FINAL

GROUND WATER MODEL FOR THE BIG BLUE AND LITTLE BLUE RIVER BASINS

Nebraska Department of Natural Resources

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Ground Water Model For The Big Blue And Little Blue River Basins

1.0 Introduction and Background

The Nebraska Department of Natural Resources (Nebraska DNR) 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. This includes the Big Blue and Little Blue river basins (Basin).

Nebraska DNR has developed a new methodology to evaluate a basin's status. This new methodology involves using historic stream gage and diversion records to compute a natural flow hydrograph, or Basin Water Supply (BWS), for various stream reaches within a basin. The BWS is calculated from historic streamflow, historic surface water consumptive use, and historic groundwater depletions. Since this methodology requires the ability to assess historic groundwater depletions, Nebraska DNR is working to develop numerical models in areas which are currently not represented by numerical groundwater models. Tasked with performing these evaluations using the best available science and methods, Nebraska DNR has undertaken the development of a groundwater flow model for the Basin and has contracted with HDR Engineering, Inc. (HDR) to complete this work (DNR Contract Number 476), generally following the scope of work outlined by Nebraska DNR in request for proposal (RFP) Number 3750Z1. This document presents the groundwater flow model developed for the Big Blue and Little Blue river basins.

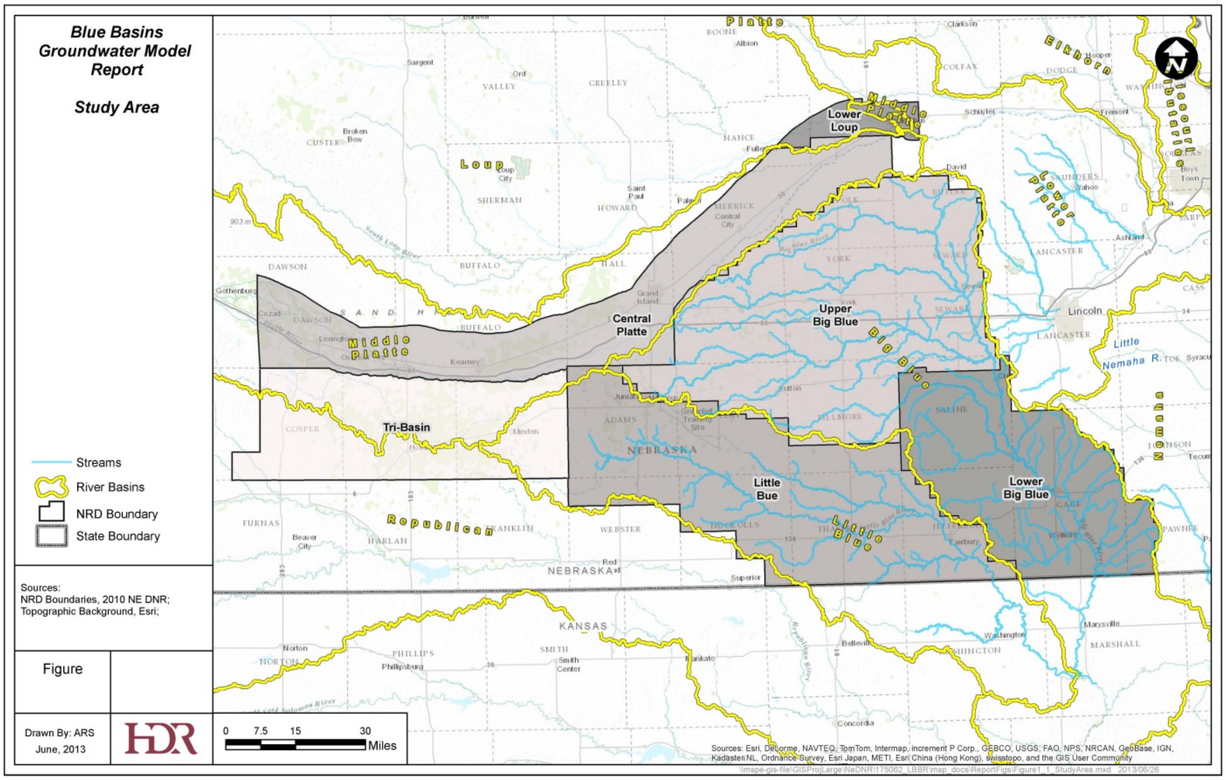
1.1 Project Purpose and Scope

The purpose of this project was to develop a groundwater flow model that can be used by Nebraska DNR to evaluate the appropriation status of the Basin. This report presents the construction and calibration of a groundwater flow model that was developed as a tool that can be used by Nebraska DNR to evaluate the effect of well pumping on stream base flow in the Big Blue and Little Blue river basins of south central Nebraska (see Figure 1-1). The focus area of the model includes the Little Blue Natural Resources District (NRD), the Lower Big Blue NRD, the Upper Big Blue NRD, and the eastern portion of the Tri-Basin NRD.

To achieve the project objective, the groundwater flow model must be able to reasonably reproduce the transient base flow conditions measured for the major streams within the Basin, while also reasonably reproducing the transient groundwater level changes as measured in wells located throughout the Basin. The objective of this model was not to reproduce every detail of the hydrogeologic system, but rater rather to develop a tool that can be used to evaluate groundwater-management scenarios over a regional spatial scale that includes multiple counties and a time period of multiple years. Development of the regional model focused on generalized hydrogeologic characteristics within the Basin and did not attempt to describe local-scale variations that can impact groundwater flow at the local scale. Due to the regional scale of the study, the model is not intended or suited for analysis of local scale problems, where the desired detail may require simulation of local aquifer heterogeneity or local aquifer stresses at a spatial and temporal scale that is smaller than the cell size and time steps used in this model.

This report describes the construction and calibration of the groundwater flow model developed to reproduce the observed changes to groundwater elevations and stream base flow within the Basin. The model was constructed in phases, including: 1) a steady state model to depict predevelopment, 2) a sensitivity analysis, and 3) a transient groundwater flow model to simulate a period from 1935 through 2011.

Figure 1-1 Study Area



1.2 Report Organization and Previous Documents

The report is organized as follows:

- Section 1.0 – Introduction
- Section 2.0 – Background and Conceptual Flow Model
- Section 3.0 – Model Construction
- Section 4.0 – Steady State Model
- Section 5.0 – Sensitivity Analysis
- Section 6.0 – Transient Model
- Section 7.0 - Summary

Previous reports were prepared by HDR that presented the datasets available to construct the groundwater flow model and the general procedure for construction and calibration of the groundwater flow model presented within this report. These reports include: 1) *Assessment of Available Datasets to*

Construct a Groundwater Model in the Blue River Basin (June, 2012), and 2) *Groundwater Model Development Plan for the Big and Little Blue River Basins* (August, 2012). Both reports are related to the groundwater flow model and therefore; for ease of reference, a copy of these reports has been included as Appendix A to this document.

Figures have been included within the body of this report following the reference of each figure. However, in an effort to improve the readability of the figures, a full size copy of the 11 inch by 17 inch figures is also included in Appendix B.

2.0 Background and Conceptual Flow Model

A conceptual model of the study area geology, hydrogeology, and hydrology is discussed in this section and forms the basis for development of the numerical model presented within this document.

2.1 Data Sources Available for Model Construction

A previous report prepared by HDR, *Assessment of Available Datasets to Construct a Groundwater Model in the Blue River Basin* (June, 2012), summarized the data sets that are available for model construction. This previous report is closely related to the Groundwater Model Development Plan and has been included as Appendix A to this document.

2.1.1 Georeferencing

Georeferencing is a procedure of adding geodetic information to individual images, vector files, drawings, map sheets, or a list of known points. To ensure that all data collected for the study are represented in the most accurate way possible, all data used in the study have been georeferenced. The coordinate system used for the study is the Nebraska State Plane Coordinate System of 1983 (in U.S. feet). It is based upon a network of geodetic control points referred to as the North American Datum of 1983 (NAD 83). The vertical datum used for the study was the North American Vertical Datum of 1988 (NAVD 88).

2.2 Surface Water Basin Description

In Nebraska, the Blue River Basin includes all surface areas that drain into the Big Blue River and the Little Blue River and all aquifers that impact surface water flows of the basins. The total area of the Blue River surface water basin in Nebraska is approximately 7,100 square miles of which 4,600 square miles are in the Big Blue River Basin and 2,500 square miles are in the Little Blue River Basin. The Blue River Basin is subdivided based on the drainages of the two major surface water bodies within the Basin, the Big Blue and Little Blue rivers. NRDs with significant area in the basins are the Little Blue, the Lower Big Blue, the Upper Big Blue, and the Tri-Basin NRDs. The Basin boundary is shown in Figure 1-1.

The Blue River Basin is subdivided based on the drainages of the two major surface water bodies within the Basin, the Big Blue and Little Blue rivers. These basins are described below.

2.2.1 Big Blue River Basin

The Big Blue River is located in south central Nebraska and flows into Kansas where it becomes a tributary of the Kansas River. Major tributaries of the Big Blue River in Nebraska include Lincoln Creek, West Fork of the Big Blue River, Turkey Creek, Swan Creek, and Big Indian Creek. The Big Blue Basin in Nebraska is approximately 4,600 square miles and includes all of York County and portions of Adams, Butler, Clay, Fillmore, Gage, Hall, Hamilton, Jefferson, Lancaster, Pawnee, Polk, Saline, and Seward counties.

2.2.2 Little Blue River Basin

The Little Blue River in Nebraska is located in south central Nebraska and flows into Kansas where it becomes a tributary of the Big Blue River. The major tributaries to the Little Blue River in Nebraska are South Fork of Sandy Creek, Big Sandy Creek, Little Sandy Creek, and Dry Sandy Creek. The total area of the Little Blue River Basin in Nebraska is approximately 2,500 square miles and includes all of Thayer County and portions of Adams, Clay, Fillmore, Franklin, Jefferson, Kearney, Nuckolls, Saline, and Webster counties.

2.3 Topographic Regions

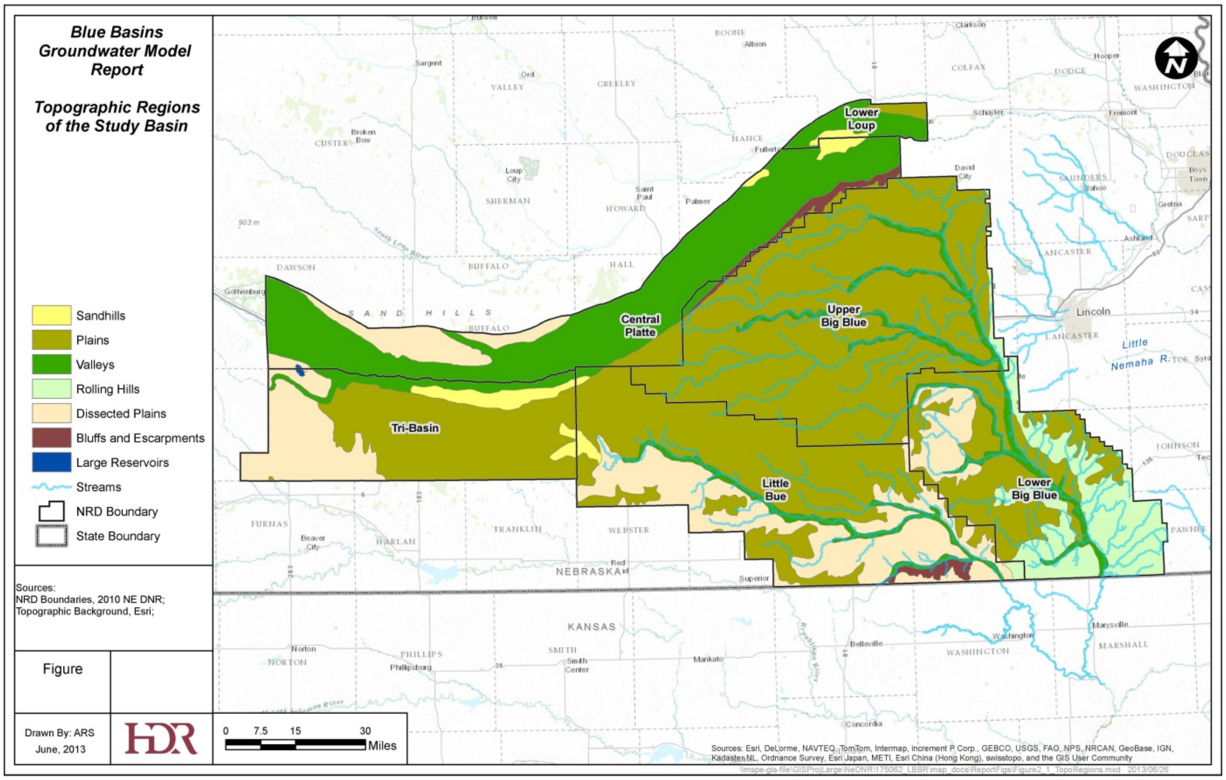
The land surface generally slopes from west-northwest to east-southeast across the Basin with a maximum elevation of approximately 2,200 feet above mean sea level (amsl) in Kearney and Adams counties to 1,200 feet amsl in Gage County. The topography is characterized as relatively flat uplands and gently rolling hills with narrow valley regions of low relief found along the major streams and rivers (University of Nebraska Lincoln Conservation and Survey Division [UNL CSD] 1998).

There are three primary distinct topographic regions within the Basin (see Figure 2-1), as characterized in the Groundwater Atlas of Nebraska (UNL CSD 1998). The majority of the Basin is located in the Plains topographic region, which consists of relatively flat uplands. The Plains topographic region within the study area is generally comprised of stream-deposited silt, clay, sand, and gravel overlain by wind deposited silt (loess). Runoff in the Plains topographic region is low (UNL CSD 1998).

The portion of the Basin that is generally south of the Little Blue River is located in the Dissected Plains topographic region. The Dissected Plains topographic region consists of hilly land with moderate to steep slopes, sharp ridge crests, and remnants of the old plain. Generally, the soils that have formed in this region allow comparatively good infiltration of precipitation, but runoff is high because of the topographic variability (UNL CSD 1998).

The eastern portion of the Basin is located in the Rolling Hills topographic region, which is characterized by regions of hilly lands with moderate to steep slopes and rounded ridge crests. These topographic features (ridges and valleys) were formed by glaciers and then modified by erosion and more recent deposition. The glacial deposits consist largely of low permeability glacial till. Loess overlies the entire eastern region of the Basin allowing moderate infiltration (UNL CSD 1998).

Figure 2-1 Topographic Regions



2.4 Climate

The climate within the Basin includes warm summers and cold winters. There are wide seasonal variations in temperature as well as in the amount of rainfall. The average annual total precipitation across the study area ranges from approximately 25 inches at Minden in the northwest corner of the Basin to approximately 31 inches at Beatrice in the southeast corner of the Basin (Nebraska DNR 2006).

According to precipitation summaries presented by Nebraska DNR in the Annual Evaluation of Availability of Hydrologically Connected Water Supplies (Nebraska DNR 2006), rainfall in the Basin is generally light in early spring and fall, with more than 65 percent of the mean annual precipitation occurring during the growing season from May through September. The average growing season precipitation ranges from approximately 17 inches at Minden to approximately 20 inches at Beatrice.

2.5 Geologic Setting

The geology underlying the Basin consists of Permian-age to Tertiary-age bedrock that is overlain by unconsolidated Pliocene-age to Quaternary-age sediments. The following section summarizes the bedrock and unconsolidated geology within the Basin.

2.5.1 Bedrock Geology

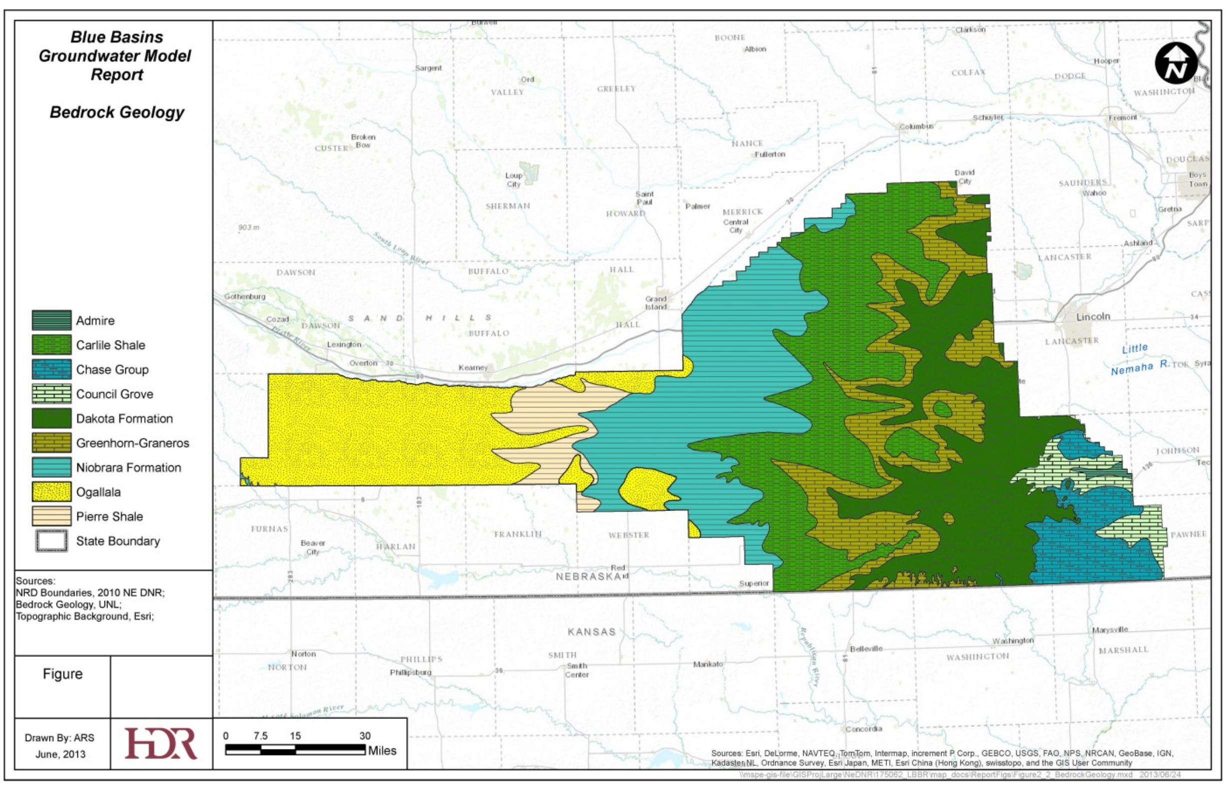
The bedrock units that are present within the Basin are summarized in Table 2-1. The bedrock geology map in Figure 2-2 shows older rocks on the south eastern portion of the Basin. These older rocks are overlain by progressively younger rocks as they dip gently to the west. The oldest rocks are Permian in age and consist primarily of undifferentiated units of shale, limestone, siltstone, or sandstone while the youngest bedrock formation is the Tertiary-age Ogallala.

Within the Basin, the bedrock units are not considered to be primary aquifers. Although the Tertiary Ogallala group is a primary aquifer throughout much of Nebraska, it is considered to be a secondary aquifer within the Basin (Table LB-2, Nebraska DNR 2006) because of its limited extent. As shown in Figure 2-2, the Tertiary Ogallala group is only present in the far western portion of the Basin.

Table 2-1 Bedrock Geology of the Study Basin (Nebraska DNR 2006)

System	Hydrogeologic Unit	Material Characteristics	Hydrogeologic Characteristics
Tertiary	Ogallala group	Moderately to well-cemented zones of silt, sandy and clayey silt with lenses of sand and gravels. Partly calcareous.	Not an important supply of water in the Basin. May yield sufficient water to domestic wells.
Cretaceous	Pierre Shale, Niobrara Formation, Carlile Shale, and Greenhorn-Graneros	Shale, Chalk, or Limestone	Generally not known as a source of water, but yield water to wells at a moderate rate where it is fractured.
	Dakota group	Interbedded clay shale, sandy shale, and sandstone.	Moderately to highly mineralized water. Sandstone layers yield water at a moderate rate to wells.
Permian	Undifferentiated limestone and shale	Interbedded limestone and shale.	Limestone used as minor aquifers yield water to wells where secondary porosity has developed.

Figure 2-2 Bedrock Geology of Study Basin



2.5.2 Unconsolidated Deposits

The unconsolidated sediments that overlie bedrock within the majority of the Basin consist of alluvial deposits of silt, sand, or gravel and are summarized in Table 2-2. The easternmost portion of the Basin includes unconsolidated sediments that are of glacial origin that consist primarily of glacial till, but also include loess and buried outwash. The glacial boundary limit is shown in Figure 2-3.

The thickness of these unconsolidated deposits ranges from zero feet to more than 400 feet, and is generally thickest in the western portion of the Basin and thinnest in the eastern portion of the Basin. In some of the larger stream and river valleys located in the southeastern portion of the Basin, the unconsolidated materials have been eroded away and bedrock is likely to be found at or very near the ground surface.

Table 2-2 Unconsolidated Deposits within the Study Basin (Nebraska DNR 2006)

System	Hydrogeologic Unit	Material Characteristics	Maximum Saturated Thickness (feet)	Hydrogeologic Characteristics
Quaternary deposits	Undifferentiated fluvial and terrace deposits, Todd Valley sand.	Clay, silt, sand, and fine gravel; underlie valley-side terraces and valley floor of drainage courses. Sand and gravel valley and terrace deposits, mostly along stream valleys.	30	Generally saturated, wells yield water at a moderate rate.
	Crete Formation, Undifferentiated fluvial, lacustrine and eolian deposits.	Sand and gravel channel-fill deposits. Silt, sand, and gravel restricted to broad valleys.	130	Generally saturated where thick and coarse textured, yields water to wells at a high rate.
	Sappa Formation	Stratified deposits of silt, clay, sand, and gravel.	60	Sand lenses yield water at a slow rate in wells.
	Grand Island Formation	Stream deposited sand and gravel with a persistent aqueous-eolian deposited silt and clay layer.	200	Yields abundant water to wells.
	Red Cloud sand and gravel and Holdrege Formation	Stream deposited sand and gravel with non-persistent silt and clay, probably of aqueous or eolian origin.	200	Yields abundant water to wells.

2.6 Hydrogeology

Groundwater in the study area originates mainly as infiltration from precipitation, although some ground water also flows into the study area from neighboring basins to the west. Groundwater exits the Basin primarily either through pumping from wells or as base flow into streams.

There are three primary distinct groundwater provinces within the Basin as characterized in the Groundwater Atlas of Nebraska (UNL CSD 1998). The north central portion of the Basin is located in the South Central Plains groundwater province. This region is described as having abundant groundwater, with the primary aquifers being the sand and gravel of Pliocene and Pleistocene age. The eastern portion of the Basin is located in the Glacial Drift groundwater province, which is described as an area comprised primarily of glacial till where groundwater resources are generally limited to the Pleistocene deposits of sand and gravel that are in buried paleovalleys or along stream valleys. The south and southwest portion of the Basin is located in the Republican River Valley and Dissected Plains groundwater province. This province is described as having limited available groundwater that is located in the floodplain deposits of the Republican River and its tributaries and in some buried paleovalleys.

2.6.1 Hydrogeologic Units

The geologic units located within the Basin and their water bearing properties are presented in Table 2-1 and Table 2-2. The principal aquifer in the study area consists of unconsolidated sediments of Quaternary age that overlie bedrock. For purposes of this report, all saturated unconsolidated sediments of Quaternary age above bedrock inclusive of the paleovalley alluvial aquifers and the alluvial aquifers are combined into the principal aquifer unit for the Basin. Within the western portion of the Basin, these unconsolidated deposits can have a saturated thickness of as much as 200 feet. These unconsolidated deposits cover the bedrock surface over most of the Basin except in small areas to the east and southeast, along sections of the larger streams which have incised through the overburden and into bedrock. Throughout much of the Basin, the principal aquifer is overlain by a mantle of loess that either does not supply a significant amount of ground water or is not saturated. Large expanses of glacial till are present in the eastern portion of the Basin. These materials are generally of low permeability, but have been cut in several areas by present-day alluvial valleys and by buried paleovalleys. Within the area that has been impacted by glaciation, the valleys which are filled with permeable sand and gravel are the primary aquifers. These valleys are considered part of the principal aquifer system because they serve as conduits to groundwater flow in an otherwise low permeability matrix.

The principal aquifer is generally under unconfined conditions across most of the Basin. Confined conditions may exist in areas where discontinuous silt and clay layers are present, or in areas where thicker low permeable materials overlie sands and gravels such as in the glaciated region in the eastern portion of the Basin. Discontinuous silt and clay layers may also be found in the principal aquifer; however, due to the discontinuity of these layers, the sands and gravels are generally hydraulically connected and behave as a single groundwater flow system (Nebraska DNR 2006). In U.S. Geological Survey (USGS) Water-Resources Investigations Report 81-29 (Ellis 1981), Ellis states, “All the stratigraphic units that have been described are hydrogeologically interrelated. Conceptually, these deposits can be thought of as forming either a single unconfined aquifer in which there are large lateral and vertical differences in thickness and hydrogeologic properties, or as an unconfined aquifer system composed of hydraulically interconnected aquifers and local confining or semi-confining beds.” To illustrate the discontinuous nature of these silt and clay units within the principal aquifer, geologic cross sections (developed by others) are included in Appendix C.

The base of the principal aquifer is defined by the Groundwater Atlas of Nebraska (UNLCSD, 1998) as the contact between the lowermost aquifer and rocks or sediment that, although they may be saturated, would yield water mostly at slow rates or would yield water of poor quality. A contour map that depicts the base of the principal aquifer is presented in the Groundwater Atlas of Nebraska (UNLCSD, 1998) and is also available on the UNL CSD website (UNL CSD 2013a). Within the Basin, the base of the principal aquifer is comprised of the Cretaceous and Permian age bedrock units.

As previously described, the Tertiary Ogallala group is the only bedrock aquifer within the Basin. The Tertiary Ogallala group is a primary aquifer throughout much of Nebraska, but it is considered to be a secondary aquifer within the Basin (Table LB-2, Nebraska DNR 2006) because, as shown in Figure 2-2, it is only present in the far western portion of the Basin. Since the Tertiary Ogallala group is described as a secondary aquifer and because it is only available within a small portion of the Basin, it is not considered significant with regard to determining areas that are hydrogeologically connected to surface water within the Basin.

2.6.2 Configuration of the Groundwater Table

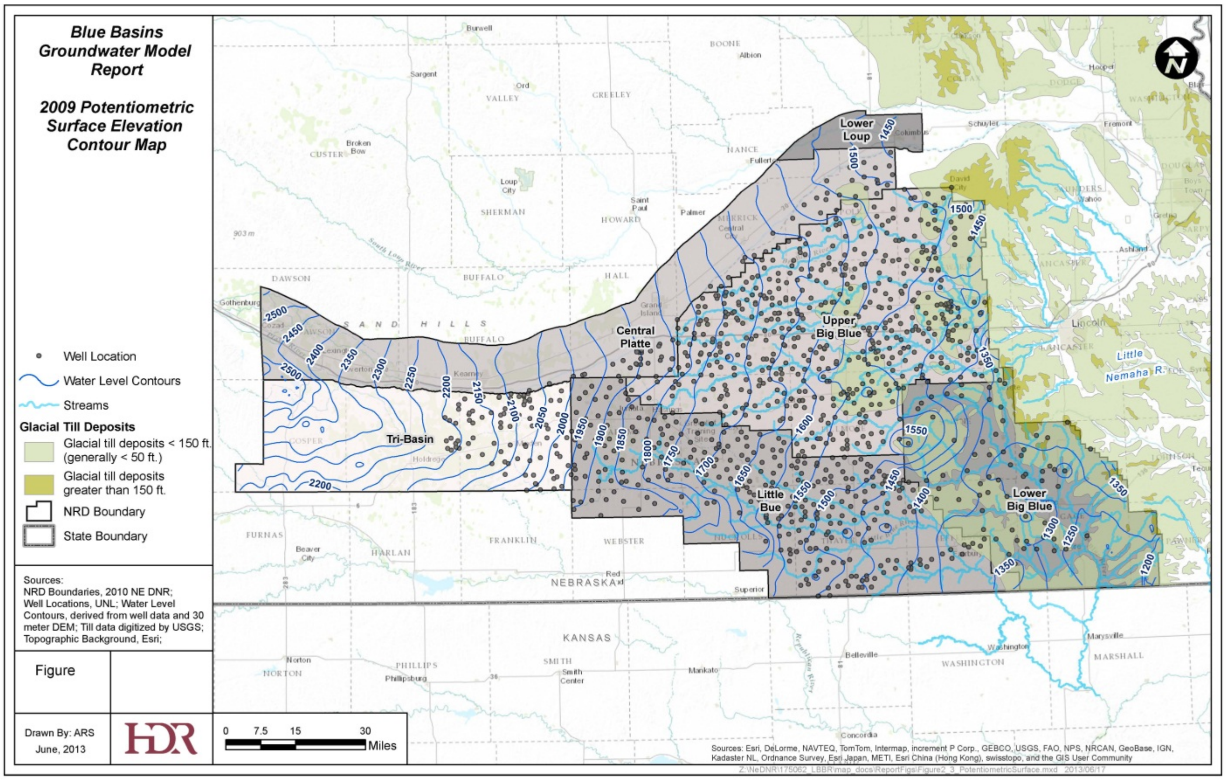
Statewide groundwater potentiometric surface maps were previously developed by UNL CSD. These maps present an interpretation of the potentiometric surface of the principal aquifer within Nebraska for 1979 and 1995, and are available online. A review of these potentiometric surfaces indicates that groundwater in the Basin generally flows from northwest to southeast, but is diverted southward along the alluvial channels where the till has been eroded (UNL CSD 2013a).

To improve the conceptual model of the hydrogeology of the Basin, a recent potentiometric surface map showing generalized groundwater flow directions developed using recent water level data (spring 2009) is shown below in Figure 2-3. The 2009 water level elevation map includes approximately 1,300 wells located in the Little Blue, Lower Big Blue, Upper Big Blue, and the Tri-Basin NRDs. These water level data were obtained from UNL CSD, which operates and maintains a water level measurement program to observe and document changes in groundwater levels throughout Nebraska (UNL Statewide Groundwater-Level Observation Program [Burbach 2006]). The location and distribution of these groundwater level observation points is very consistent across the study area (see Figure 2-3), with only the extreme southeastern portion of the study area having a noticeably lower well density. The large number of water level data points facilitated the development the potentiometric surface using the automated geographic information system (GIS) interpolation technique. The potentiometric surface was developed using an automated GIS interpolation technique (Kriging) within ArcGIS software. The parameters used in the Kriging algorithm are presented below:

- Kriging method: Ordinary
- Semivariogram model: Spherical
- Output cell size: 2500
- Search radius: Variable
- Search radius number of points: 12

The resulting surface was checked by a hydrogeologist, but required little to no modification from what was produced by the automated GIS interpolation technique. The shape of this potentiometric surface was checked against documented potentiometric surfaces developed by UNL CSD for 1979 and 1995, is very similar in both magnitude and direction of the hydraulic gradient.

Figure 2-3 2009 Potentiometric Surface Map



2.6.3 Saturated Thickness and Transmissivity Distribution of the Principal Aquifer

An initial estimate of the horizontal hydraulic conductivity (K_H) distribution within the principal aquifer was developed using available geologic data from the UNL CSD Test Hole database. Horizontal conductivity values were estimated from grain size, degree of sorting, and silt content of the saturated aquifer sediments using the soil boring log from the UNL CSD Test Hole database in a manner consistent with that used for calculating specific yield found in "Mapping of Aquifer Properties - Transmissivity and Specific Yield - for Selected River Basins in Central and Eastern Nebraska" (OFR-71) (Summerside et al. 2005). This process assigns hydraulic conductivity data based on the geology reported in a boring log using the GeoParam program developed by UNL CSD (Kern, undated).

The saturated thickness of the aquifer at each test hole location was determined using 2009 water level data elevation in the UNL Statewide Groundwater-Level Program database (Burbach 2006). This water level elevation was used as the top of saturated material. Any lithology above this water level or below the surface of bedrock was not included in the overall transmissivity analysis for each respective soil boring. Transmissivity values for each individual lithologic unit were calculated by multiplying the GeoParam assigned hydraulic conductivity by the saturated thickness of each individual lithologic unit. Transmissivity values were then summed to reflect the total aquifer transmissivity value for that test hole. The resulting aquifer transmissivity values were then imported as data points into ArcGIS and gridded using an automated interpolation GIS technique.

Only geologic logs from UNL CSD test borings were used to develop the transmissivity and hydraulic conductivity distribution maps. The geologic logs used included all boring logs reported for the four study area NRDs, plus boring logs from other surrounding NRDs to reduce the possibility of inconsistencies at the boundary of the interpretation grid. A total of 465 test holes completed in the four study area NRDs (Little Blue, Lower Big Blue, Upper Big Blue, and the Tri-Basin) were used for this analysis. A summary of the number of test holes, by NRD, included in the hydraulic conductivity and transmissivity interpretation is presented below in Table 2-3.

Table 2-3 Summary of Test Hole Logs by NRD

NRD	Number of Test Hole Logs Included
Central Platte	207
Lewis and Clark	78
Little Blue	119
Lower Big Blue	118
Lower Elkhorn	374
Lower Loup	31
Lower Platte North	130
Lower Platte South	209
Nemaha	400
Papio-Missouri River	95
Tri-Basin	96
Upper Big Blue	132

The hydraulic conductivity, saturated thickness, and transmissivity distribution obtained from the process previously described are presented in Figure 2-4, Figure 2-5, and Figure 2-6, respectively. The interpretation of hydraulic conductivity was used as the starting point for model construction and was used as the initial input array for that hydraulic property in the model.

Figure 2-4 Hydraulic Conductivity (feet/day)

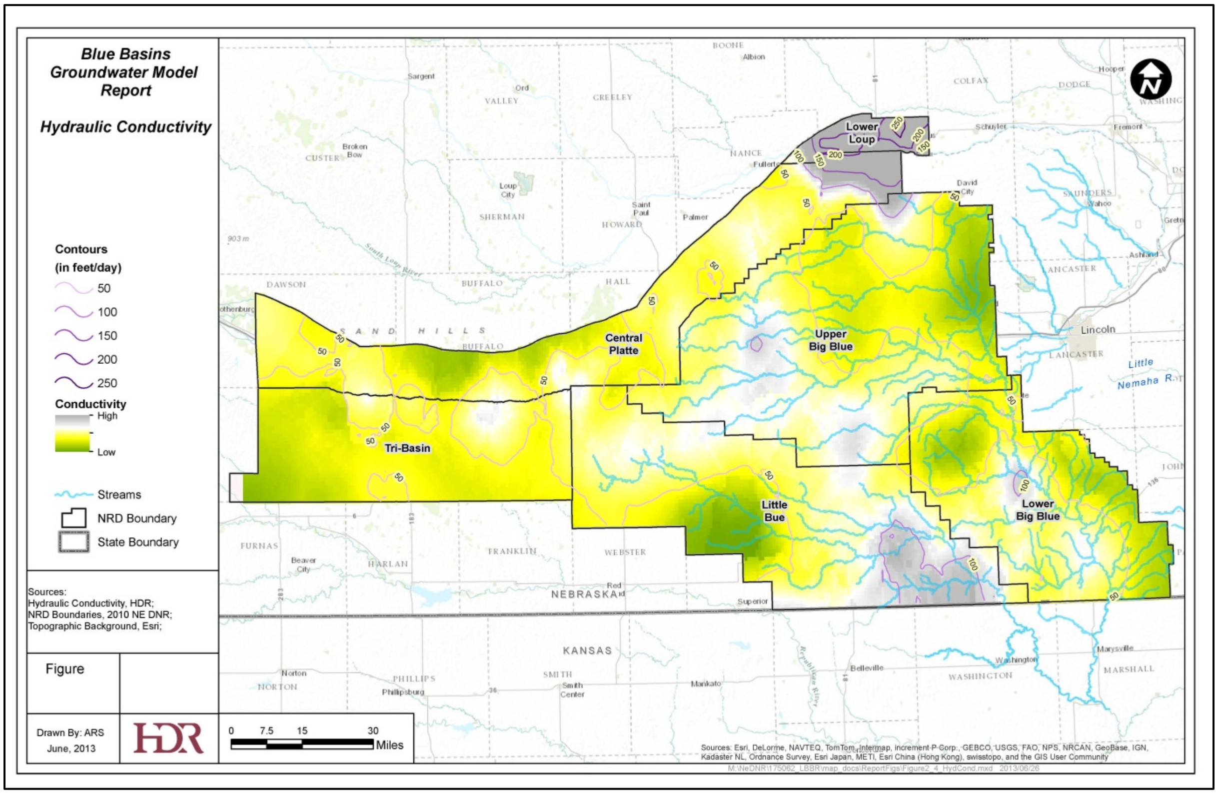


Figure 2-5 Aquifer Saturated Thickness (feet)

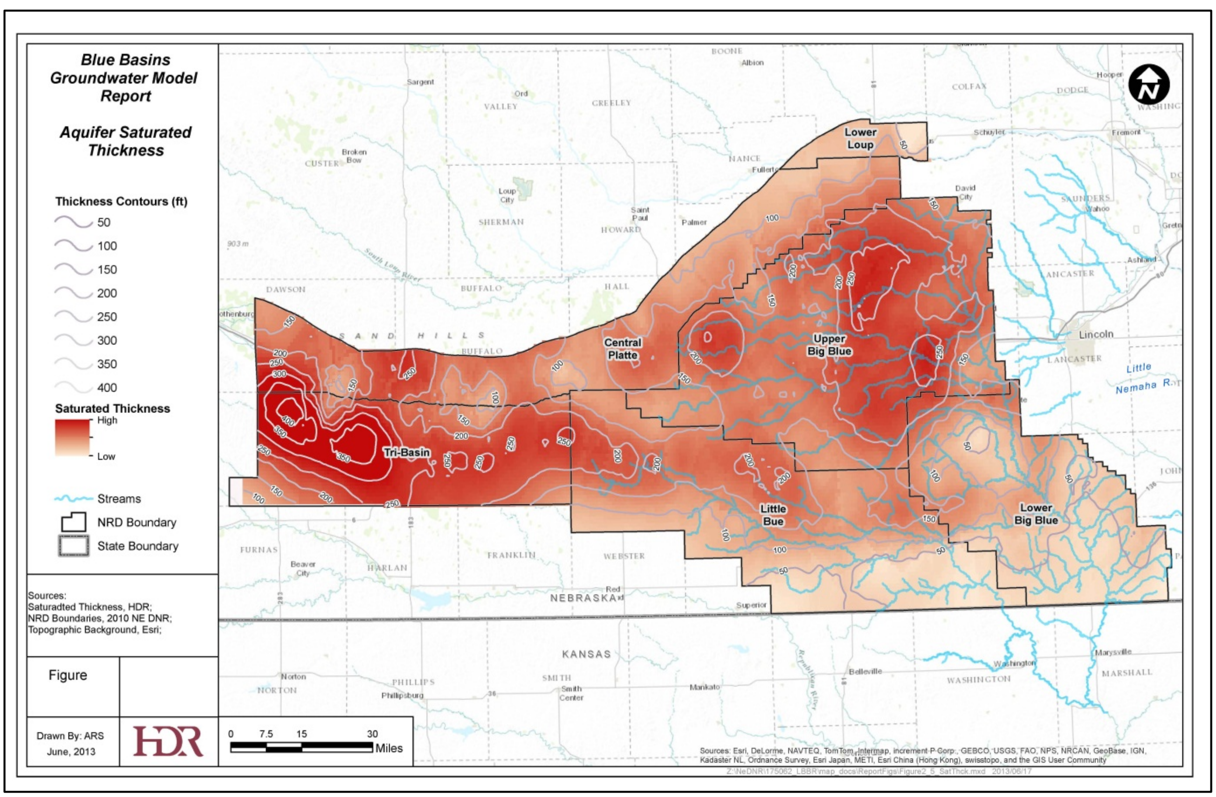
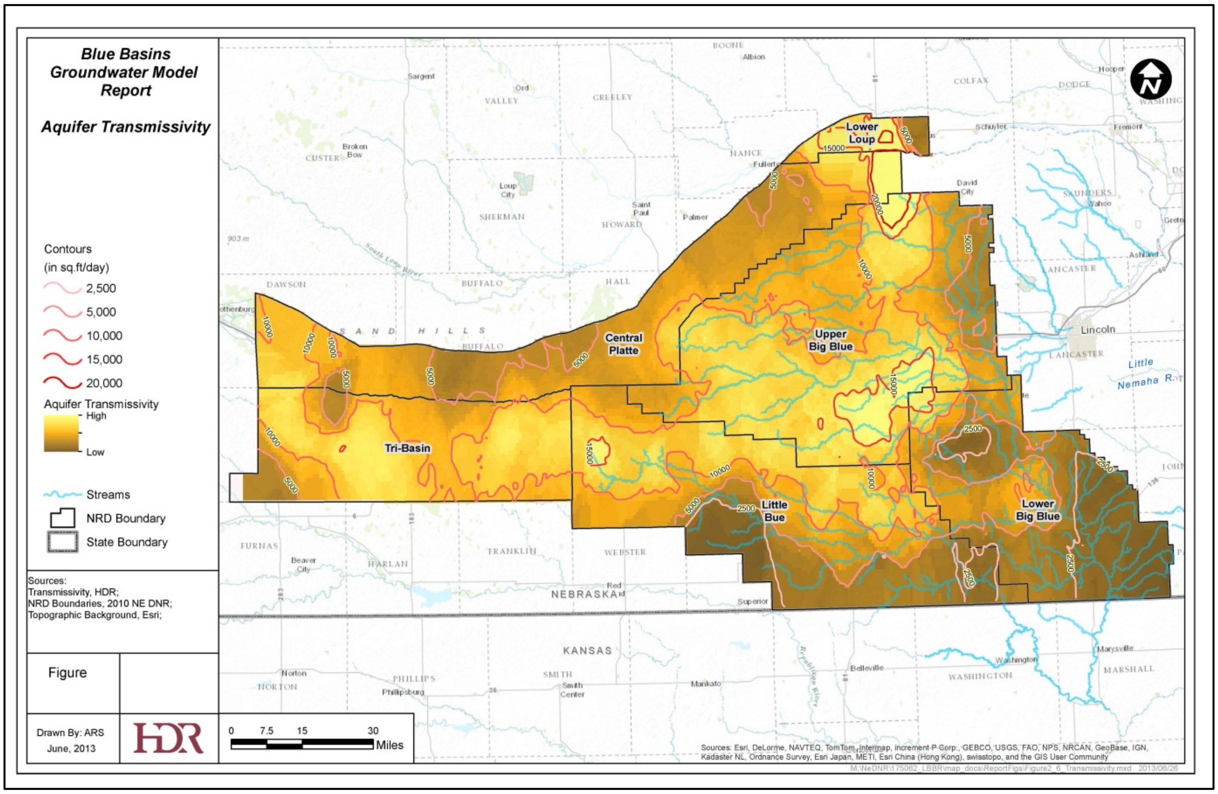


Figure 2-6 Aquifer Transmissivity (feet/day)



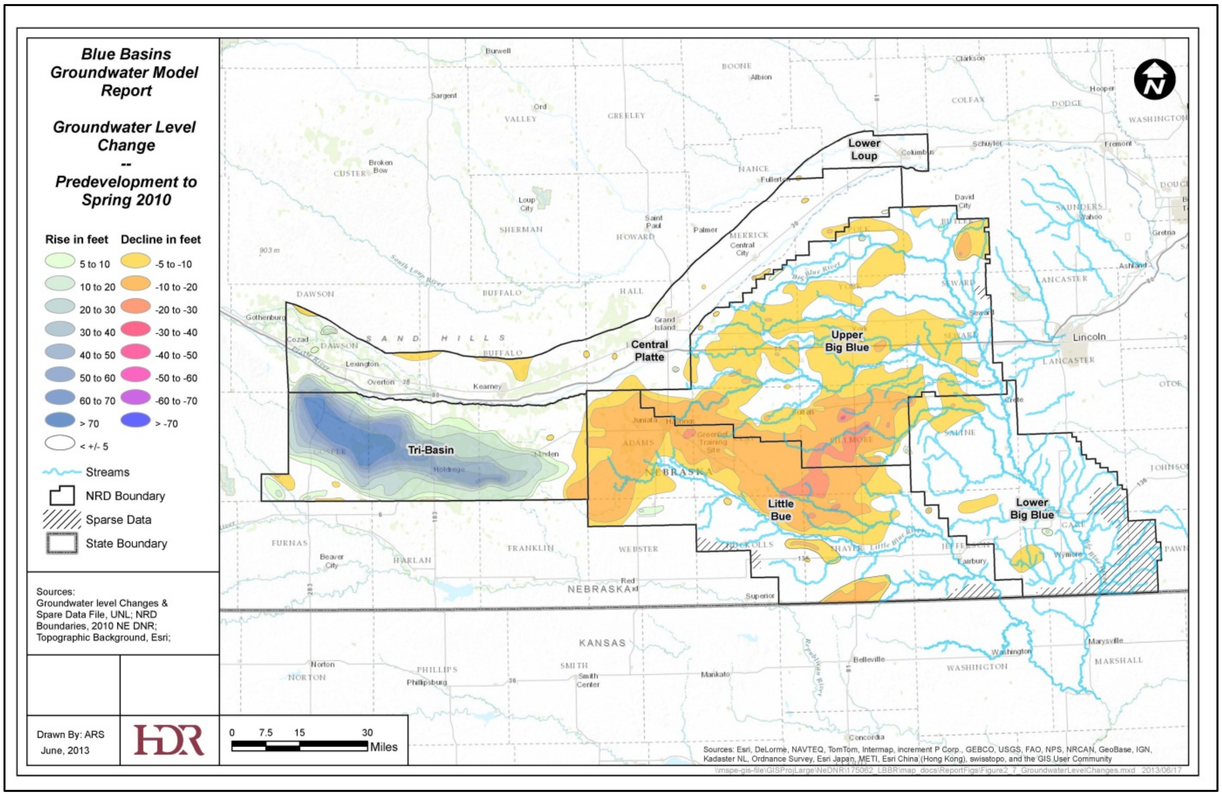
2.6.4 Groundwater Level Changes

A large portion of south central Nebraska, including much of the Basin area, has experienced groundwater declines from the predevelopment period. UNL CSD develops groundwater level change maps annually (UNL CSD 2013b). These maps depict the change in water level elevation throughout the state, using predevelopment as the frame of reference. Groundwater development within Nebraska was not uniform; therefore the estimated predevelopment water level is not fixed to a specific date or time, but rather is the approximate average water level at a well site prior to any development that significantly affected that water level. All available water level data collected prior to or during the early stages of groundwater development are used to estimate predevelopment water levels (Burbach 2006).

A review of the available maps indicates that there was little to no documented change in groundwater elevations within the Basin study area as of 1954. By 1959, groundwater elevations had begun to decline within the Basin with several large areas experiencing declines between 2 to 5 feet and some isolated areas experiencing declines of more than 10 feet. The majority of the groundwater declines from predevelopment conditions observed within the Basin appear to have occurred during the late 1950s to the mid to late 1970s.

Groundwater levels in parts of Adams, Clay, Custer, Fillmore, Hall, Hamilton, Polk, Seward, and York counties have declined between 10 and 20 feet. UNL CSD interpreted change in groundwater level elevations from predevelopment to spring 2010 is presented in Figure 2-7.

Figure 2-7 Groundwater Level Change – Predevelopment to 2010



2.7 Surface Water Analysis

Base flow at gaged streams was evaluated both to assist with the development of a conceptual mass balance for the Basin and to provide calibration targets for the steady state and transient model calibration. Base flow is the component of streamflow that can be attributed to groundwater discharge into streams. Base flow was evaluated at a total of 10 USGS gage locations. Eight of those gage locations have data that extend back to the 1950s or earlier.

The streamflow statistic determined was the base flow index (BFI), defined as the ratio of mean annual base flow to mean annual streamflow. To calculate the BFI, an automated base flow separation technique was used. The automated procedure consisted of a Microsoft Excel® spreadsheet that contains a Visual Basic® application that implements an algorithm to determine base flow using time series data of daily mean flows, which were obtained from USGS streamflow gages. The algorithm used is based on the calculation procedures developed by the United Kingdom Institute of Hydrology (1980). The program separates the base flow from the total streamflow and outputs the BFI as well as annual hydrographs. For purposes of this report, streamflow is an accumulation of base flow, not base flow plus runoff. The streamflow data of each stream gage was passed through this program and annual BFI over the Period of Record (POR) were recorded and hydrographs over the same POR were produced. BFI can be a useful tool to evaluate the catchment geology, with values of 0.9 (which implies that 90 percent of the observed flow is base flow) typical for a permeable catchment, and values of 0.15 to 0.35 typical for an impermeable catchment with a flashy flow regime (Tallaksen 2004).

As shown in Table 2-4, the BFI values for each of the gaged sites included within the Basin are summarized below. The BFI values shown indicate that the base flow component of total streamflow is relatively low for both Basins, indicating a high degree of runoff. The BFI is lower in the Big Blue River Basin than in the Little Blue River Basin, which is consistent with the topographic regions in these basins.

Table 2-4 Summary of BFI Values for Gaged Sites

	Big Blue River Basin Gage					Little Blue River Basin Gage				
	Seward	Dorchester	Crete	Beatrice	Barneston	DeWeese	Alexandria	Fairbury	Hollenberg, Kansas	Barnes, Kansas
Site Number	06880500	06880800	06881000	06881500	06882000	06883000	06883570	06884000	06884025	06884400
BFI (entire data set)	0.26	0.45	0.40	0.36	0.33	0.46	0.40	0.40	0.41	0.40
Mean of annual BFIs	0.30	0.51	0.44	0.44	0.35	0.54	0.45	0.46	0.46	0.44

Note: BFI is dimensionless.

2.7.1 Nebraska DNR Archived Point Measurements

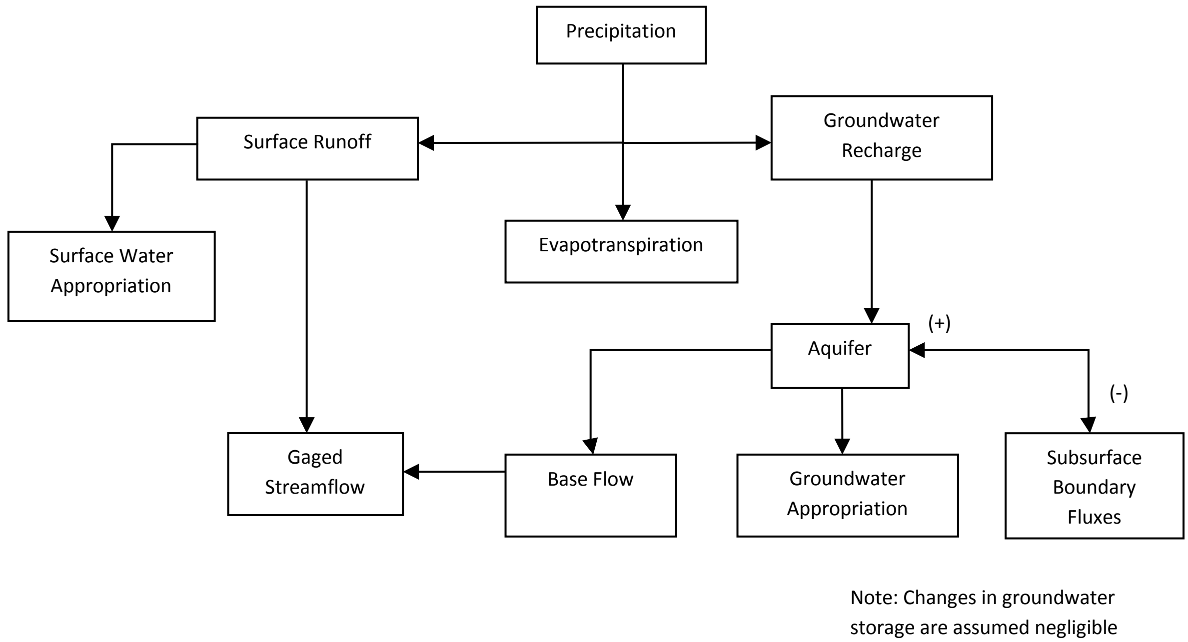
The Nebraska DNR provided HDR with a database of field measurements of streamflow, obtained from Nebraska DNR archive files. These field measurements were made at existing gage sites (USGS or Nebraska DNR), or at various un-gaged points along streams and are referred to as seep run data in this document. The majority of the streamflow values came from published hydrographic reports; however some also came from unpublished field office records. The data were converted by Nebraska DNR from their original form through paper-to-digital record conversion process. The data were then provided to HDR in database format. HDR evaluated the spatial and temporal distribution of these data using ArcGIS. The seep run data are studies in which streamflow was measured at intervals along a stream during a period in which there was no precipitation to cause surface water runoff. These studies allow the determination of the extent to which streamflow is enhanced by base flow from the aquifer.

