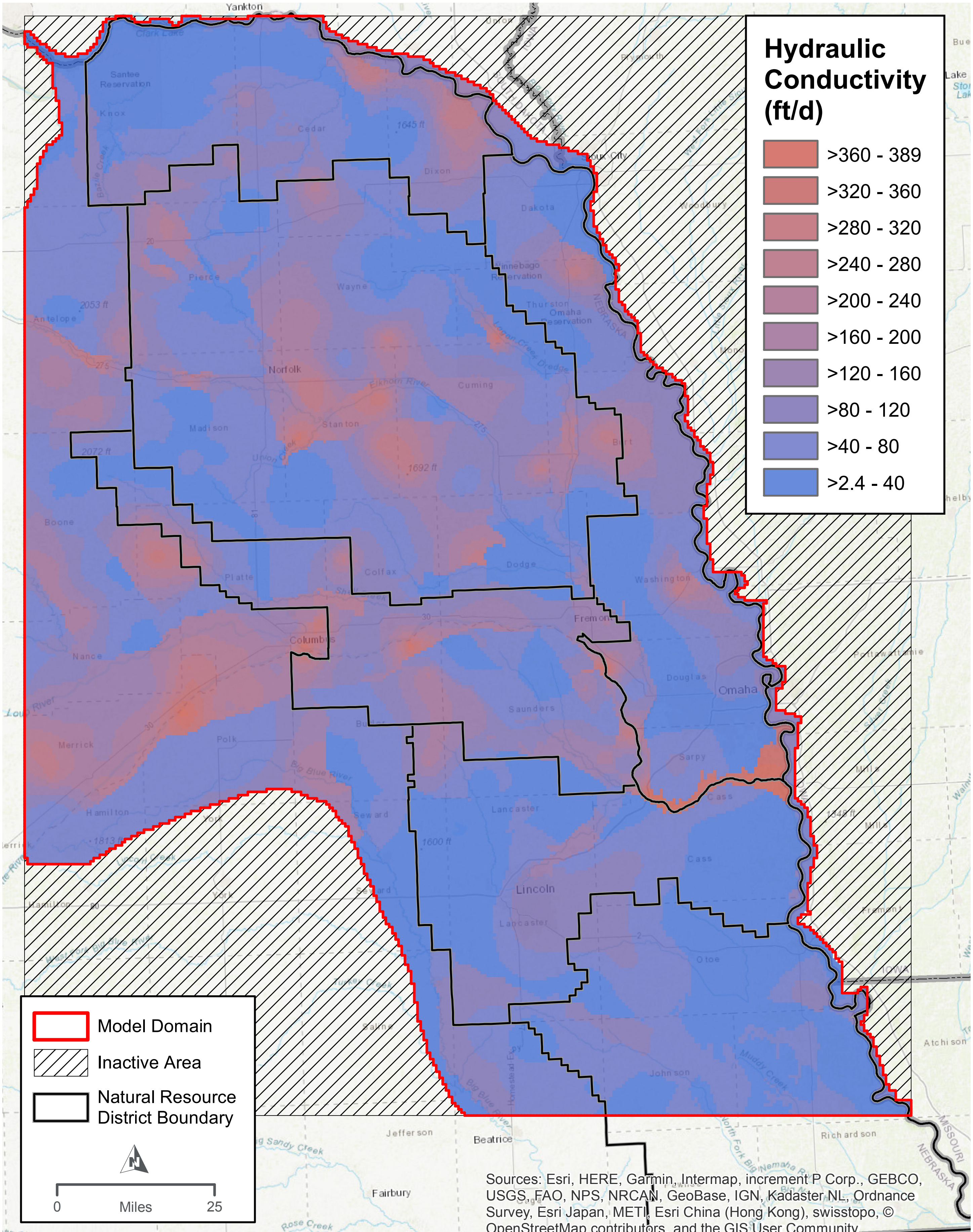

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FIGURE 6-13 - CALIBRATED HYDRAULIC CONDUCTIVITY

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6.8.3 Storage

The specific yield in the principal aquifer and storativity in the bedrock units were calibration parameters and were manually adjusted during the calibration process. A value of 0.15 for specific yield and 0.01 for storativity of the bedrock units provided a suitable match to the observed head and streamflow data.