These streamflow data provide a series of point streamflow measurements and discontinued gages that were used to supplement the long historical record data from the USGS National Water Information System (NWIS) gages. These point measurements were used to assist with the steady state and transient model calibration which are presented in Sections 4.0 and 6.0.

2.8 Conceptual Water Budget

A primary calibration objective for the model will be for the steady state mass balance to approximately match the conceptual mass balance presented below. A conceptual model for the water budget is shown in Figure 2-8, and has been used to make preliminary estimates of the water budget for the model area.

Figure 2-8 Conceptual Water Budget



The basic equation for the conceptual model is:

$$P = ET + SRO + GWR$$

Where P = precipitation, ET = evapotranspiration, SRO = surface run-off, and GWR = groundwater recharge. The water budget was developed using the surface watersheds presented in Figure 2-4. The watershed data was obtained from the Nebraska DNR GIS databank website (Nebraska DNR, 2012). The watershed boundaries approximate the area of the Little Blue, Lower Big Blue, and Upper Big Blue NRDs. A USGS streamflow gage is located at or near the downstream end of both the Big Blue River and Little Blue River watersheds.

Precipitation and evapotranspiration data are available from UNL CSD as mapped data sets. The average annual precipitation in the Big Blue River watershed ranges from 27.3 inches at Hastings at the western end of the Basin to 30.6 inches at Beatrice in the southeast corner of the watershed (Nebraska DNR 2006). In the Little Blue River watershed, the average annual precipitation ranges from 24.9 inches at Minden in the northwest corner of the Basin to 30.5 inches at Fairbury in the southeast corner of the watershed. For preliminary purposes, the average annual precipitation estimated from the mapped data was estimated to be about 30 inches per year (in/yr) in the Big Blue River watershed and about 29 in/yr in the Little Blue River watershed. Evapotranspiration was initially estimated to be 26 in/yr in both watersheds, based on data provided by UNL CSD (Szilagyi 2012). These initial evapotranspiration values were subsequently adjusted to fit the water balance. Surface run-off and groundwater recharge were estimated as results from other calculations, as described below.

Gaged streamflow (GSF) was obtained from the USGS stream gage database for a predevelopment period (1943–1953). The selected USGS stream gages (Barneston on the Big Blue River and Fairbury on the Little Blue River) are the farthest downstream gages within Nebraska. Area calculations for the watersheds were based on the cumulative sub-watershed areas upstream of these gages, as reported by USGS. The GSF is given by:

$$GSF = SRO - SWA + BF$$

Where SRO = surface run-off, SWA = surface water use, and BF = base flow. Surface water uses were quantified by downloading the Nebraska DNR database or registered surface water rights. An automated base flow separation technique was used to calculate the BFI for the predevelopment period, as described in the previous section. The relationships between the surface water terms and the BFI are given by the following equations:

$$BFI = \frac{BF}{BF + SRO} = \frac{BF}{GSF + SWA}$$

Thus, expressed in terms of known quantities, base flow is determined as:

$$BF = BFI\ (GSF + SWA)$$

And surface run-off is calculated from:

$$SRO = GSF + SWA - BF$$

With precipitation, evapotranspiration, and surface run-off quantified, the groundwater recharge can be calculated as:

$$GWR = P - ET - SRO$$

Within the subsurface, the groundwater budget is given by:

$$GWR = GWA - \ NSBF + \Delta S + BF$$

Where GWA = groundwater use, NSBF = the net subsurface boundary flux, and ΔS = the change in storage. For the purposes of the preliminary water budget, ΔS is assumed to be zero because the water balance represents the pre-1953 period. Prior to 1953, little to no groundwater elevation changes were noted within the Blue River basins (UNL CSD 2013b).

The net subsurface boundary flux was estimated by evaluating the 2009 potentiometric surface map for areas on the perimeter of the watersheds where groundwater flow is occurring across the boundary. This particular potentiometric surface map was selected for this analysis because the large number and good spatial coverage of the wells used to develop the map provide a comprehensive data set to evaluate the magnitude and direction of the hydraulic gradient. Hydraulic gradients and flow widths were estimated in the areas which are shown in Figure 2-9. To estimate these subsurface fluxes, representative transmissivity values were estimated from the regional transmissivity map (see Figure 2-6). The calculated boundary fluxes are shown in Table 2-5.

Figure 2-9 Locations of Subsurface Boundary Flux Calculations

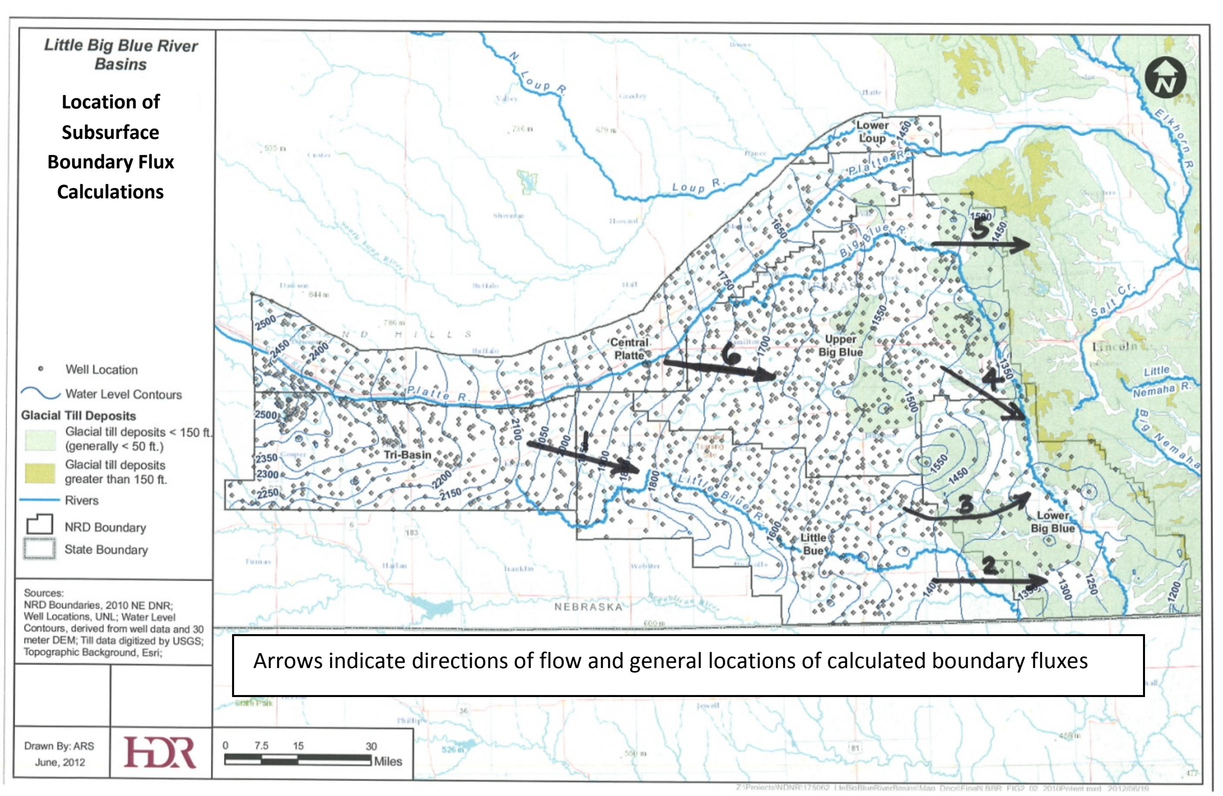


Table 2-5 Summary of Estimated Groundwater Boundary Fluxes During Predevelopment Condition

Area	Flow Direction	T (ft²/day)[a]	dh/dl (-)[b]	Q_0 (cfd/ft)[c]	Width (mi)[d]	Q (cfd)[e]	Q (ac-ft/yr)[f]
Little Blue Basin							
1	In	12,000	1.9E-03	22.7	30	3,600,000	30,165
2	Out	2,500	-8.9E-04	-2.2	15	(175,781)	(1,473)
3	Out	8,000	-9.5E-04	-7.6	15	(600,000)	(5,028)
Net Flux							23,665
Big Blue Basin							
2	In	2,500	8.9E-04	2.2	15	175,781	1,473
3	In	8,000	9.5E-04	7.6	15	600,000	5,028
4	Out	10,000	-1.1E-03	-11.4	12.5	(750,000)	(6,284)
5	Out	15,000	-9.5E-04	-14.2	12.5	(937,500)	(7,856)
6	In	12,000	1.4E-03	16.8	25	2,217,600	18,582
Net Flux							10,942

a. Transmissivity, in square feet per day (ft^2/day)
b. Hydraulic gradient (dimensionless)
c. Flow per unit width across the boundary, in cubic feet per day per foot (cfd/ft)
d. Width of boundary, in miles (mi)
e. Boundary flux, in cubic feet per day (cfd)
f. Boundary flux, in acre feet per year (ac-ft/yr)

Table 2-6 summarizes the resulting water budget calculations. The evapotranspiration values in Table 2-6 were adjusted to approximately match the calculated net subsurface boundary fluxes. The resulting evapotranspiration values (26.5 in/yr for the Big Blue River and 26.1 in/yr for the Little Blue River), appear to be consistent with regional evapotranspiration estimates presented in the UNL CSD study (Szilagyi 2012) and with evapotranspiration estimates presented in the Water Atlas for the United States (Geraghty et al. 1973). The calculated groundwater recharge rates, which are significantly lower than previously published estimates (Szilagyi et al. 2003), appear to be reasonably consistent with the updated UNL CSD study (Szilagyi 2012) (see Figure 3-3 in HDR 2012b), as well as with the Republican River Compact Administration (RRCA) model (RRCA 2003) and the previous Cooperative Hydrology Study (COHYST) Eastern Model Unit (EMU) model (COHYST 2007).

The resulting water budget balances the water balance of the surface watershed with the water balance of groundwater basin, which does not exactly overlap the surface watersheds. It is proposed to use this conceptual water balance as a calibration guide for the development of the steady state groundwater flow model.

Table 2-6 Summary of Conceptual Water Balance for the Big Blue and Little Blue River Basins During Predevelopment Condition

Budget Term	Units	Big Blue	Little Blue
Area	mi^2	4,447	2,350
	acres	2,846,080	1,504,000
Precipitation	in/yr	30.0	29.0
	ac-ft/yr	7,115,200	3,634,667
Evapotranspiration	in/yr	26.5	26.1
	ac-ft/yr	6,285,093	3,271,200
Streamflow	cfs	1,116	505
	ac-ft/yr	807,862	365,603
Surface water use	ac-ft/yr	36,860	20,920
Base flow index (BFI)	-	0.30	0.35
Base flow	ac-ft/yr	228,736	121,084
Runoff	ac-ft/yr	615,986	265,440
Groundwater recharge	ac-ft/yr	214,120	98,027
	in/yr	0.9	0.8
Groundwater use	ac-ft/yr	0	0
Subsurface boundary fluxes	ac-ft/yr	14,616	23,057

Units:
mi^2 – square miles
in/yr – inches per year
cfs – cubic feet per second
ac-ft/yr – acre feet per year

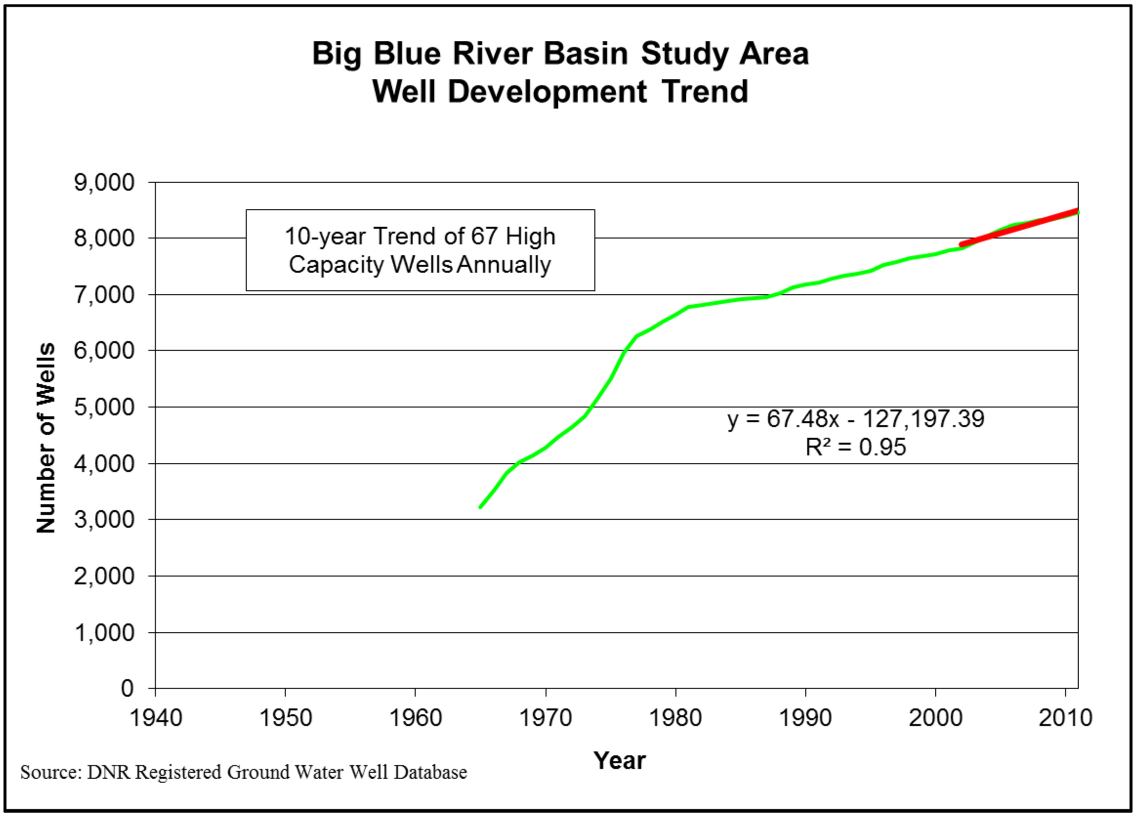
2.9 Groundwater Use

Groundwater in the Basin is used for a variety of purposes, including: domestic, industrial, livestock, and irrigation. As of December 31, 2011, there were a total of 23,535 registered groundwater wells in the Basin (Nebraska DNR 2013). Approximately 81 percent of these wells are irrigation wells, 12 percent are domestic wells, and the remaining wells are primarily livestock, industrial, commercial, or public water supply.

2.9.1 Development of High Capacity Wells

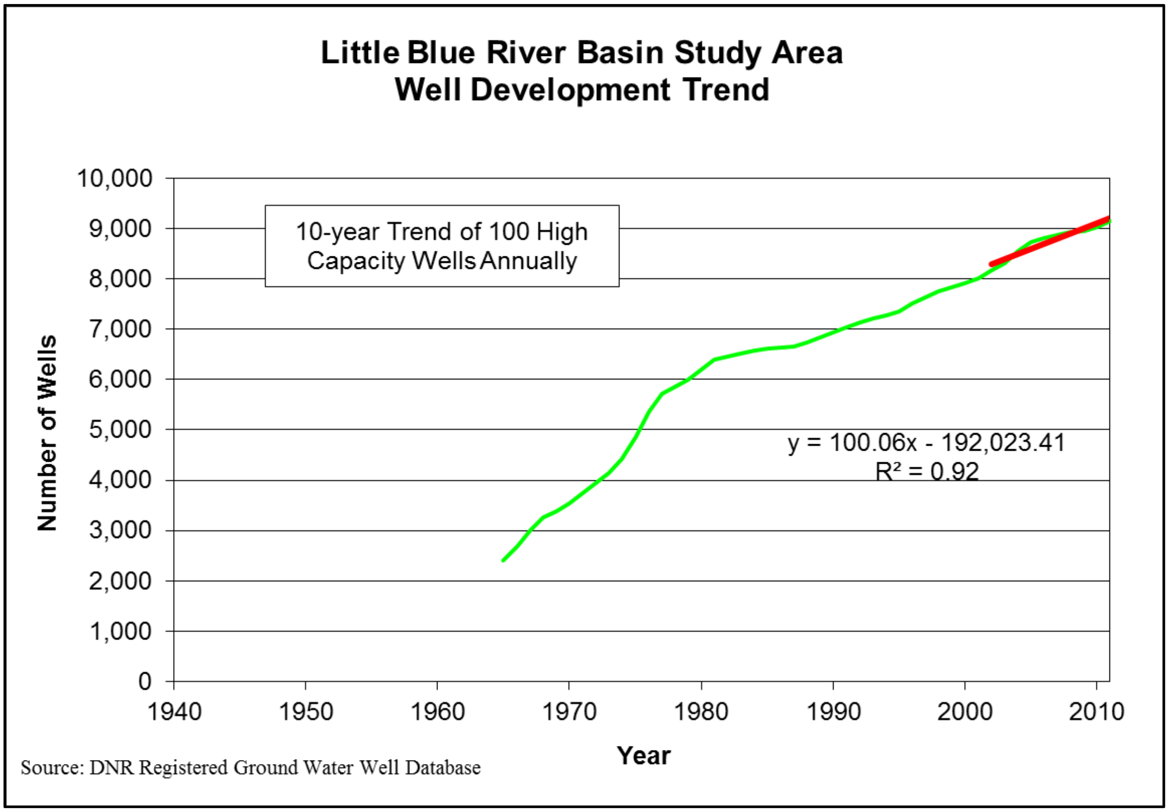
Figures 2-10a and 2-10b presented below show the rate of high capacity well development with the Big Blue and Little Blue river basins, respectively. The figures were obtained from the *2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies* (Nebraska DNR 2006). High capacity wells are defined as those with a pumping capacity in excess of 50 gallons per minute (gpm).

Figure 2-10a Well Development in Big Blue River Basin



Source: 2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies (Nebraska DNR 2006).

Figure 2-10b Well Development in Little Blue River Basin



Source: 2006 Annual Evaluation of Availability of Hydrologically Connected Water Supplies (Nebraska DNR 2006).

As shown in the figures above, well development within the Basin occurred at a high rate between the 1960s to the early 1980s. Well development since the 1980s has remained relatively steady.

2.10 Summary

The conceptual model presented summarizes the data sets available to develop and calibrate a groundwater model for the Basin. The conceptual model presented is also our interpretation of the geology, hydrogeology, and hydrology within the Basin.

The potentiometric surface of the Basin presented provides a method to understand groundwater movement within the Basin and also provides a means to assign the perimeter boundaries of the model. The interpretation of aquifer hydraulic conductivity, saturated thickness, and transmissivity provide a reliable means to develop an initial parameterization of the hydraulic conductivity field in the model and also provides a means to assign model layer elevations. The availability of aquifer recharge data provides a reliable means to develop the initial parameterization of this input in the steady state model. The mass balance presented provides a method to check the groundwater model computed mass balance to ensure that the volume and movement of water in the model reasonably approximates values estimated by hand calculations. The analysis of surface water data provides a summary of base flow targets that are available for the model calibration. The review of groundwater usage data tells us that many thousands of wells exist within the Basin. The data and analyses presented within the conceptual model forms the foundation for the development of the numerical model presented in Section 3.

3.0 Model Construction

This section describes the methods for construction of a groundwater model to simulate groundwater flow, groundwater withdrawals, and stream-aquifer interactions within the Big Blue and Little Blue river basins.

3.1 Model Code and Processing Software

To develop the groundwater model, large amounts of hydrogeologic data from numerous sources were needed to describe aquifer characteristics and properties and hydrologic stresses. These data were assembled as spatially referenced data layers within GIS and then assigned to the simulation at discrete intervals in space and time.

The model was constructed using MODFLOW 2000 (Harbaugh et al. 2000), and utilizes the layer property flow (LPF) package and preconditioned conjugate gradient (PCG) solver. The model was developed using Groundwater Vistas, Version 6.35, Build 1 (Rumbaugh and Rumbaugh 2011) for pre- and post-processing.

Model output was evaluated using Groundwater Vistas, Surfer Version 10 (Golden Software 2012), Microsoft Excel® 2010, and ArcGIS 10.1. Groundwater Vistas was used when possible to provide contoured model results (model predicted heads and drawdowns) and numerical data output. Additional data contouring and evaluation was completed using Surfer. Surfer is a grid-based contouring and three-dimensional surface plotting program. Surfer was used to interpolate the irregularly spaced model-predicted data onto regularly spaced grids and to produce contoured results. Microsoft Excel® was used for processing of tabular model output, including model streamflow. ArcGIS was used for advanced geospatial analysis and graphical display.

3.2 Model Dimensions and Boundary Conditions

Correct selection of boundary conditions is a critical step in model design. Although the focus area of the model is the area within the Little Blue River NRD, the Lower Big Blue NRD, the Upper Big Blue NRD, and the eastern portion of the Tri-Basin NRD, the domain of the groundwater model was extended outside of the focus area to incorporate as many physical boundaries and regional groundwater divides that bound the groundwater basin as possible.

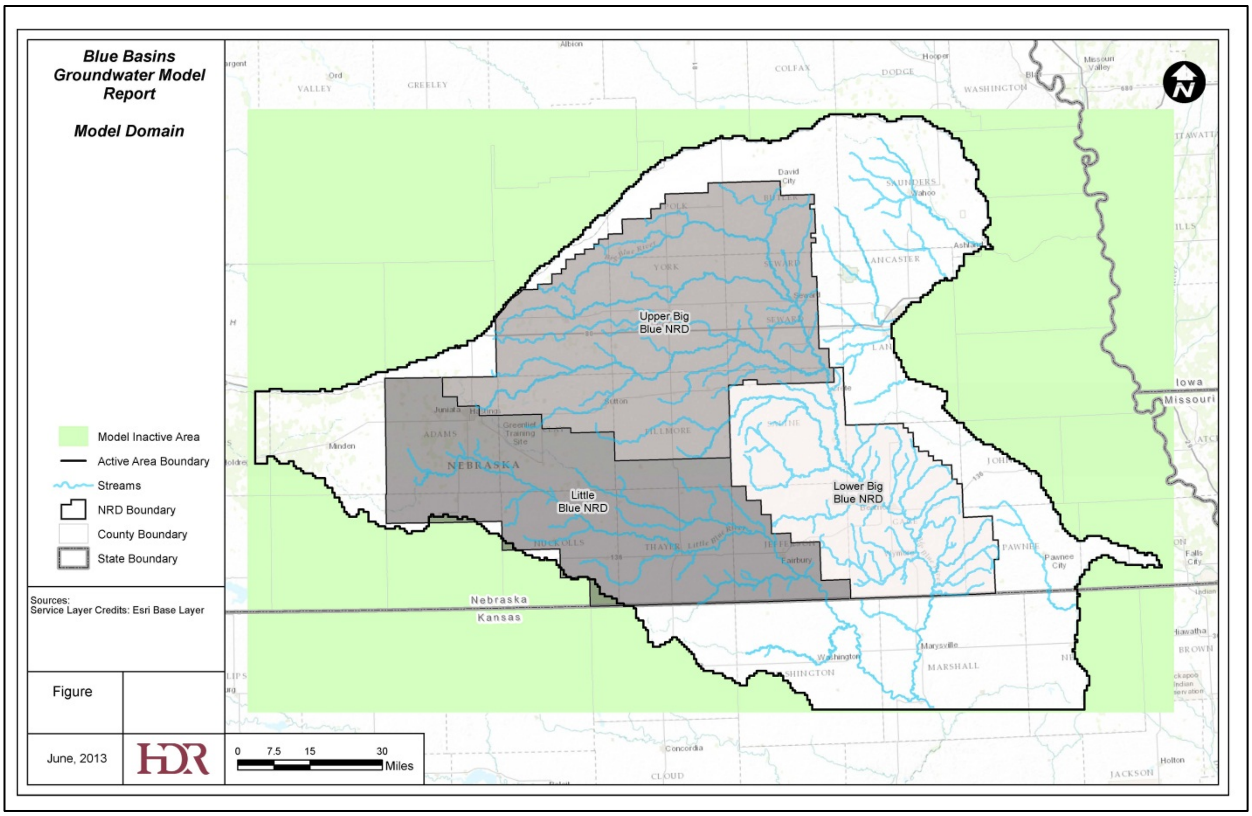
In *Applied Groundwater Modeling Simulation of Flow and Advective Transport* (Anderson and Woessner 1992)*,* the authors recommend selecting physical boundaries and regional groundwater divides as model boundaries whenever possible. Physical boundaries typically include low permeability rock units or large surface water bodies. However, the use of physical boundaries and regional groundwater divides is not always practical. In these instances, the authors recommend the use of hydraulic boundaries, which are boundaries that do not coincide with regional flow boundaries but result from hydraulic conditions (Anderson and Woessner, pg 100). Hydraulic boundaries are used to mimic observed flow conditions and can be defined from a potentiometric surface map (Anderson and Woessner, pg 103).

The decision to extend the model to incorporate as many physical boundaries and regional groundwater divides as practical was undertaken by the model designers for several reasons. The primary reason for this approach was to locate the model boundaries *outside* of the focus area of the model. This was done to serve the purpose of the model by ensuring that any impact from boundaries on the model solution would be minimal within the model focus area. A secondary reason for extending the model outside of the focus area was to minimize the need for the use of hydraulic (or artificial) boundaries. A third reason was that in steady state simulations, the aquifer geometry (boundary conditions) largely determines the flow pattern (Anderson and Woessner 1992). The following section describes the model domain, perimeter boundary conditions, and internal boundary conditions used to construct the groundwater model.

3.2.1 Model Dimensions

The model consists of 250 rows, 384 columns, and 2 layers. Of the 96,000 cells per layer, 48,603 are active. The lateral cell size of the grid is 2,640 feet by 2,640 feet. The model domain is shown in Figure 3-1.

Figure 3-1 Model Domain



3.2.2 Model Layers

The model was originally conceived with a single layer (HDR 2012b) that would simulate the unconsolidated principal aquifer, under the assumption that the impacts of the incised stream valleys in the southern portion of the model would be negligible. However, original model runs produced areas with dewatered (dry) model cells in the southern portion of the model area, and these dry cells created problems with model convergence and stability.

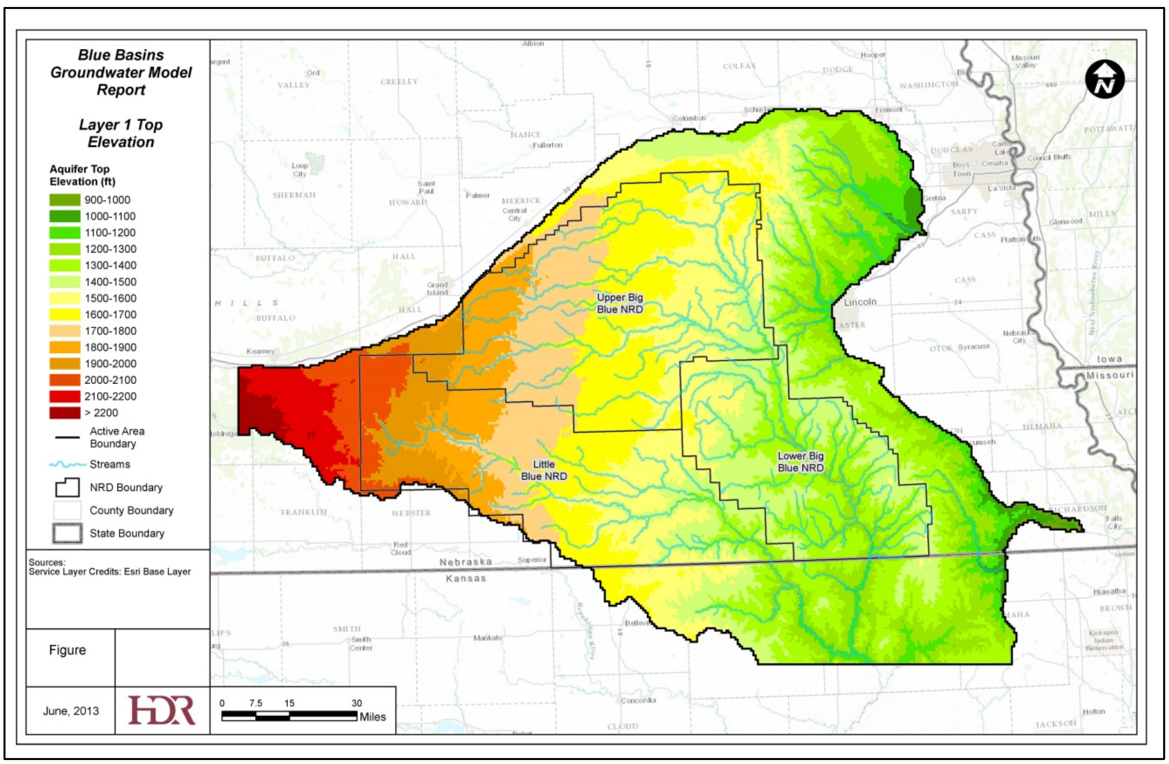
As described in the conceptual model, some streams have incised through the unconsolidated deposits and into bedrock, predominantly in the southern portion of the model domain. As a result, to better replicate this feature, a second model layer was added underlying the principal aquifer. The second model layer represents the bedrock units that underlie the principal aquifer.

In areas where streams have incised into bedrock the degree of interconnection with any primary aquifers is likely limited, as the streams have eroded through the unconsolidated materials that form the principal aquifer and have cut into bedrock. In the southern portion of the model where these incised streams occur, the bedrock units are typically low permeability units and not designated as primary aquifers within the study Basin. When the streams have incised into the Cretaceous Dakota, some degree of interconnection with the bedrock unit is possible (Nebraska DNR 2006); however, the Dakota aquifer is not a primary aquifer within the Basin and groundwater development within this aquifer is limited (within the study area).

3.2.2.1 Layer 1 Top Elevation

The elevation of the top of the aquifer was taken to be land surface, using Light Detection and Ranging (LiDAR) and Digital Elevation Model (DEM) data sets as the data source. LiDAR data for the area has a 2-meter resolution, but did not encompass the complete model domain. There is complete DEM coverage of the area, but at a lower resolution of 10 meters. Both data sets were used, with LiDAR data used as the source where available and DEM used where LiDAR was unavailable. Raster files that spatially correspond to the model grid were created for both source data sets using GIS spatial analysis methods, then combined to create a surface elevation mosaic (see Figure 3-2). Model cell elevation values were assigned using the ArcGIS Extract Values to Points utility. The assigned value is the LiDAR or DEM raster elevation at the center of the model grid cell. The top elevation for Layer 2 of the model was assigned the same elevation as the bottom of Layer 1.

Figure 3-2 Layer 1 Top Elevation



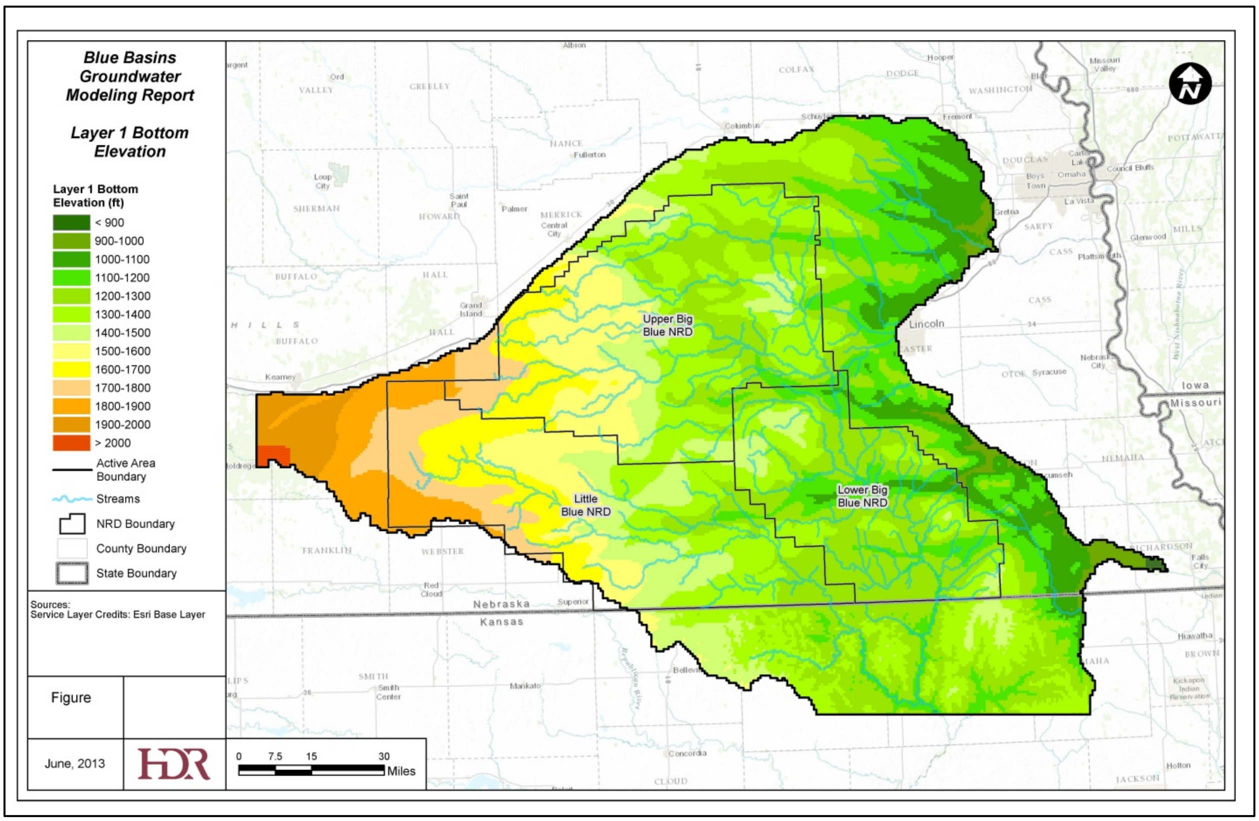
3.2.2.2 Layer 1 Bottom Elevation

For model areas within Nebraska, the elevation of the bottom of Layer 1 was taken from the UNL CSD contour map of the Base of the Principal Aquifer (UNL CSD 2013a). The base of the principal aquifer was originally developed from interpretation of test hole data presented in the Groundwater Atlas of Nebraska (UNL CSD 1998). GIS spatial analysis methods were used to derive a raster from the elevation contours. The raster encompassed the model domain and was constructed with a finer resolution (250 foot cells) than the model grid. As with the surface elevation data, the raster cell values were then extrapolated to the model grid using GIS spatial analysis methods.

For model areas within Kansas, aquifer thicknesses in discrete areas were estimated from existing geologic cross-sections and structural contour maps. The base elevation was then determined for each model cell by subtracting the extrapolated thickness from the surface elevation.

The areas of Nebraska and Kansas were then combined in GIS to create a single mapped feature (see Figure 3-3). The bottom elevation for Layer 2 was set to provide a uniform thickness of 125 feet.

Figure 3-3 Layer 1 Bottom Elevation



3.2.3 Perimeter Boundary Conditions

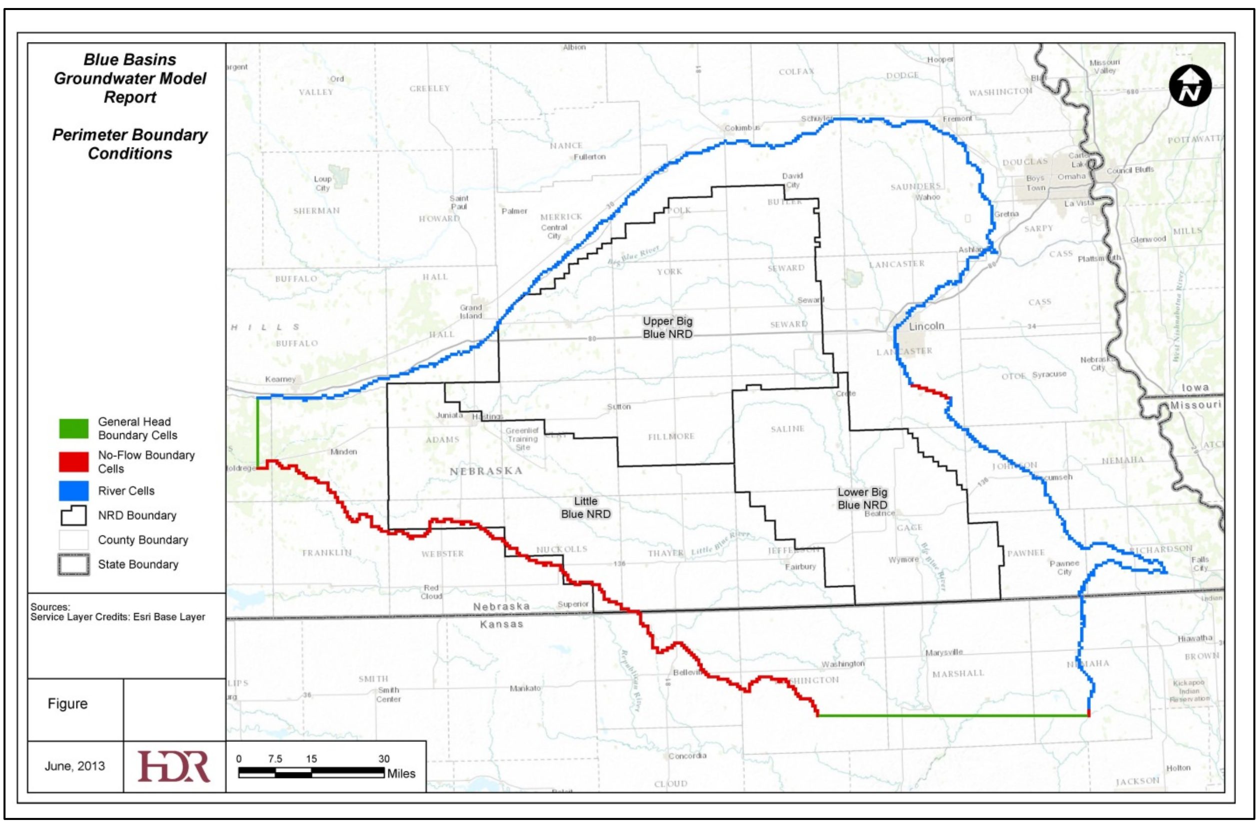
Perimeter boundary conditions were implemented for Layer 1 as discussed in the Model Development Plan (HDR 2012b), and are shown in Figure 3-4. As previously described, the objective in assigning perimeter model boundaries was to incorporate as many physical boundaries and regional groundwater divides as practical and to limit the number of hydraulic (or artificial) boundaries. Large surface water features that represent a physical boundary of the aquifer system were represented as MODLFOW river boundaries, while prominent regional groundwater divides were simulated as no flow cells.

The northern boundary of the model is a physical boundary of the aquifer system that represents the Platte River. This boundary was implemented as a MODFLOW river boundary to permit head-dependent fluxes in and out of the model. The southwestern boundary is defined as a regional groundwater divide between the Little Blue and Republican River basins, and is represented as a no-flow boundary. In the northeast portion of the domain, two physical boundaries were included to represent Salt Creek and the Platte River to its confluence with Salt Creek. These boundaries were implemented as MODFLOW river boundaries. In the southeast, the perimeter model boundary coincides with the physical boundary of the aquifer system that occurs at the South Fork and North Fork of the Big Nemaha River, which were both represented as MODFLOW river cells. The area between these boundaries is a short length of no-flow boundary, coinciding with the headwater areas for Salt Creek, the Big Nemaha River, and the Little Nemaha River.

Two hydraulic boundaries were used to allow groundwater to enter and exit the model domain to represent the subsurface boundary fluxes described in Section 2.8. These two boundaries were used to simulate observed groundwater conditions along the perimeter of the model domain because extension of the model to include a physical boundary or a regional groundwater divide was not practical. MODFLOW general head boundary (GHB) conditions were used to simulate hydraulic boundaries because a GHB allows head-dependent fluxes to flow into or out of the model domain. The western end of the model domain is an area where groundwater flow into the Basin, and is represented as a MODFLOW general head boundary (GHB). The final perimeter boundary segment is the extreme eastern portion of the southern boundary. This is a GHB on an east-west line lying just south of the confluence of the Big Blue and Little Blue rivers in Marshall County, Kansas.

For Layer 2, the perimeter river cells were converted into no-flow cells. The base of Layer 2 forms the lower boundary of the modeled system. Low permeability rock units typically form the base of most modeled systems (Anderson and Woessner, pg 100).

Figure 3-4 Perimeter Boundary Conditions



3.2.4 Internal Boundary Conditions

Internal boundary conditions included both streams and rivers (see Figure 3-5). Both of these boundary condition types model the interaction between a stream and an aquifer by calculating head-dependent fluxes at each model cell, but stream cells are networked to permit calculation of accumulated net gains and losses in the stream. These gains and losses can be compared to observed stream base flow data.

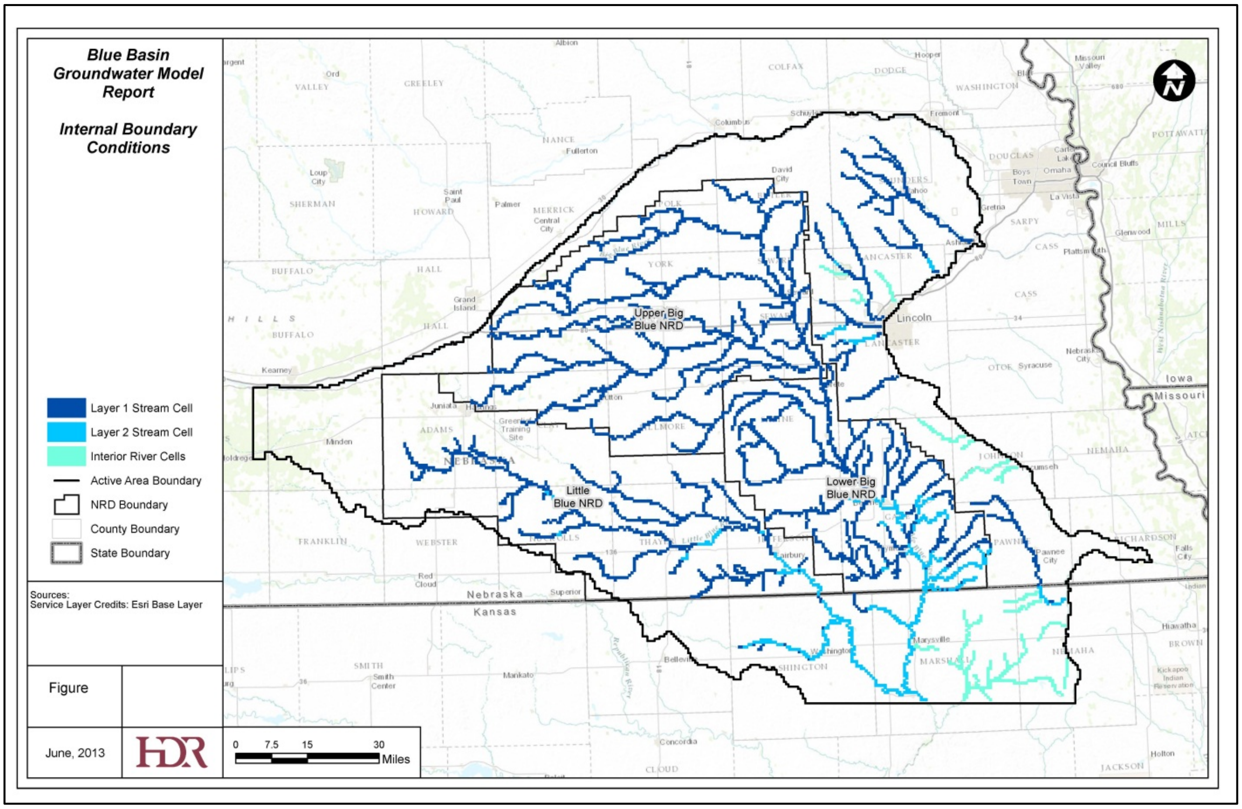
Stream cells were included in the model by examining three mapped data sets for the Little Blue and the Big Blue rivers and their tributaries:

- Stream reaches identified as perennial in the National Hydrographic Dataset database (USGS 2013).
- Stream reaches identified by Nebraska DNR (as discussed in Section 2.7.1) with spot measurements of flow greater than zero during low flow periods; and,
- Stream reaches included in previous groundwater modeling of the Basin by others. The previous model for stream inclusion comparison was the recent Upper Big Blue NRD (UBBNRD) model (UBBNRD 2008).

The stream reaches included in the model are shown in Figure 3-5. The stream cells consist of all reaches meeting any of the above criteria.

River cells were added to the interior of the model after initial model runs to reduce heads in cells where computed heads were greater than land surface. These boundaries were added in areas that previously did not include a boundary condition to simulate these large tributary streams. This modification occurred in the areas within the model domain but outside of the model focus area of the model, generally in areas of glacial till and where topographic slopes were particularly steep. Because these boundaries are located outside of the focus area of the model, and computation of streamflow was not necessary, these boundaries were simulated as MODFLOW rivers boundaries and not as streams.

Figure 3-5 Interior Boundary Conditions



3.3 Model Parameterization

Parameterization of the model was relatively straightforward for the areas of the model domain within Nebraska. Areas within Kansas, however, were more challenging due to the general lack of detailed hydrogeologic data. The available data consist primarily of state geologic maps and a very limited number of county-scale bulletins.

There are three general hydrogeologic terrains within this area of Kansas: glacial till in the east, low permeability bedrock in the west, and an alluvial aquifer in the vicinity of the Big Blue and Little Blue rivers. These areas were mapped onto the model grid as zones in which the hydrogeologic properties are constant.

3.3.1 Hydraulic Conductivity

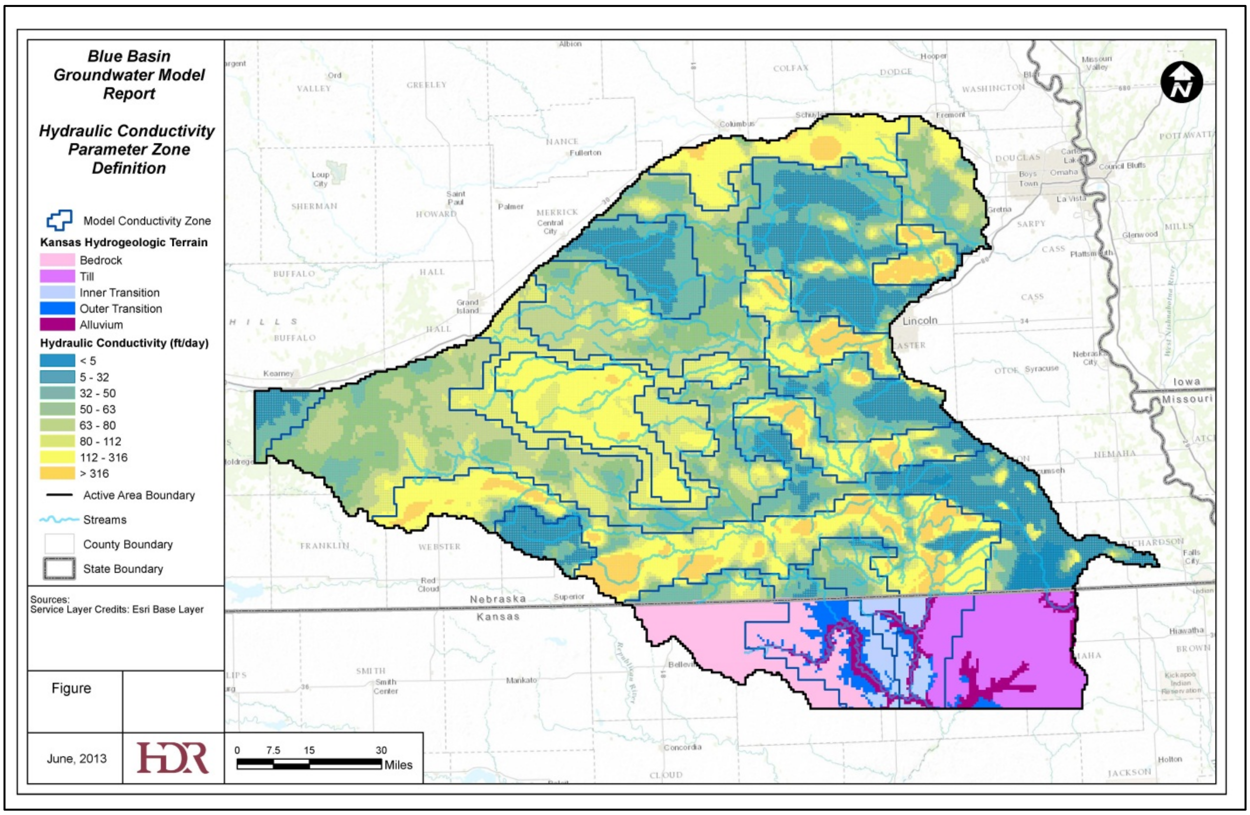
For model areas within Nebraska, the initial hydraulic conductivity data set is described in the conceptual model (see Figure 2-4). On both layers, the hydraulic conductivity was assumed to be laterally isotropic, that is, $K_x = K_y = K$. The vertical hydraulic conductivity (K_z) was assumed to be one order of magnitude less than the lateral hydraulic conductivity, that is, $K_z = 0.1\ K_x$.

K values in the model were determined by processing the base data set as follows. The initial hydraulic conductivity raster data set was resampled using GIS spatial analysis methods to make preliminary value assignments to the model grid cells. For model areas within Nebraska, the cell values were categorized by histogram analysis of log-transformed K values to produce eight categories containing relatively equal populations of model cells. For model areas within Kansas, five categories were assigned: the three hydrogeologic terrains (that is, bedrock, till, and alluvium) were each treated as homogeneous areas, and two additional zones were added to transition from lower permeability bedrock and till zones to the highly conductive alluvium.

The model domain was then subdivided into geographical zones based on apparent spatial patterns of the hydraulic conductivity categories. These geographic zones were used as the basis for assigning initial hydraulic conductivity values and changing values during model calibration. The interpreted K distribution and zones for Layer 1 are shown in Figure 3-6.

The Layer 2 lateral hydraulic conductivity was set to a uniform value of 5 feet per day, while the vertical hydraulic conductivity was set equal to 0.5 feet per day. This conductivity value was selected because it is representative of either limestone or fine grained sandstone (Domenico and Schwartz 1990), which is consistent with the bedrock geology in the Basin.

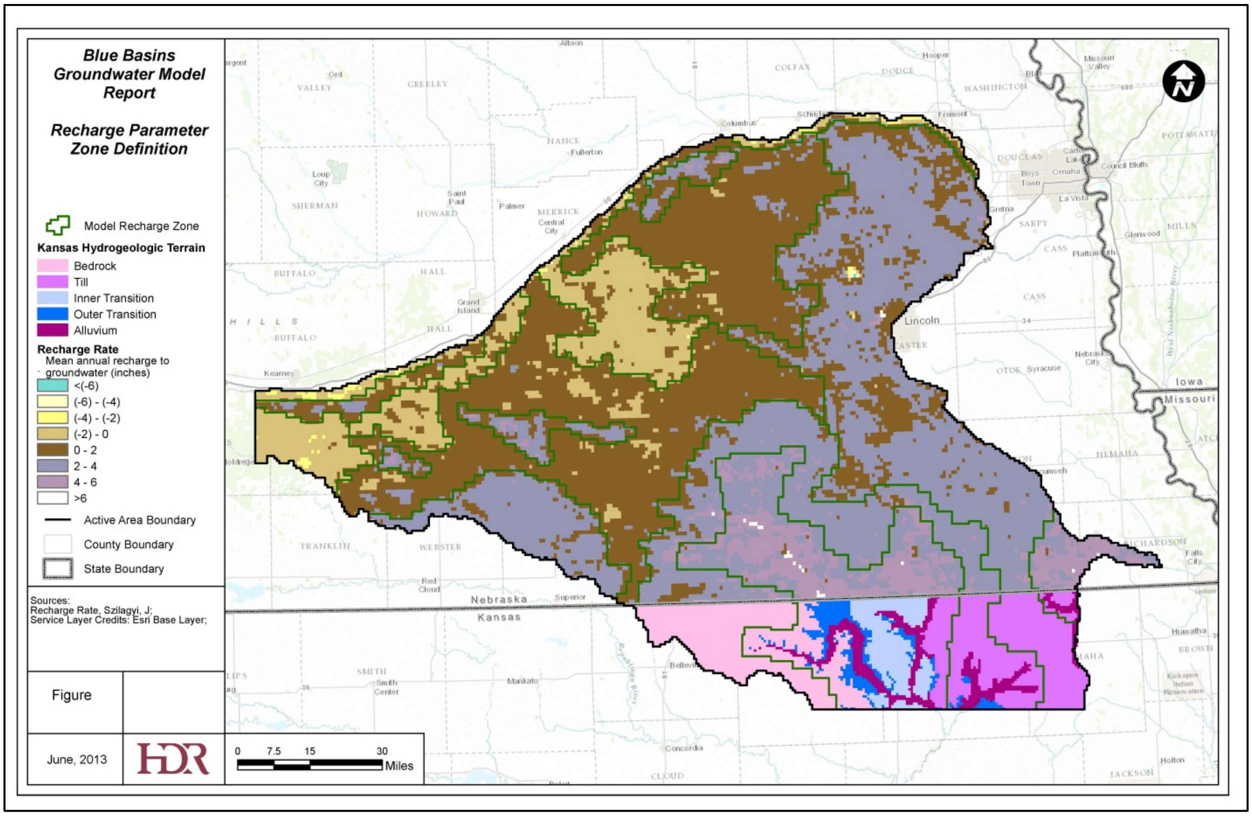
Figure 3-6 Hydraulic Conductivity Parameter Zone Definition



3.3.2 Recharge

For model areas within Nebraska, the base data set for recharge was set equal to values developed by Szilagyi (2012) in a statewide study of net recharge to groundwater. These data were presented in *Groundwater Model Development Plan for the Big Blue and Little Blue River Basins* (HDR 2012b). The recharge distribution is shown in Figure 3-7. As in the case of the hydraulic conductivity distribution, the base data set was resampled to the model grid, and then categorized by histogram analysis, in this case to produce ten categories. For model areas within Kansas, the five hydrogeologic terrains were used as the base categories, as shown in Figure 3-7. Geographic zones with similar recharge were then visually determined. These zones, all from Layer 1, also shown in Figure 3-7, were used for spatial variation of recharge during model calibration. Layer 2 recharge was set to zero. Recharge zones were used only in the steady state model simulation. Groundwater recharge in the transient model was simulated through the use of a soil-moisture balance model (CropSim), which is described in Section 6.

Figure 3-7 Recharge Parameter Zone Definition



3.3.3 Boundary Conditions

A groundwater model is a mathematical representation of a physical groundwater system. The conceptualization of how and where water originates in the groundwater basin, along with how and where it leaves the basin, is critical to the development of a reasonable model. The mathematical representation of these basin boundaries within the model is important because many hydrologic boundary conditions can be mathematically represented in more than one way. Therefore, to reduce the uncertainty associated with the placement of artificial basin boundaries, the model domain and study area were extended to incorporate the physical boundaries of the groundwater basin, thereby minimizing the need for the use of hydraulic (or artificial) boundaries.

3.3.3.1 Rivers and Streams

River and stream cells in the model grid were identified by geographic overlay. In total, there are 1,124 river cells and 4,441 stream cells. All of the river cells are located on Layer 1. Stream cell layer assignments were made by comparing land surface elevation to the respective Layer 1 bottom elevation for each stream cell; in all, 3,849 stream cells are located on Layer 1 and the remaining 582 cells are located on Layer 2.

The stream network segment and reach numbers were assigned manually, consistent with documentation for the MODFLOW SFR package (Prudic et al. 2004). In addition to the stream network definitions, five parameters are required for both stream and river cells. Table 3-1, below, shows how these parameters were initially assigned.

Table 3-1 River and Stream Parameterization

Parameter	Parameterization Method
Head	The land surface elevation in the model cell.
Stream length	Determined by GIS overlay as the length of the National Hydrography Dataset stream polyline within the model cell. Cells with stream lengths less than 1320 feet were eliminated as stream cells.
Stream width	The approximate stream width visually estimated from aerial photographs.
Streambed thickness	Assumed to be 1 foot.
Streambed hydraulic conductivity	Assumed to be equivalent to the vertical hydraulic conductivity (K_z) in the model cell, that is, $K_z = 0.1\ K_x$.

The hydraulic connection between the stream and the aquifer are defined by the head in the aquifer, the stream stage, the conductance of the stream bed, and the elevation of the bottom of the river bed. The conductance of the stream bed is illustrated by the equation below:

$$C = \frac{K * L * W}{M}$$

Where:

C = river boundary conductance (L2/T)

K = vertical conductivity of the riverbed (L/T)

L = length of the river in the model cell (L)

W = width of the river in the model cell (L)

M = thickness of the riverbed sediments (L)

The degree of connection between an aquifer and a stream is proportional to the ratio of K/m, or its inverse (streambed flow resistance) which is defined as the streambed thickness (m) divided by the streambed conductivity (K_z). Streambed thickness data is not available for all the streams within the model domain, therefore the calibration approach focused on the modifying the m/K_z ratio. A value of one foot was used for streambed thickness, which simplifies the calibration process by making the streambed resistances in this model are simply the inverse of the streambed hydraulic conductivity. A similar approach to assigning streambed thickness was used by the USGS in *Simulation of Groundwater Flow and Effects of Groundwater Irrigation on Stream Base Flow in the Elkhorn and Loup River Basins, Nebraska, 1895–2055—Phase Two* (USGS 2010).

Some guidance is available when developing the m and K values used in the conductance term to simulate streams or rivers. For example, Anderson (2007) provides some guidelines in setting the flow resistance (m/K_z), as follows:

- River with sandy bottom – m/K_z 1 day or less;
- Small stream with silty bottom – m/K_z should be 1–10 days;
- Stream/lake in till – m/K_z should approximately equal 100 days.

In another study, Kelson (EPA 2000) provided similar guidance as Anderson (2007), and also stated that a resistance term greater than 100 days indicates the stream has little to no interaction with the aquifer. In a third study (GeoTrans 1993), the authors performed a sensitivity analysis of the conductance term on the degree of connection between a MODFLOW drain boundary and the surrounding aquifer. A MODFLOW drain boundary has a similar conductance term as stream and river boundaries. For these simulations, the thickness of the filter material surrounding the drain was held constant at 1 foot and the hydraulic conductivity of the filter material was varied from 0.0001 foot per day to 10 feet per day. The following conclusions were presented:

> The sensitivity analysis for this problem shows that a hydraulic conductivity value of 0.001 ft/d (resistance of 1,000 days) effectively shuts off discharge (to the drain) whereas a value of 10 ft/d (resistance of 0.1 days) causes a direct connection between the drain and aquifer. GeoTrans 1993

The initial streambed resistance values for the stream and perimeter river cells are summarized in Table 3-2.

Table 3-2 Initial Streambed Resistance Values (days)

Parameter	Stream Cells	Perimeter River Cells
Number	4441	741
Minimum	0.05	0.03
Maximum	40	2
Mean	0.125	0.14
Median	0.2	0.28

Stream conductance values in this model were varied by changing the streambed hydraulic conductivity. As a result, the initial values for the streambed resistance were re-evaluated during model calibration by comparing to the above guidelines. The range of initial resistance values were deemed appropriate for the perimeter river cells, but appeared to be too small for the smaller streams on the interior of the study area. Early calibration runs empirically indicated that the model results, particularly predicted streamflow, were not highly sensitive to streambed conductance. As a result, to bring streambed resistance values in line with the guidelines, all streams were re-assigned a homogeneous streambed conductivity of 0.1 foot per day, which is equivalent to a streambed resistance of 10 days, given an assumed 1 foot streambed thickness. The streambed resistance of 10 days is consistent with a stream that is connected to the aquifer but has a lower permeability streambed.

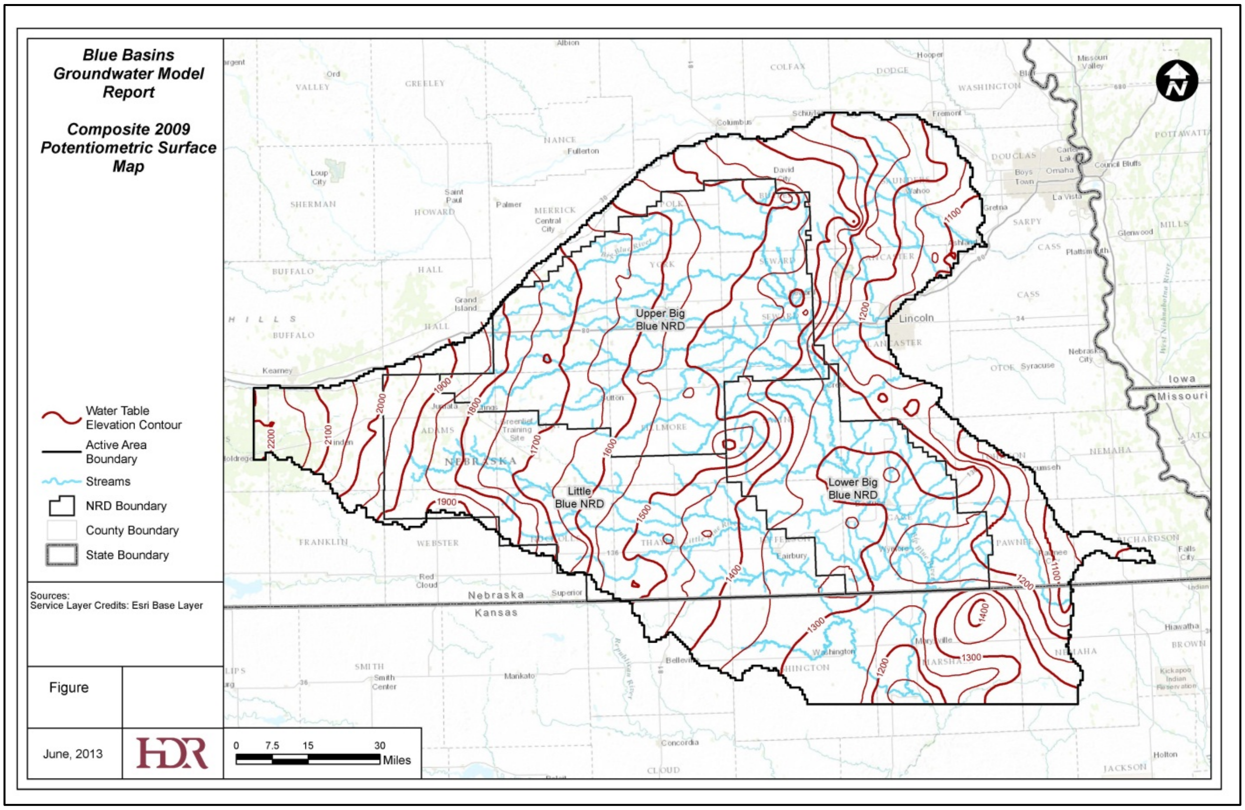
For comparison, streambed hydraulic conductivity values used in the Elkhorn Loup Model (USGS 2010) ranged from 0.1 to 6.0 feet per day and streambed thickness was set uniformly to 1 foot. Streambed conductivity values for the majority of the streams within this model were less than 1 foot per day, meaning the hydraulic resistance for the majority of the streams in this model was set between 1 and 10 days.

3.3.3.2 General Head Boundaries

A GHB is used to simulate flux boundaries that allow water to flow in to or out of the model. The conceptual model forms general head boundaries (GHBs) along the western and the southern ends of the model. The western GHB allows water to flow into the Basin while the southern GHB allows water to flow out of the boundary. The flux into or out of the model is controlled by the difference in head across the model boundary and the conductance across the model boundary. Data input includes the boundary location, a reference head, and the conductance.

The GHBs on the eastern end of the southern boundary lie within Kansas. To facilitate parameterization of the GHBs, a single, continuous water table map for the entire model domain was developed. This map relied upon the 2009 surficial aquifer potentiometric surface map within Nebraska. Within Kansas, water table contours were developed using data from several Kansas Geological Survey (KGS) on-line data sources, including Plate 3 of Bulletin 106, Plate 3 of Ground Water Series 2 (Walters 1954), and monitored observation well data. The resulting water table map is shown in Figure 3-8.

Figure 3-8 Composite Potentiometric Surface Map



The GHB conductance was calculated using the hydraulic conductivity from adjacent active model cells, the saturated thickness at the boundary, and flow widths and lengths equal to the cell width. Groundwater flow rates were calculated at several points along the boundaries and were used in conjunction with the conductance to calculate the GHB reference head.

GHBs were assigned to the same cell positions on both layers and were parameterized identically. However, the reference heads on both ends of the eastern end of the southern boundary were lower than the Layer 1 bottom elevation. As a result, these cells were converted to no-flow cells. This conversion is further justified by the fact that groundwater flow directions in these areas are generally parallel to the boundary, meaning that little or no flow is occurring across the model boundary. With these conversions, the final model includes 25 GHB cells in Layer 1 located along the southern model border, approximately centered on the Big Blue River.

4.0 Steady State Model

The following section presents the results of the steady state model calibration. The steady state model represents a period of time that approximates predevelopment conditions in the Basin, meaning there was little irrigation well development. Well development within the Basin prior to 1955 is sparse (UBBNRD 2008); therefore the general time frame for this calibration is in the early 1950s.

4.1 Calibration Data Sets

The available data sets for model calibration included:

- Groundwater level measurements from wells. This set typically includes spring and fall measurements, and has grown with time and development of the shallow aquifer. However, particularly in the early years, the annual data set size swells and shrinks between events.
- Stream gage data throughout the area. However, few gauging stations have continuous records over the period of interest.
- Seep run data (Section 2.7.1) from the Nebraska DNR. These data are often collected as a dense set of synoptic measurements. The quantitative accuracy may be less than at a fixed station. As a result, their greatest value is in recording where groundwater discharge to streams has occurred over time.

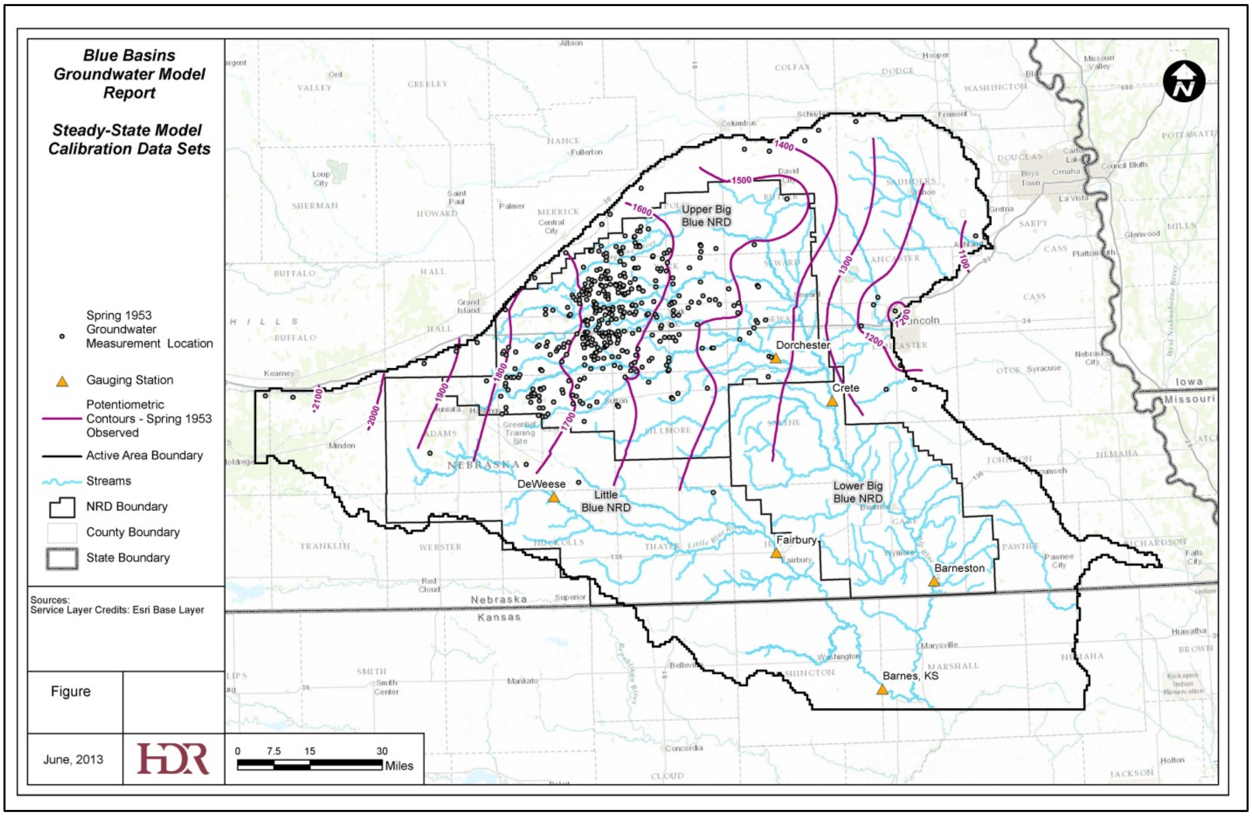
4.1.1 Steady State Model Calibration Data Sets

The calibration data set for the steady state model was selected by balancing the availabilities of relatively large, well-distributed, predevelopment synoptic groundwater level data concurrent with several active stream gages. The selected time period was spring 1953. In March through May of that year, data were available from 396 wells. Figure 4-1 shows the locations of wells and gauging stations used to develop the calibration data set, and the interpreted spring 1953 potentiometric surface contours developed from groundwater data. As shown in Figure 4-1, the distribution of head targets available for the predevelopment model calibration is not ideal, as the large majority of these targets are located in the central and western portion of the Upper Big Blue NRD. To improve the distribution of the calibration data set, a number of flux targets (in the form of streamflow targets) were added to the model calibration. The streamflow targets are discussed below.

The steady state calibration data set included eight gauging stations: Seward, Dorchester, Crete, and Barneston on the Big Blue River, and DeWeese, Alexandria, Fairbury, and Barnes, Kansas on the Little Blue River. The locations of these gages are shown in Figure 4-1. Only three gages (Barneston, DeWeese, and Fairbury) were active in spring 1953, but the remaining gages came on-line later in the 1950s. Time-averaging of the data was performed to reduce the variability of the streamflow data and produce a single value for comparison. Several alternatives were considered, including averages of mean daily base flows for spring 1953, averages of mean daily base flows for all of 1953, and averages of mean daily base flows in spring for the decade from 1953 to 1963.

From these evaluations, a range of plausible base flow values was developed for each gage for comparison during calibration (see Section 4.2.3, Table 4-4). It should also be noted that the range of observed flows at the Seward gage spans three orders of magnitude and none of the calculated mean is representative of typically observed flows. For the Seward gage, the median of predevelopment spring flows was selected.

Figure 4-1 Calibration Data Sets



4.2 Steady State Model Calibration

Calibration parameters for the steady state model were lateral hydraulic conductivity, recharge, and stream conductance. Parameters were adjusted in zones that were developed from the initial parameterization values presented in Section 3 using manual trial and error techniques. Parameter zones for hydraulic conductivity and recharge were discussed in Section 3.3.1 and 3.3.2, respectively. Stream conductance zones were defined to include the stream segments in the watershed between a given stream gage and the next upstream gage.

4.2.1 Steady State Model Calibration Goals

The Model Development Plan (HDR 2012b) outlined the several criteria to be accomplished during model calibration, as reiterated below:

1. The model should have a mass balance error that is less than 1 percent (Anderson and Woessner 1992). The mass balance 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 predicted mass balance should be reasonably consistent with the conceptual water balance, presented in Section 2.0.
3. The Normalized Root Mean Squared error (NRMS) will be less than 10 percent at a minimum, with a goal of achieving less than 5 percent. An NRMS of less than 10 percent is generally considered appropriate for a calibrated groundwater model. A lower NRMS

indicates a better statistical model calibration. The NRMS can be described as the standard deviation of the residuals divided by the observed range of head values.

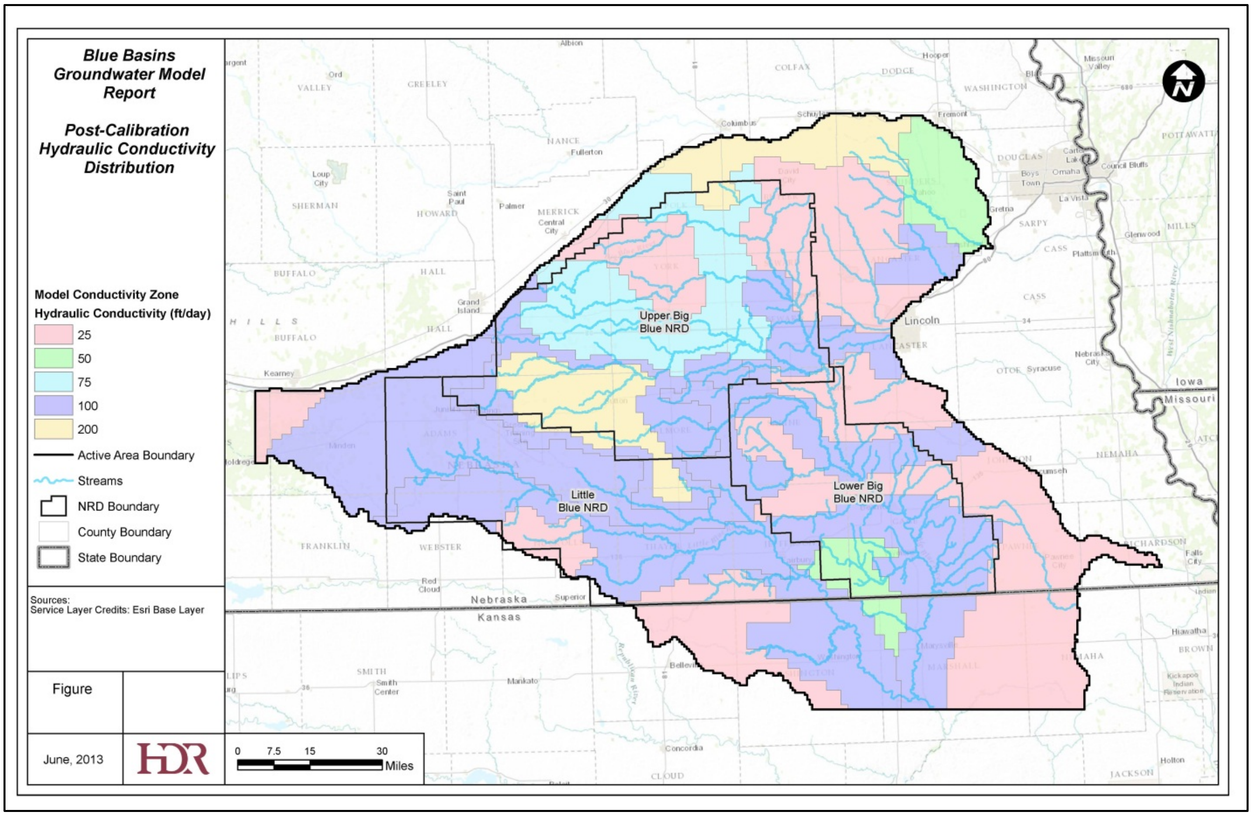
4. The Absolute Residual Mean (ARM) will be less than 10 percent of the total head difference within the model, with a goal of achieving less than 5 percent.
5. The model should have a random error distribution. A plot of the residual versus observed value should indicate no obvious trend in the model.
6. There should be a reasonable visual match between the model predicted and observed potentiometric surfaces. When calibrated, the model should be able to reproduce the direction and magnitude of the hydraulic gradient observed within the study area.
7. The calibrated model should predict river base flow approximately equal the base flow value as develop using the BFI. Streamflow comparisons will occur with gages distributed across the model domain and with a continuous period of record spanning the anticipated modeled period (that is, prior to 1950 and extending to 2011). The preliminary set of gages consists of the following:
   a. Big Blue River near Dorchester (USGS Gage ID 6880800)
   b. Big Blue River near Barneston (ID 6882000)
   c. Big Blue River near Crete (ID 6881000)
   d. Little Blue River near DeWeese (ID 6883000)
   e. Little Blue River near Fairbury (ID 6884000)

Developing a steady state model that achieves the calibration goals listed above would provide a model that produces a reliable initial head condition for use in the transient model. Additionally, achieving the steady state calibration goals above would show that the calibrated input parameters and boundary conditions used in the model produce simulated streamflow values that match observed predevelopment conditions, which directly correlates to the objectives of the model.

4.2.2 Post-Calibration Hydraulic Conductivity Distribution

The final hydraulic conductivity field following model calibration utilized five values ranging from 25 to 200 feet per day, as shown in Figure 4-2. The final conductivity field is somewhat more generalized than the initial hydraulic conductivity mapping, but continues to reflect both the range of observed values and the general distribution of property values.

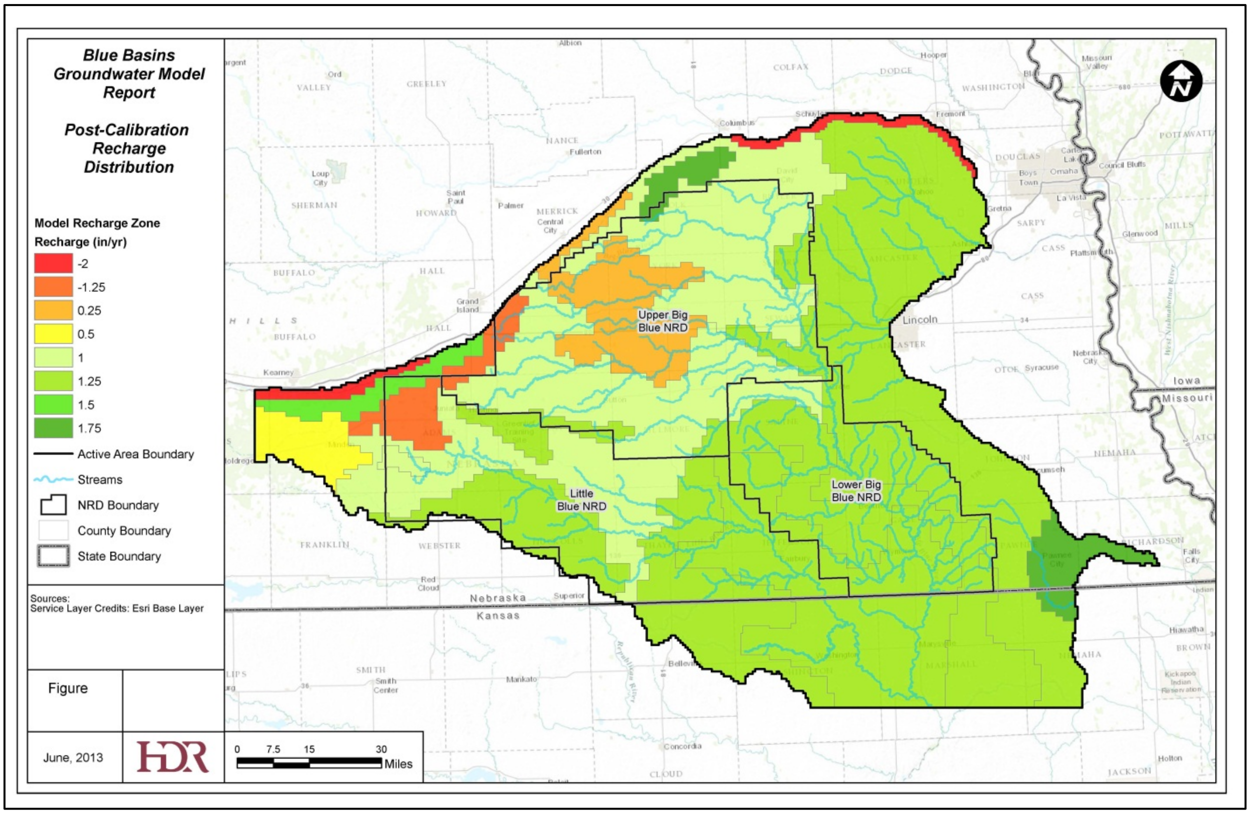
Figure 4-2 Post-Calibration Hydraulic Conductivity Distribution



4.2.3 Post-Calibration Recharge Distribution

The spatial pattern of recharge in the final calibrated steady state model is generally similar to Szilagyi (2012), increasing from northwest to southeast, but the range of values is significantly less. Szilagyi calculated recharge rates between -6.2 in/yr to +7.4 in/yr in the extreme southern portion of the model domain. Szilagyi 's calculated recharge rates include areas with a net negative recharge. A negative recharge rate is indicative of an area where evaporation and transpiration is larger than precipitation. The final distribution of recharge following model calibration utilized eight values ranging from -2 in/yr to 1.75 in/yr, with about 85 percent of the area assigned recharge rates of 1 to 1.25 in/yr. The distribution of calibrated recharge rates is shown in Figure 4-3. The calibrated recharge rates are consistent with the approximate range of values resulting from the conceptual mass balance.

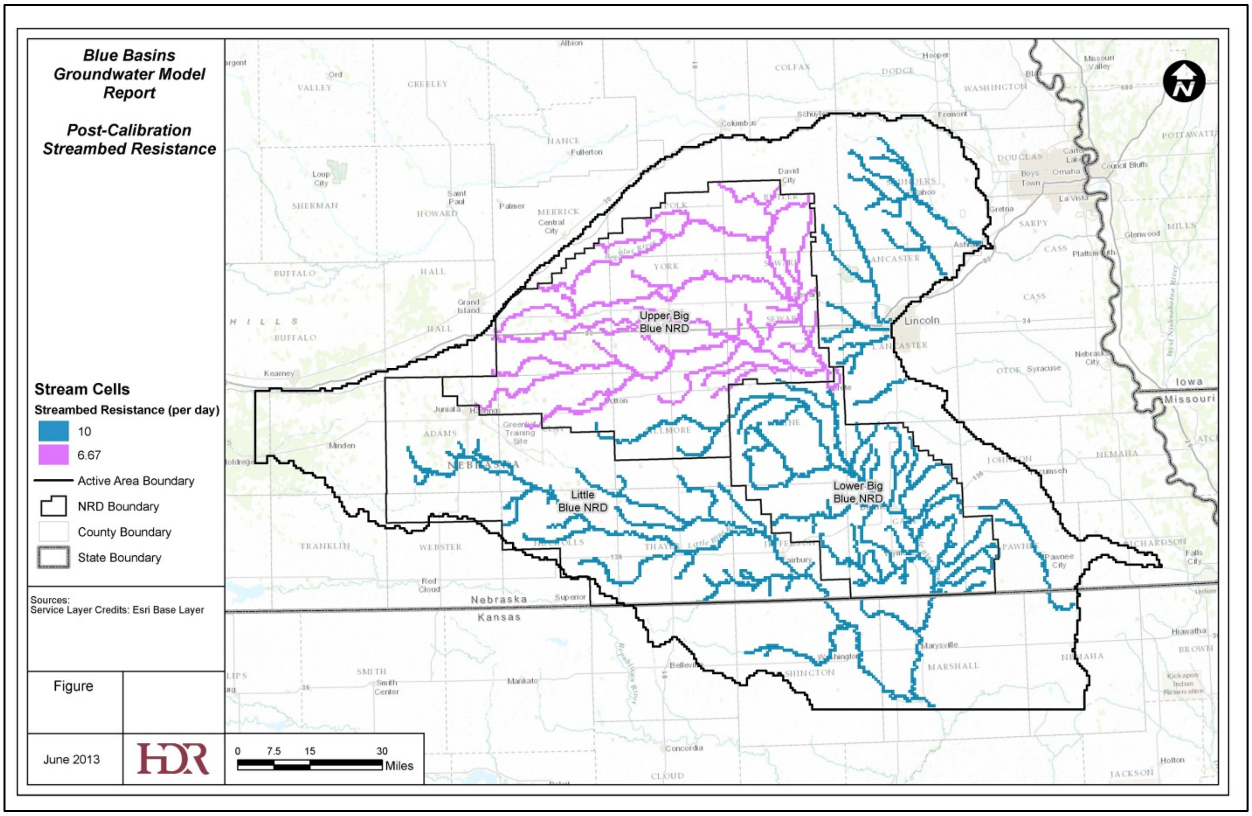
Figure 4-3 Post-Calibration Recharge Distribution



4.2.4 Post-Calibration Streambed Conductance

The calibration process produced only one significant change to streambed conductance values. The streambed hydraulic conductivity in all stream segments of the Big Blue River and tributaries upstream of the Crete gauging station was changed from the initial value of 0.1 foot per day to 0.15 foot per day (that is, streambed resistance reduced from 10 day to 6.67 day). This area affects most of the streams in the Upper Big Blue NRD, as shown in Figure 4-4.

Figure 4-4 Post-Calibration Streambed Resistance



4.2.5 Steady State Model Calibration Results

4.2.5.1 Mass Balance

The first two criteria for the model calibration relate to the model mass balance. Table 4-1 provides the mass balance for the entire model domain. The mass balance error is 0.03 percent, well below the goal of 1 percent.

Table 4-1 Steady State Model Mass Balance (acre-feet/day)

Flux	Inflows	Outflows
Storage	-	-
Constant head	-	-
River leakage	159,881	270,645
Head dependent boundaries	11,822	2,227
Recharge	672,489	37,738
Stream leakage	12,095	545,385
Total	856,288	855,996

Table 4-2 presents the results for the Hydro Stratigraphic Unit (HSU) that represents the three NRDs that are the focus of the study (Little Blue, Lower Big Blue, and Upper Big Blue NRDs). This mass balance was developed using the HSU option for mass balance in Groundwater Vistas. The HSU mass balance computes the flows into and out of each assigned zone and shows the amount of water exchanged between each zone.

The comparable elements from the conceptual mass balance from the pre-modeling documentation (HDR 2012b) are also included. The model results compare very favorably with the conceptual mass balance.

Table 4-2 Mass Balance Summary for the Little Blue, Lower Big Blue, and Upper Big Blue NRDs (acre-feet/day)

Flux	Model Inflows	Model Outflows	Model Net Flux	Conceptual Mass Balance
Rivers	3,831	287	3,544	-
Streams	10,129	341,147	(331,018)	(349,820)
Recharge	335,467	13,569	321,898	312,147
Subsurface Boundary Fluxes	127,707	122,228	5,479	37,673
TOTAL	477,134	477,231	(98)	-

Note: ( ) indicates flux out of model area

4.2.5.2 Head Calibration

Calibration criteria three through six set the head calibration goals. Table 4-3 presents the calibration statistics for the calibrated steady state model. A total of 396 wells were available for the steady state calibration and the range in observed heads was 1,123 feet.

Table 4-3 Steady State Model Calibration Statistics

Calibration Metric	Value
Residual Mean (feet)	-3.09
Absolute Residual Mean (ARM) (feet)	9.17
Root Mean Squared Error (RSME) (feet)	13.57
Normalized Absolute Residual Mean (NARM)	0.8%
Normalized Root Mean Squared error (NRMS)	1.2%

The goals for the Normalized Absolute Residual Mean (NARM) and NRMS are, at a minimum, to be less than 10 percent, but ideally to be less than 5 percent. The calibrated model achieves approximately 1 percent for each parameter.

Figure 4-4a shows a plot of calculated versus observed heads, and Figure 4-4b depicts residual (the difference between the observed and calculated heads) versus elevation. There are no apparent trends with change in elevation.

Figure 4-5a Observed v. Calculated Heads

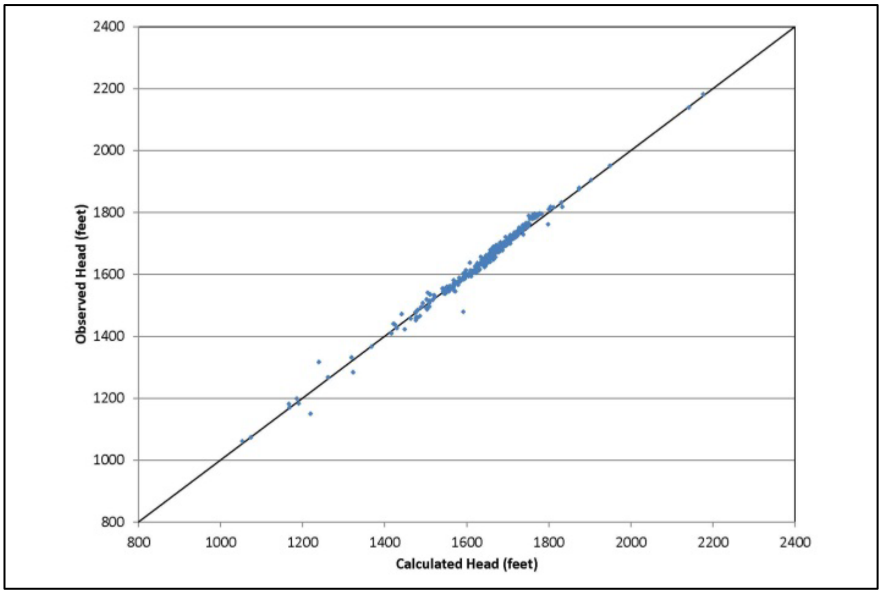


Figure 4-5b Residuals v. Elevation

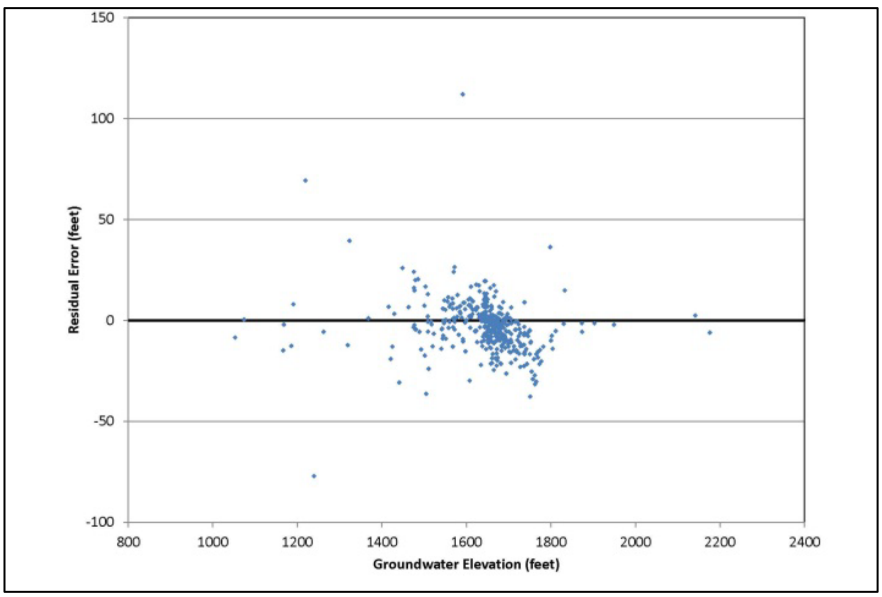
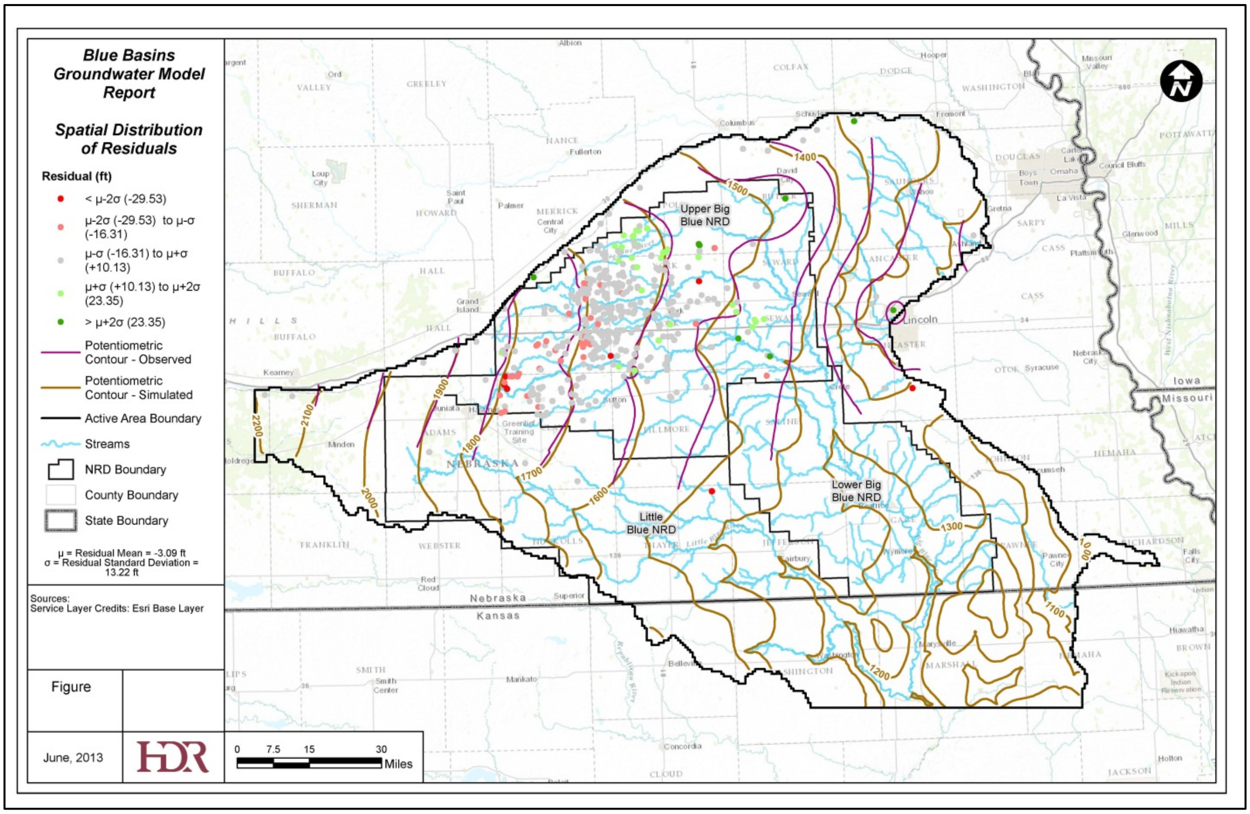


Figure 4-6 contains a plot of the two-dimensional spatial distribution of the residuals, and also shows potentiometric contours generated from the 1953 target data (observed heads) and by the steady state model (simulated heads). There appears to be a slight spatial trend to the residual values, with greater tendencies for negative residuals in the western portion of the data cluster and positive residuals to the east. This can be seen in the relative positions of the simulated and observed potentiometric contours, where the 1,700- and 1,800-foot-contours of the simulated results lie slightly east of the respective observed contours, and the 1,500- and 1,600-foot-contours of the simulated result lie on or slightly west of the respective observed contours. Taken as a whole, however, the position and orientation of the simulated contours compare very favorably with the observed, so that the magnitude and direction of the hydraulic gradient is reasonably reproduced.

Figure 4-6 Spatial Distribution of Residuals



Note: Red values, model is predicting high. Grey values, model is prediction roughly equal. Green values, model is predicting low.

4.2.5.3 Streamflow Calibration

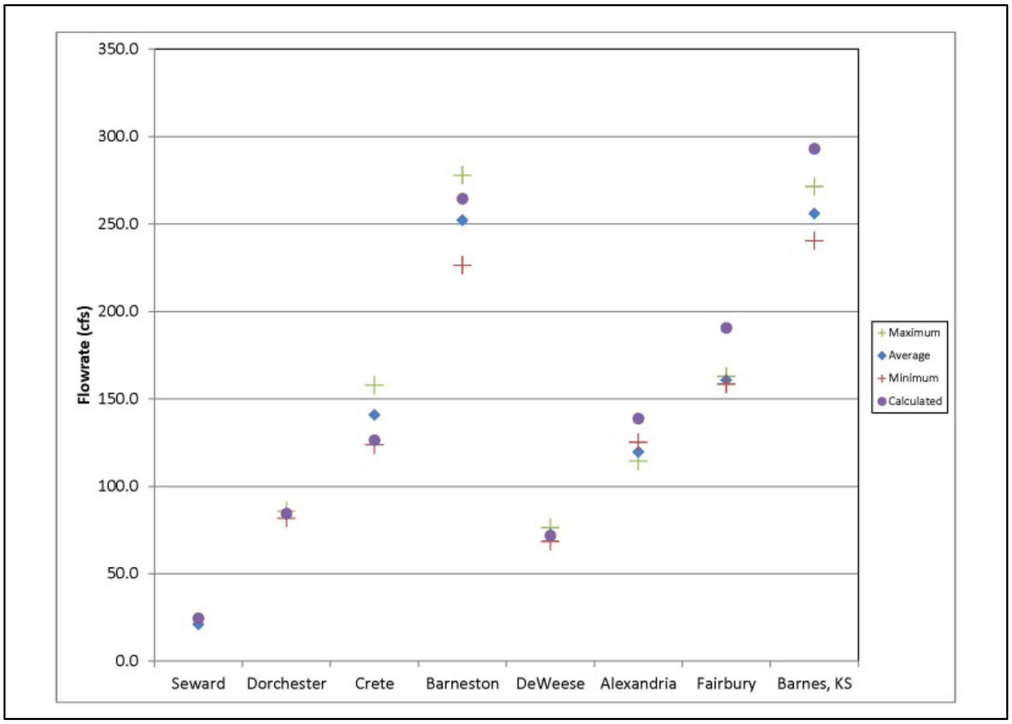
Table 4-4 presents the streamflow calibration target ranges and the streamflow calculated by the steady state model. The methodology for development of streamflow targets was presented in Section 4.1. These data are presented graphically in Figure 4-7. The predicted streamflow for four of the six gages fell within the target range. Predicted streamflow at the other two gages are greater than the upper end of the respective target range, but are within 20 percent of the midpoint of the range. Thus, the magnitude of simulated streamflow is generally correct.

Table 4-4 Streamflow Calibration Targets and Results (cfs)

Gauging Station		Seward	Dorchester	Crete	Barneston	DeWeese	Alexandria	Fairbury	Barnes, Kansas
Calibration Range	Maximum		85.9	157.8	277.9	76.3	114.4	162.9	271.5
	Average	21.0*	83.8	140.8	252.2	72.5	119.7	160.7	256.0
	Minimum		81.7	123.8	226.4	68.6	125.2	158.5	240.5
Model Calculated Flow Rate		24.5	84.4	126.3	264.5	71.8	138.7	190.6	293.1

*due to extreme range in flow, comparison for Seward gage is made to predevelopment median spring flow

Figure 4-7 Streamflow Calibration Targets and Results



4.3 Summary

The steady state model achieved all the calibration goals listed at the beginning of Section 4, including matching the conceptual mass balance, observed groundwater elevations, and observed streamflow at eight gage locations. Achieving the calibration goals indicates that the model input parameters and boundary conditions used in the steady state model produce simulated streamflow values that match observed predevelopment conditions, which directly correlates to the objectives of the model. As a result, the model input parameters and the model boundary conditions are an appropriate starting point for the transient model calibration

5.0 Sensitivity Analysis

An evaluation of the sensitivity of the model to changes in model input parameters was performed following the calibration of the steady state model. A two-step process was performed to evaluate the sensitivity of changes in model input parameters to both head and flux (streamflow) targets. The first step was to conduct a detailed sensitivity analysis of the head residuals to identify which model inputs have the most impact on the calibration of head targets. The second step was to conduct a sensitivity analysis of changes to model input parameters on model predicted streamflow at the gage locations used to evaluate the steady state model.

It should be noted that evaluation of the model sensitivity relative to head targets is skewed by the location of the predevelopment calibration targets, which are not well distributed throughout the Basin. The predevelopment flux targets are reasonably well distributed throughout the model domain and provide a good data set for evaluation of the sensitivity of the model relative to flux targets. The following section presents the methods and results of the sensitivity analysis.

5.1 Sensitivity Analysis – Head Targets

Prior to developing the transient groundwater model, a sensitivity analysis was performed to evaluate the impact of changes in model input parameters on the model calibration, relative to the available head targets. This sensitivity analysis was performed using an automated process in Groundwater Vistas. The following model input parameters or boundary conditions were modified to evaluate the sensitivity of the numerical model to each model parameter individually:

- Hydraulic conductivity values by zone
- Recharge rates by zone
- Recharge rates by Basin (Big Blue River or Little Blue River), and
- Conductance of stream boundaries by Basin

The sensitivity of each model parameter or boundary condition was evaluated by using the calibration targets in the steady state model and comparing the statistical data of each modified model run, specifically the NRMS and the residual mean, to the base case NRMS and residual mean of the calibrated model. Model parameters were modified, one at a time, by a range of plausible values for that parameter. Hydraulic conductivity and recharge rate were modified on a scale from 0.1 to 10 times the base case used in the calibrated steady state model. For these parameters, each parameter zone was modified one at a time.

A second sensitivity analysis was performed using recharge rates and stream conductance values on a by-basin basis. Recharge rates were modified on a basin wide level; evaluating the Big Blue River and the Little Blue River basins in separate model sensitivity runs. The same by-basin strategy was used to evaluate the sensitivity of model predicted heads to changes in stream boundary conductance. Conductance values were modified on a log scale from 0.01 to 100 times the base case value used in the steady state model.

5.2 Sensitivity Analysis – Flux Targets

The sensitivity of each model parameter or boundary condition was evaluated by using the streamflow values calculated by the steady state model as the base case. Model calculated streamflow values from the same ten gages used in the steady state calibration were used in the sensitivity analysis. Five gages for each river basin (ten gages total) were included in the sensitivity model runs.

Recharge rates and stream boundary conductance values were modified to evaluate the sensitivity of these model parameters to predicted streamflow values. Stream boundary conductance values were modified on a log scale from 0.01 to 100 times the base case value used in the steady state model. For the head or flux target sensitivity analysis, the conductance value for all stream reaches within the model were modified by basin, meaning the conductance of all stream reaches in the Big Blue River Basin were modified for one model simulation, the all the stream reaches in the Little Blue River Basin were modified in a separate model run.

Recharge rates were modified on a basin wide level; evaluating the Big Blue River and the Little Blue River basins in separate model sensitivity runs. To perform this sensitivity analysis, all recharge zones which are part of the Big Blue surface watershed were modified by a factor of 0.5 to 2.0 of their calibrated value. A summary of all model simulations performed as part of the sensitivity is presented below.

Table 5-1 Summary of Sensitivity Analysis Simulations

Model Parameter	Number of Zones or Reaches	Parameter multipliers (times base case in model)	Total Simulations Performed
Hydraulic conductivity	19	0.1, 0.2, 0.33, 0.5, 0.67, 1, 1.5, 2, 3, 5, 10	209
Stream boundary conductance	2 (By Basin)	0.01, 0.1, 1, 10, and 100	10
Recharge rate	17	0.1, 0.2, 0.33, 0.5, 0.67, 1, 1.5, 2, 3, 5, 10	187
Recharge rate (by-basin)	2 (By Basin)	0.5, 1, 2.0	6
Total steady state sensitivity simulations performed			412

As indicated in the above table, the sensitivity analysis consisted of a total of 412 separate model simulations. The results of the sensitivity analysis are presented in in graphical format in Appendix D.

5.3 Sensitivity Results

A discussion of the model sensitivity analysis, by model input parameter, is presented below:

1. Hydraulic Conductivity – Changes in the hydraulic conductivity within the majority of the hydraulic conductivity zones did not result in large changes in the NRMS or residual mean error in the model, indicating heads in the steady state model are relatively insensitive to changes in this input parameter. This is, at least in part, a result of the distribution of the calibration targets, which are mostly located in zones 3, 6, and 9.

For zones 3, 6, and 9, the sensitivity analysis shows that the final calibrated hydraulic conductivity produced the lowest or near lowest NRMS and residual mean error, which supports the final calibrated value for these zones.

2. Recharge Rates – The sensitivity analysis indicates that the model is most sensitive, both to predicted heads and streamflow values, to changes in the input values of aquifer recharge. The recharge sensitivity analysis showed that the final selected recharge values for the steady state model generally produced the lowest NRMS and residual mean error.

   The by-basin recharge sensitivity analysis showed that the calibrated steady state recharge rates (the base case) also produce streamflow values that were closest to the calculated base flow values for the gaged calibration targets. This analysis showed that changes in the aquifer recharge rates result in large changes in predicted streamflow, which do not match the observed base flow data at the gages.

   The results of the sensitivity analysis support the selection of the recharge rates in the steady state model.

3. Streambed Conductance – The sensitivity analysis performed on this stream bed conductance showed that this is not a sensitive parameter, relative to either the head of flux calibration. Relative to the head calibration, changes in this model input parameter did not result in large changes in the NRMS or the residual mean error. The results of this analysis showed that the selected streambed conductance values produced the lowest or near the lowest NRMS and residual mean error, supporting the selection of the calibrated values.

   The by-basin analysis relative to the streamflow flux targets showed that changing this parameter by an order of magnitude (either increased or decreased) did not significantly change the model predicted streamflow values at the gage locations. Changes in the model predicted streamflow only occurred when the stream bed conductance value was increased by two orders of magnitude. For these simulations, the model was unstable and created a large (more than 10 percent) error in the mass balance, indicating these higher streamflow values are not reliable.

   The results of the sensitivity analysis support the selection of the stream bed conductance values in the steady state model.

6.0 Transient Model Calibration

The following section presents the results of the transient model calibration and model run. The transient builds upon the steady state model presented in Section 4 and the sensitivity analysis presented in Section 5 and attempts to reproduce both the climatic and pumping changes that occurred within the Basin from a period starting in 1935 and ending in 2011.