6.8.4 Leakance

The final calibrated hydraulic leakance between layers 1 and 2 ranges from a low of 1E-06 per day in the western part to a relatively higher value of 5E-06 per day along the Missouri River.

7.0 Sensitivity Analysis

Sensitivity analyses have been conducted with the calibrated model to quantify and document the sensitivity of the model parameters on the simulation results. In particular, the sensitivity analysis quantifies the influence of changes in magnitude to model input parameters on the average residuals at the groundwater level calibration targets.

The following parameters were tested during the sensitivity analysis:

1) Horizontal hydraulic conductivity
2) Recharge rate
3) Specific yield
4) Streambed conductance

The results of the sensitivity simulations are presented in Figure 7-1. The calibrated heads are most sensitive to recharge and hydraulic conductivity, and are negligibly affected by variations in the storage coefficient (specific yield) and streambed conductance. These were the same conclusions from the previous CENEB (Brown and Caldwell 2013) and Blue River Basins (HDR 2013b) models, located west of the study area in Nebraska. As discussed above, recharge was well calibrated using the MODFLOW and watershed models. The magnitude of hydraulic conductivity is within the range of values calculated from aquifer tests and estimated from earlier LPMT studies (HDR 2013a). Therefore, the parameters that are the most sensitive are well derived in the LPMT model.