Transient modeling differs from steady state modeling in that time varying stresses on the aquifer are allowed and aquifer storage coefficients must be assigned. In addition, the model time must be discretized into time steps and stress periods. Time discretization and aquifer storage parameters were determined by HDR. Per the scope of services for this project (Nebraska DNR Contract Number 476) the well pumping files and the transient recharge rates were developed by Nebraska DNR and provided to HDR for use in the model.

6.1 Discretization of Time

The time discretization used in the transient model is summarized in Table 6-1. Three intervals of time are defined. The first stage is 5 years in length, from 1935 to 1940, where there was no pumping within the model and the recharge rate remained steady. This initial stage is used to transition from the initial steady state heads to the 1940 conditions. The second stage represents the period from 1940 through 1985, and consists of 45 stress periods of approximately 1 year in length. There are 12 time steps of variable length in each stress period, with the length of each time step 1.2 times greater than the previous. The third stage represents a period from 1986 through 2011, consists of 313 monthly stress periods, each consisting of two variable length time steps. The third stage is intended to provide greater temporal resolution, which allows for a better representation of the irrigation pumping season

Table 6-1 Stress Period Set-up

Simulation Stage	Stress Periods	Stress Period Length (days)	Time Steps
1 (1935–1940)	5	365	12
2 (1940–1985)	45	365	12
3 (1986–2011)	313	30	2

6.2 Initial Head Conditions

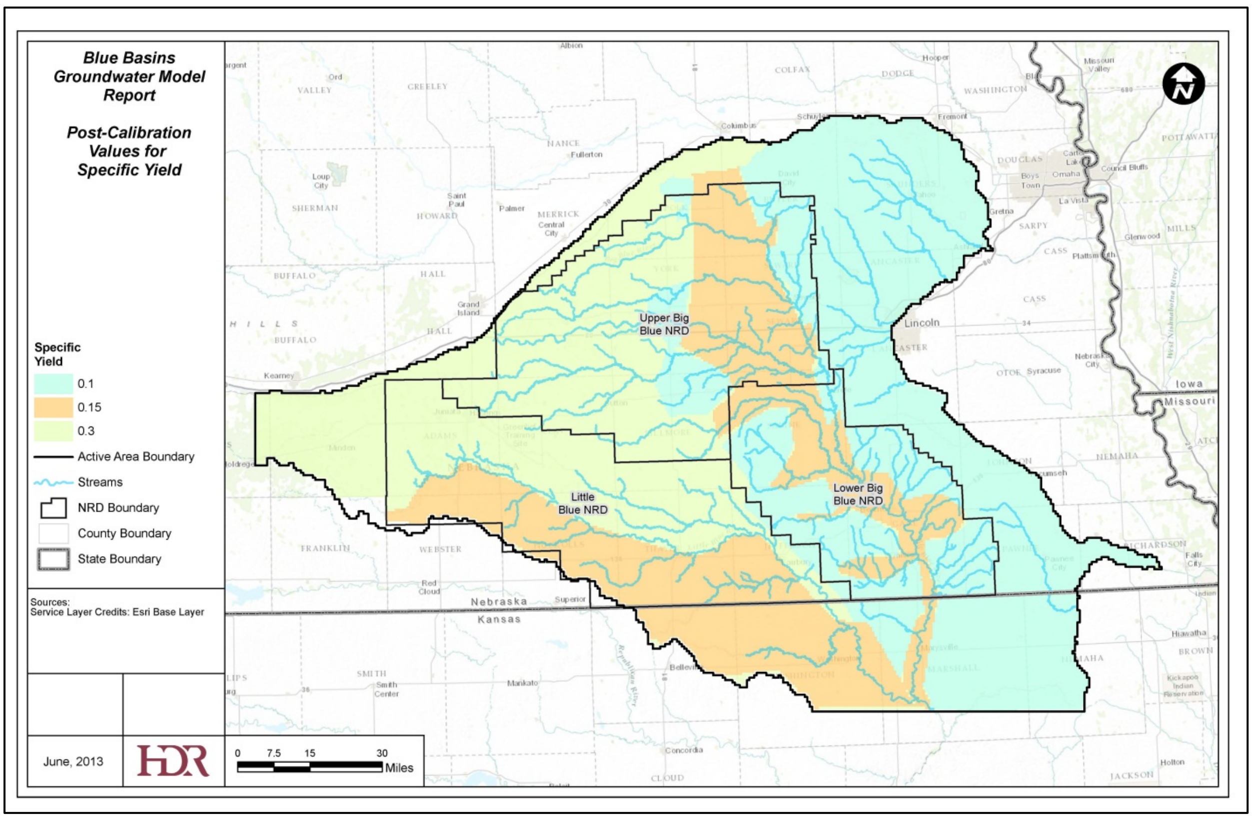
The initial starting head distribution for all transient simulations was set equal to the head distribution from the steady state model. This is consistent with state of the practice modeling techniques for transient models (Anderson and Woessner 1992).

6.3 Post Calibration Specific Yield Distribution

The specific yield of Layer 1 was determined through calibration of the transient model. Calibration of the specific yield was performed primarily by comparison of model predicted to observed hydrographs of transient head in the 19 observation wells that had an extensive dataset. Initially, a uniform specific yield value of 0.1 was assigned for Layer 1. However, during the calibration process it was noted that a better match to the transient water level elevations could be obtained by making specific yield spatially variable in Layer 1. Therefore, a total of three (3) property zones were defined for specific yield in Layer 1. The zones are loosely based on the topographic regions within the study area, but also include the glacial till deposits. The final distribution of specific yield for Layer 1 is shown in Figure 6-1. The values are consistent with established ranges of specific yield for an unconfined aquifer (Heath and Trainer 1992), and are spatially variable based on the unconsolidated geology.

A specific yield value of 0.3 was used to represent the unglaciated portion of the Plains topographic region. This region is underlain mostly by sand and gravel deposits (UNL CSD 1998). Sands and gravel typically have a higher primary porosity value than the finer grained materials that underlie the other topographic regions. A higher primary porosity correlates to a higher specific yield. Slightly lower specific yield values were used to represent the dissected plains topographic region and the area of glacial till deposits. These topographic regions are underlain by fine grained deposits that have a lower primary porosity compared to the deposits in the Plains topographic region. A constant value of 1×10^{-6} for specific storage and 0.05 for specific yield were used in Layer 2.

Figure 6-1 Post Calibration Values for Specific Yield



6.4 Transient Pumping and Recharge

For the purposes of this modeling project, Nebraska DNR developed an updated land use dataset, which was incorporated into the soil-moisture balance model CropSim (Martin, et.al, 1984). CropSim is a soil-moisture balance model that estimates crop irrigation requirements on various time scales. The model is specific to Nebraska and uses a set of quality- controlled weather stations, along with other detailed datasets, to estimate crop irrigation needs. CropSim is a water-driven soil-water balance point model used to investigate the system response to different forms of vegetative growth. Crop production is based upon the availability of water in the root zone to the crop when needed. The amount of water present in the root zone can be estimated throughout the simulation period by systematically monitoring water inflows and outflows in the form of a water balance (Equation 1).

$$P + I = ET + RO + DP + \Delta SW \qquad \text{Eq.1}$$

P	precipitation [in]
I	Irrigation [in]
ET	Evapotranspiration [in]
RO	Runoff [in]
DP	Deep percolation [in]
ΔSW	Change in soil water content [in]

Inputs

The CropSim water balance considers five different categories of inputs; 1) weather data, 2) soil properties, 3) crop characteristics, 4) irrigation system characteristics, and 5) management practices.

1) The hydrologic response of the system is highly dependent upon the climatic conditions. CropSim uses precipitation, temperature, and reference ET (ET_r) to simulate vegetative growth, water usage, and irrigation demand. Further information on the weather data can be found in Section 2.4.

2) Soil can be thought of as a small reservoir, accumulating water from precipitation and irrigation up to its maximum holding capacity or saturation, and releasing it when needed for vegetative growth (ET). The presence of water in excess of the holding capacity is either restricted from infiltrating resulting in runoff, or allowed to drain out the bottom of the soil profile as deep percolation after a soil specific period of time.

There are numerous soil series, each with differing physical properties. To simplify the modeling process soils are compiled into 28 different soil classes based on water holding capacity, hydrologic soil group, and distance to groundwater.

3) CropSim considers many crop specific attributes; such as crop phenology and growth, rooting depth, harvest index, residue, crop coefficients, response to insufficient available water, among others; with many of these attributes varying with geographic location.

4) Irrigation system characteristics provide a description of the irrigation sources and methods. Examples of these parameters include: system capacity, application efficiency, and irrigation limits.

5) Management characteristics take into account the human effect of crop production. Planting time, tillage practices, operational downtime, management allowed depletion, and rainfall allowances are all dependent upon producer decisions. Practices common to the region were utilized during the simulations.

The inputs discussed above were used in the CropSim model to simulate crop growth and the soil water balance (Equation 1). Precipitation data were obtained directly from the weather files. Irrigation was applied to supplement precipitation during time of insufficient supply based upon the specific needs of the various vegetation types, while using a management allowed depletion to schedule irrigation events with consideration being made for operational downtime and irrigation system capacity. The irrigation system's application efficiency was used to reduce the gross irrigation depth to a net irrigation requirement.

Output

Evapotranspiration is split between evaporation and transpiration. Evaporation is the non-productive consumption portion of ET. A two stage method is used to estimate ET depending on whether energy or available water near the soil surface is the limiting factor, with considerations taken into account for vegetative coverage and residue. Transpiration is the productive consumptive use. CropSim uses the crop coefficient to relate transpiration to the reference ET_r. Insufficient water in the root zone will subject the crop to stress and reduce transpiration.

Runoff and deep percolation are the results of system inefficiencies. Runoff which is computed using an adjusted curve number approach occurs when the precipitation exceeds the initial abstraction. Deep percolation occurs when the depth of water in the soil profile exceeds the holding capacity and the excess water drains below the root zone.

CropSim simulations were made for irrigated and dryland cropping scenarios for each of the principal crops identified in the Land Use Analysis (Section 2.3). Each scenario was run continuously (i.e., irrigated corn on irrigated corn) for the duration of the simulated period. This process was repeated for each soil type at each weather station.

Regional Soil Water Balance Model (RSWB)

CropSim is an idealized model in which water is the only limiting production factor. Many other mechanisms affect crop growth, yields, and consumptive use; and therefore affect the overall water balance: pests, disease, inclement weather, management decisions, technology adaptation, etc…, all can have an impact. The RSWB is used to account for these exogenous influences by adjusting the water balance parameters to reflect local and regional field conditions while maintaining the water balance shown in Equation 1.

The primary purpose of the RSWB is to spatially distribute and maintain the CropSim water balance (Equation 1) for the various agricultural crops while being used as a calibration tool for the ground water model.

Numerous soil types were present in the BBM domain. For simplicity and compatibility with the CropSim model, they were re-characterized into the CropSim soil classes. Each cell within the BBM model domain was assigned to one of sex different CropSim soil classes that are present in the BBM domain based upon the predominant soil within that cell.

The water balance results from the CropSim model were spatially distributed from the weather stations to the BBM model cells. This was accomplished using the inverse weighted distance (IWD) technique from the three nearest stations to the centroid of each cell. The IDW process was applied to each vegetation type according to the soil class assigned to each cell.

Through calibration, the RSWB is used to regionally estimate irrigation demand based upon crop water needs (NIR[1]) and compute consumptive use; while splitting the excess water between stream flow, recharge, and indirect ET. Finally, the RSWB is used to compile the pumping and recharge results into formatted files for inclusion into the ground water model.

The output from the CropSim model served as the basis for recharge and pumping files used in the transient model. Four iterations of the pumping and recharge files were required before a satisfactory calibration was achieved.

6.5 Transient Model Calibration Data Sets

The data sets used to evaluate the transient model consist of well hydrographs developed from the UNL CSD groundwater level measurement data, streamflow hydrographs from selected gauging stations, and seep run streamflow measurements from spring 1979 (a wet or high flow period), fall 1988 (a near-normal period), and fall 1981 (a dry or low flow period). There are 19 well hydrograph locations distributed across the model domain and 12 stream gauging stations, 6 gages in addition to the 6 used in steady state calibration. Well and stream hydrograph locations are shown in Figure 6-2.

6.6 Comparison of CropSim Runs

A total of four model runs were performed using different iterations of the pumping and recharge files developed using CropSim. Initial recharge values in the supplied CropSim files appeared to be much higher than the range of values indicated by the steady-state MODFLOW model, and resulted in higher than observed streamflow values for the majority of the target locations. Therefore, each CropSim scenario worked to successively reduce the amount of recharge to the model with the objective of aligning model predicted streamflow with observed base flow. Appendix E contains streamflow and groundwater hydrographs that illustrate the results of the model runs performed using the CropSim003 and CropSim004 pumping and recharge files.

6.6.1 Streamflow Hydrographs

Comparison of the streamflow hydrographs does not universally favor either CropSim003 or CropSim004, although, on balance, the results of CropSim004 better match observed base flow especially at the down stream gage locations. The CropSim003 hydrographs for gages at Dorchester, Crete and Surprise on the Big Blue River compare very favorably to the hydrographs of observed data at those locations. However, the CropSim004 hydrographs do not compare as well at these locations, and under predict observed streamflow. It should be noted that these gages are all in upstream locations on the Big Blue River, and flow rates at these gages are small relative to the flow at downstream gages. The CropSim004 simulation produced a much better match to the observed flow conditions for the downstream gages on the Big Blue River (i.e., Barneston, Beatrice and Marysville) relative to the CropSim003 simulation. The CropSim004 simulation also produced a better match to observed streamflow for each of the gages on the Little Blue River.

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[1] NIR – Net Irrigation Requirement; the depth of irrigation water efficiently added to the soil profile to meet a crops full ET requirement

The predicted flow rates at the downstream gages nearest to the state border on both the Big Blue and Little Blue Rivers closely approximate the observed stream base flow in CropSim004. By comparison, the model predicted flow rate at these downstream gages was higher than the observed flow in the CropSim003 simulation. At the downstream gage locations on both the Big Blue and Little Blue River, the model results of CropSim004 were a clear improvement from CropSim003.

6.6.2 Well Hydrographs:

In most cases, the differences between predicted and observed groundwater levels on the well hydrographs were improved by CropSim004. However, a problem exists in some areas of the model under CropSim004. In some wells, the predicted heads closely match the observed pattern of declining head during the early years of the simulation period but, after about 1980, the observed data either stabilize or recover while the simulated heads continue to decline. Since CropSim004 successfully predicted the groundwater decline observed during the early years, the cause for this departure likely lies in the CropSim004 late-time recharge and/or pumping data. The affected wells include: 402333097540801, 402504097341501, 404749098044201, 405306097470901, 405514097573901, 405701097275701, and 410718097345301. The latter five wells are located in the extreme northern and western upstream reaches of the Big Blue River basin.

6.6.3 Non-Pumping Scenarios:

Simulations were performed in which the transient CropSim pumping wells were eliminated. The difference in the predicted streamflow between the pumping and non-pumping scenarios would theoretically represent the effect of groundwater pumping on the discharge of groundwater to streams. However, the recharge (deep percolation) associated with irrigation pumping was not eliminated from these model runs; therefore, the model runs were performed as a qualitative sensitivity comparison between the two CropSim iterations and do not represent actual pumping diversions.

Graphs of the difference between model predicted streamflow for the pumping and non pumping runs using CropSim003 and CropSim004 are included in Appendix E. The difference between pumping and non pumping streamflow is less in CropSim004 than in CropSim003. Based on these comparisons, the CropSim004 simulation predicts less reduction in streamflow as a result of pumping.

6.6.4 CropSim Run Selection

The model run completed using the pumping and recharge files from the CropSim004 simulation produced a much better match to the observed flow conditions for the downstream gages on the Big Blue River (i.e., Barneston, Beatrice and Marysville). The CropSim004 simulation also better matched observed flow conditions at the downstream gage locations on the Little Blue River (i.e., Fairbury and Hollenberg, KS).

The groundwater model will be used by the Nebraska DNR as a tool in the annual assessment of Basin status to calculate the historic groundwater depletions within the Basin. The point along the stream at which these evaluations occur is the most downstream gaged location within the Basin. Given that the CropSim004 model best matched the observed stream base flow at the downstream gage locations for both the Big and Little Blue Rivers, the CropSim004 model iteration was selected as the most representative. The following section presents a summary of the transient model with the pumping and recharge files from CropSim004.

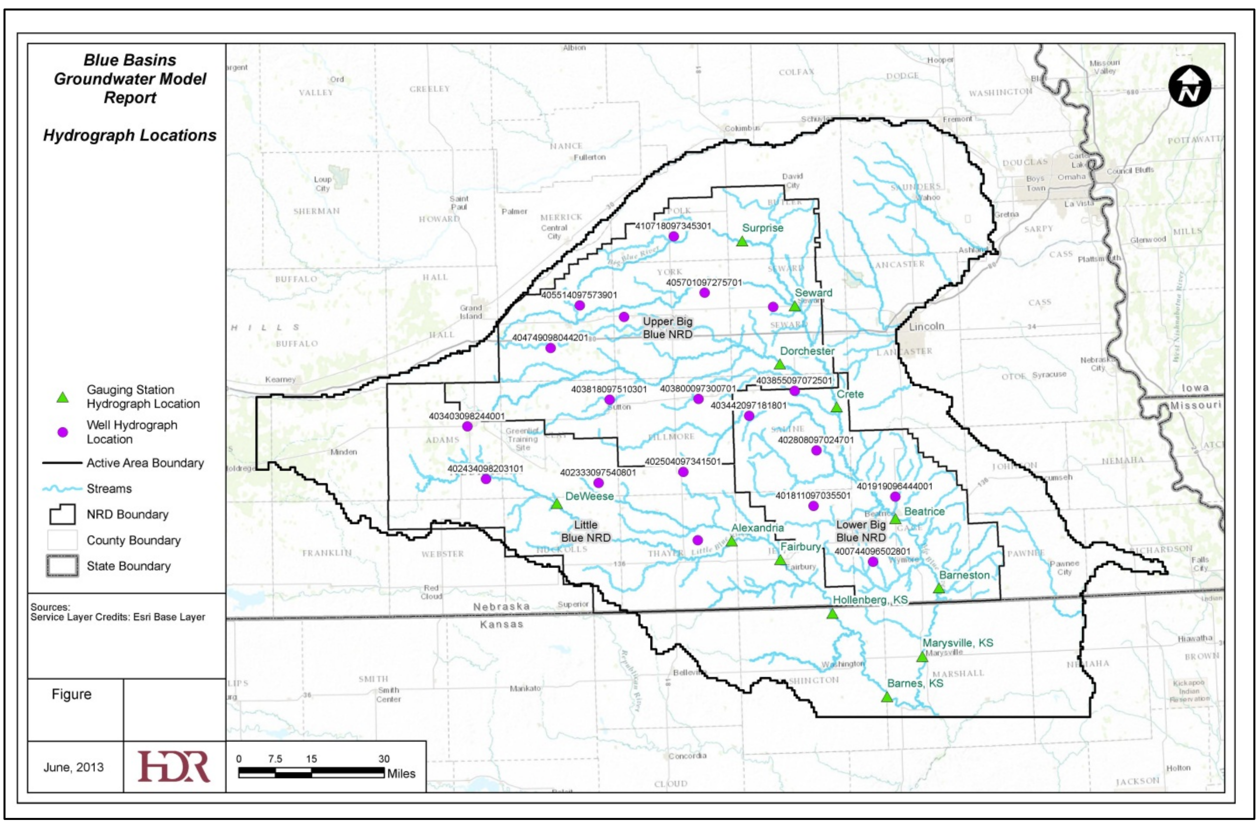
6.7 Evaluation of Transient Model

The following section presents an evaluation of the transient model output for the model run that included the final iteration of CropSim, CropSim004. The evaluation consists of a comparison between the model predicted and observed groundwater elevations and stream base flow throughout the Basin.

6.7.1 Groundwater Hydrographs

Model-calculated transient groundwater hydrographs were compared to observed historical groundwater elevations at 19 observation well locations. The location of the observation wells is shown in Figure 6-2. As shown, these transient observation wells are reasonably well distributed within the Basin and provide a good spatial distribution of calibration targets.

Figure 6-2 Hydrograph Locations



This comparison is a qualitative evaluation that was performed to ensure that the pattern of model predicted changes in groundwater elevation reasonably matched the observed data. The qualitative evaluation included a review of the model generated well hydrographs to evaluate the models ability to reproduce both the magnitude, and the timing, of the observed groundwater elevation changes. The results of this analysis are presented on Figures 6-3a through 6-3d. The hydrograph plots are included in Appendix F. Examination of the groundwater hydrographs indicates that, for the most part, the model reasonably approximates the transient changes in groundwater elevation within the Basin. The one exception is the seven observation wells in the central and western portion of the UBBNRD (see Figure 6-3b and 6-3c), in which the model predicts that groundwater elevations continue to decline beyond the early 1980s. The observed data show a general recovery of groundwater elevations in this portion of the Basin following the early 1980s.

Figure 6-3a Transient Groundwater Hydrographs

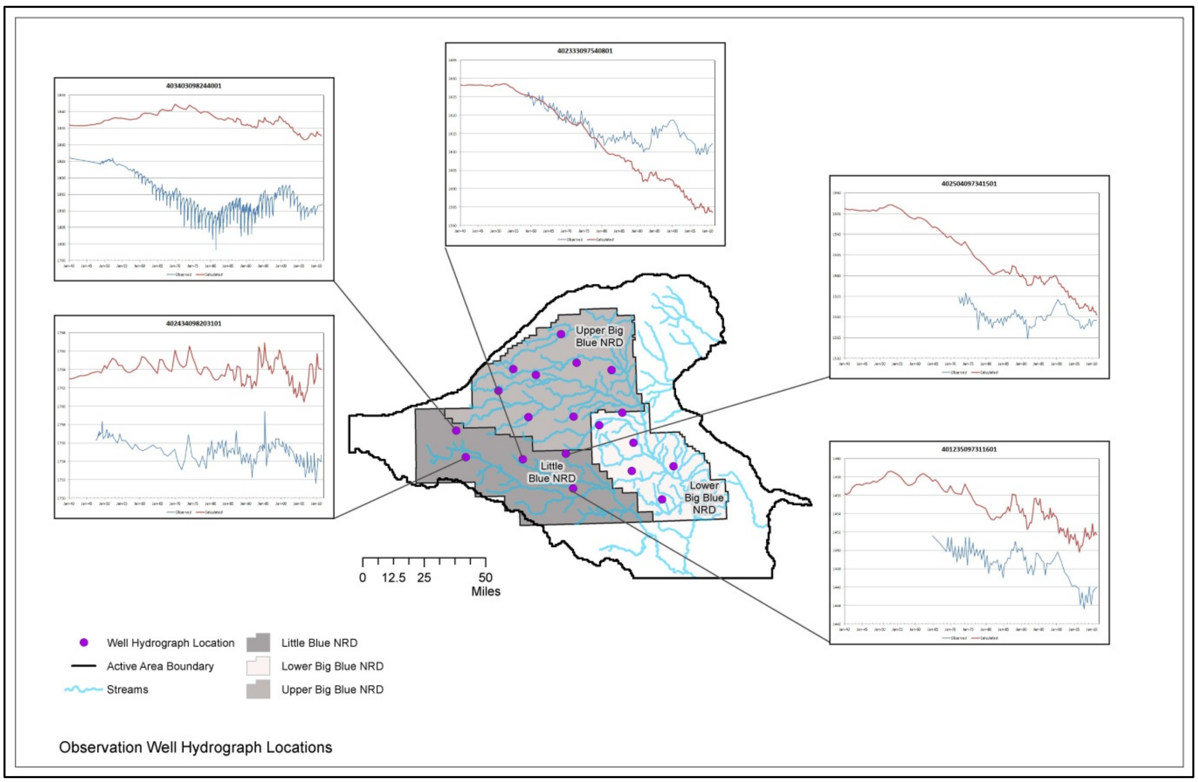


Figure 6-3b Transient Groundwater Hydrographs

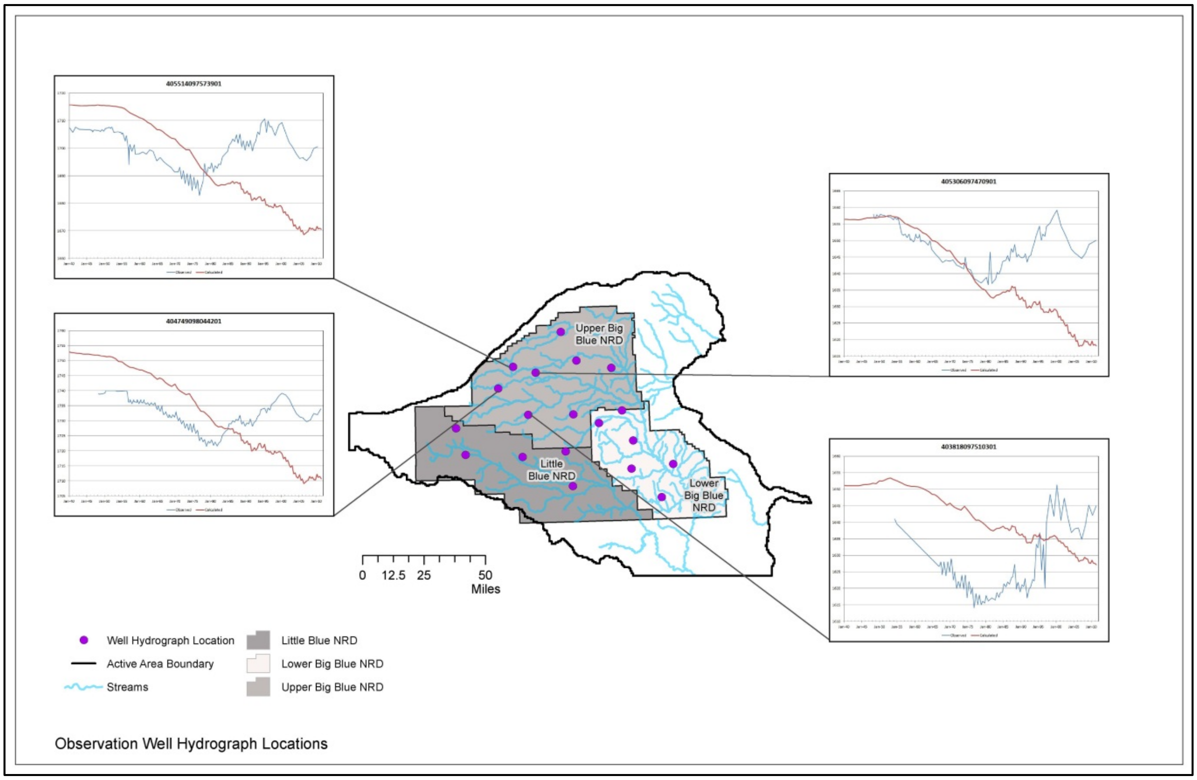


Figure 6-3c Transient Groundwater Hydrographs

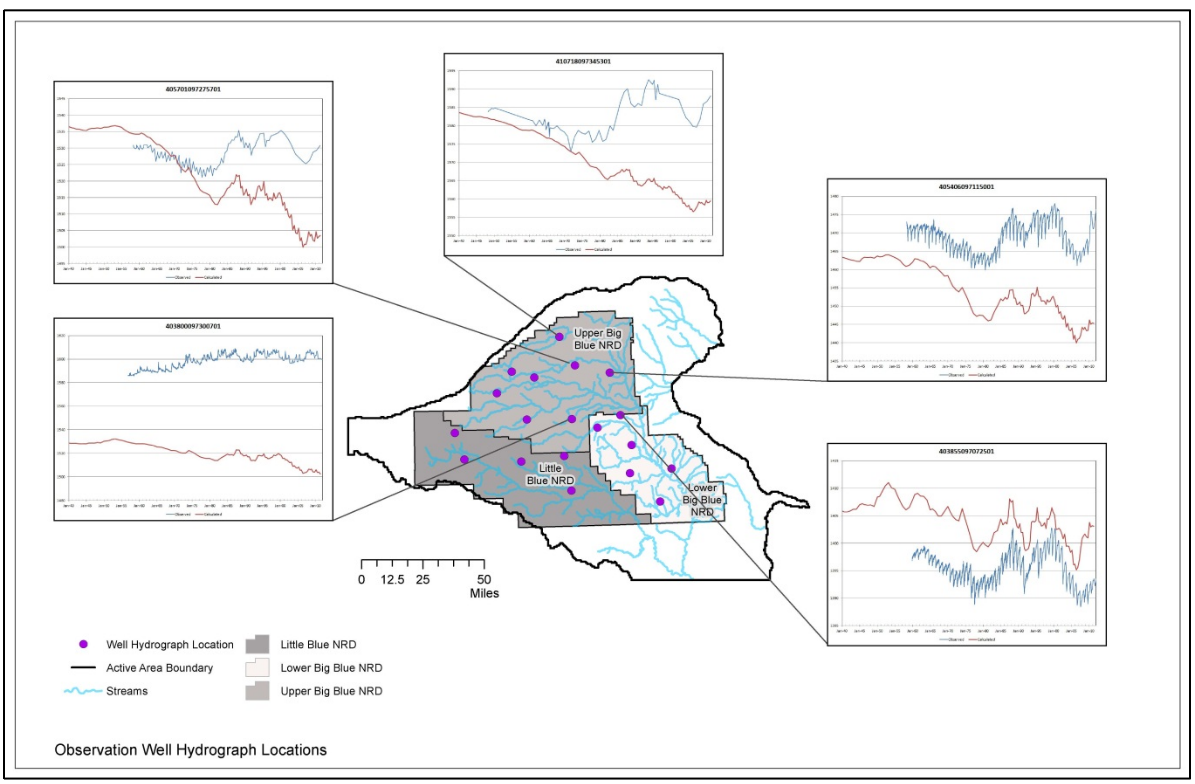
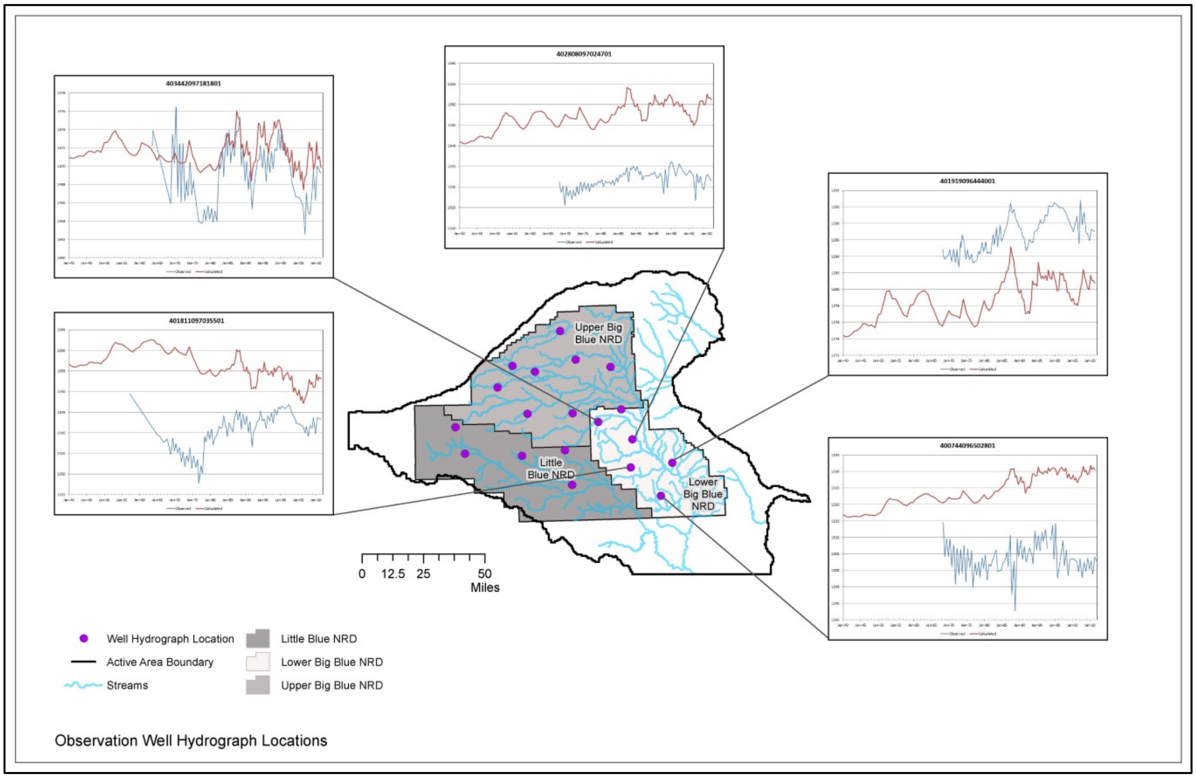


Figure 6-3d Transient Groundwater Hydrographs



6.7.2 Streamflow Hydrographs

Model-calculated transient stream base flow was compared to base flow calculated at 12 streamflow gauging stations. The locations of the streamflow gages are shown in Figure 6-2. As shown in Figure 6-2, the gage locations are reasonably well distributed within the Basin and provide a good spatial distribution of calibration targets.

The comparison of these model calculated versus observed stream base flow values is a qualitative evaluation that was performed to ensure that the pattern of model predicted changes in stream base flow reasonably matches the observed base flow. The results of this analysis are presented on Figures 6-4a through 6-4b. The hydrograph plots are included in Appendix G. The observed base flow values presented on these figures were developed using the BFI technique previously described. The observed data points shown on the streamflow hydrographs are the annual average base flow for that gage location, along with the 5-year moving average calculated from the annual averages. The qualitative evaluation included a review of the streamflow hydrographs to evaluate the models ability to reproduce changes in both the magnitude and timing of streamflow at these gaged sites.

Examination of the stream base flow hydrographs indicates that, for the most part, the model accurately reproduces both the magnitude and the temporal changes of stream base flow within the Basin. Exceptions are the gages in the upstream reaches of the Big Blue River Basin (specifically Crete, Dorchester, Seward, and Surprise) where the model predicted stream base flow reasonably approximates the observed base flow until the early 1980s. At that time, there is a departure between the model predicted and observed data, with the model predicting less streamflow compared to what was observed.

Figure 6-4a Transient Streamflow Hydrographs

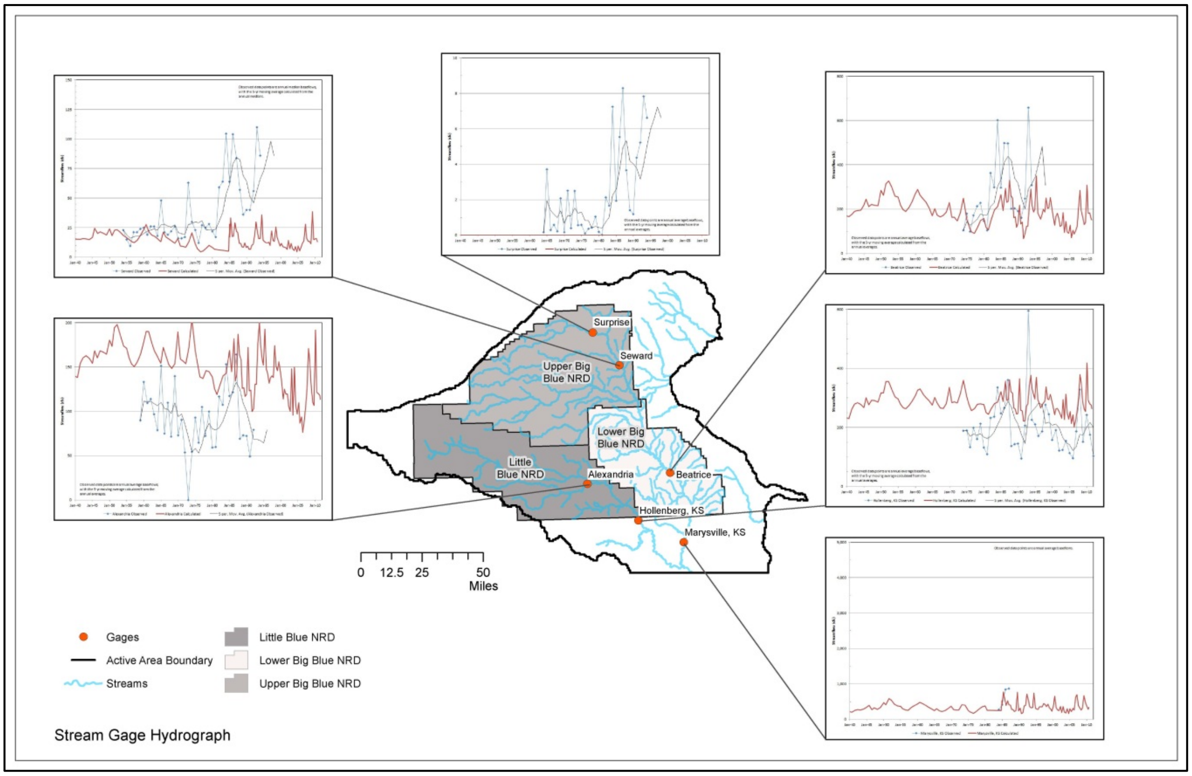
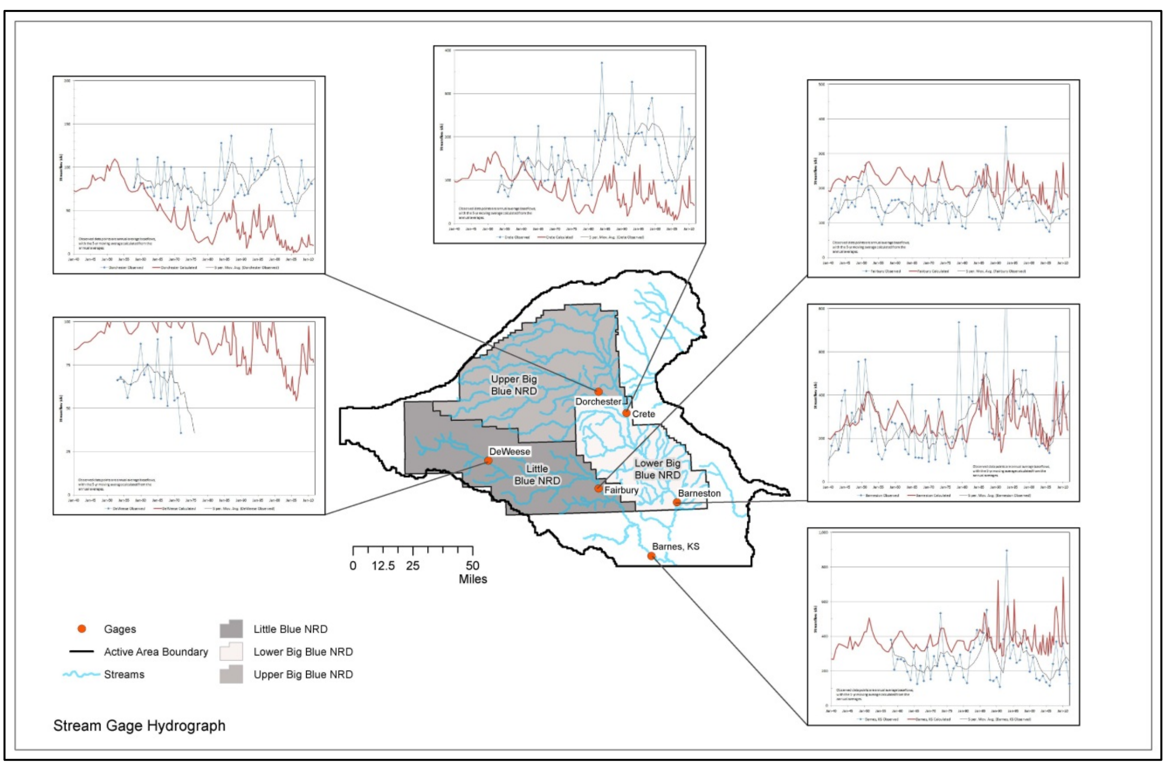


Figure 6-4b Transient Streamflow Hydrographs



6.7.3 Comparison to Mapped 2009 Potentiometric Surface

A quantitative and qualitative comparison of the model predicted water levels versus observed water level elevations for the 2009 synoptic measurement was performed to evaluate the performance of the transient groundwater model. The same quantitative normalized residual error objectives were used to quantify the calibration of the transient model. Additionally, the shape of the model-calculated potentiometric surfaces for 2009 was compared to the interpreted potentiometric surface presented in Section 2.0.

The observed groundwater data are maintained by the UNL CSD database, as described in Section 2.0. Water level data from a total of 1,135 wells was available to perform the comparison of model predicted groundwater elevations to the measured groundwater elevations for the spring 2009 synoptic event. The range in observed heads was 1,011 feet. A summary of the calibration statistics for this calibration check are presented in Table 6-2.

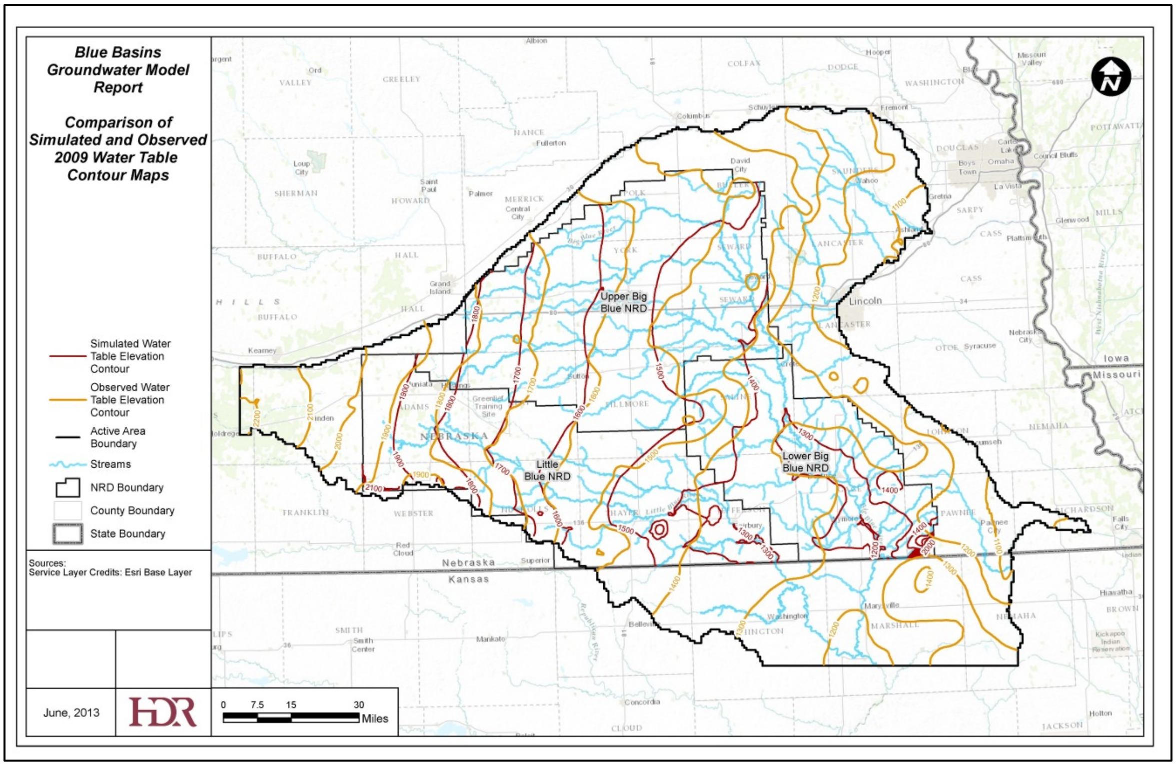
Table 6-2 Transient Model Calibration Statistics – 2009 Synoptic Event

Calibration Metric	Value
Residual Mean (feet)	15.5
Absolute Residual Mean (ARM) (feet)	27.2
Root Mean Squared Error (RSME) (feet)	35.1
Normalized Absolute Residual Mean (NARM)	2.7%
Normalized Root Mean Squared error (NRMS)	3.4%

The transient model exceeds the preferred statistical calibration goals that were established for the steady state model of an NRMS and a normalized ARM of less than 5 percent.

A qualitative comparison of the shape of the model-predicted potentiometric surface against the interpreted potentiometric surface for this synoptic groundwater measurement is presented in Figure 6-5. Although there are some local scale divergences between the observed and simulated potentiometric surfaces, given the scale of the model, the model reasonably reproduces the magnitude and direction of the Spring 2009 hydraulic gradient (see Figure 2-3).

Figure 6-5 Comparison of 2009 Observed and Simulated Water Table Contour Maps

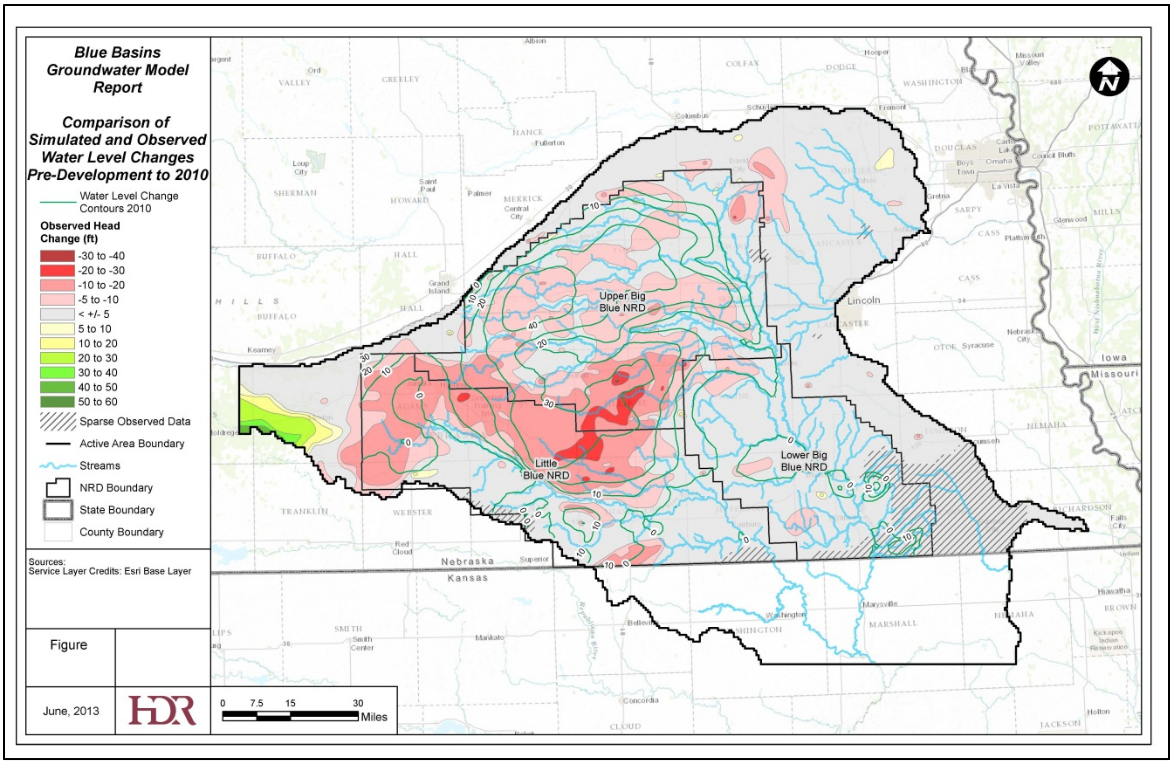


6.7.4 Comparison to Observed Groundwater Elevation Change

An additional evaluation of the transient model was performed by comparing the model predicted versus the observed change in groundwater elevation since predevelopment. The comparison was performed using the 2010 groundwater elevation change map published by UNL CSD as a comparison for the model predicted data, which is the change in groundwater elevation calculated by the model for the time period from 1940 to 2010. The model predicted changes in groundwater elevation are presented in Figure 6-6.

As shown in Figure 6-6, the model predicts groundwater elevation declines in areas where groundwater declines have been observed, and predicts little or no change in areas where groundwater elevations have remained relatively constant over time. Generally, the model also reproduces the magnitude of groundwater decline except in the north central and western portion of the UBBNRD, where the model over predicts the drawdown within the Basin. The model also under predicts observed changes in groundwater elevations in the far western portion of the LBNRD.

Figure 6-6 Comparison of Observed and Simulated Water Level Changes – Predevelopment to 2010



Note: Green contours are simulated water level change contours and the color flood values are observed water level change.

6.7.5 Seep Run Comparison

The final evaluation of the transient model included a comparison of model calculated stream base flow to spot synoptic streamflow measurements that were collected during periods of low, average, and high streamflow. The calibration data for this comparison consisted of seep run data collected during spring 1979 (a wet or high flow period), fall 1988 (a near-normal period), and fall 1981 (a dry or low flow period). Seep run data are Nebraska DNR archived point measurements of streamflow and were described in Section 2.7.1.

The primary objective of this comparison was to ensure that the model generally predicted the existence of streamflow when stream base flow was measured, and vice versa. The use of seep data provided an improved spatial distribution of streamflow records that were used to evaluate active stream reaches. A secondary objective of this comparison was to evaluate the ability of the model to simulate changes in hydrologic connection throughout the basin over time. The third use of the seep data was to evaluate the numerical difference between the model calculated and measured stream base flow values. The results of this comparison are presented in Figures 6-7a through 6-7c. For these figures, the residuals presented are the observed flow rate minus the simulated flow rate.

Figure 6-7a Seep Run Comparison – Low Flow Conditions (1981)

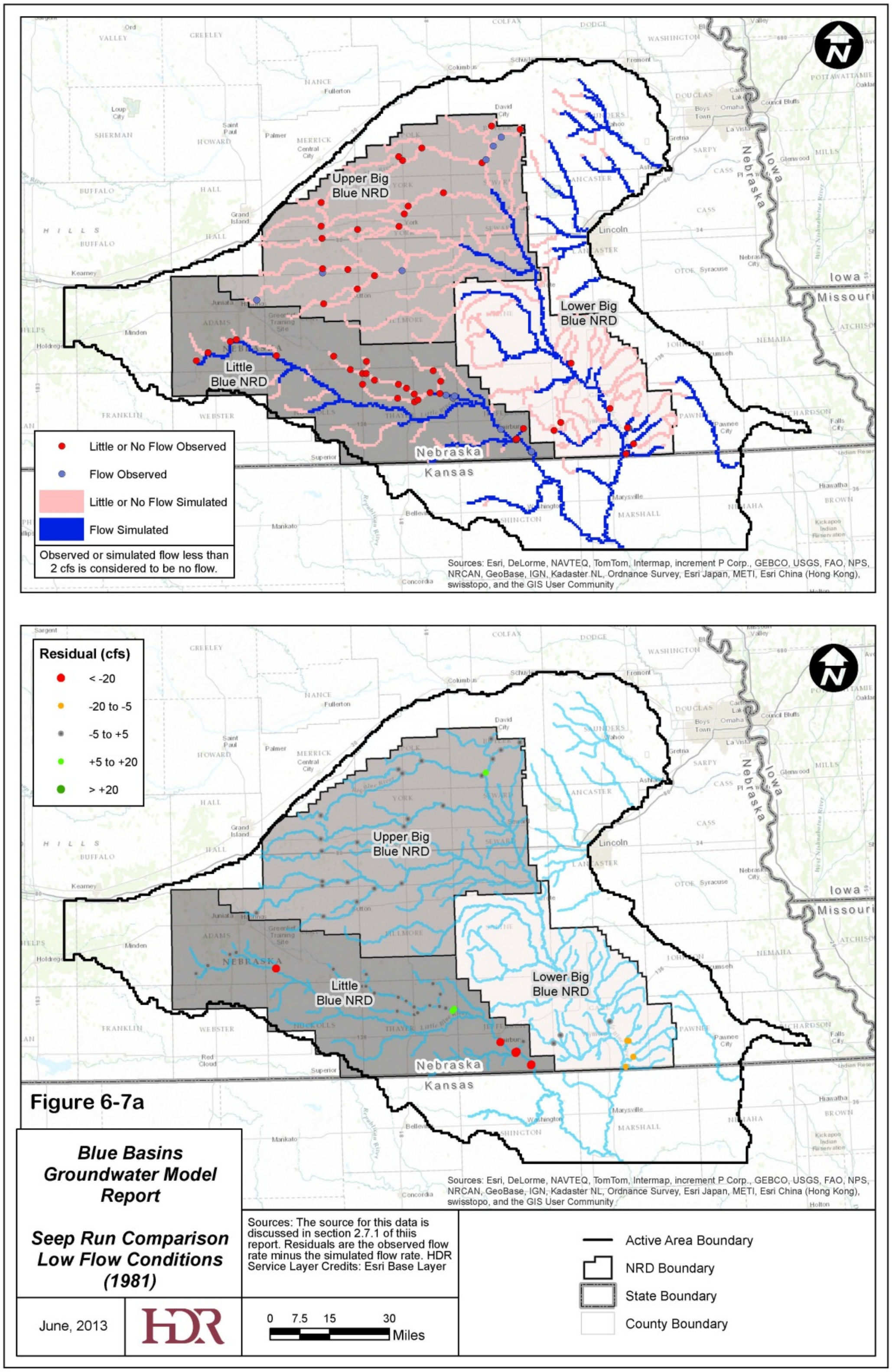


Figure 6-7b Seep Run Comparison – Normal Flow Conditions (1988)

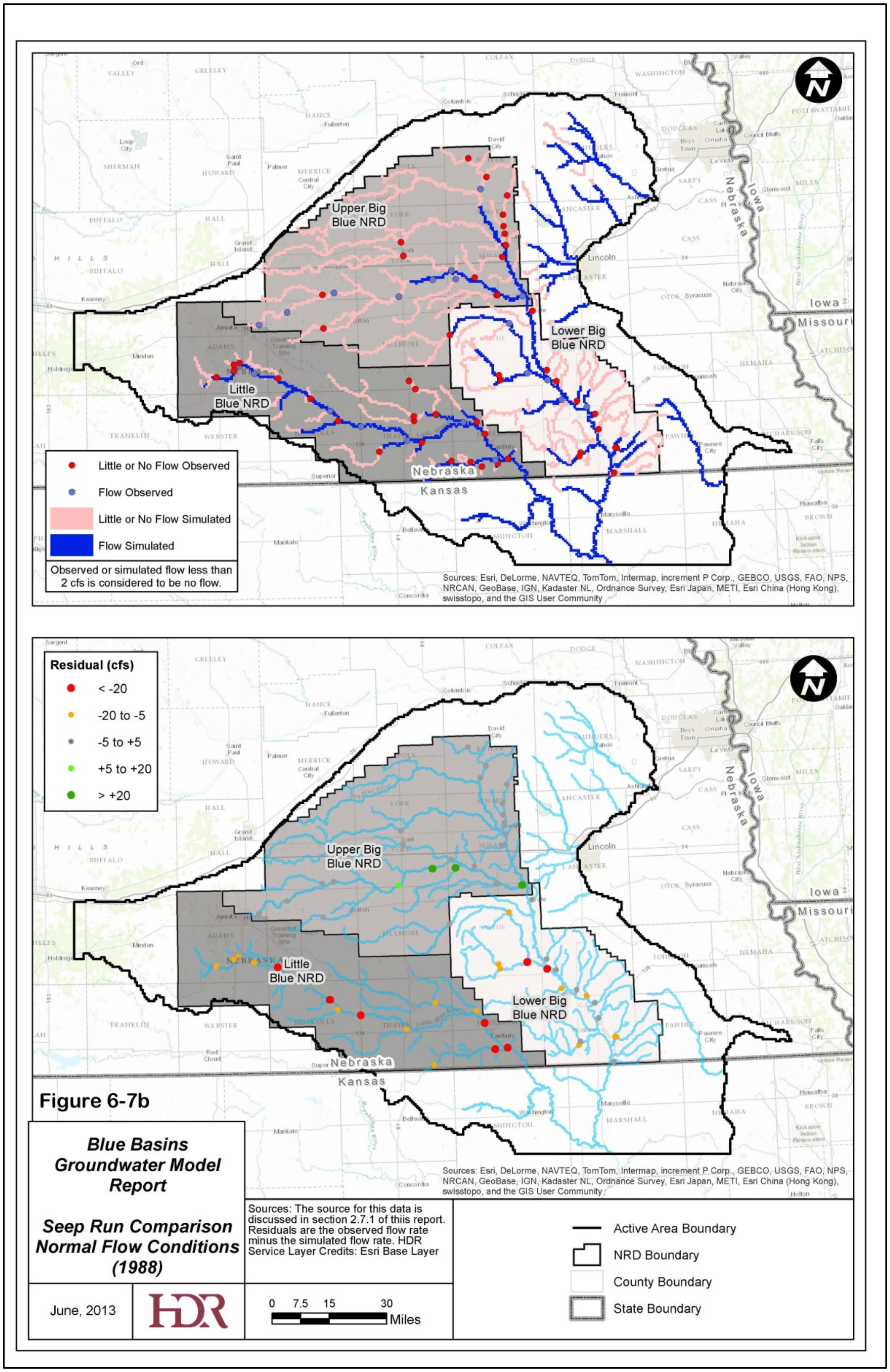
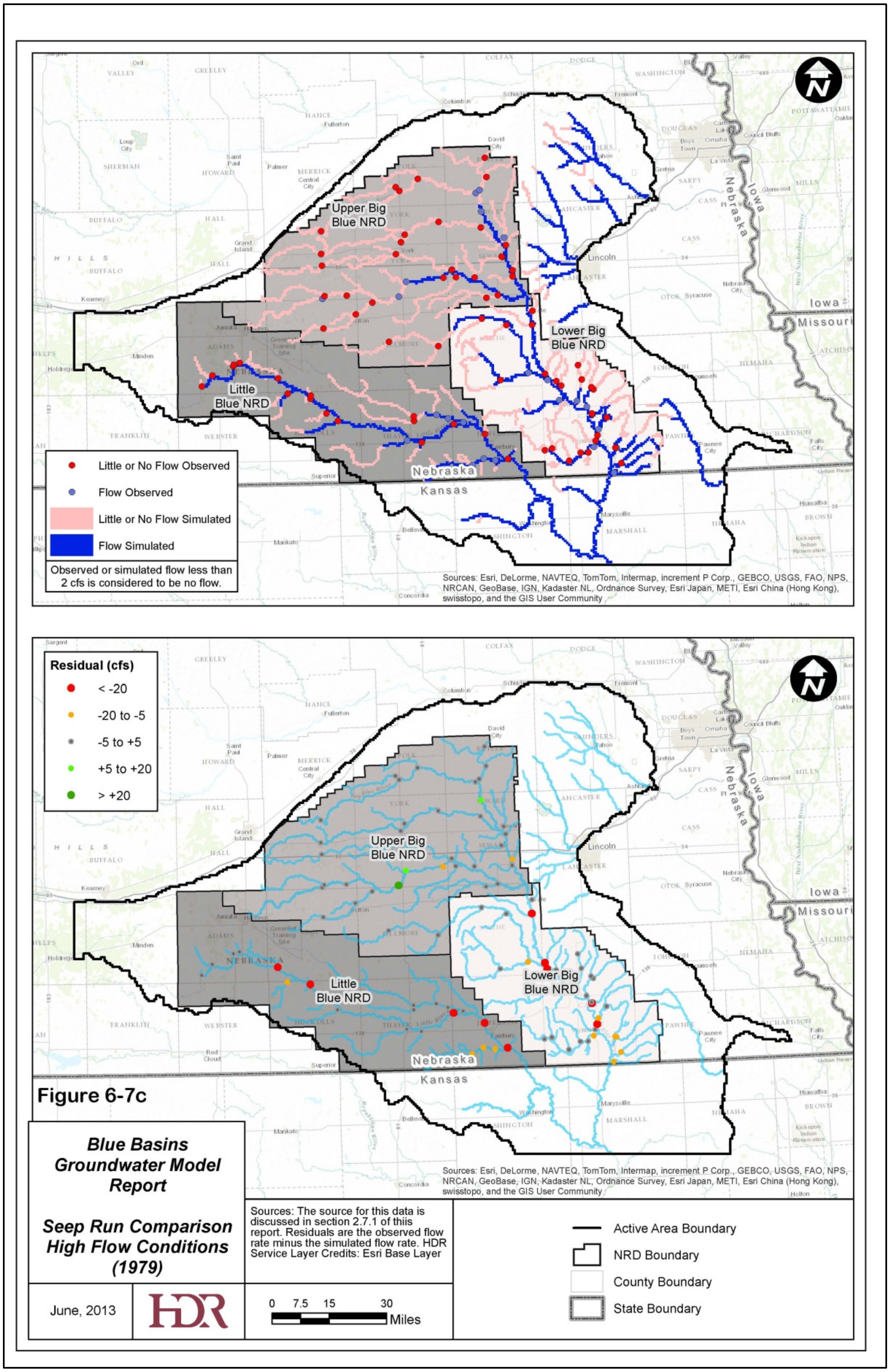


Figure 6-7c Seep Run Comparison – High Flow Conditions (1979)



As shown in the above figures, there generally is good overall agreement between the presence/absence of model calculated streamflow and observed stream base flow at the locations of these spot measurements. The model generally does well in predicting where flow was observed or where it was not observed. Also, if the model incorrectly predicted flow to occur where it had not been observed, the calculated flow residual is typically small. As shown on Figures 6-7a through 6-7c, the number of seep run locations with large flow residual greater than ±20 cfs is small.

The match between predicted flow and observed flow is somewhat better for the low flow (1981) and normal conditions (1988) comparisons than under the high flow condition (1979). The most notable discrepancy between predicted flow and observed flow occurs in the northern and western portion of the UBBNRD, where the streamflow was observed during the normal and high flow conditions, but was not predicted by the model. This observation is consistent with the previously described discrepancies between transient stream base flow and groundwater elevations in this portion of the study area.

6.8 Areas of Potential Refinement

The groundwater model presented was developed to evaluate changes in stream base flow that result from an increase in groundwater pumping on a basin level scale. The goal for development of the model was to characterize and simulate the regional-scale hydrogeologic processes that can impact streamflow depletions due to pumping. For a model to be appropriate for that type of regional scale analysis, the model should be able to reasonably approximate the time varying stream base flow conditions within the study basin. The objective of this model was not to reproduce every detail of the hydrogeologic system, but rater rather to develop a tool that can be used to evaluate groundwater-management scenarios over a regional spatial scale that includes multiple counties and a time scale of multiple years.

Development of the regional model focused on generalized hydrogeologic characteristics within the Basin, and did not attempt to describe local-scale variations that can impact groundwater flow at the local scale. The spatial scale selected (1/2 mile square cells) is consistent with most regional scale models. For example, the Elkhorn and Loup River Basin model (USGS, 2010) was developed with a similar purpose and used 1 mile square cell size. The temporal discretization used in this model included seasonal sub-periods to simulate irrigation and non-irrigation seasons using monthly time steps and is also appropriate for regional scale modeling. Overall, the spatial and temporal discretization scales selected for this model are most appropriate for evaluating groundwater-management scenarios over large areas and over long periods of time, and are not as reliable for analysis of local scale problems, where the desired detail may require simulation of local aquifer heterogeneity or local aquifer stresses at a spatial and temporal scale that is smaller than the cell size and time steps used in this model.

The transient model calibration presented showed that the model adequately represents the changes in groundwater elevations that have been observed within the Basin. Most importantly, the model is also capable of representing the observed time varying stream base flow conditions at most of the gages within the Basin, and best matches observed stream base flow at the downstream gages within both the Big and Little Blue River Basins.

The transient model simulation (using the recharge and pumping data sets from CropSim004) produced a good overall match to the historical stream base flow and groundwater elevation data sets. Most importantly, the model produces a good match to observed stream base flow at the most downstream gage locations within the Basin, for both the Big and Little Blue Rivers. However, as previously discussed, the model over predicts the decline in water level elevations and under predicts stream base flow in the northern and western portion of the UBBNRD. The model predicted change in water level elevation within this portion of the model area does match the declines in water level elevation observed from the early 1950s to the early 1980s. Following the early 1980s, observed groundwater elevations appear to rebound in this portion of the Basin, however the model predicts that water level elevations will continue to decline. As a result, model predicted streamflow in this portion of the Basin are less than observed streamflow at several upstream gages in the Big Blue Basin (Crete, Dorchester, Seward, and Surprise gages).

Even though the model presented produced a good match to observed data; it is possible that the model could be improved with future refinements. Future iterations of the model could attempt to address this discrepancy through additional refinements of the pumping and recharge files developed by CropSim. The focus of these future refinements should be to decrease pumping or increase recharge within the northern and western portion of the UBBNRD. The objective of any future refinements should be to reproduce the rebound in water level elevations that were observed in this portion of the Basin following the early 1980s.

6.9 Model Review Process

All documents produced by HDR in support of the development of this model were reviewed by members of the project team and were also reviewed by an independent peer reviewer. Those documents include:

1. Assessment of Available Datasets to Construct a Groundwater Model in the Blue River Basin;
2. Groundwater Model Development Plan for the Big Blue and Little Blue River Basins; and
3. Ground Water Model for the Big Blue and Little Blue River Basins.

The review process generally consisted of: 1) a review by project team members that were not intimately involved with the development of the documents, and 2) a review by an independent peer reviewer that was in no way involved with the development of the document.

As a member of the project team, Mr. Mike McDonald (McDonald Morrissey Associates, Inc.) served as a senior technical advisor to HDR and participated in the development and review of documents 1 and 2 listed above. Mr. McDonald also provided advice to HDR during the construction and calibration of the groundwater model. Another project team member, Mr. John Engel (HDR), also reviewed all three documents listed above.

The independent peer reviewer for this project was Mr. Larry Land (HDR). Mr. Land has over 37 years experience as a water resources engineer and his career includes over 30 years of experience with the U.S. Geological Survey-Water Resource Division. Mr. Land reviewed all three documents listed above and his involvement in the project was limited to peer review only. Mr. Land’s comments on the final modeling report were generally editorial and all comments were incorporated. After incorporation of his comments, Mr. Land noted that the model was technically sound and can be used by the DNR.

7.0 Summary

This report presented the construction and calibration of a groundwater flow model that was developed as a tool that will be used by Nebraska DNR to evaluate the effect of well pumping on stream base flow in the Big Blue River and Little Blue River basins of south central Nebraska. The focus area of the model includes the Little Blue NRD, the Lower Big Blue NRD, the Upper Big Blue NRD, and the eastern portion of the Tri-Basin NRD. The objective of the project was to construct a groundwater model that approximates the transient base flow conditions that have been measured from the major streams within the Basin, while also replicating the transient groundwater changes as measured in wells located throughout the Basin. This report included an analysis of the conceptual model of the Basin, a summary of the model construction practices, a summary of the steady state and transient model calibration, and a the results of a sensitivity analysis that was performed on the steady state model.

The groundwater model presented was developed to support the DNR's annual evaluation of the expected long term availability of surface water supplies and hydrologically connected groundwater supplies in the Big Blue and Little Blue River basins. For a model to be appropriate for that type of regional scale analysis, the model should be able to reasonably approximate the time varying stream base flow conditions within the Basin. The model was constructed so that the domain of the model would extend outside of the model focus area 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 model solution within the model focus area of the model. The model was developed to asses the historic groundwater depletion component of the annual basin status assessment, meaning the model should be able to assess changes in stream base flow that result from an increase in groundwater pumping. Therefore, the goal for development of the model was to characterize and simulate the regional-scale hydrogeologic processes that regulate streamflow depletions due to pumping in order to provide an appropriate tool for use in water-management decisions. The model is not intended to reproduce every detail of the hydrogeologic system. Rather, the simulations presented are appropriate for analyzing groundwater-management scenarios over a regional spatial scale that includes multiple counties and a time scale of multiple years. Due to the regional scale of the model, it is not intended or suited for analysis of small areas or short time periods. However, this calibrated model could be used to define boundary conditions for local-scale simulations.

The model was calibrated to steady state conditions that represent predevelopment conditions within the Basin. Predevelopment is a time period when there was little irrigation well development. Within the Big and Little Blue River basins, this approximately equates to the early 1950s. The steady state model was calibrated to several datasets to minimize the non-uniqueness of the model solution. The steady state calibration targets included: a conceptual mass balance of the Basin, spring 1953 groundwater elevations from 396 wells, and stream base flow targets for eight gauging stations: Seward, Dorchester, Crete, and Barneston on the Big Blue River, and DeWeese, Alexandria, Fairbury, and Barnes, Kansas on the Little Blue River.

Following the steady state model calibration, a sensitivity analysis was performed to evaluate the sensitivity of the model solution to changes in several key model input parameters. The sensitivity analysis included over 400 model simulations performed using a two step process that evaluated the sensitivity of changes in model input parameters to both head and flux (streamflow) targets. The results of the sensitivity analysis concluded that the model is most sensitive to the aquifer recharge rates and is relatively insensitive to stream bed conductance. The sensitivity analysis indicated the values used for the key parameters in the calibrated steady state model are reasonable.

The final step in the modeling process was to convert the steady state model into a transient model that approximates the observed transient changes in both groundwater elevation and stream base flow. The time period for the transient analysis is 1940 through 2011, although a five (5) year transitional period from 1935 to 1940 was included to allow the model solution to stabilize prior to the introduction of well pumping. The performance of the transient model was evaluated using several different metrics, including:

1. A qualitative comparison between modeled and observed groundwater hydrographs at 19 observation well locations.
2. A qualitative comparison between modeled and observed stream base flow hydrographs at 10 streamflow gage locations.
3. A quantitative and qualitative comparison between the model and observed potentiometric surface for spring 2009.
4. A qualitative comparison between the model predicted and observed change in groundwater elevations within the Basin since predevelopment.
5. A comparison to spot streamflow measurements collected during periods of low, average, and high streamflow conditions.

Section 4.0 (Steady State Model) and Section 6.0 (Transient Model Calibration) document the calibration of the model. The results of the calibration indicate that the model successfully matched the conceptual predevelopment mass balance for the Basin and adequately reproduced the predevelopment head and stream base flow conditions within the Basin. The transient model calibration showed that the model adequately represents the changes in groundwater elevation that have been observed within the Basin and that the model is capable of representing the observed time varying stream base flow conditions at the downstream gages within both the Big and Little Blue River Basins. Since the objective of the model was to approximately reproduce the historical time varying stream base flow conditions within the Basin, and the model has been shown to do that, the model appears adequate for use to calculate the historic groundwater depletions in Nebraska DNR's annual assessment of Basin status.

8.0 References

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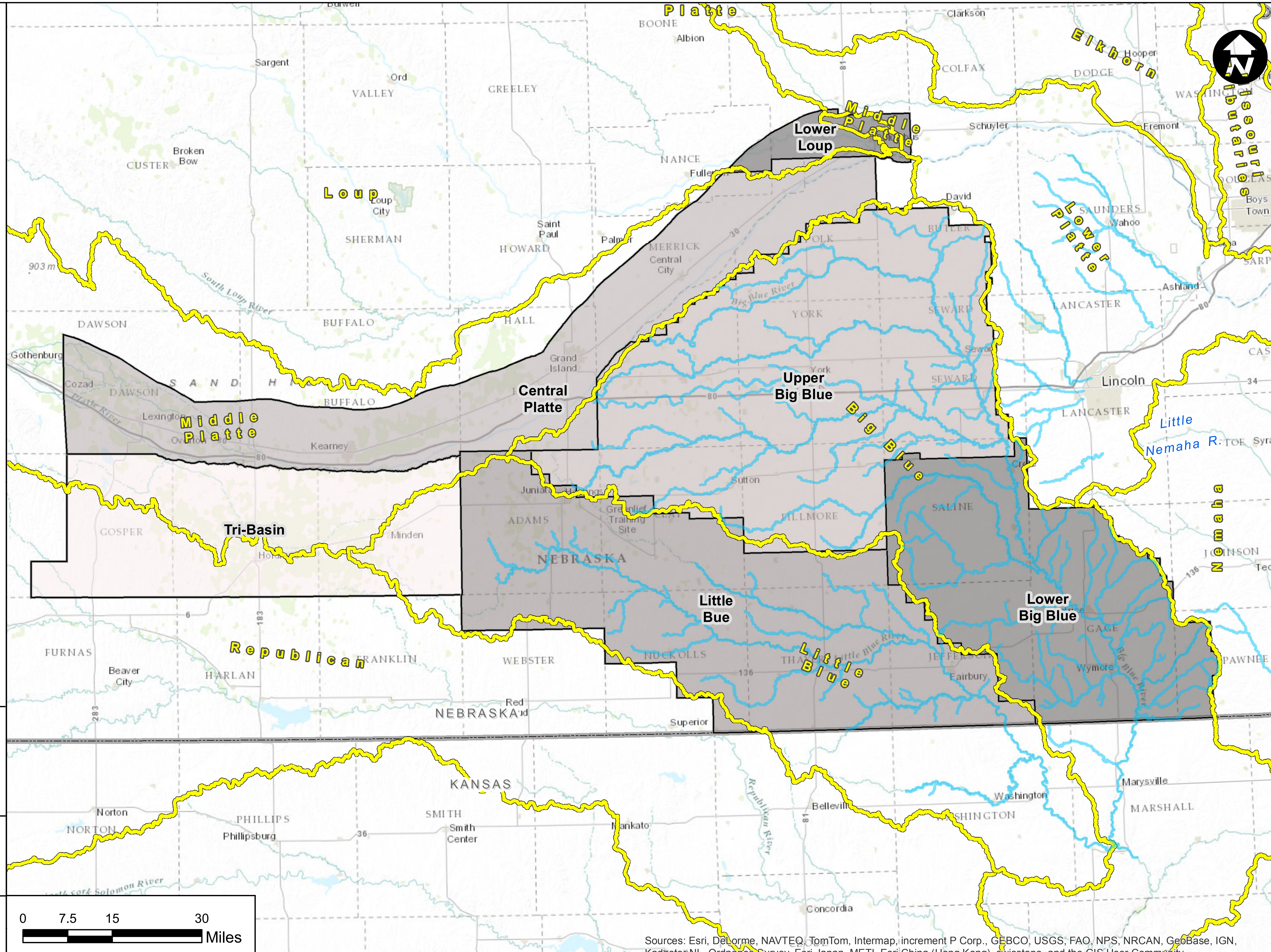
Appendix A – Report Figures (Full Size)

Appendix A contains a full size copy of each figure referenced within the report. The full size copies are included to improve the readability of the figures.

Blue Basins Groundwater Model Report

Study Area



Streams

River Basins

NRD Boundary

State Boundary

Sources:
NRD Boundaries, 2010 NE DNR;
Topographic Background, Esri;

Figure 1-1

Drawn By: ARS
June, 2013

HDR

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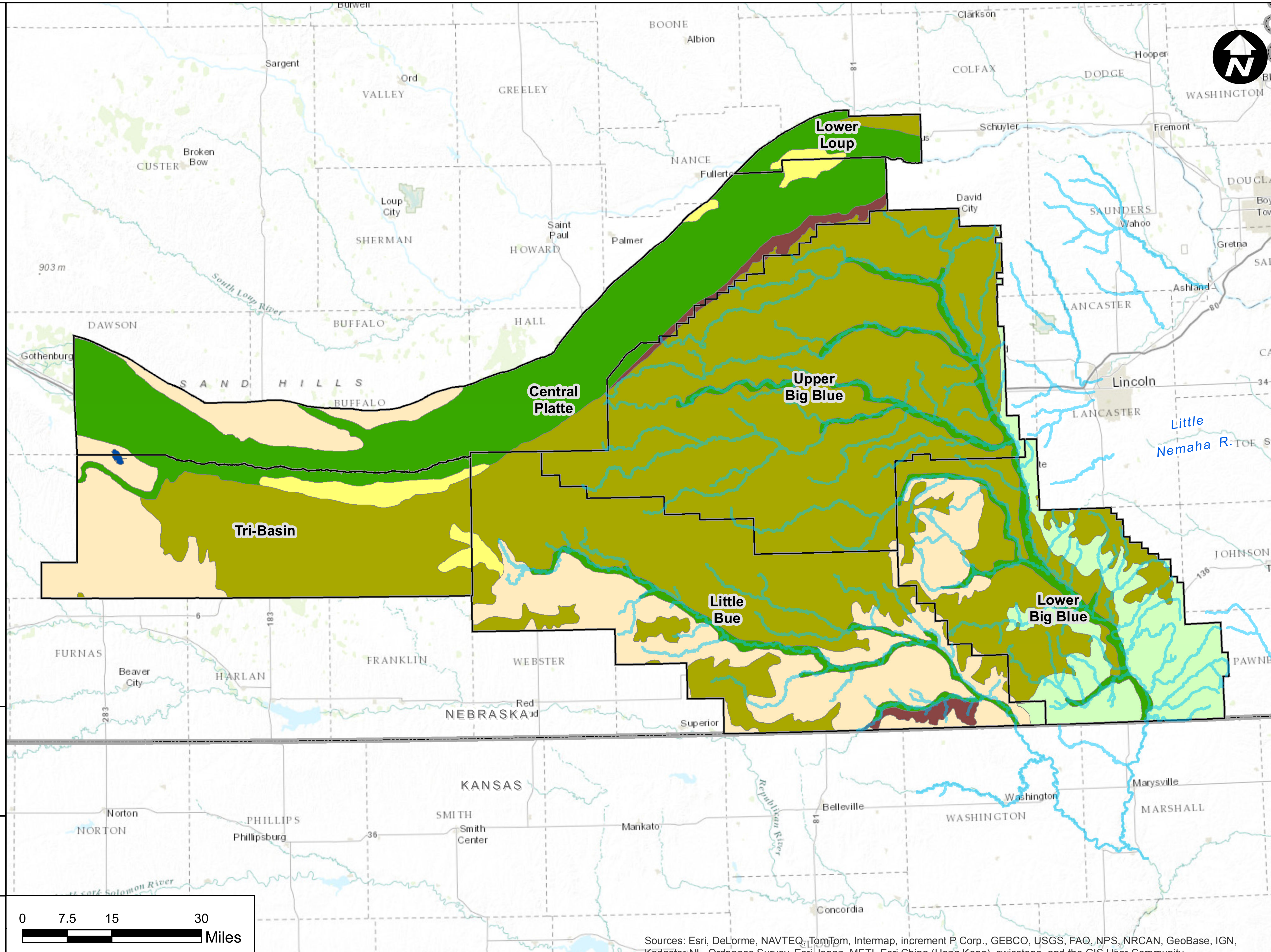
Blue Basins Groundwater Model Report

Topographic Regions of the Study Basin



Sources:
NRD Boundaries, 2010 NE DNR;
Topographic Background, Esri;

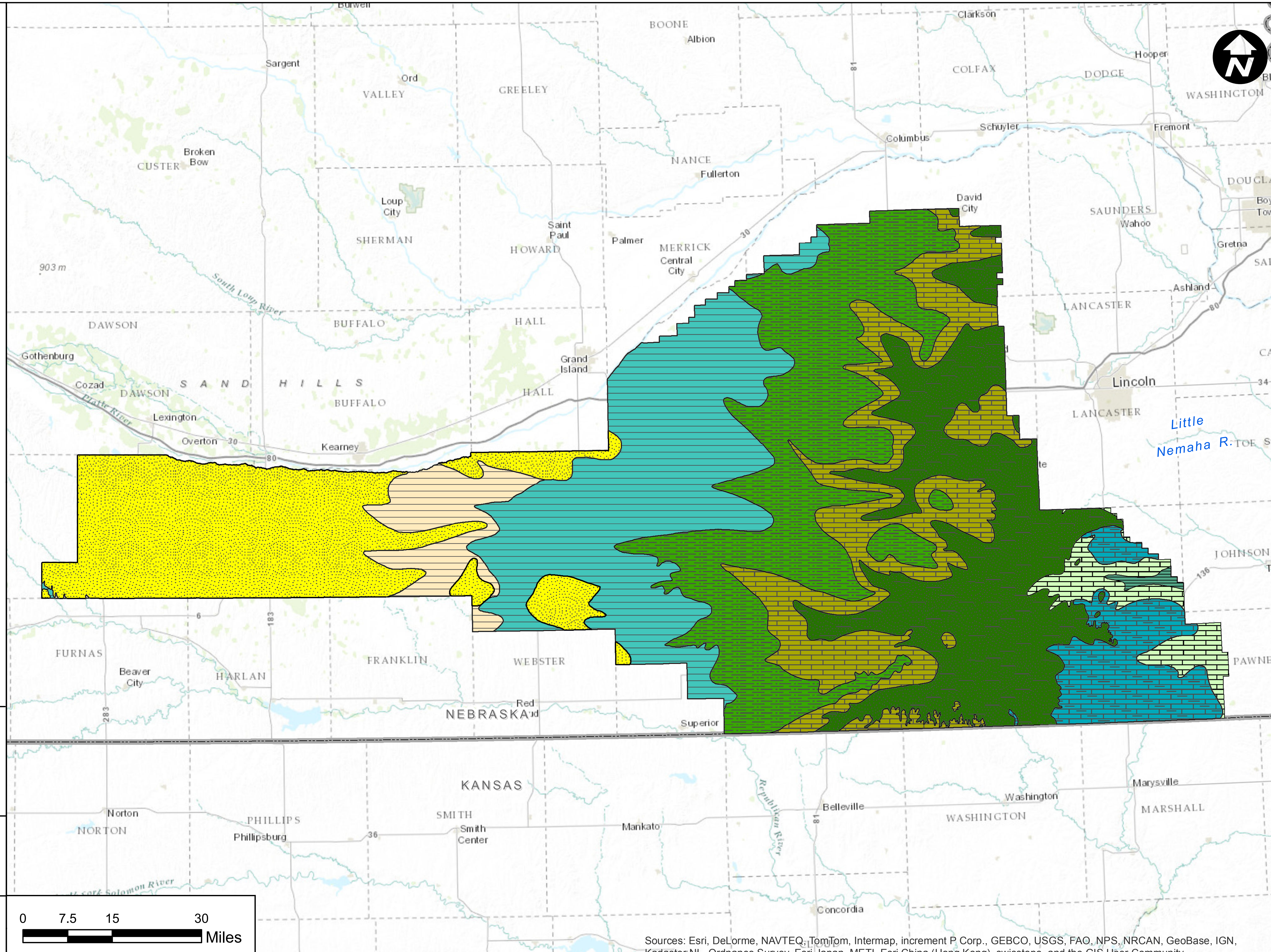
Figure 2-1

Drawn By: ARS
June, 2013

HDR

Blue Basins Groundwater Model Report

Bedrock Geology



- Admire
- Carlile Shale
- Chase Group
- Council Grove
- Dakota Formation
- Greenhorn-Graneros
- Niobrara Formation
- Ogallala
- Pierre Shale
- State Boundary

Sources:
NRD Boundaries, 2010 NE DNR;
Bedrock Geology, UNL;
Topographic Background, Esri;

Figure **2-2**

Drawn By: ARS
June, 2013

0 7.5 15 30 Miles

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

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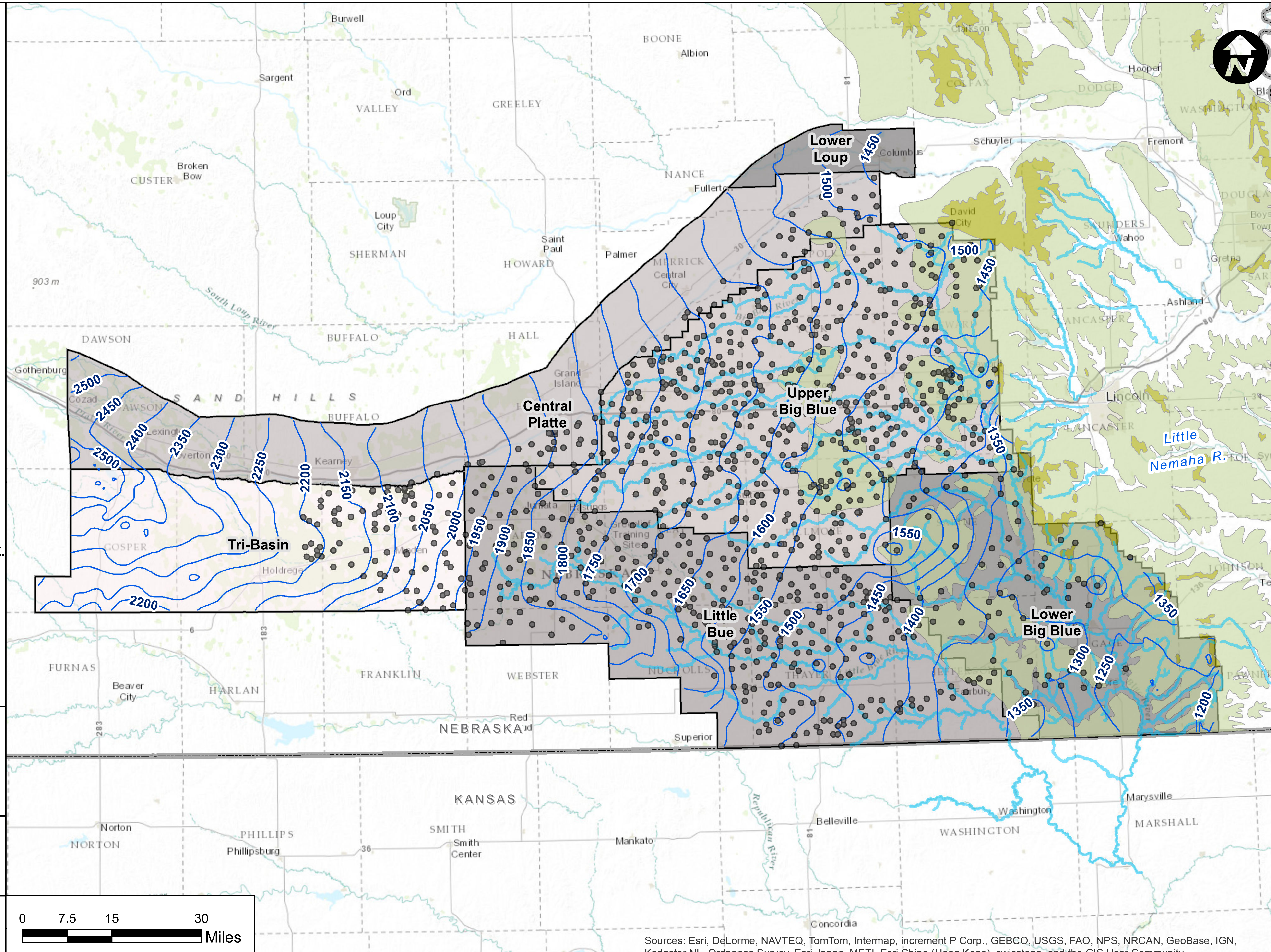
Blue Basins Groundwater Model Report

2009 Potentiometric Surface Elevation Contour Map



- Well Location
- Water Level Contours
- Streams

Glacial Till Deposits

- Glacial till deposits < 150 ft. (generally < 50 ft.)
- Glacial till deposits greater than 150 ft.
- NRD Boundary
- State Boundary

Sources:
NRD Boundaries, 2010 NE DNR;
Well Locations, UNL; Water Level Contours, derived from well data and 30 meter DEM; Till data digitized by USGS; Topographic Background, Esri;

Figure **2-3**

Drawn By: ARS
June, 2013

HDR

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

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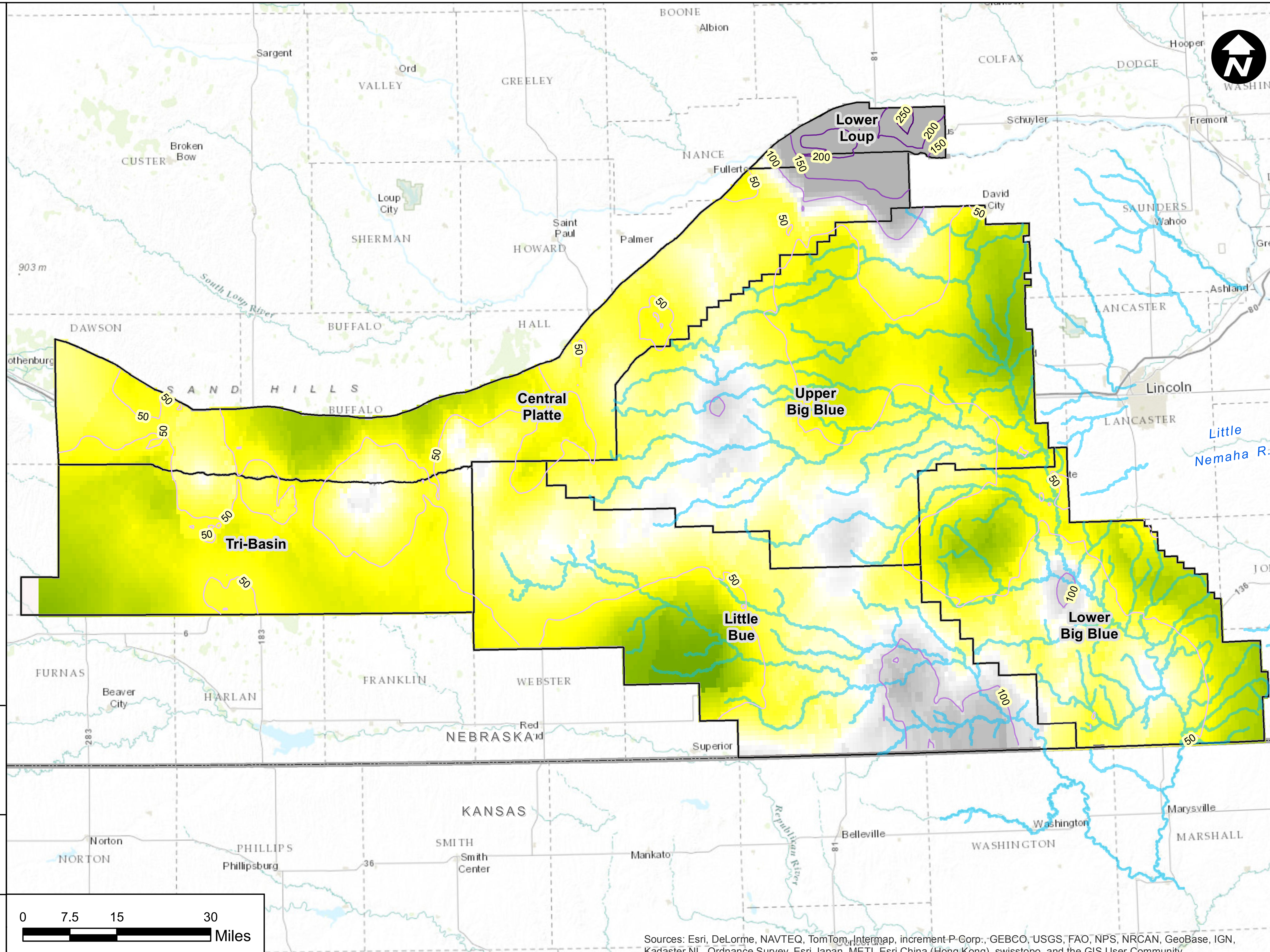
Blue Basins Groundwater Model Report

Hydraulic Conductivity



Sources:
Hydraulic Conductivity, HDR;
NRD Boundaries, 2010 NE DNR;
Topographic Background, Esri;

Figure **2-4**

Drawn By: ARS
June, 2013

Blue Basins Groundwater Model Report

Aquifer Saturated Thickness

Thickness Contours (ft)

- 50
- 100
- 150
- 200
- 250
- 300
- 350
- 400

Saturated Thickness

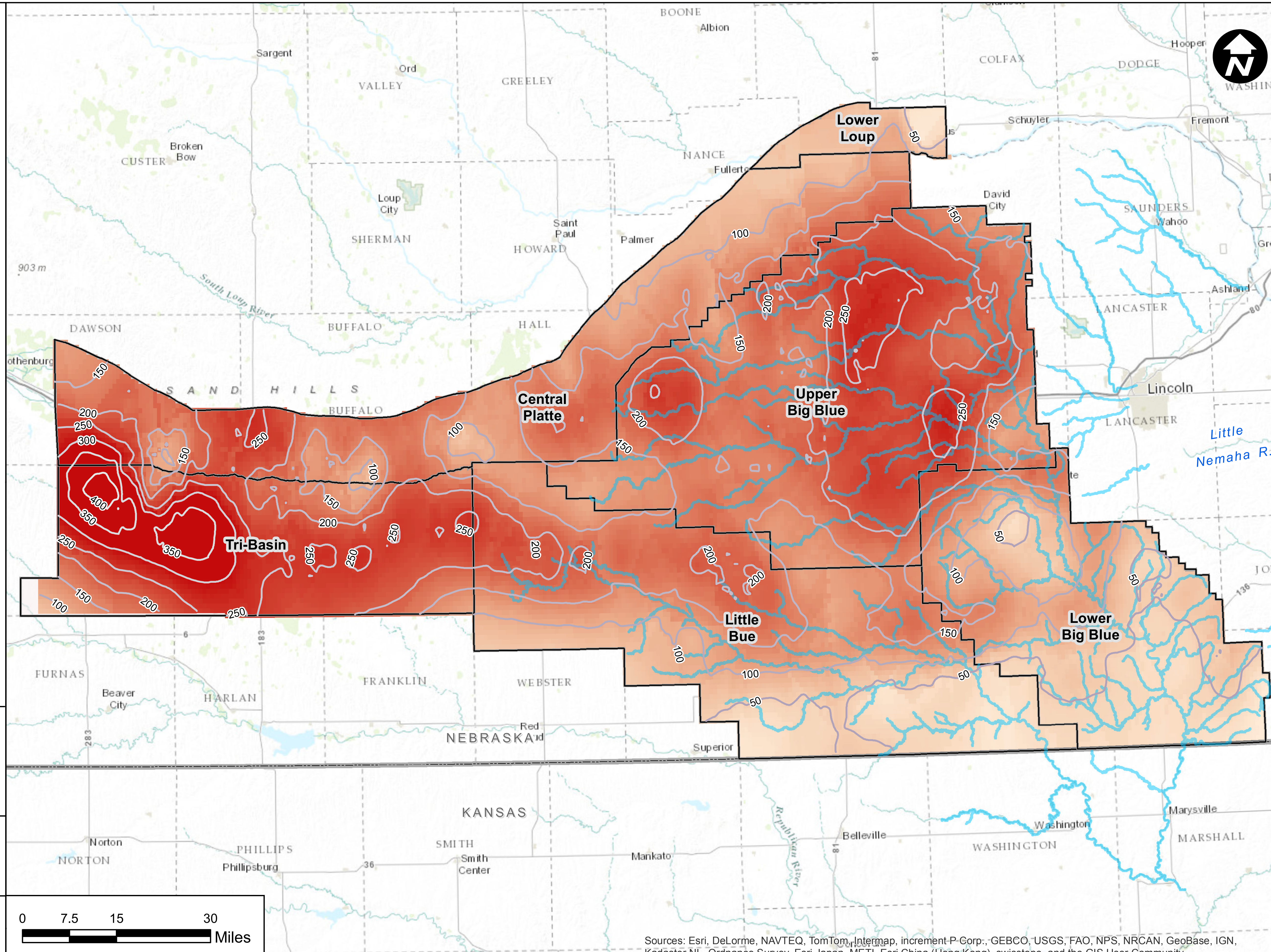
High

Low

Streams

NRD Boundary

State Boundary



Sources:
Saturadted Thickness, HDR;
NRD Boundaries, 2010 NE DNR;
Topographic Background, Esri;

Figure 2-5

Drawn By: ARS
June, 2013

HDR

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Blue Basins Groundwater Model Report

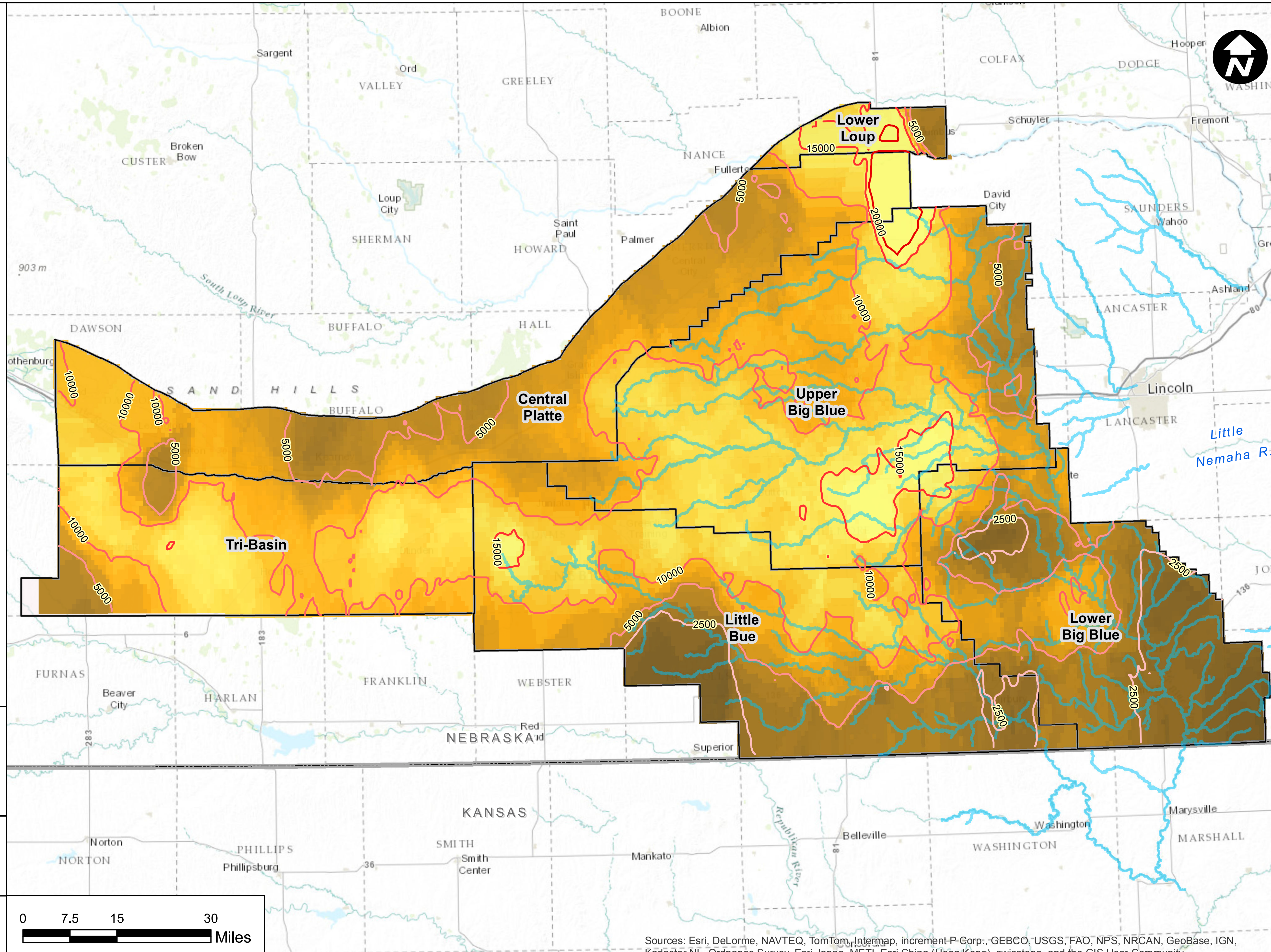
Aquifer Transmissivity

Contours (in sq.ft/day)

- 2,500
- 5,000
- 10,000
- 15,000
- 20,000

Aquifer Transmissivity
High
Low

Streams
NRD Boundary
State Boundary



Sources:
Transmissivity, HDR;
NRD Boundaries, 2010 NE DNR;
Topographic Background, Esri;

Figure 2-6

Drawn By: ARS
June, 2013

HDR

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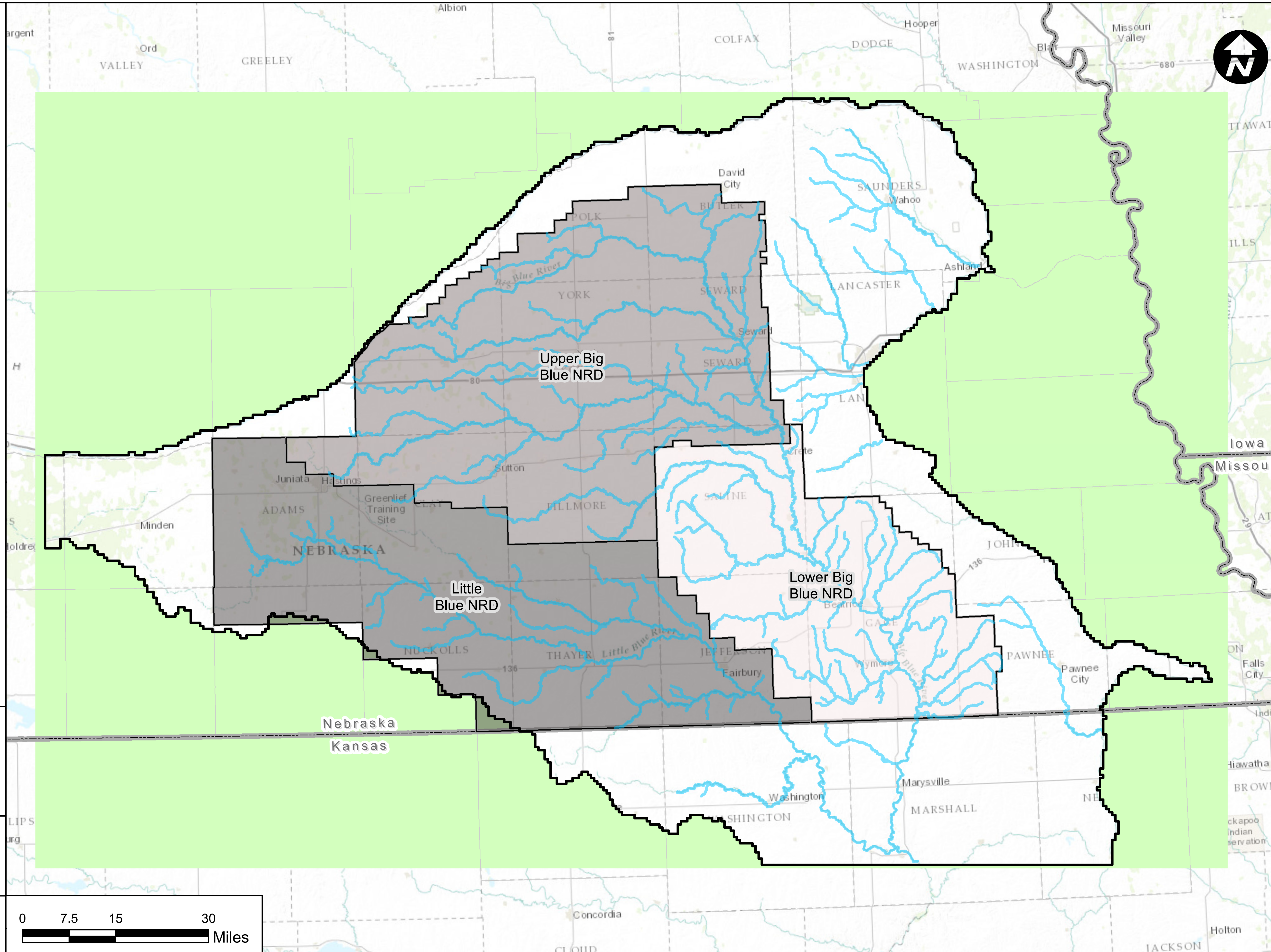
Blue Basins Groundwater Model Report

Model Domain



Legend:
- Model Inactive Area
- Active Area Boundary
- Streams
- NRD Boundary
- County Boundary
- State Boundary

Sources:
Service Layer Credits: Esri Base Layer

0 7.5 15 30 Miles

Figure 3-1

June, 2013

HDR

Blue Basins Groundwater Model Report

Layer 1 Top Elevation

Aquifer Top Elevation (ft)

- 900-1000
- 1000-1100
- 1100-1200
- 1200-1300
- 1300-1400
- 1400-1500
- 1500-1600
- 1600-1700
- 1700-1800
- 1800-1900
- 1900-2000
- 2000-2100
- 2100-2200
- > 2200