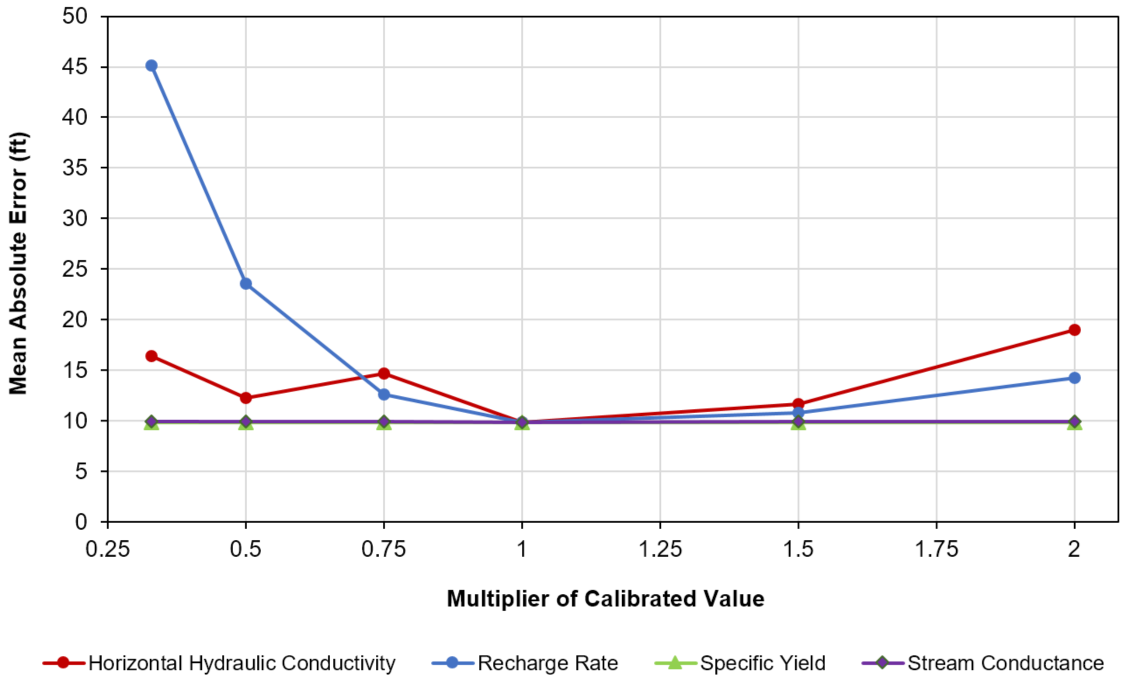

Figure 7-1. Sensitivity Analysis Results

8.0 Discussion

The approach to development and calibration of the LPMT groundwater model was more complex than for models in other parts of Nebraska. This is evident in the physiographic character of the LPMT study area being so diverse and different from other areas of the state. This difference causes agricultural irrigation to be a much smaller part of the overall water budget. As a result, the traditional approach of using CROPSIM to directly estimate pumping and recharge with a crop-based soil water budget had to be adjusted. The values of recharge from the watershed model were within ranges that are consistent with other groundwater models in Nebraska.

In the final stages of the iterative calibration process, the tightly constrained and accurate determination of the recharge and pumping values, and the target controls of water budget error, baseflow in particular, and groundwater levels, greatly constrained the potential variability of hydraulic conductivity. As shown in Figure 7-1, the sensitivity of hydraulic conductivity is much greater than specific yield and leakance. A review of the calibrated and estimated horizontal hydraulic conductivity values (Figure 6-13 and Figure 3-5, respectively) suggest that the final values in the study area are approximately within the range of values calculated from pump tests and estimates from test hole grain size/sorting in the LPMT study area (HDR 2013a). Of great importance, the regionalized hydraulic conductivity values produce calculated groundwater levels, baseflows, and global volumetric water budget flows that are well within the calibration criteria and are generally consistent with water budget flows determined prior to modeling. With this in mind, the central and northern LPMT groundwater model is considered to be calibrated and suitable for its intended use.

9.0 Model Application and Limitations

The primary purpose in the development of this groundwater model is to calculate the groundwater depletion component of NDNR's annual basin status evaluations. The central and northern LPMT model represents the balance of flows entering the model domain from recharge and underflow, and exiting as pumping, ET, and baseflow to surface water. This central and northern model of the LPMT basins is suited for the NRDs that are north of the Nemaha NRD. This area includes the Salt Creek watershed and other watersheds to the north. The southern LPMT (Nemaha Basin) model will be suited for the steam depletion analyses in the Nemaha NRD.

Limitations related to the intrinsic uncertainty of model simulations occur during all model studies, which are simplified representations of a real-world system. Groundwater model limitations can generally be grouped into several categories, including (1) limitations in the data supporting a model, (2) limitations in the implementation of a model that may include assumptions inherent to the model application, and (3) limitations regarding model applicability related to how well the model represents the physical system being modeled (that is, conceptual model bias). The major data limitation is believed to be the lack of reliable aquifer (pump) test data to estimate aquifer hydraulic properties and overall lack of characterization and definition of the bedrock aquifer (base and parameter values). The model has a simplified representation of the aquifers in space and the hydrologic conditions simulated in time. In this case, the horizontal spatial discretization is 0.5 mile by 0.5 mile, and the finest temporal discretization is 1 month. The design of the model and its calibration are structured to minimize the negative effects of the assumptions, or at least to not systematically bias the modeling results. Applicability of the model is best suited for analyzing groundwater-management scenarios over a regional spatial scale and a long-term temporal scale (generally no shorter than monthly). It is generally not suited for local-scale applications such as well field evaluation and designs, or for simulating baseflow to tributary streams smaller than the scale included in the stream package.

Comparisons were made between simulated and observed/estimated baseflows generated within a large area of the domain along a reach between gages on major streams and their numerous tributaries. Similarly, a comparison was made to investigate how well the model simulates baseflow generated within headwater portions of streams (seepage runs). These comparisons provide further indication that the model is capable of reproducing these flows, albeit with limited accuracy in some areas, perhaps largely explained by inaccuracies of estimating stream baseflow particularly during high flow periods, and by a limited representation of the flows to headwater stream reaches. Future attempts to improve estimates of baseflow at gages and near the headwater of streams would be helpful if paired with efforts to refine and more accurately match such hydrologic flows with regional groundwater models. Particularly, this study could have been improved if sampling of seepage run flows was conducted during low-flow periods, and within the same window of time as the model calibration period.