Active Area Boundary

Streams

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

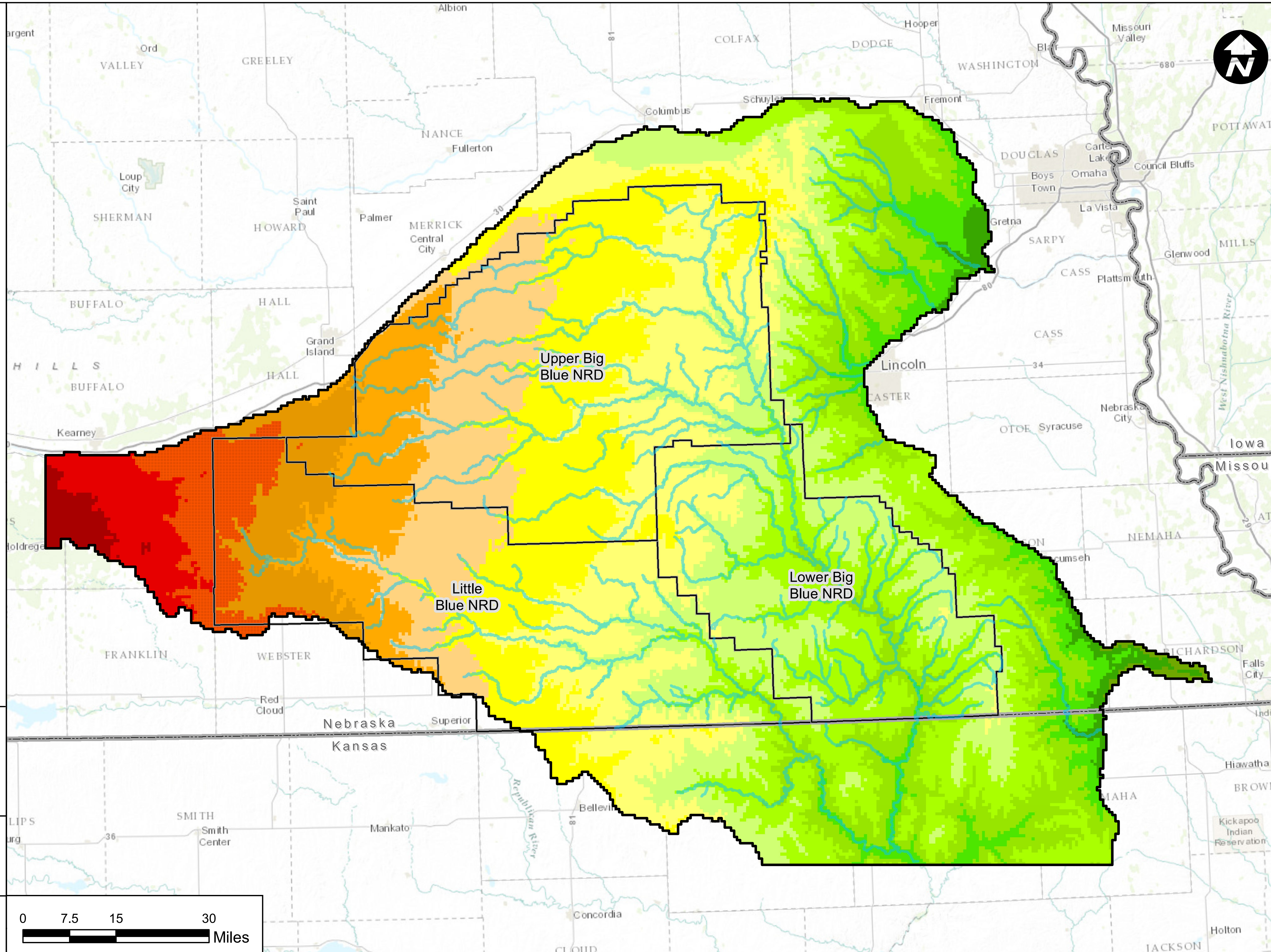


Figure	3-2
June, 2013	HDR

Blue Basins Groundwater Modeling Report

Layer 1 Bottom Elevation

Layer 1 Bottom Elevation (ft)

- < 900
- 900-1000
- 1000-1100
- 1100-1200
- 1200-1300
- 1300-1400
- 1400-1500
- 1500-1600
- 1600-1700
- 1700-1800
- 1800-1900
- 1900-2000
- > 2000
- Active Area Boundary
- Streams
- NRD Boundary
- County Boundary
- State Boundary

Sources:
Service Layer Credits: Esri Base Layer

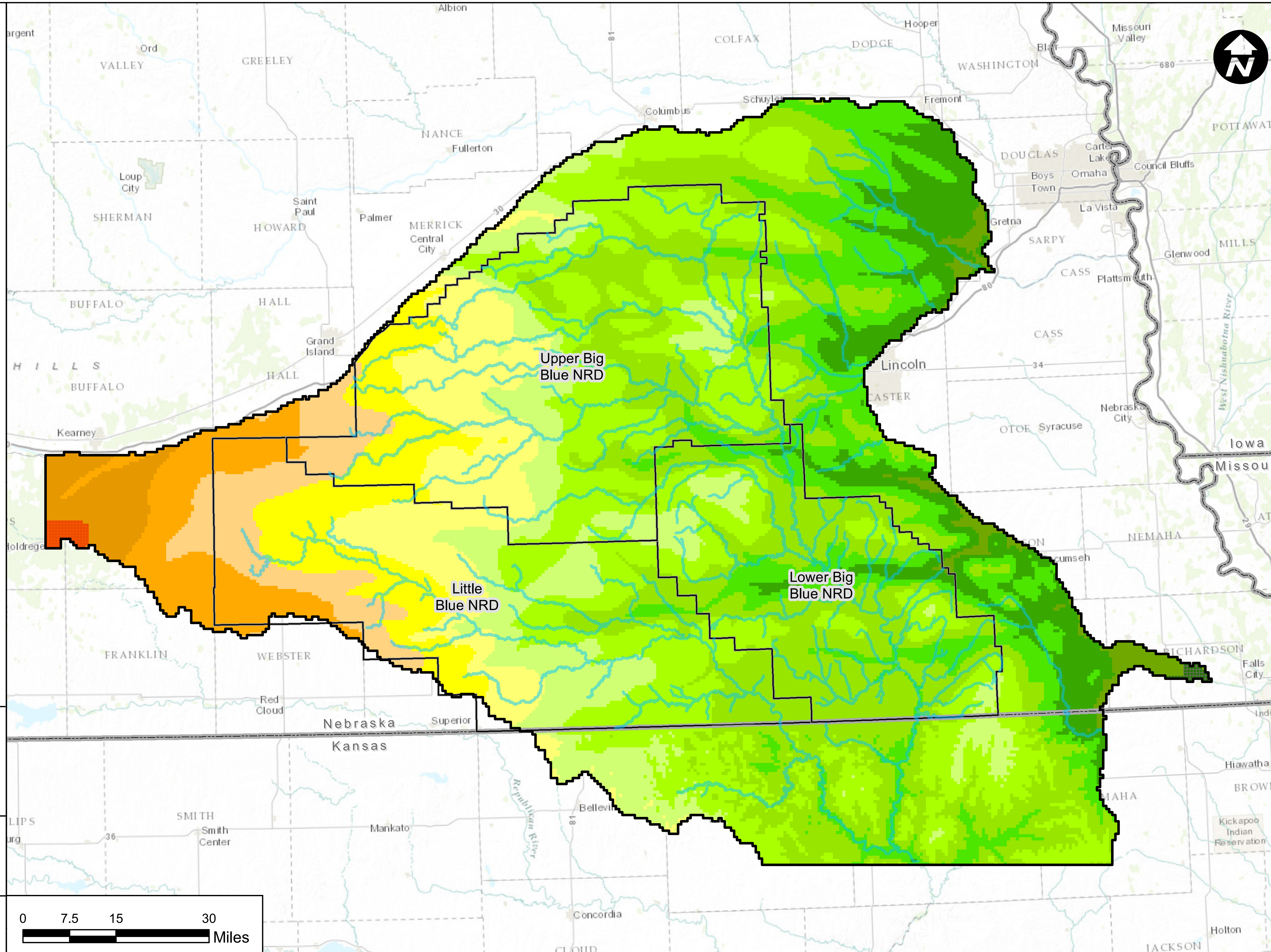
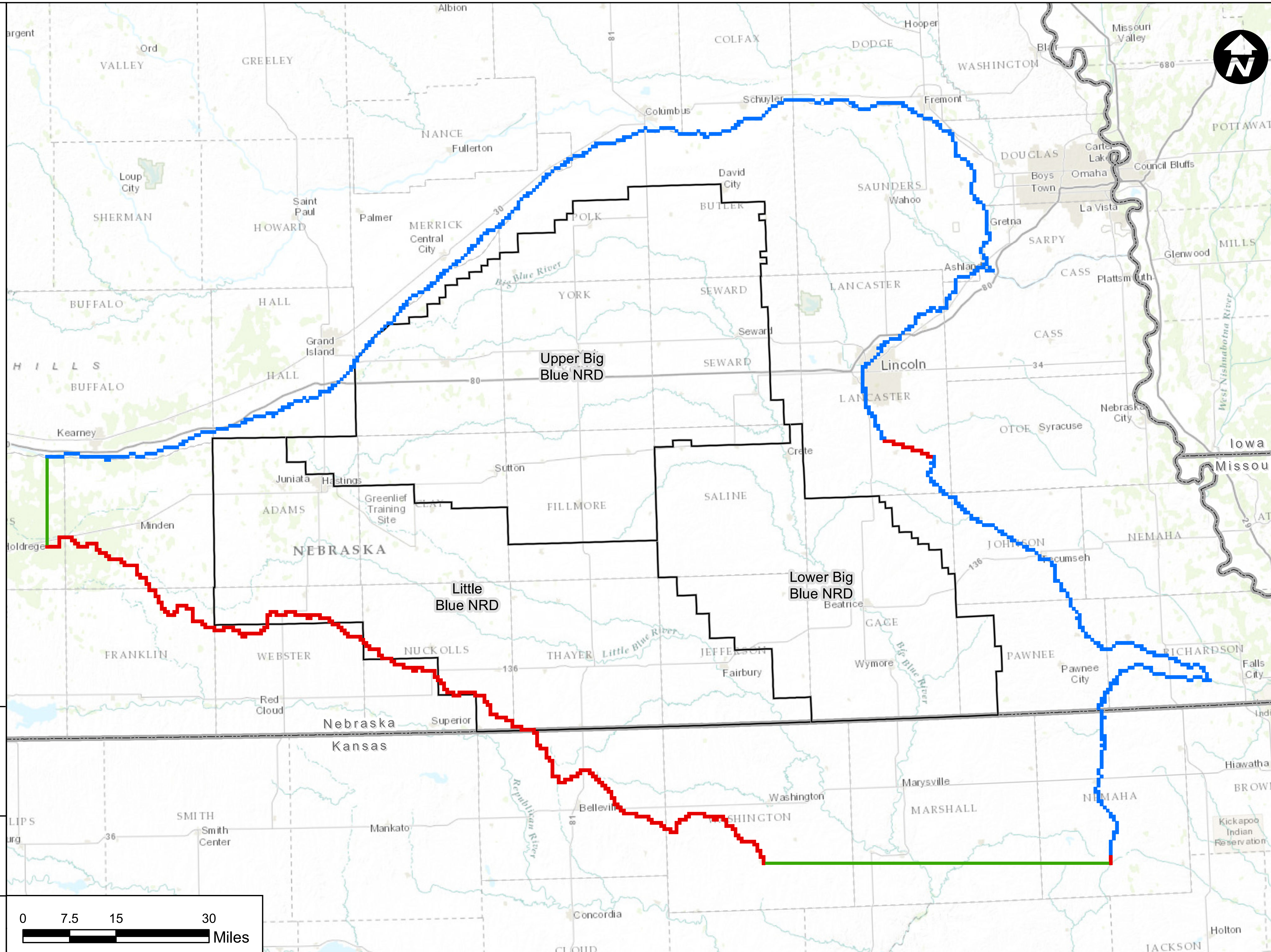


Figure	3-3
June, 2013	HDR

Blue Basins Groundwater Model Report

Perimeter Boundary Conditions



General Head Boundary Cells

No-Flow Boundary Cells

River Cells

NRD Boundary

County Boundary

State Boundary

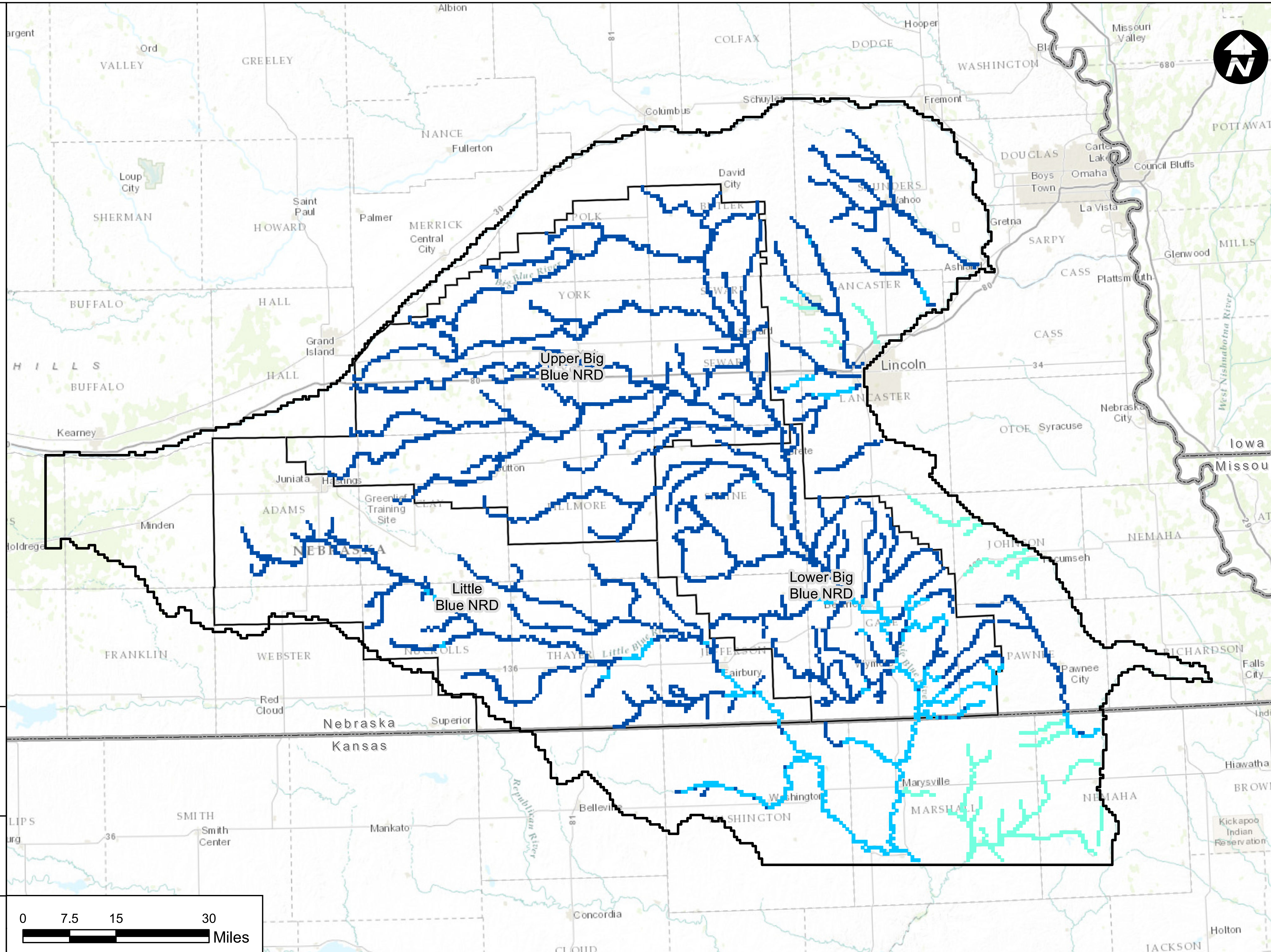
0 7.5 15 30 Miles

Sources:
Service Layer Credits: Esri Base Layer

Figure	3-4
June, 2013	HDR

Blue Basin Groundwater Model Report

Internal Boundary Conditions



Layer 1 Stream Cell

Layer 2 Stream Cell

Interior River Cells

Active Area Boundary

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

Figure 3-5

June, 2013

HDR

Blue Basin Groundwater Model Report

Hydraulic Conductivity Parameter Zone Definition

Model Conductivity Zone

Kansas Hydrogeologic Terrain

- Bedrock
- Till
- Inner Transition
- Outer Transition
- Alluvium

Hydraulic Conductivity (ft/day)

- < 5
- 5 - 32
- 32 - 50
- 50 - 63
- 63 - 80
- 80 - 112
- 112 - 316
- > 316

Active Area Boundary

Streams

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

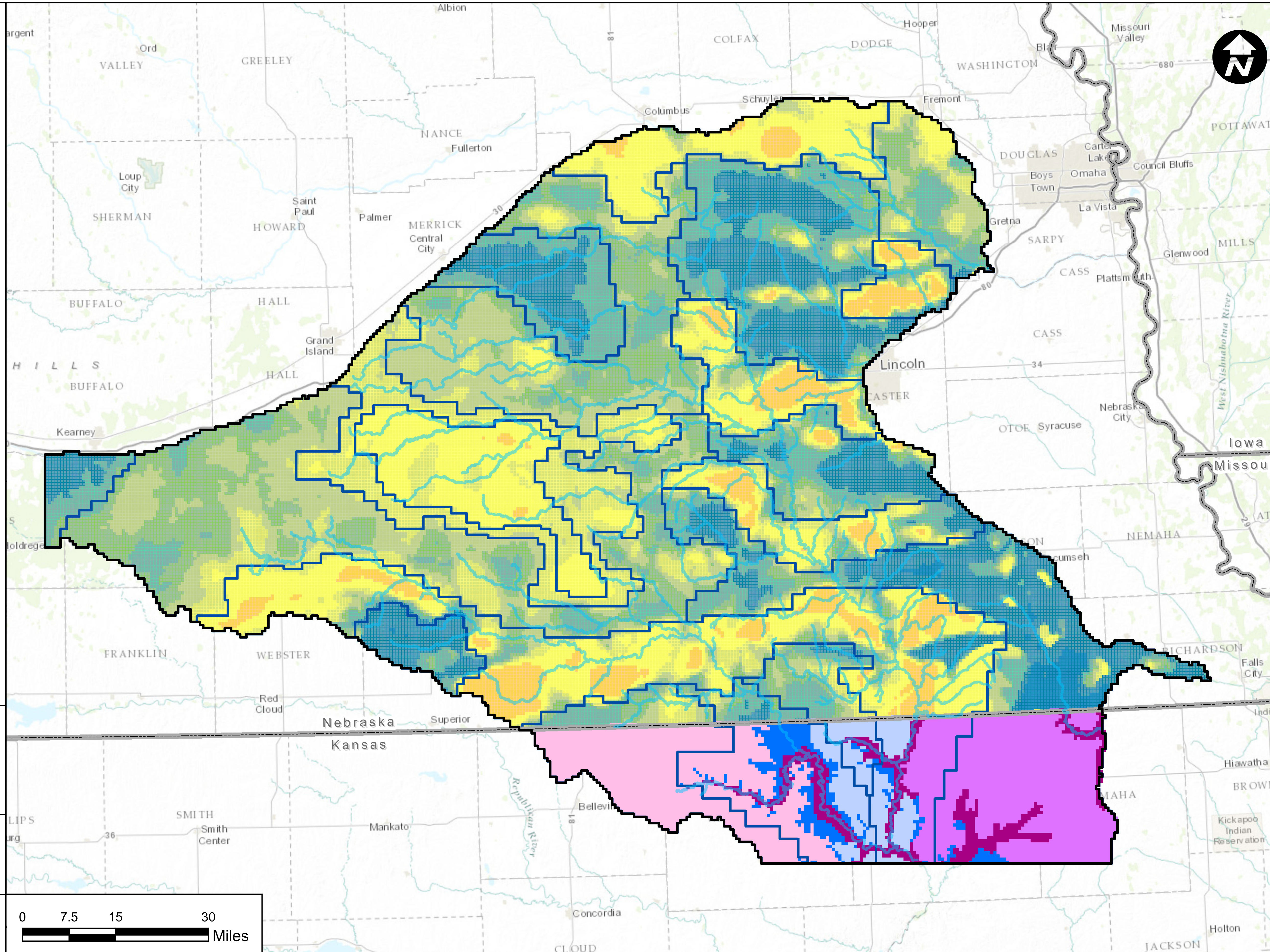


Figure 3-6

June, 2013

HDR

Blue Basins Groundwater Model Report

Recharge Parameter Zone Definition

Model Recharge Zone

Kansas Hydrogeologic Terrain

- Bedrock
- Till
- Inner Transition
- Outer Transition
- Alluvium

Recharge Rate
Mean annual recharge to groundwater (inches)

- <(-6)
- (-6) - (-4)
- (-4) - (-2)
- (-2) - 0
- 0 - 2
- 2 - 4
- 4 - 6
- >6

Active Area Boundary

County Boundary

State Boundary

Sources:
Recharge Rate, Szilagyi, J;
Service Layer Credits: Esri Base Layer;

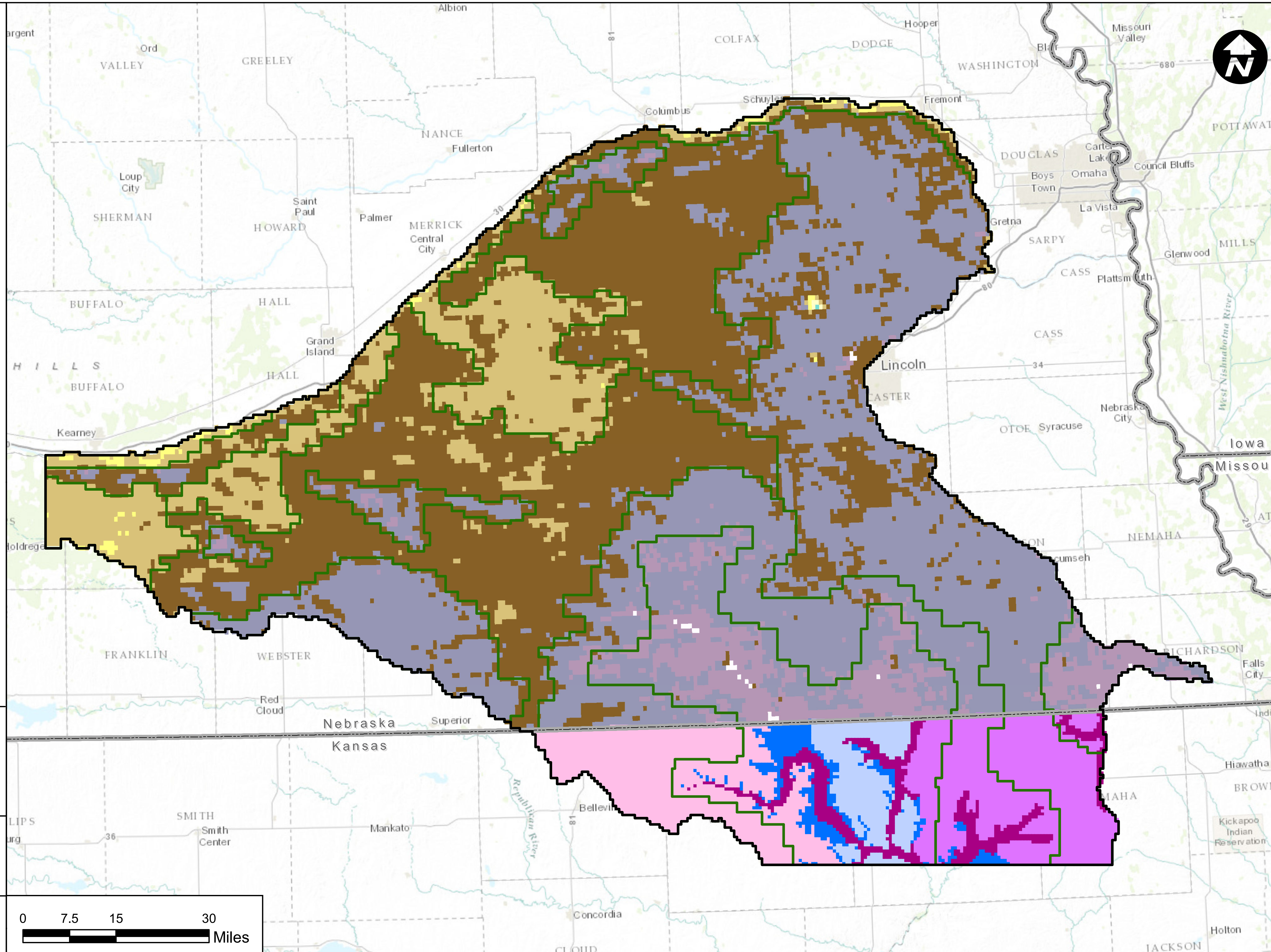


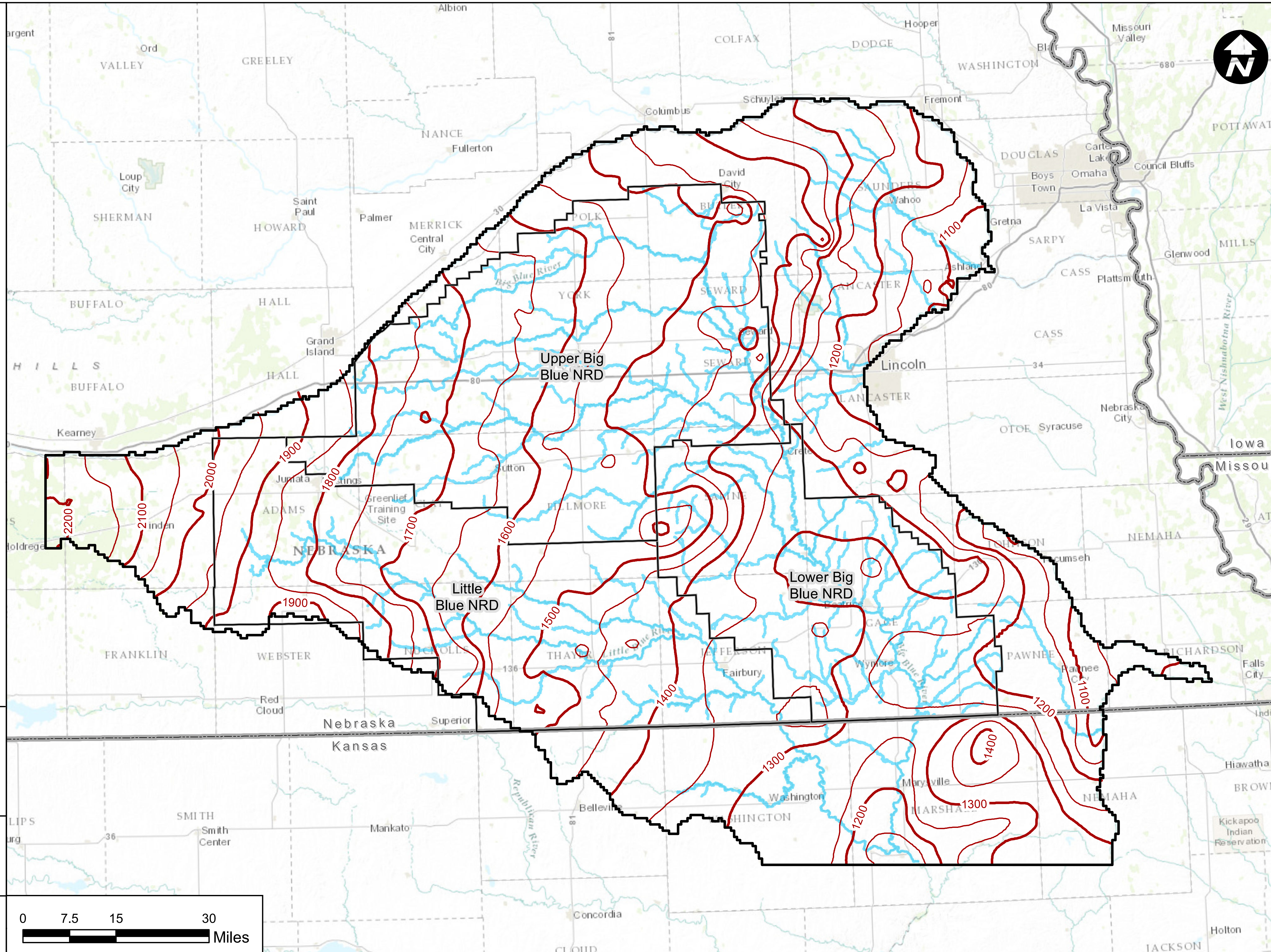
Figure 3-7

June, 2013

HDR

Blue Basins Groundwater Model Report

Composite 2009 Potentiometric Surface Map



Water Table Elevation Contour

Active Area Boundary

Streams

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

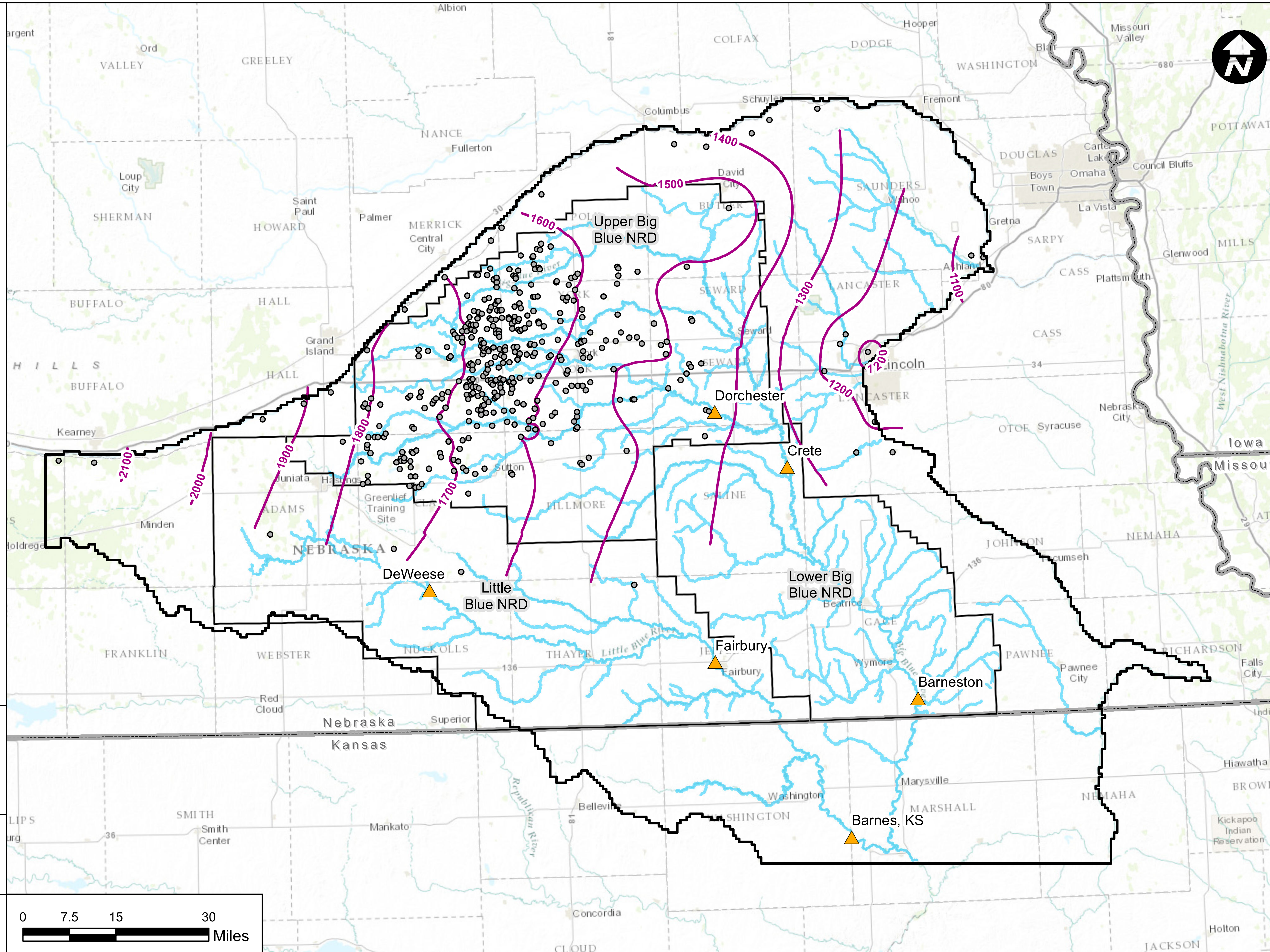
Figure 3-8

June, 2013

HDR

Blue Basins Groundwater Model Report

Steady-State Model Calibration Data Sets



Sources:
Service Layer Credits: Esri Base Layer

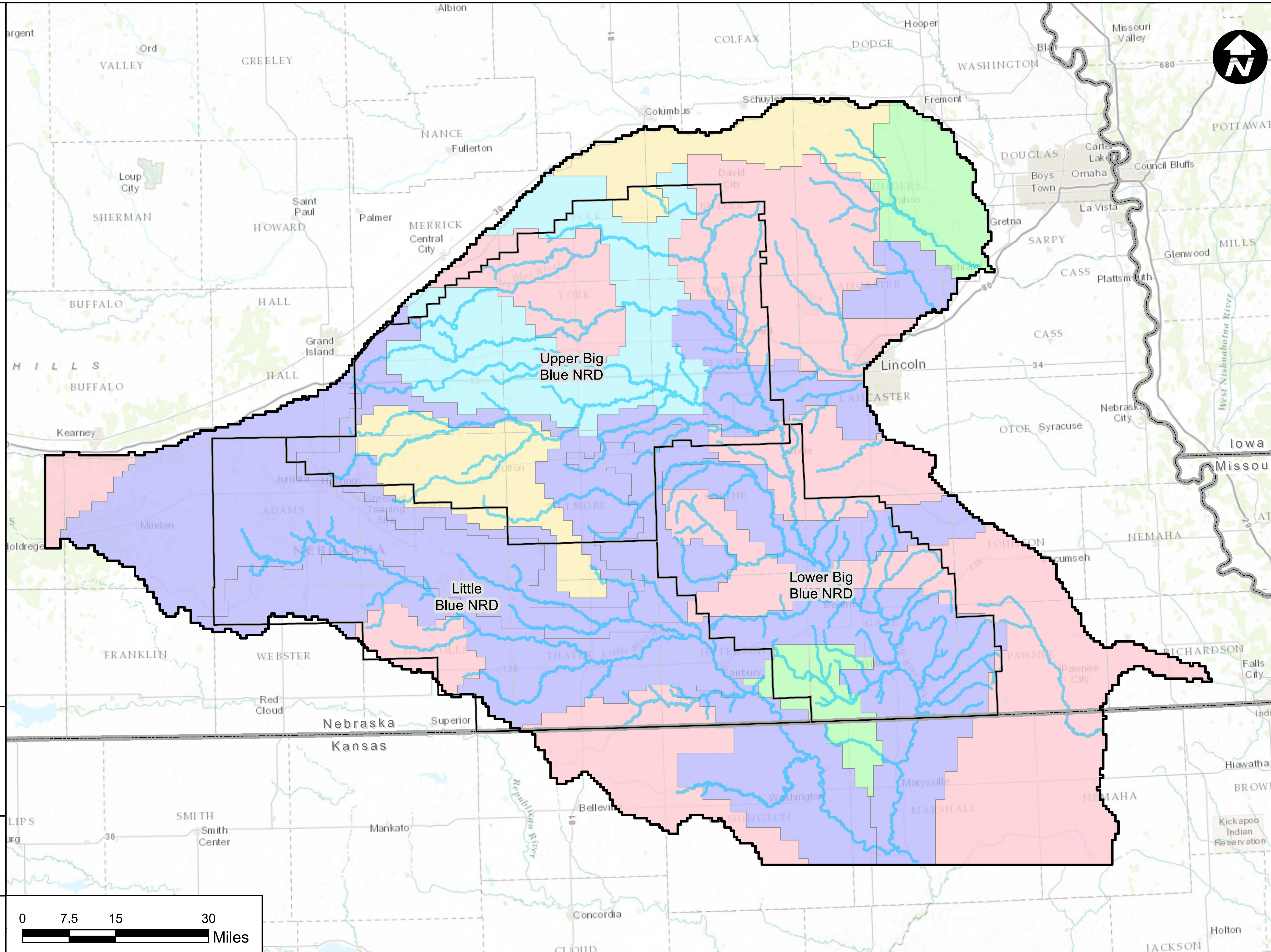
Figure 4-1

June, 2013

HDR

Blue Basins Groundwater Model Report

Post-Calibration Hydraulic Conductivity Distribution



Model Conductivity Zone

Hydraulic Conductivity (ft/day)

- 25
- 50
- 75
- 100
- 200
- Active Area Boundary
- Streams
- NRD Boundary
- County Boundary
- State Boundary

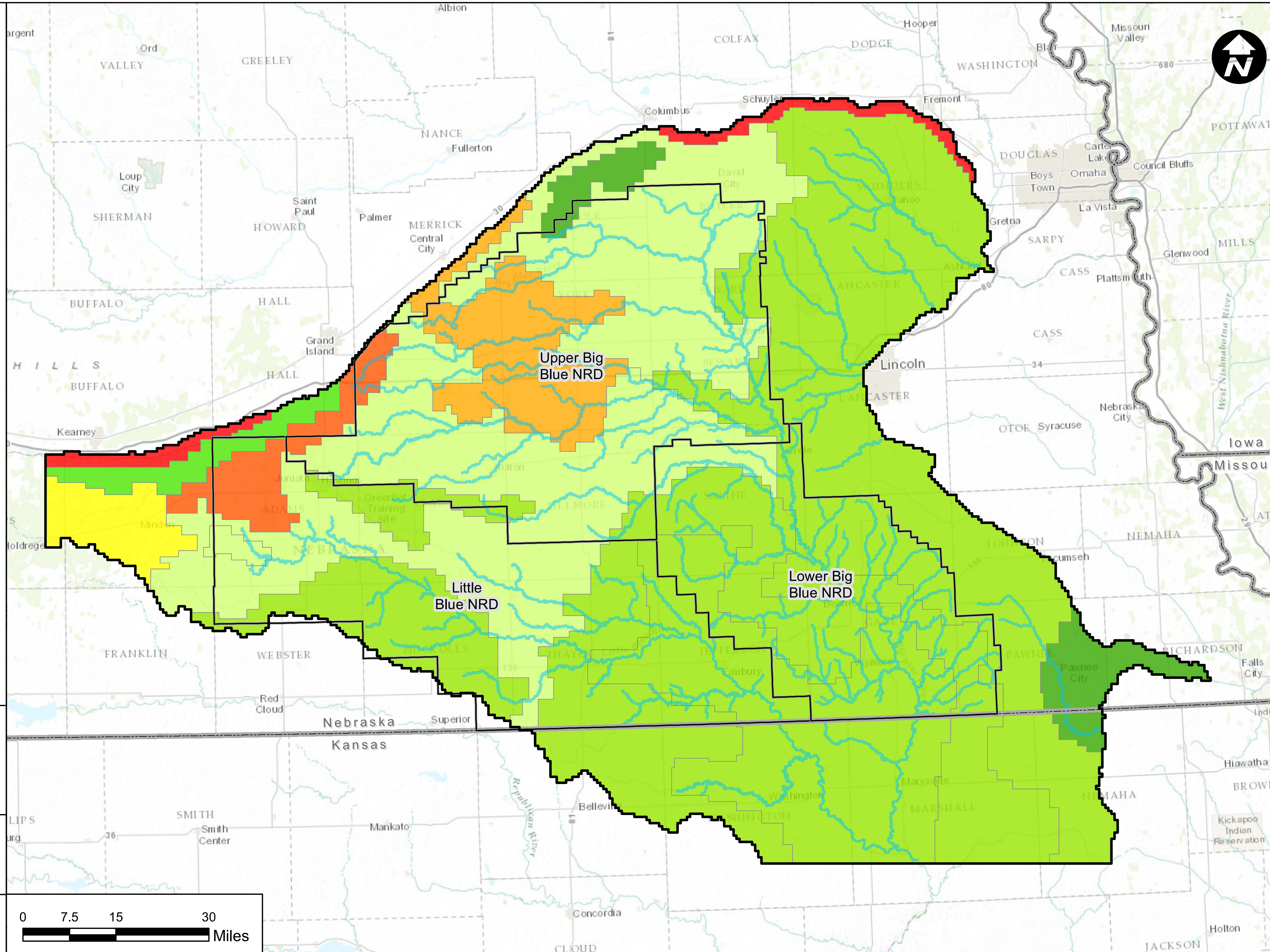
Sources:
Service Layer Credits: Esri Base Layer

Figure 4-2

June, 2013

Blue Basins Groundwater Model Report

Post-Calibration Recharge Distribution



Model Recharge Zone

Recharge (in/yr)

- -2
- -1.25
- 0.25
- 0.5
- 1
- 1.25
- 1.5
- 1.75

Active Area Boundary

Streams

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

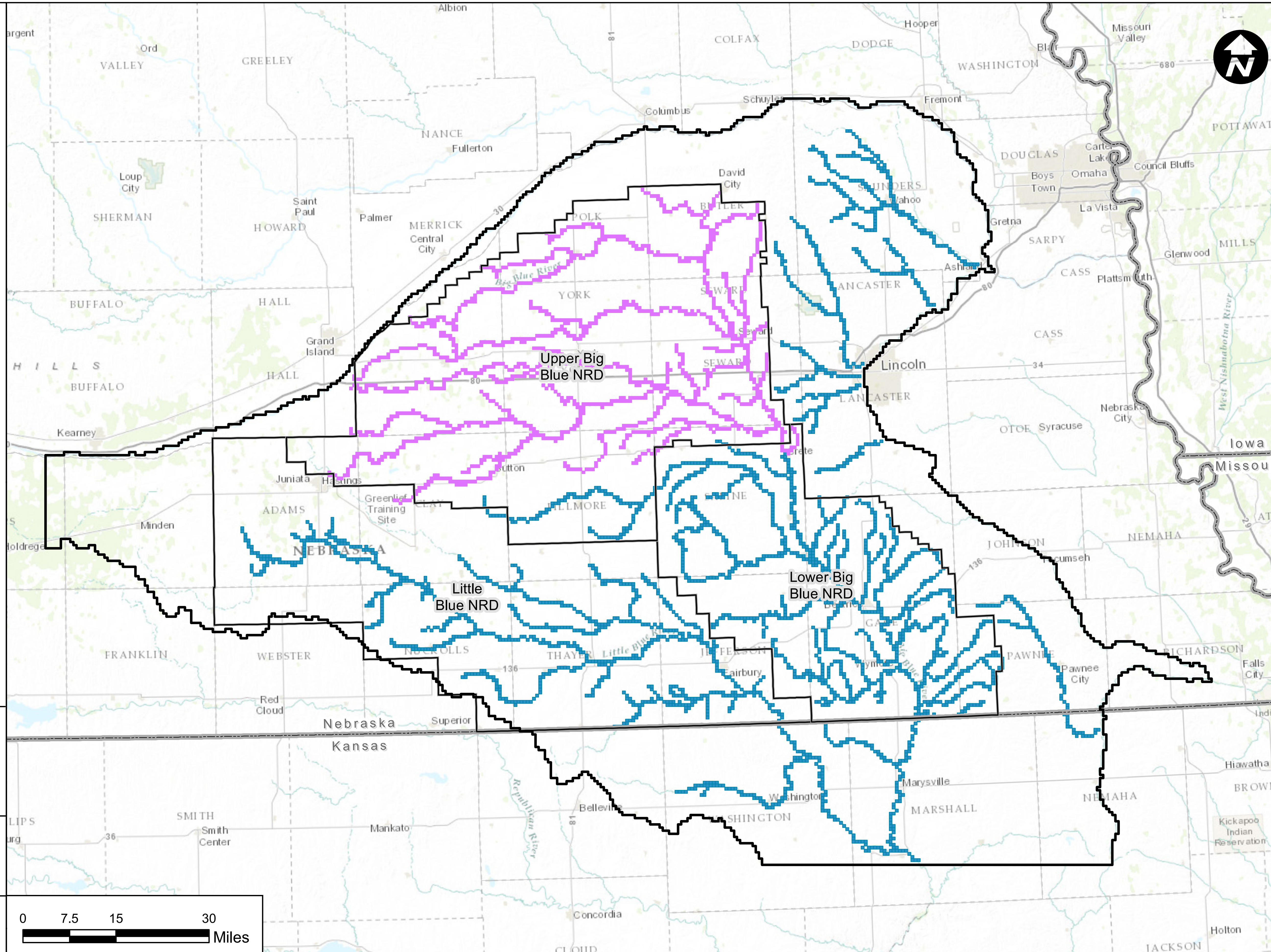
Figure 4-3

June, 2013

HDR

Blue Basins Groundwater Model Report

Post-Calibration Streambed Resistance



Stream Cells

Streambed Resistance (per day)

10

6.67

Active Area Boundary

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

Figure 4-4

June 2013

HDR

Blue Basins Groundwater Model Report

Spatial Distribution of Residuals

Residual (ft)

- < μ-2σ (-29.53)
- μ-2σ (-29.53) to μ-σ (-16.31)
- μ-σ (-16.31) to μ+σ (+10.13)
- μ+σ (+10.13) to μ+2σ (23.35)
- > μ+2σ (23.35)

Potentiometric Contour - Observed

Potentiometric Contour - Simulated

Active Area Boundary

Streams

NRD Boundary

County Boundary

State Boundary

μ = Residual Mean = -3.09 ft
σ = Residual Standard Deviation = 13.22 ft

Sources:
Service Layer Credits: Esri Base Layer

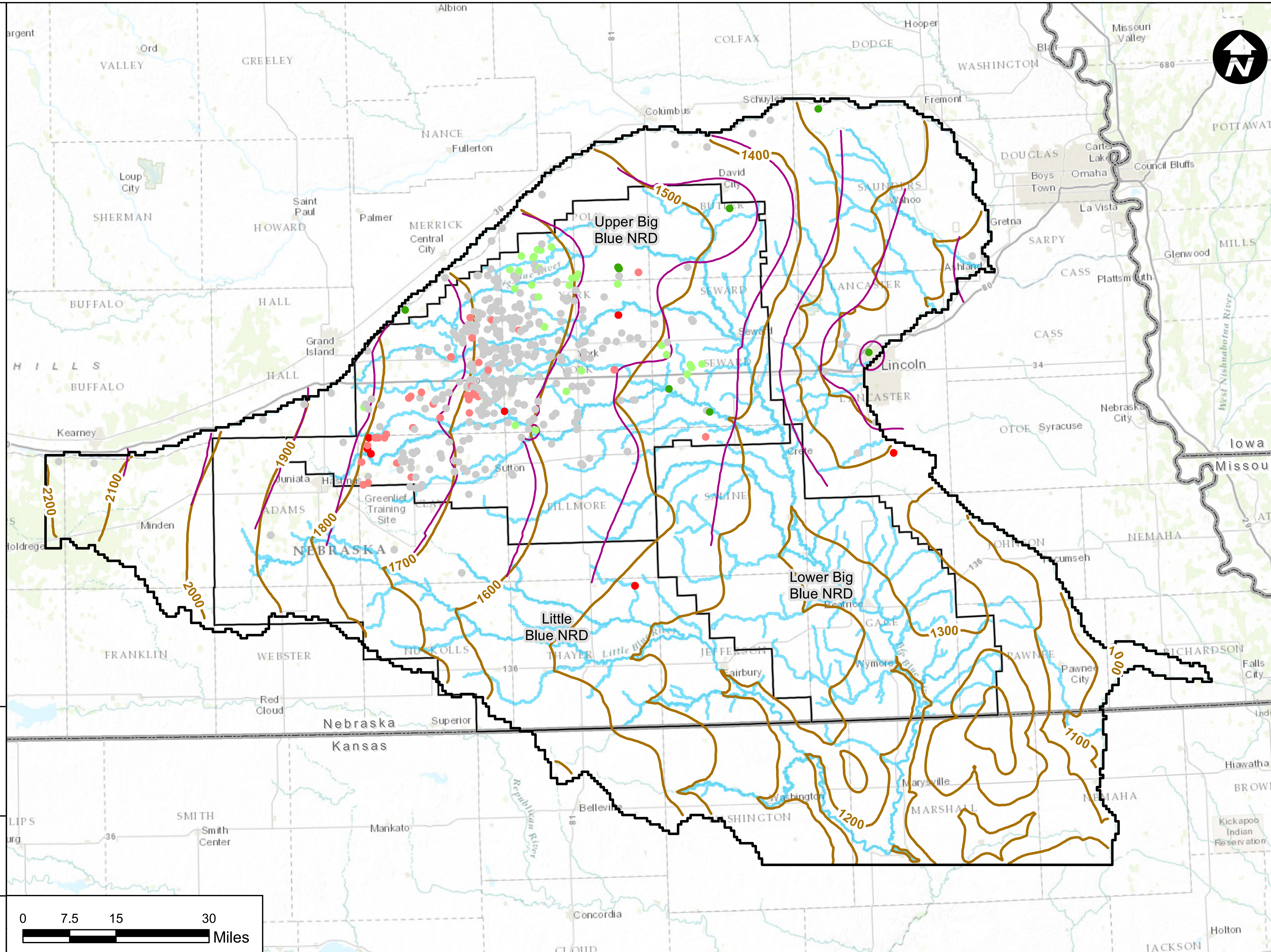


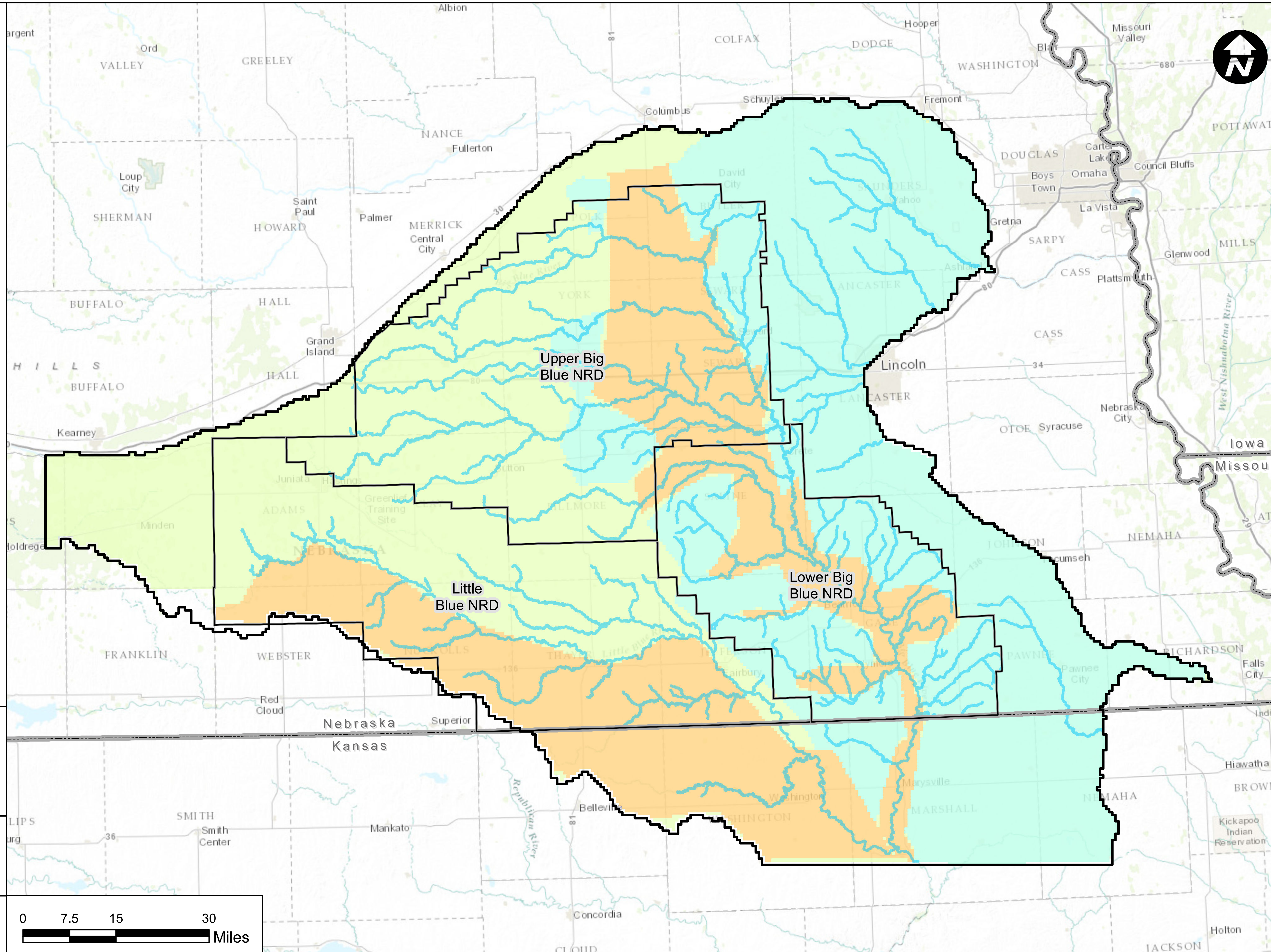
Figure 4-6

June, 2013

HDR

Blue Basins Groundwater Model Report

Post-Calibration Values for Specific Yield



Specific Yield

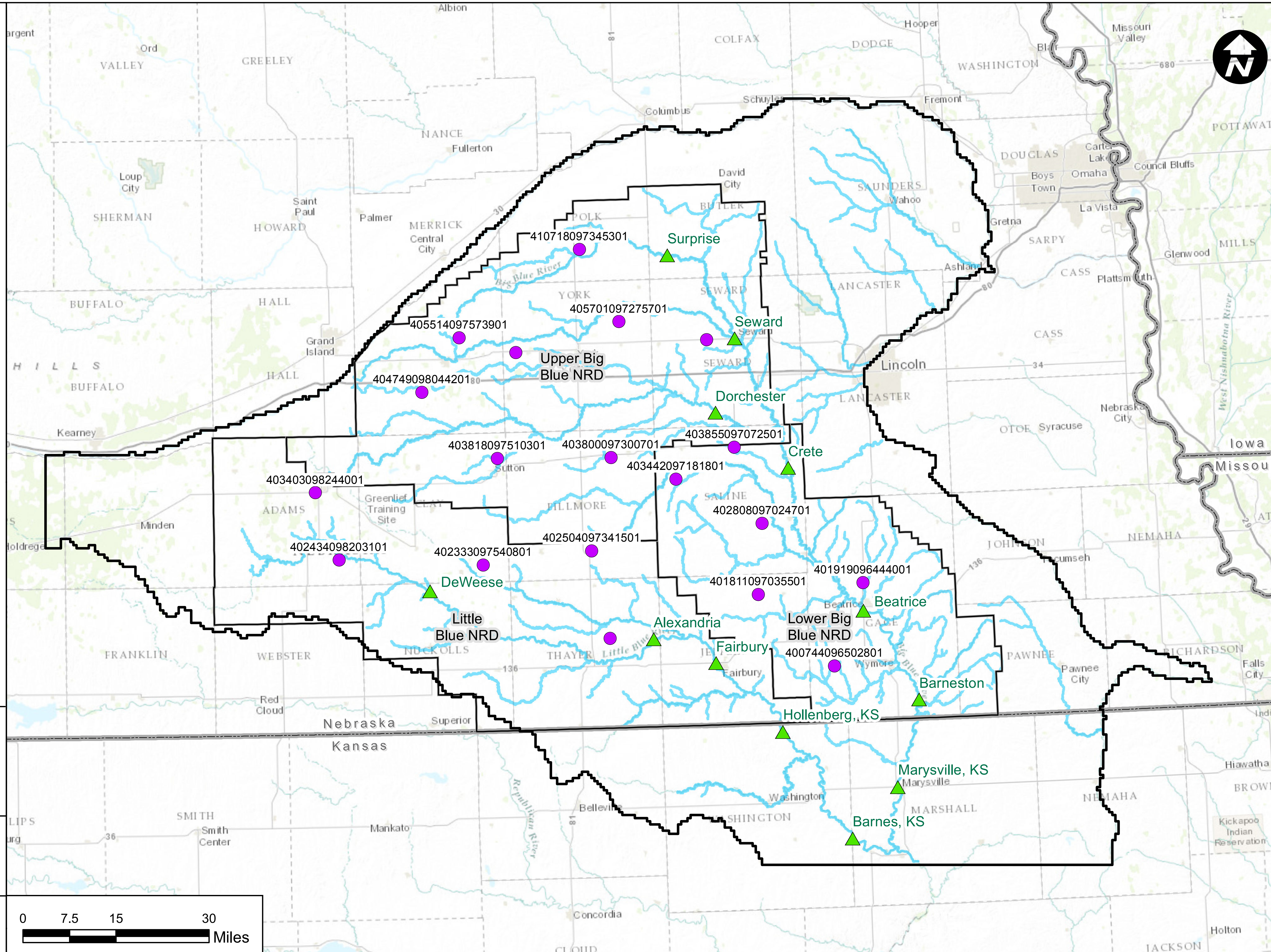
- 0.1
- 0.15
- 0.3
- Active Area Boundary
- Streams
- NRD Boundary
- County Boundary
- State Boundary

Sources:
Service Layer Credits: Esri Base Layer

Figure	**6-1**
June, 2013	HDR

Blue Basins Groundwater Model Report

Hydrograph Locations



Gauging Station Hydrograph Location

Well Hydrograph Location

Active Area Boundary

Streams

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

Figure 6-2

June, 2013

HDR

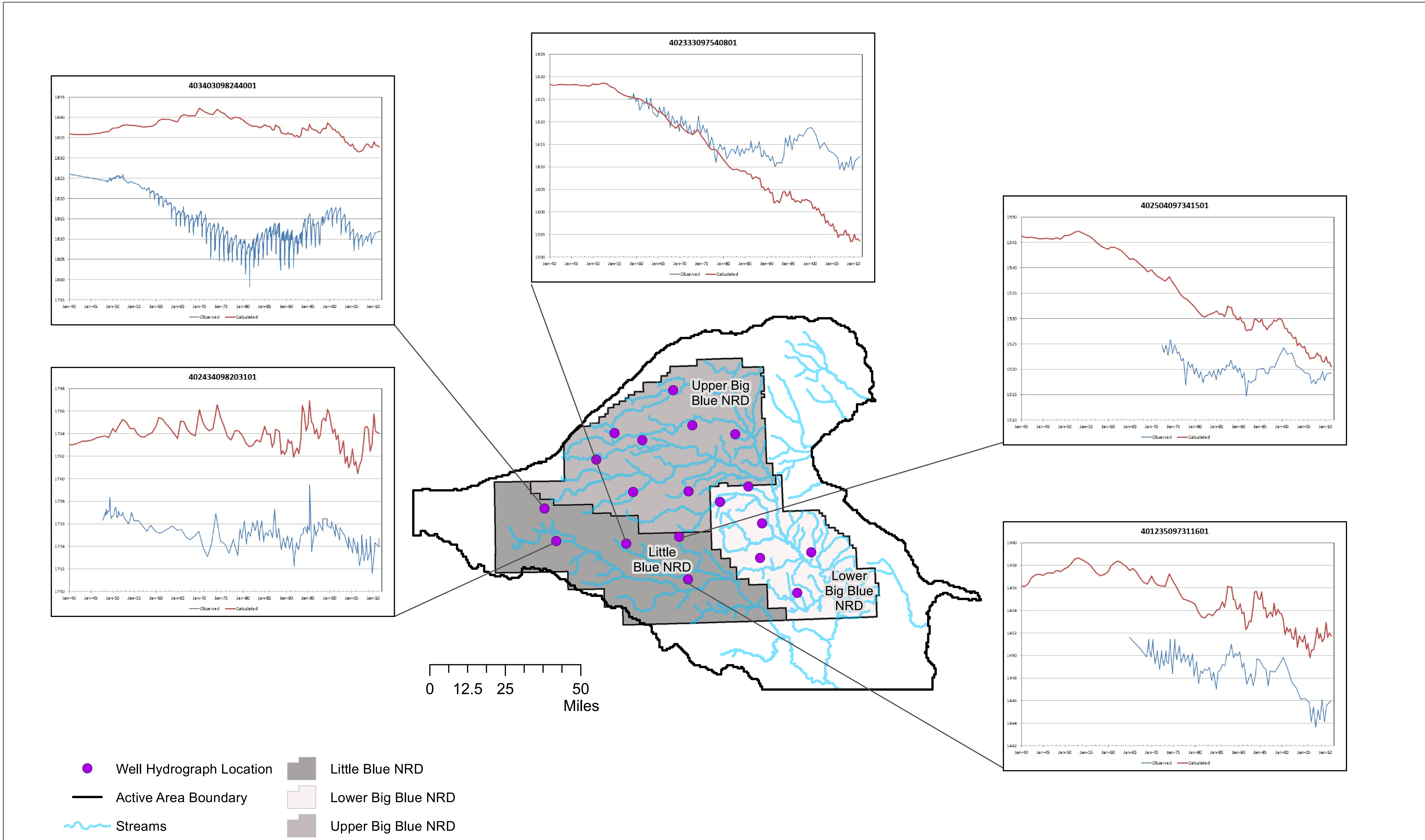


Figure 6-3a

Observation Well Hydrograph Locations

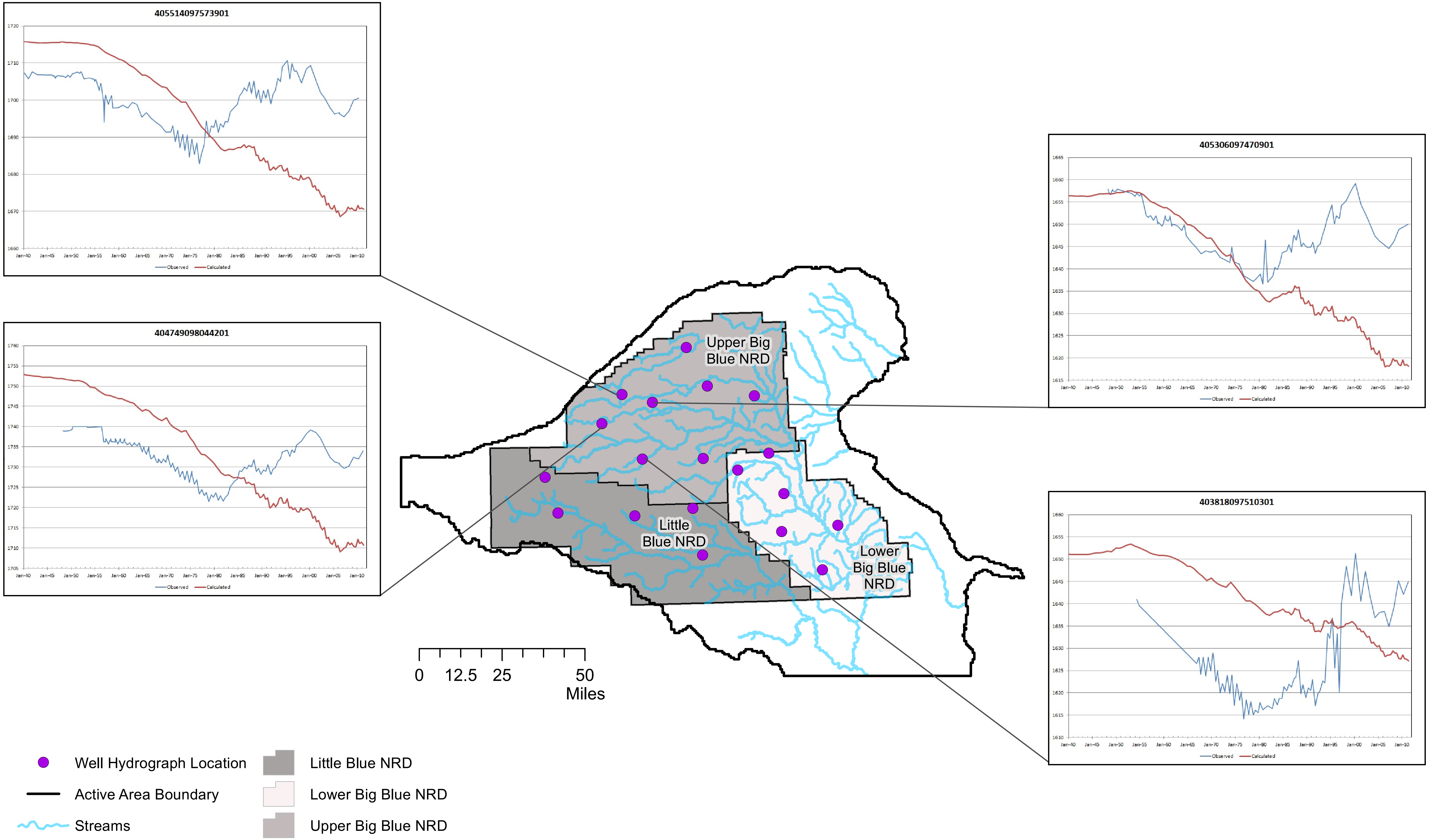


Figure 6-3b

Observation Well Hydrograph Locations

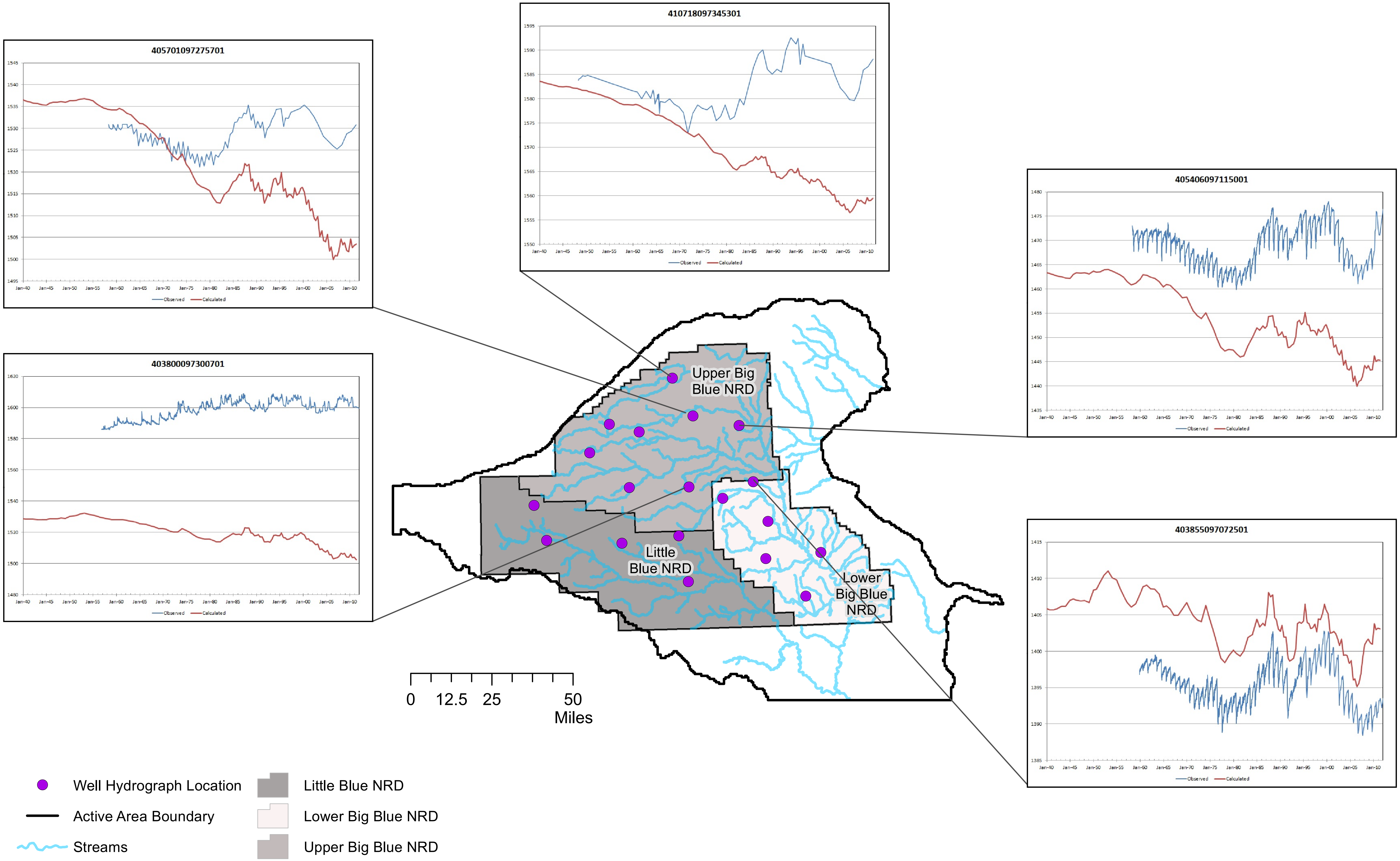


Figure 6-3c

Observation Well Hydrograph Locations

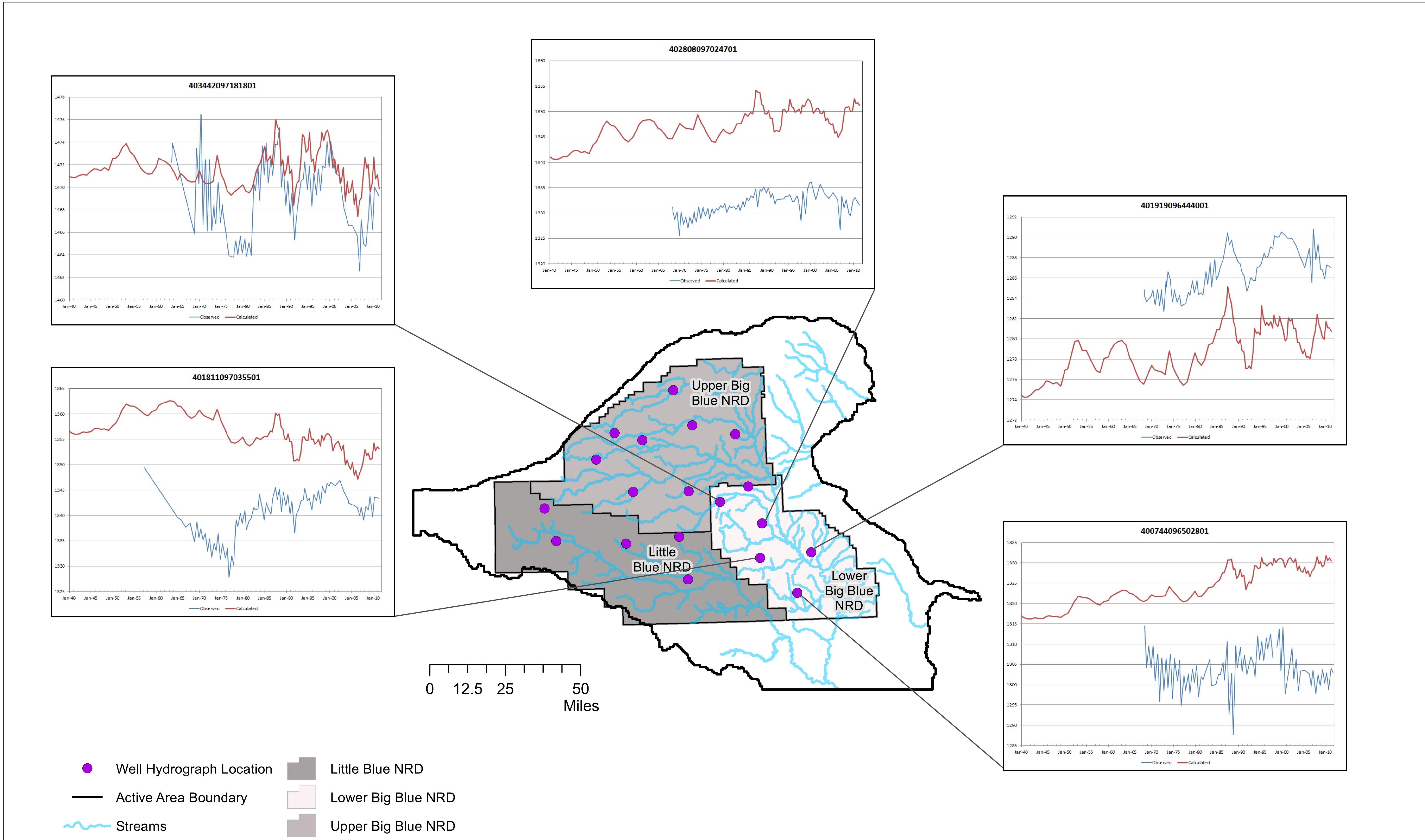


Figure 6-3d

Observation Well Hydrograph Locations

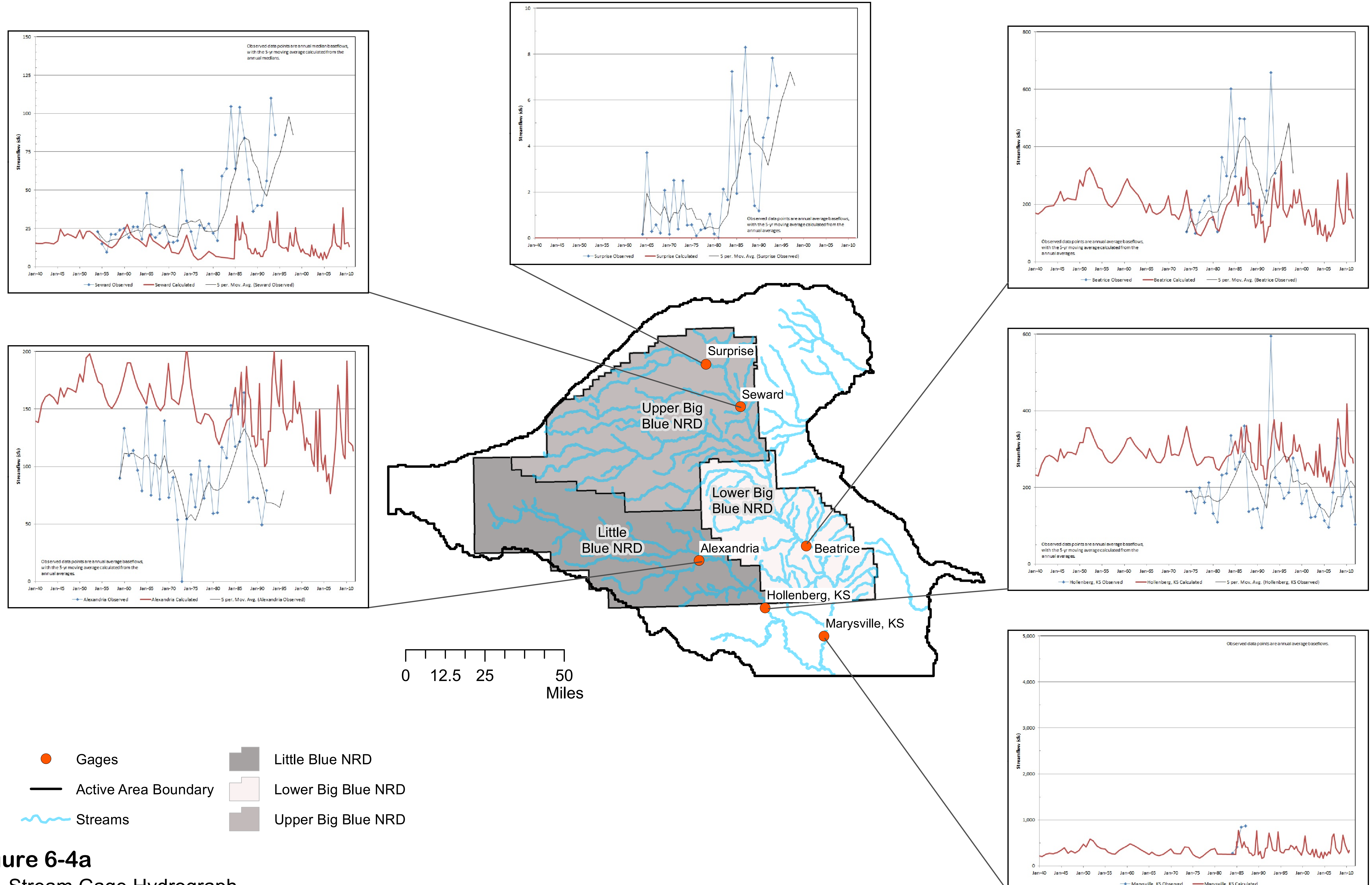


Figure 6-4a
Stream Gage Hydrograph

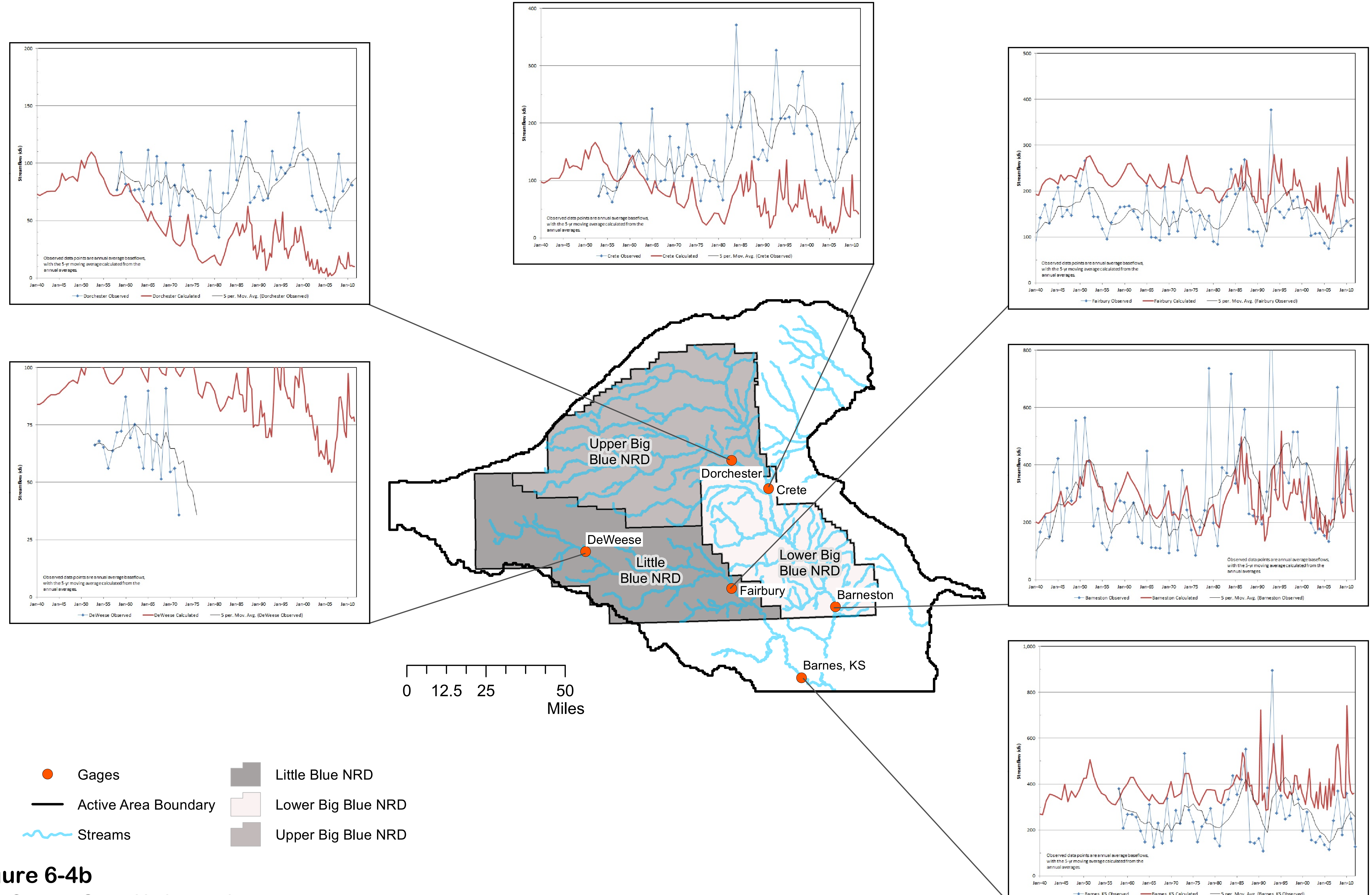
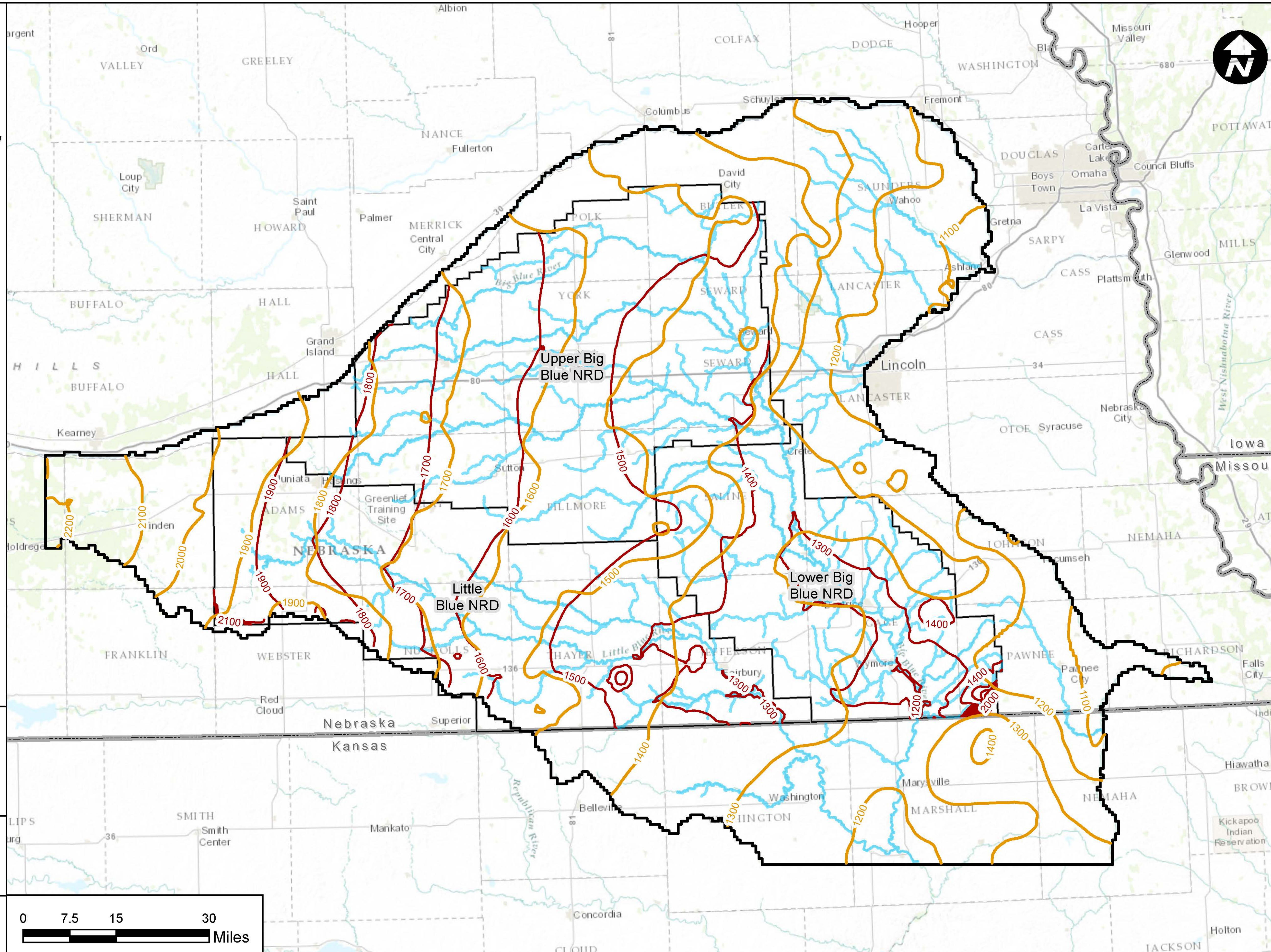


Figure 6-4b
Stream Gage Hydrograph

Blue Basins Groundwater Model Report

Comparison of Simulated and Observed 2009 Water Table Contour Maps



Simulated Water Table Elevation Contour

Observed Water Table Elevation Contour

Active Area Boundary

Streams

NRD Boundary

County Boundary

State Boundary

Sources:
Service Layer Credits: Esri Base Layer

Figure	**6-5**
June, 2013	HDR

Blue Basins Groundwater Model Report

Comparison of Simulated and Observed Water Level Changes Pre-Development to 2010

Water Level Change Contours 2010

Observed Head Change (ft)

- -30 to -40
- -20 to -30
- -10 to -20
- -5 to -10
- < +/- 5
- 5 to 10
- 10 to 20
- 20 to 30
- 30 to 40
- 40 to 50
- 50 to 60

Sparse Observed Data

Active Area Boundary

Streams

NRD Boundary

State Boundary

County Boundary

Sources:
Service Layer Credits: Esri Base Layer

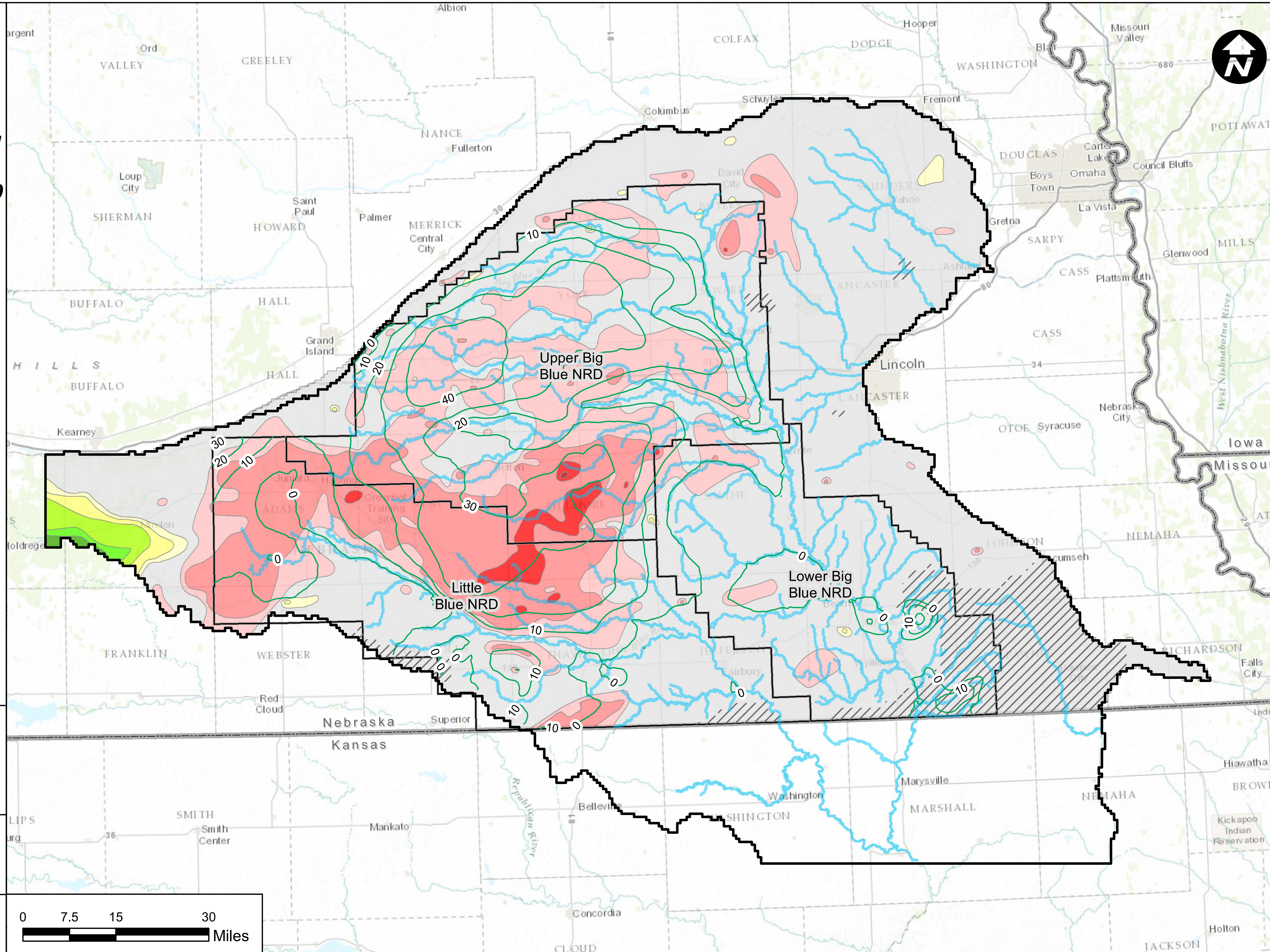
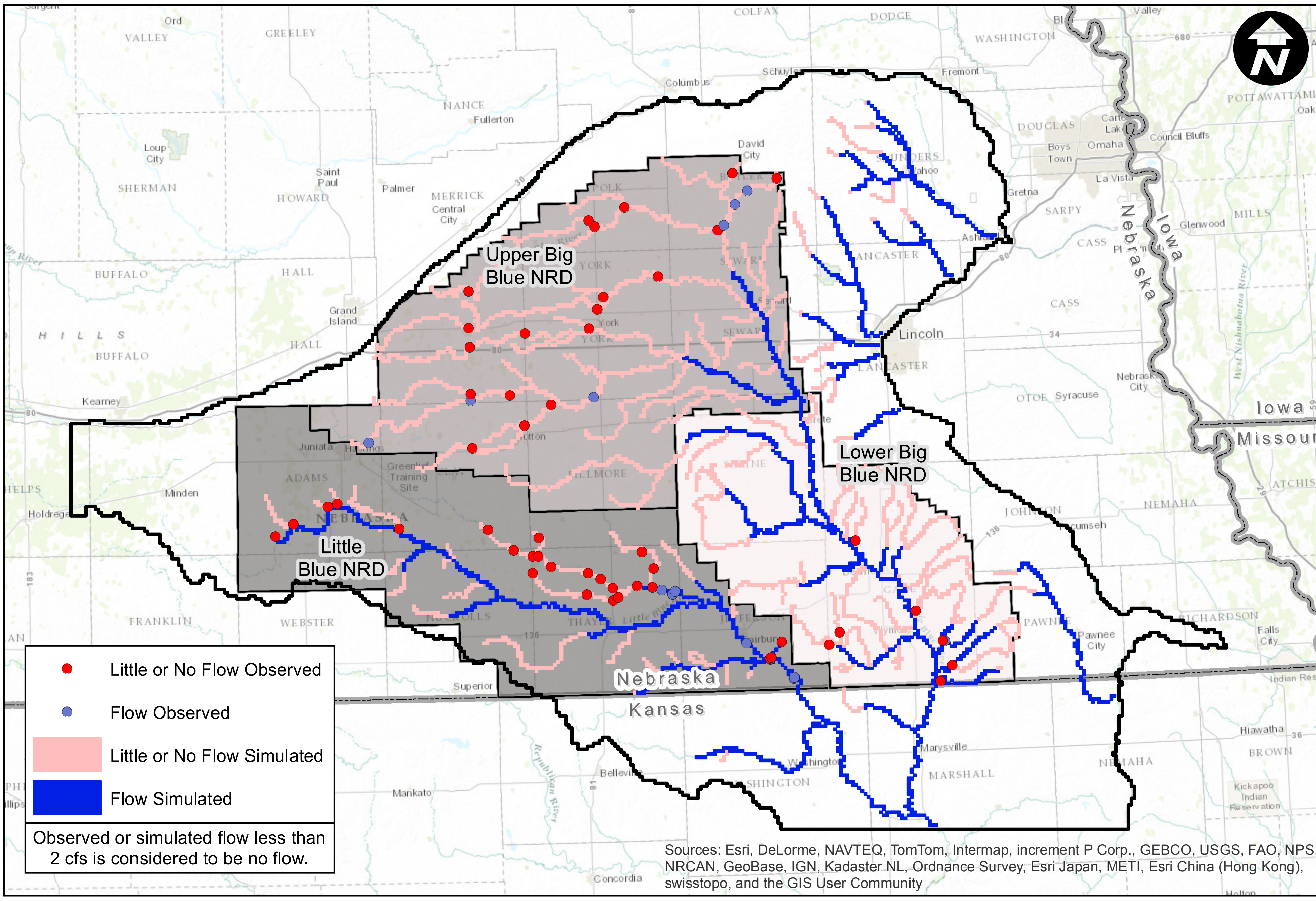


Figure	6-6
June, 2013	HDR



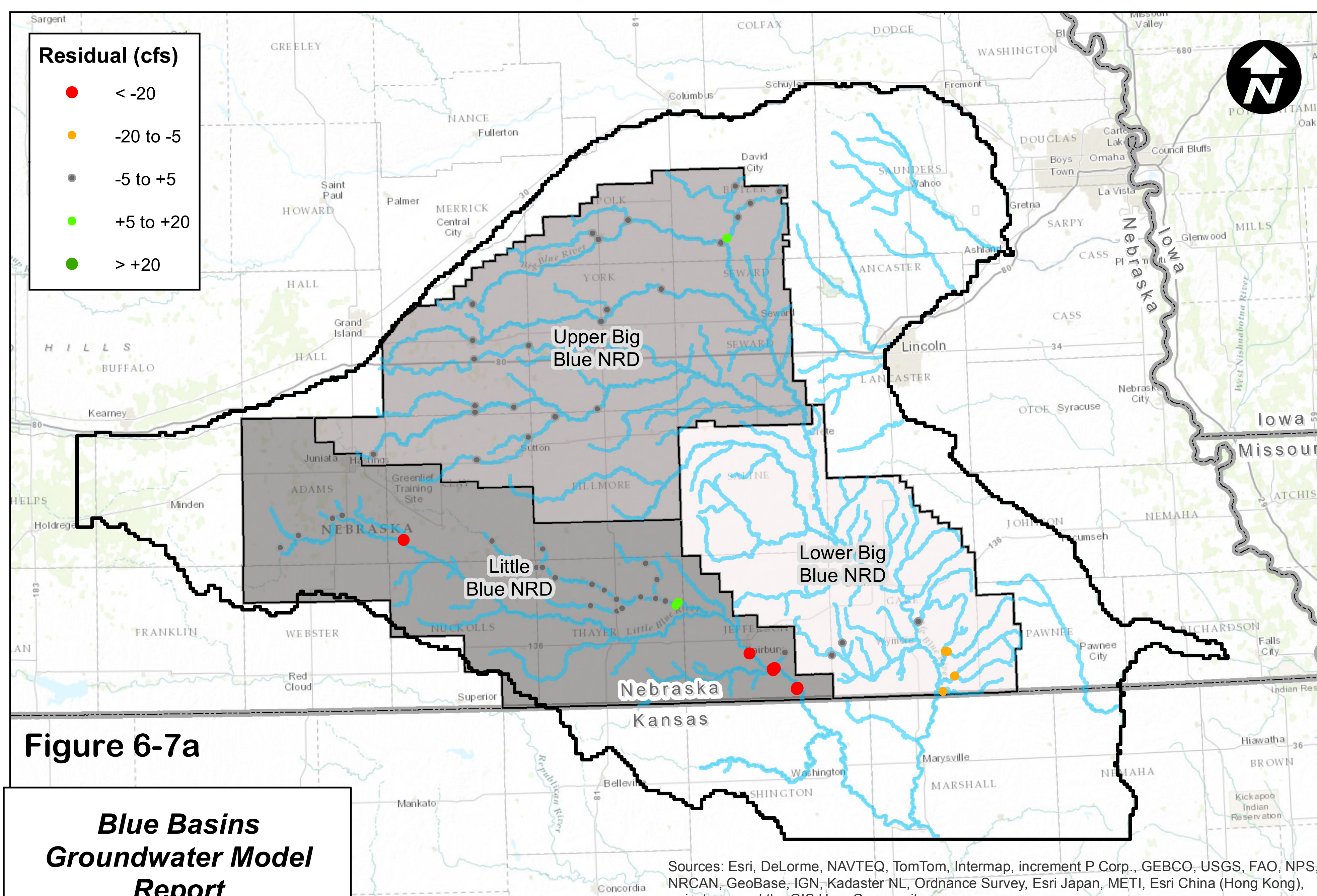


Figure 6-7a

Blue Basins Groundwater Model Report

Seep Run Comparison Low Flow Conditions (1981)

June, 2013

HDR

Sources: The source for this data is discussed in section 2.7.1 of thiis report. Residuals are the observed flow rate minus the simulated flow rate. HDR Service Layer Credits: Esri Base Layer

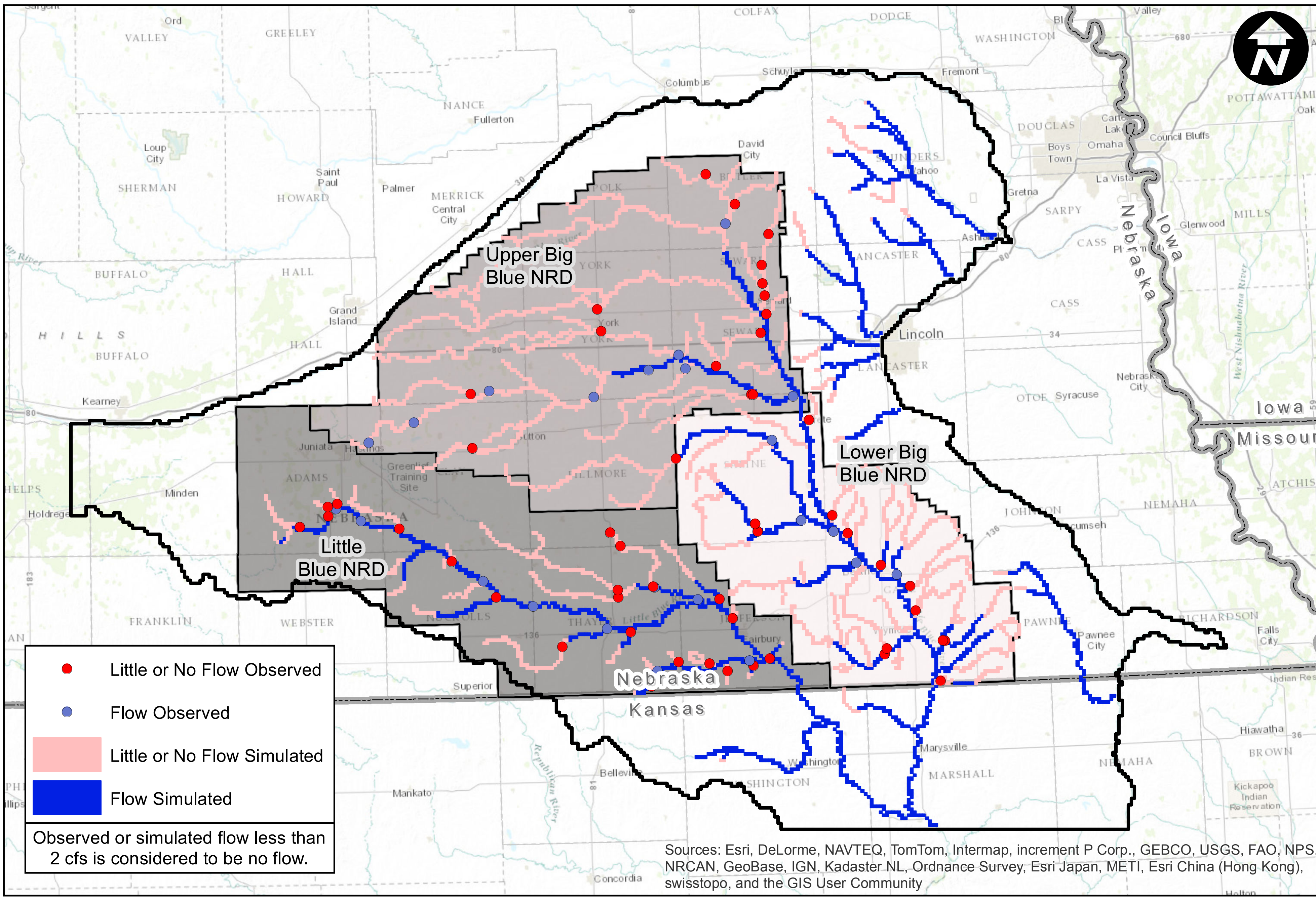
0 7.5 15 30 Miles

Active Area Boundary

NRD Boundary

State Boundary

County Boundary



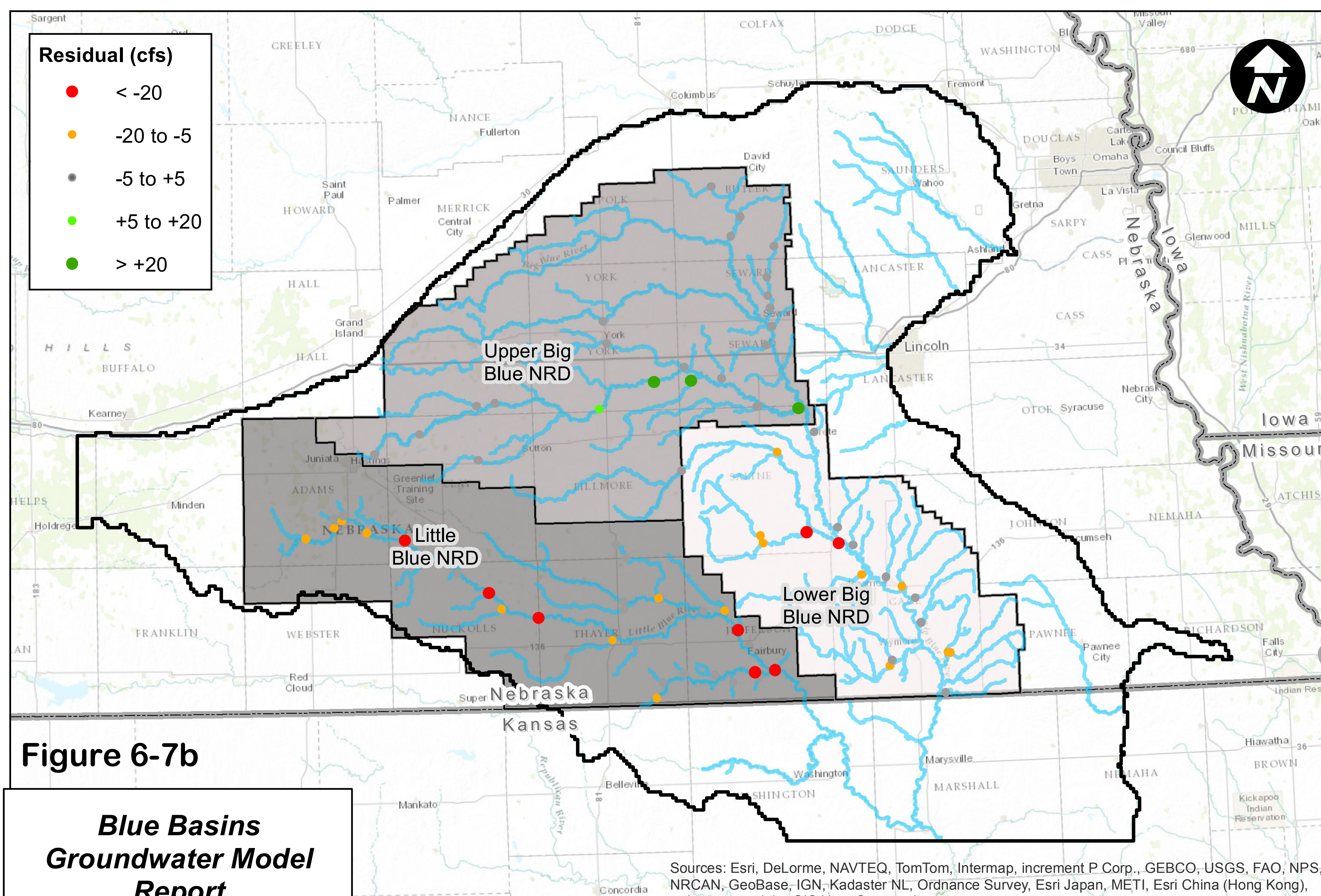


Figure 6-7b

Blue Basins Groundwater Model Report

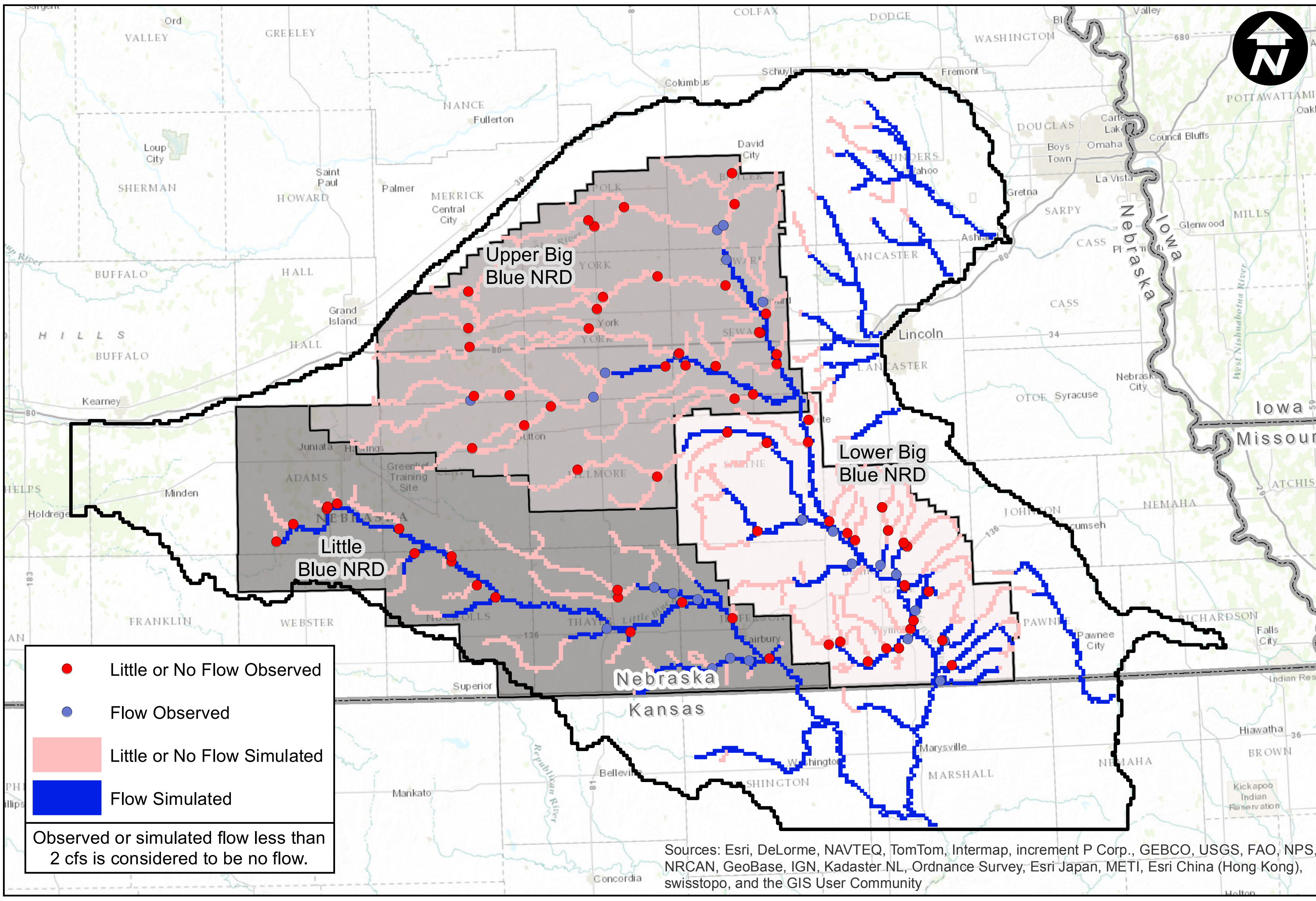
Seep Run Comparison Normal Flow Conditions (1988)

June, 2013

Sources: The source for this data is discussed in section 2.7.1 of thiis report. Residuals are the observed flow rate minus the simulated flow rate. HDR Service Layer Credits: Esri Base Layer

0 7.5 15 30 Miles

- Active Area Boundary
- NRD Boundary
- County Boundary
- State Boundary



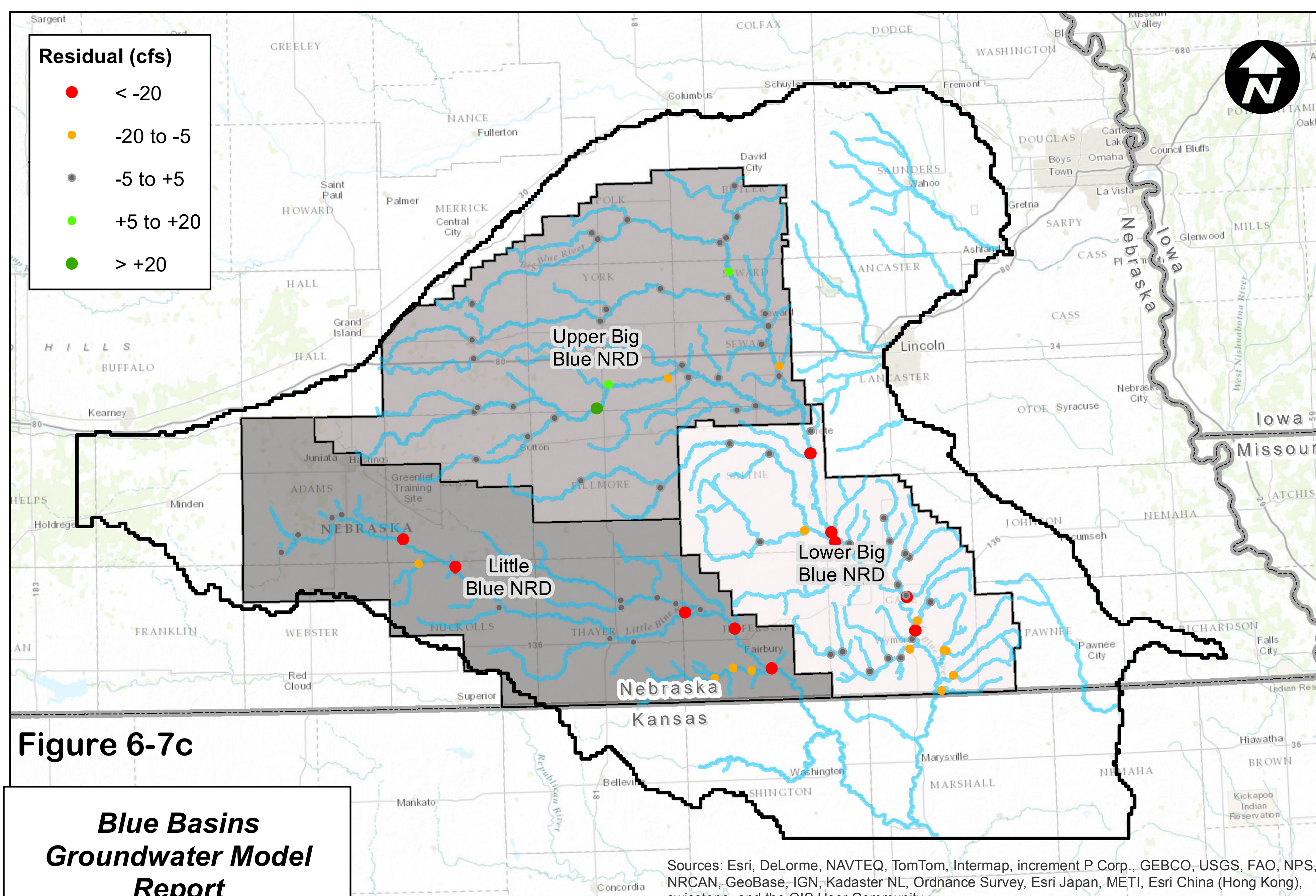


Figure 6-7c

Blue Basins Groundwater Model Report

Seep Run Comparison High Flow Conditions (1979)

Sources: The source for this data is discussed in section 2.7.1 of thiis report. Residuals are the observed flow rate minus the simulated flow rate. HDR Service Layer Credits: Esri Base Layer

0 7.5 15 30 Miles

Active Area Boundary

NRD Boundary

County Boundary

State Boundary

June, 2013

HDR

Appendix B – Available Dataset Report

Appendix B contains a copy of HDR's previous report *Assessment of Available Datasets to Construct a Groundwater Model in the Blue River Basin* (June, 2012).