10.0 Summary

This report presents the construction and calibration of a groundwater flow model that was developed as a tool that will be used by NDNR to evaluate the effect of well pumping on stream baseflow in the LPMT in eastern Nebraska. The focus area of this model is the central and northern part of the Lower Platte River and Missouri River Tributary Basins, which includes six Nebraska NRDs. The objective of the project was to construct a groundwater model that approximates the transient baseflow conditions that have been measured from the major streams within the model domain, while replicating the transient groundwater changes as measured in wells located throughout the model domain. The foundation for the development of the groundwater flow model includes three earlier HDR reports. This report includes selective summaries from these earlier project reports.

The groundwater model presented was developed to support NDNR's annual evaluation of the expected long-term availability of surface water supplies and hydrologically connected groundwater supplies in the LPMT basins. The model was constructed so that the domain of the model would extend far enough outside of the boundaries of the NRDs to incorporate the physical boundaries of the aquifer system or any regional groundwater divides whenever practical. This was done intentionally to minimize any impact from boundary conditions on the simulation within the focus area of the model. The model was developed to assess the historic groundwater depletion component of the annual basin status assessment, meaning the model should be able to assess changes in stream baseflow that result from an increase in groundwater pumping. Therefore, the goal for development of the model was to characterize and simulate the regional-scale hydrogeological processes that regulate streamflow depletions due to pumping, and to provide an appropriate tool for use in regional-scale water management decisions. The model is generally not intended or suited for local-scale applications.

The calibration period spanned from January 1960 through December 2013. An annual temporal discretization (stress period) was implemented from 1960 through 1985, and was followed by monthly stress periods from 1986 through 2013. The first stress period in the model was assigned as steady state to reflect the assumption that prior to 1960 there was minimal development in the study area. The groundwater levels and streamflows during this predevelopment period fluctuate seasonally and annually based on climatic variations, but over the long term, the system was assumed to be in a state of dynamic equilibrium. The implementation of an initial steady-state stress period provided an equilibrium starting condition that was hydrologically consistent with the following transient simulations.

The model calibration is based primarily on comparison with 1,080 groundwater-level monitoring wells and baseflows derived from 40 streamflow gaging stations. The final list of wells and streamflow gages provides broad spatial coverage and adequate density of observation points across the model domain, while the gaging stations were selected to additionally provide adequate long-term records. The calibration also involved a qualitative comparison of reach gains and synoptic seepage run survey of streamflow conditions at headwater stream reaches. Calibration of the model included adjustments to horizontal hydraulic conductivity, recharge, streambed conductance, leakance between model layers 1 and 2, and the specific yield. Near the end of the calibration process, the recharge was finalized based on results from the RSWB model output (generating WEL and RCH files), and the streambed conductance, leakance, and specific yield parameters were determined to be largely insensitive. Thus, hydraulic conductivity in the principal aquifer (layer 1) became the primary calibration parameter.

The suitability of the groundwater model for the central and northern parts of the Lower Platte River and Missouri River Tributary Basins is based on its ability to reproduce the observation-based estimates of the water budget, groundwater levels, and stream baseflow in the LPMT basins. The objective of the model was to reproduce the historic transient baseflow conditions in the LPMT basins measured on the major streams, while also reproducing the transient groundwater level changes as measured in wells. The model achieves that objective reasonably well; therefore, the model appears adequate for use to calculate the groundwater depletions in NDNR's annual assessment of basin status and to evaluate groundwater-management scenarios over a regional scale.

11.0 References

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Appendix A. Work Plan for Final Model Modifications

Appendix B. Watershed Model Documentation

Appendix C. Simulated and Measured Groundwater Level Hydrographs

Appendix D. Simulated and Measured Baseflow Hydrographs