FINAL

ASSESSMENT OF AVAILABLE DATASETS TO CONSTRUCT A GROUNDWATER MODEL IN THE BLUE RIVER BASIN

Nebraska Department of Natural Resources

August 2012

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ASSESSMENT OF AVAILABLE DATASETS TO CONSTRUCT A GROUNDWATER MODEL IN THE BLUE RIVER BASIN

1.0 Introduction and Background

The Nebraska Department of Natural Resources (DNR) 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, including the Blue River Basin (Basin). The DNR is currently developing a new methodology to evaluate a basins' status. This new methodology involves using historic stream gage and diversion records to compute a virgin natural flow hydrograph, or Virgin Water Supply (VWS), for various stream reaches within a basin. The VWS is calculated from historic streamflow, historic surface water consumptive use, and historic groundwater depletions. Since this methodology requires the ability to assess historic groundwater depletions, the DNR is working to develop numerical models in areas which are currently not represented by numerical groundwater models.

Tasked with performing these evaluations using the best available science and methods, the DNR has undertaken the development of a groundwater flow model for the Basin and has contracted with HDR Engineering, Inc. (HDR) to complete this work (DNR Contract No 476), generally following the scope of work outlined by the DNR in request for proposal (RFP) Number 3750Z1. This Technical Memorandum documents the second project task, the assessment of available datasets to construct and calibrate a groundwater model.

1.1 Report Organization

The technical memorandum is organized as follows:

- Section 1.0 Introduction and Background
- Section 2.0 Available Datasets for Model Calibration
- Section 3.0 Conclusions

Figures have been included within the body of this Technical Memorandum following the reference of each figure. However, in an effort to improve the readability of the figures, a full size copy is also included in Appendix A.

1.2 Scope of Services

The following is a brief summary of the activities included in HDR's scope of services for Task Series 2 of this project. The objective of the activities in Task Series 2 is to develop a Model Development Plan. The Model Development Plan will serve as a work plan that will provide recommendations and identify procedures for the construction and calibration of the groundwater flow model. The first task in Task Series 2 is Task 2.1 Evaluation of Existing Datasets for Model Calibration. The objective of the activities associated with Task 2.1 is to develop this Technical Memorandum, which summarizes the datasets available to construct a groundwater model. The scope for Task 2.1 is included below:

> "The Model Development Plan will include a review of available datasets and will include a discussion on the suitability of available data for development of an updated or new groundwater model (Task 3). The objective of Task 2.1 will be to summarize the data sets available for model calibration. "

2.0 Available Datasets for Model Calibration

The following section describes the datasets available for the construction and calibration of a groundwater flow model.

2.1 Water Level Data

In 1930, the Conservation and Survey Division of the University of Nebraska-Lincoln (UNLCSD) and the United States Geological Survey (USGS) began a cooperative water-level measurement program to observe and document changes in groundwater levels throughout Nebraska. UNLCSD maintains this program today through the Statewide Groundwater-Level Monitoring Program. As part of the Statewide Groundwater-Level Monitoring Program, the UNLCSD maintains a database that includes all water level measurements collected and reported within Nebraska, which includes water level measurements from as far back as 1895. A copy of the Nebraska Statewide Groundwater Level Program database (groundwater database) was provided to HDR by the UNLCSD in April, 2012.

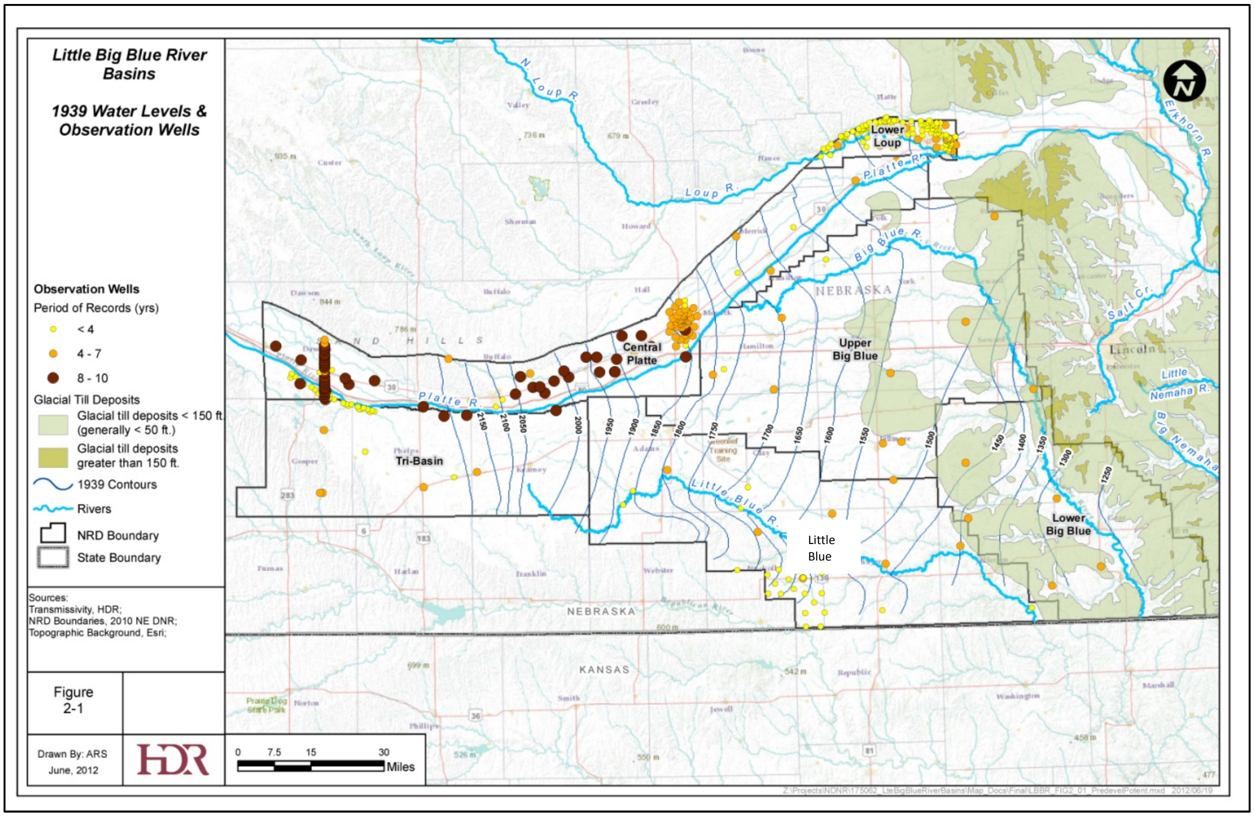
Evaluating the ability of a groundwater flow model to reproduce groundwater elevations, and also changes in groundwater elevations over time, is an important part of any model calibration process. These statewide groundwater data provide an excellent source of date to construct a groundwater model. Some of these datasets, and their potential model application, are presented below.

2.1.1 Predevelopment (Pre-1940 Period)

For the purposes of this study, the period prior to 1940 is defined as predevelopment, meaning a time when irrigation pumping within the study area was limited. Groundwater level measurements collected during this time frame are the earliest available measurements and are considered to be unaffected by groundwater irrigation. Groundwater level measurements generally were not widely made during the predevelopment period; however, measurements from 76 wells were available for this evaluation. These wells were located in the Little Big Blue, Little Blue, Tri-Basin, or Upper Big Blue NRDs during the period from 1895 to 1939. The distribution of these groundwater-level measurements was fairly consistent across the study area and is shown below in Figure 2-1. The interpreted potentiometric surface for the predevelopment timeframe is also shown in Figure 2-1.

To develop the potentiometric surface shown on Figure 2-1, groundwater elevations were determined by taking the depth to water value reported in the statewide database, and subtracting that value from the land elevation at the same location. Land elevation was determined using a 10-meter digital elevation model (DEM) created by the United States Geological Survey (USGS). The potentiometric surface was developed using an automated interpolation technique within ArcGIS software. The resulting surface was manually checked by a hydrogeologist and modified through an iterative process until the potentiometric surface presented in Figure 2-1 was developed.

Figure 2-1 – Predevelopment Groundwater Monitoring Well Locations and Interpreted Potentiometric Surface

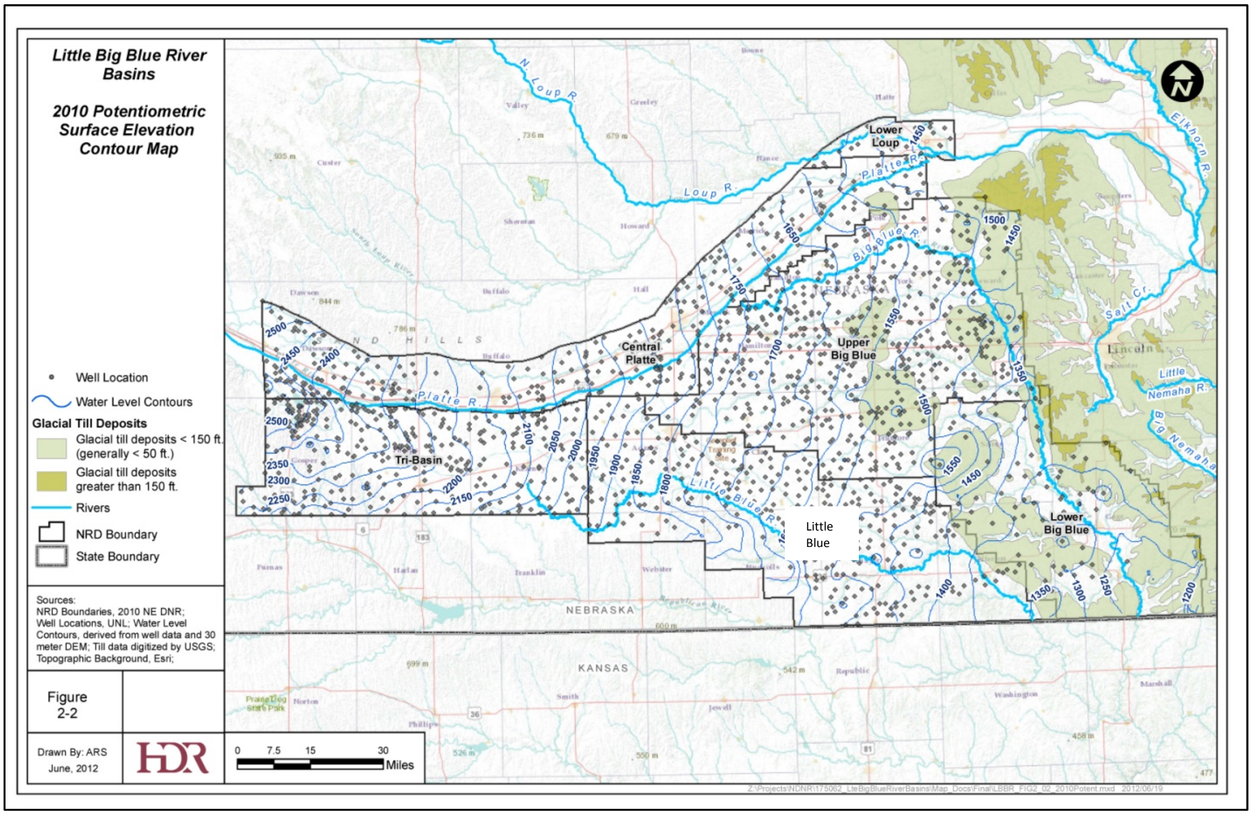


For the purposes of this study, the predevelopment conditions shown in Figure 2-1 are considered to be representative of steady state conditions. Steady state conditions occur when groundwater elevations, and consequently the magnitude and direction of the groundwater gradient, are not changing with time. Given the absence of large scale irrigation during the predevelopment period, these groundwater elevations represent as close to steady state conditions as have been documented within the Basin.

2.1.2 2010 Groundwater Elevations

A second step taken to evaluate the groundwater flow conditions in the study area was to develop a potentiometric surface elevation map using recent water level data (2010). This interpreted potentiometric surface is shown below on Figure 2-2. The 2010 water level elevation map includes approximately 1,300 wells located in the Little Big Blue, Little Blue, Tri-Basin, or Upper Big Blue NRDs. The location and distribution of these groundwater-level monitoring points is very consistent across the study area (Figure 2-2), with only the extreme southeastern portion of the study area having a noticeably lower well density. The large number of water level data points facilitated the development the potentiometric surface using the automated GIS interpolation technique. The resulting surface was checked by a hydrogeologist but required little to no modification from what was produced by the interpolation technique. The shape of this potentiometric surface was checked against documented potentiometric surfaces developed by the UNLCSD for 1979 and 1995 is very similar in both magnitude and direction of the hydraulic gradient. The shape of the potentiometric surface and the individual water level elevation measurements are a very valuable dataset that can be used during the calibration of the Blue River Basin groundwater model.

Figure 2-2 – 2010 Potentiometric Surface Elevation Contour Map – Blue River Basin

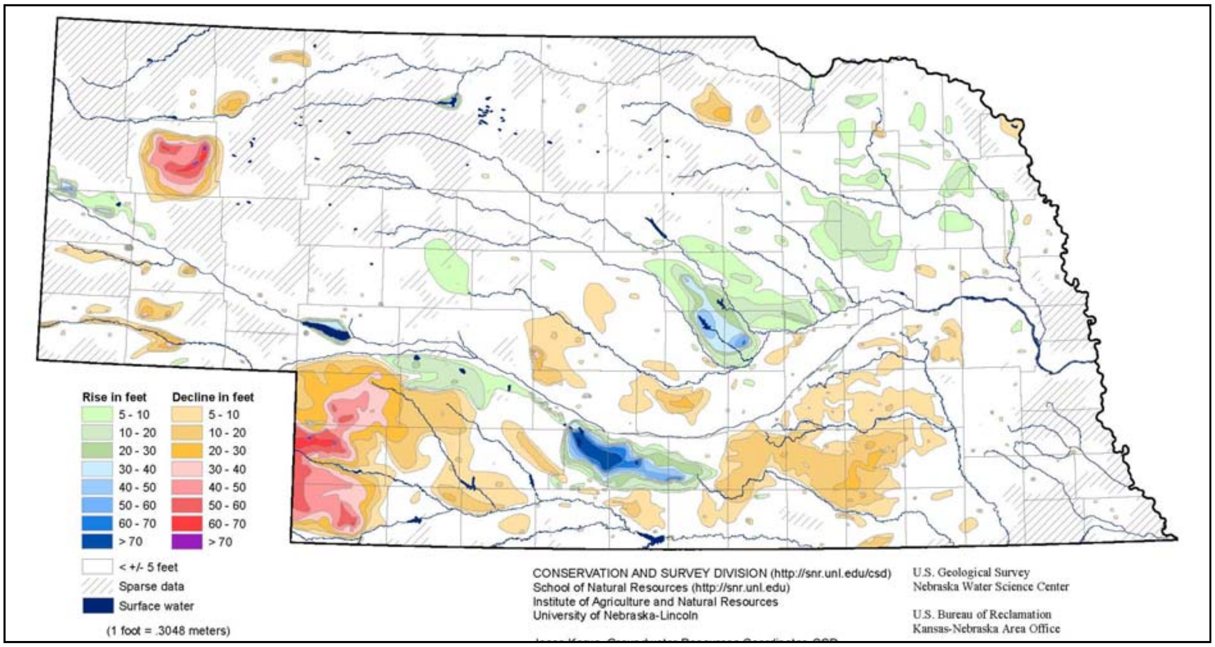


2.1.3 Groundwater-Level-Change Targets 1940 through 2009

The UNLCSD develops groundwater level change maps annually. These maps depict the change in water level elevation throughout the State, using pre-development as the frame of reference. Groundwater development within Nebraska was not uniform; therefore the estimated predevelopment water level is not fixed to a specific date or time, but rather is the approximate average water level at a well site prior to any development that significantly affected that water level. All available water-level data collected prior to or during the early stages of groundwater development are used to estimate predevelopment water levels (Burbach, 2006).

A large portion of south central Nebraska, including much of the study area, has experienced groundwater declines from the pre-development period. Groundwater levels in parts of Adams, Clay, Custer, Fillmore, Hall, Hamilton, Polk, Seward, and York Counties have declined between 10 and 20 feet. The UNLCSD interpreted change in groundwater level elevations from predevelopment to Spring 2010 is presented in Figure 2-3

Figure 2-3 – Groundwater Level Change – Predevelopment to Spring 2010



The observed **total** change in groundwater elevation from predevelopment to 2010 is a valuable dataset that can be used during the calibration of the Blue River Basin groundwater model. These data can be used as part of a transient model calibration that simulates the development of irrigation pumping from predevelopment to 2010 conditions.

2.1.3.1 Decadal Groundwater Level Changes

The UNLCSD developed maps depicting water level change, relative to predevelopment, for each year starting from 1954 (http://snr.unl.edu/data/water/groundwatermaps.asp). These data could be used to evaluate the ability of the groundwater flow model to reproduce observed decadal groundwater-level changes and could be used to perform a transient calibration of the model. A review of the available maps indicates that there was little to no documented change in groundwater elevations within the study Basin as of 1954. Examples of decadal groundwater level changes that can be used as calibration checks during a transient model calibration are shown below as Figure 2-4a (1959), Figure 2-4b (1969), and Figure 2-4c (1979).

By 1959, groundwater elevations had begun to decline within the Basin with several large areas experiencing declines between 2 to 5 feet and some isolated areas experiencing declines of more than 10 feet. The majority of the groundwater declines from predevelopment conditions observed within the Basin appear to have occurred during the late 1950s to the mid to late 1970s.

Figure 2-4a – Groundwater Level Change – Predevelopment to 1959

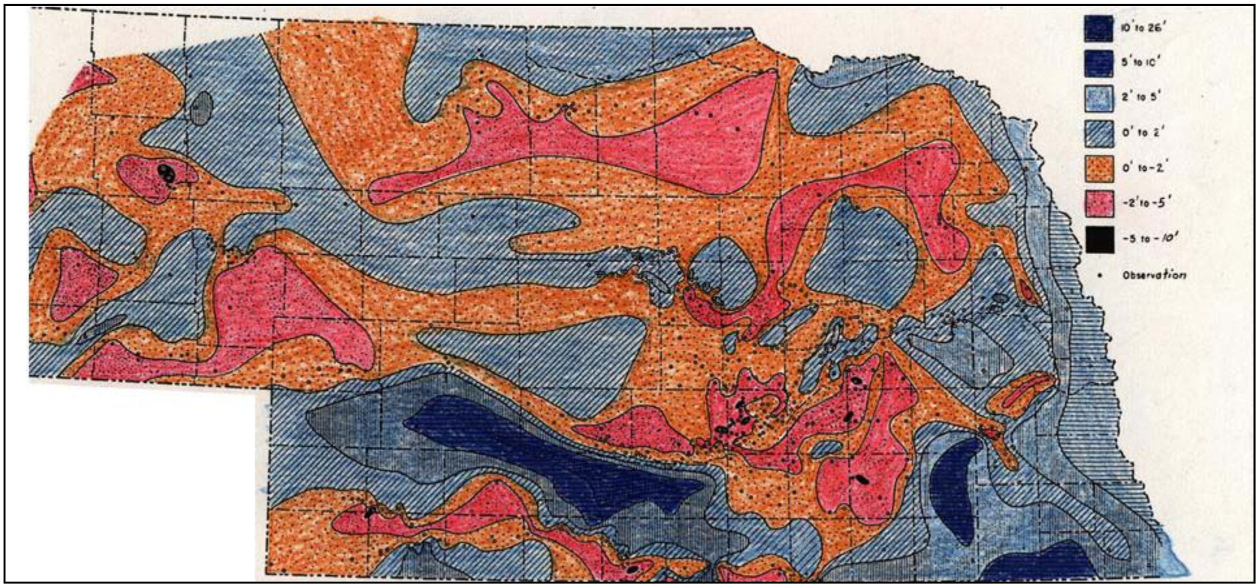


Figure 2-4b – Groundwater Level Change – Predevelopment to 1969

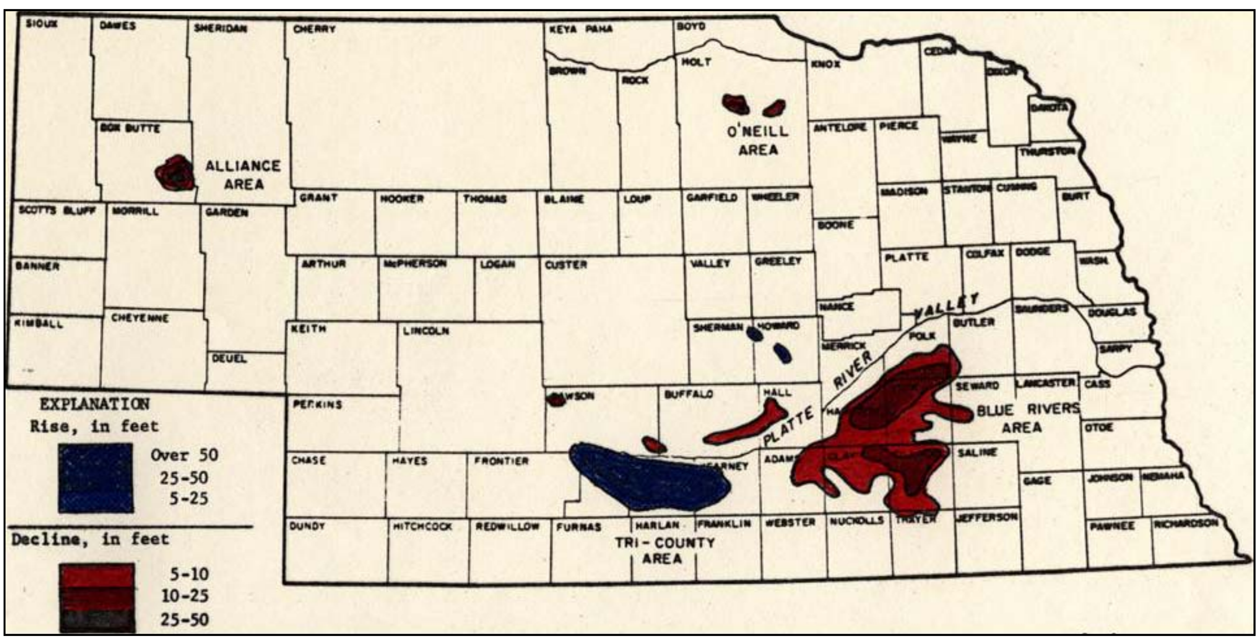


Figure 2-4c – Groundwater Level Change – Predevelopment to 1979

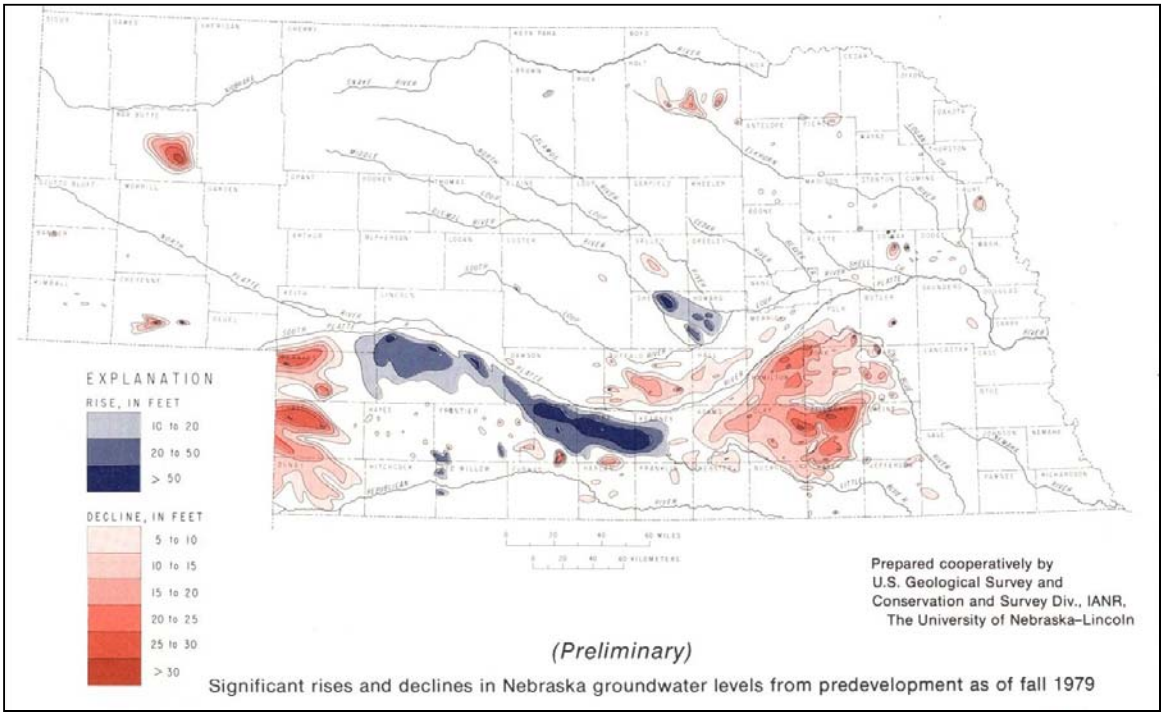
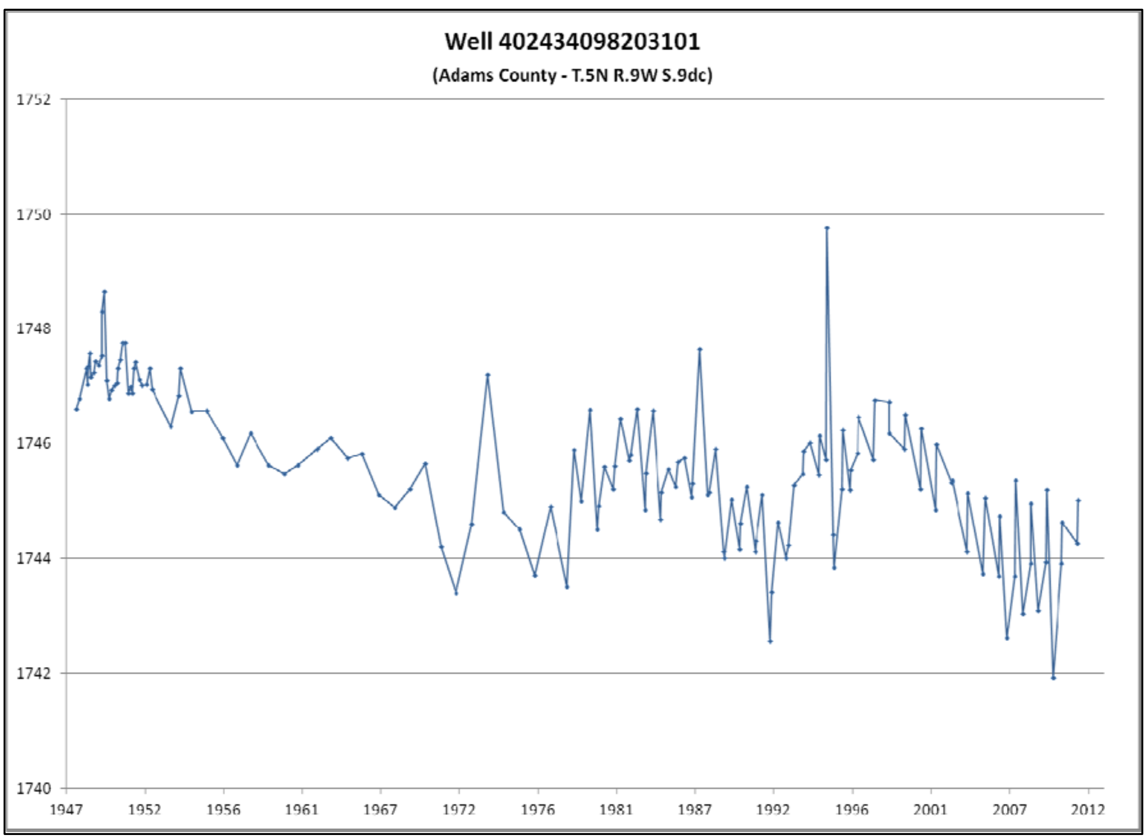


Figure 2-4d – Well Hydrograph – Predevelopment to Current



The benefit of using these data for model calibration is the contours have been already developed by a respected State agency, which both ensures a level of quality and reduces the time required to pre-process model calibration data. These documented temporal groundwater level changes can be used in the model calibration process as a check of the models ability to track declines in water surface elevation (or drawdown) over large areas. Checking the model's ability to track drawdown at individual wells (Figure 2-4d) will be included as part of the transient model calibration process. Use of time varying drawdown within the Basin provides a source of data that can be used to calibrate the aquifer storage parameter, which is needed to perform transient model runs, and will also serve as a check of the CROPSIM data provided by the DNR. CROPSIM is a soil moisture balance model that estimates crop irrigation requirements, and the output from CROPSIM will serve as the basis for recharge and pumping data in the groundwater model.

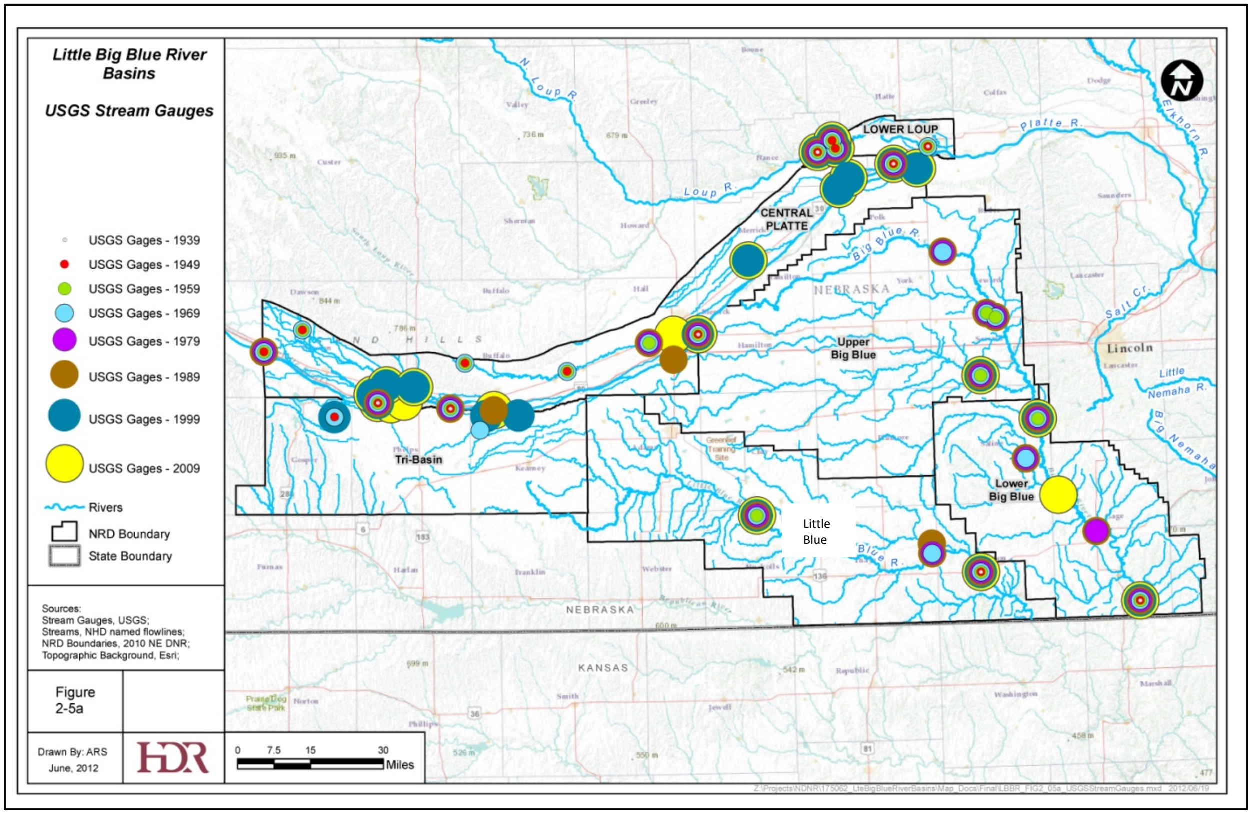
2.2 Stream Base Flow

Stream baseflow data are another important form of data used to calibrate groundwater flow models. It is anticipated that pre-development stream baseflow data will be used to calibrate the steady state model and that streamflow data from gauge sites with long term historical records will be used to calibrate the transient model.

2.2.1 USGS Network

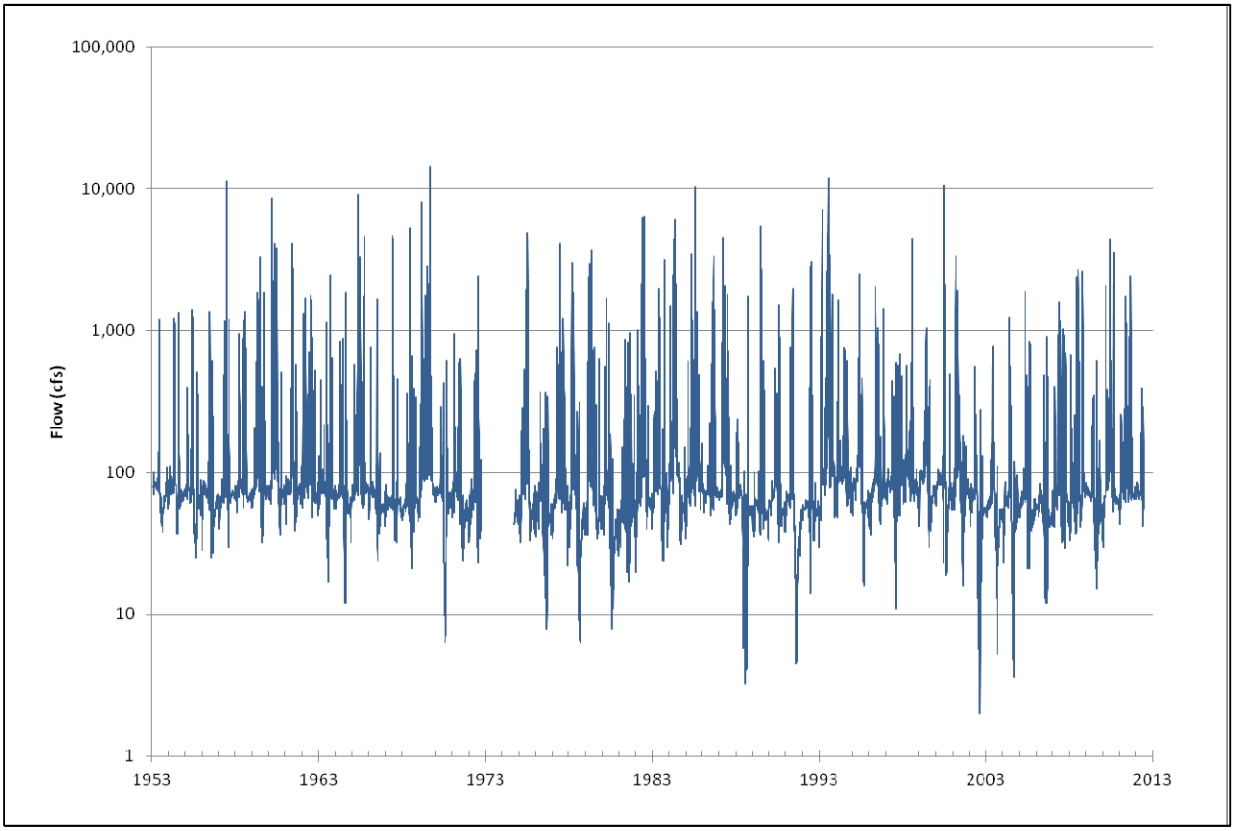
The USGS maintains the National Water Information System (NWIS), which is described by the USGS as "a comprehensive and distributed application that supports the acquisition, processing, and long-term storage of water data". Several of these USGS NWIS streamflow gauges are maintained within the Basin and this database includes the predevelopment period. The location of the USGS streamflow gauging stations within the Basin is shown on Figure 2-5a. As shown, the majority of these gauges are located the major rivers within the Basin (Blue River, Little Blue River, Platte River, and West Fork Blue River).

Figure 2-5a –USGS Streamflow Gauges in the Study Basin



The period of record of these gauges is variable; however, there are several gauges that could be used as the calibration dataset to perform a transient calibration of model predicted streamflow that includes the predevelopment period. As shown, there are at least seven (7) stream gauges located on either the Big Blue or Little Blue River that include streamflow from the late 1950's to present day. An example of one (1) of these gauges is shown on Figure 2-5b. The long period of record associated with these USGS gauges makes these stream gauges sites an ideal source of data to calibrate the transient model.

Figure 2-5b –Little Blue River at DeWeese



2.2.2 DNR Archived Point Measurements

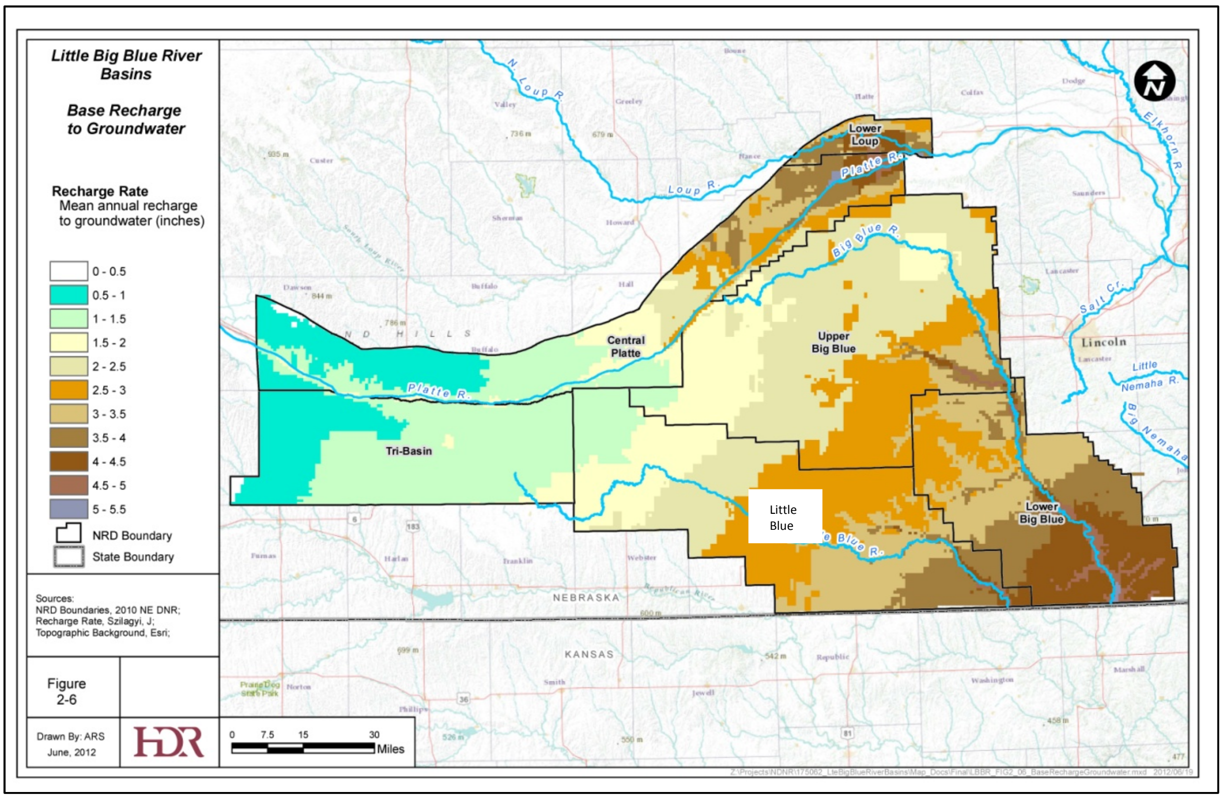
The DNR provided HDR with a database of field measurements of streamflow, obtained from DNR archive files. These field measurements were made at existing gauge sites (USGS or DNR), and at various ungauged points along streams (called seep runs). The majority of the streamflow values came from published hydrographic reports; however some also came from unpublished field office records. The data were converted by the DNR from their original form through paper-to-digital record conversion process. The data were then provided to HDR in database format. HDR evaluated the spatial and temporal distribution of these data using ArcGIS.

These streamflow data provide a series of point streamflow measurements and discontinued gages that could be used to supplement the long historical record data from the USGS NWIS gauges. These point measurements and discontinued gauge sites will be used as to increase the number of stream baseflow calibration targets for the steady state model (pre-development). The data can also be used as a method to determine which tributaries and smaller streams should be included in the model. In the Elkhorn Loup Model (USGS, 2010), the criterion used to add a stream was that it had to have at minimum of five (5) cubic feet per second (cfs) of measured base flow. A similar criterion could be used in the development of the Blue Basin model to determine which small streams should be included in the predevelopment scenario.

2.3 Groundwater Recharge

The largest source of water in the study area is from vertical recharge. Szilagy, et. al. (2003) developed an estimate of the base recharge for the state of Nebraska. Base recharge is in essence net recharge, i.e., the difference of total infiltration less losses to evapotranspiration. The Szilagy study was published in the peer reviewed journal *Ground Water,* and is typically considered the best presently available data source to estimate mean annual recharge to groundwater. Its use simplifies groundwater modeling because evapotranspiration is implicitly incorporated. A map of base recharge for the Study Area is included as Figure 2-6. This distribution of mean annual recharge to groundwater can be used as the recharge rates for the steady state simulation, which will be performed to reproduce predevelopment conditions.

Figure 2-6 –Base Recharge to Groundwater



2.4 Hydraulic Conductivity/Transmissivity Distribution

An initial estimate of the horizontal hydraulic conductivity (K_H) distribution within the primary aquifer was developed using available data from the UNLCSD Test-Hole database. Horizontal conductivity values were estimated from grain size, degree of sorting, and silt content of the saturated aquifer sediments using soil boring log from the Test Hole database in a manner consistent with that used for calculating specific yield by Summerside et al., 2005 (OFR-71) in the *Mapping of the Aquifer Properties – Transmissivity and Specific Yield – for Selected River Basins in Central and Eastern Nebraska*. This process assigns hydraulic conductivity data based on the geology reported in a boring log using the GeoParam program developed by the UNLCSD.

The saturated thickness of the aquifer at each test hole location was determined using 2010 water level data elevation in the Nebraska Statewide Groundwater Level Program database. This water level elevation was used as the top of saturated material. Any lithology above this water level or below the surface of bedrock was not included in the overall transmissivity analysis for each respective boring. Transmissivity values for each individual lithologic unit were calculated by multiplying the GeoParam assigned hydraulic conductivity by the saturated thickness of each individual lithologic unit. Transmissivity values were then summed to reflect the total aquifer transmissivity value for that test hole. The resulting aquifer transmissivity values were then imported as point data points into ArcGIS and gridded using an automated interpolation technique.

Only geologic logs from UNLCSD test borings were used to develop the transmissivity and hydraulic conductivity distribution maps. The geologic logs used included all boring logs reported for the four (4) study area NRDs, plus boring logs from other surrounding NRDs to reduce the possibility of inconsistencies at the boundary of the interpretation grid. A total of 465 test holes completed in the four (4) study area NRDs (Little Big Blue, Little Blue, Tri-Basin, and the Upper Big Blue) were used for this analysis. A summary of the number of test holes, by NRD, included in the hydraulic conductivity/transmissivity interpretation is presented below in Table 2-1.

Table 2.1 –Summary of Test Hole Logs by NRD

NRD	Number of Test Log Logs Included
Central Platte	207
Lewis and Clark	78
Little Blue	119
Lower Big Blue	118
Lower Elkhorn	374
Lower Loup	31
Lower Platte North	130
Lower Platte South	209
Nemaha	400
Papio-Missouri River	95
Tri-Basin	96
Upper Big Blue	132

The initial hydraulic conductivity, saturated thickness, and transmissivity distribution obtained from the process previously described is presented in Figure 2-7, Figure 2-8, and Figure 2-9a, respectively. For comparison purposes the transmissivity distribution used in the 2008 UBBNRD model is presented as Figure 2-9b. This figure is the sum of the transmissivity of model layers 2, 3, and 4, which correspond to the principal unconsolidated aquifer in that model. From this comparison, it can be seen that the transmissivity used in the 2008 UBBRND model is similar to the transmissivity calculated through the process previously described.

Figure 2-7 –Hydraulic Conductivity (in feet/day)

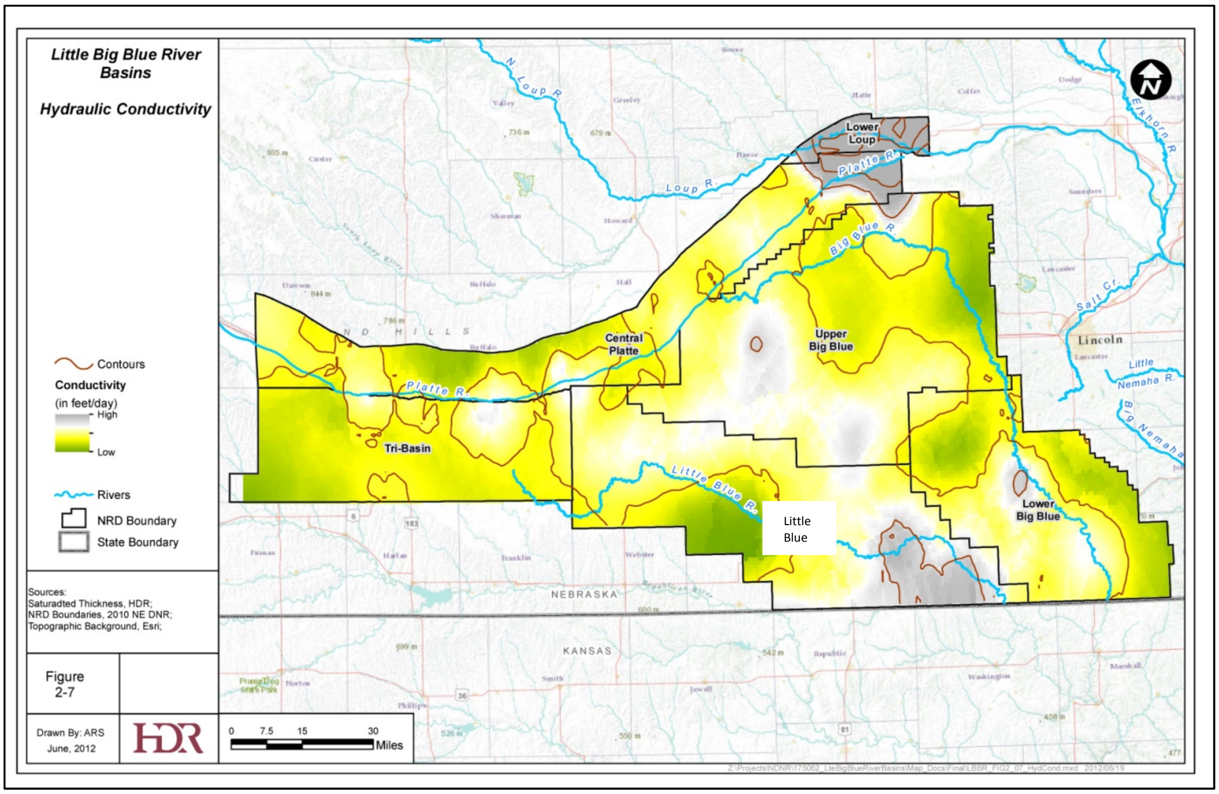


Figure 2-8 –Aquifer Saturated Thickness (in feet)

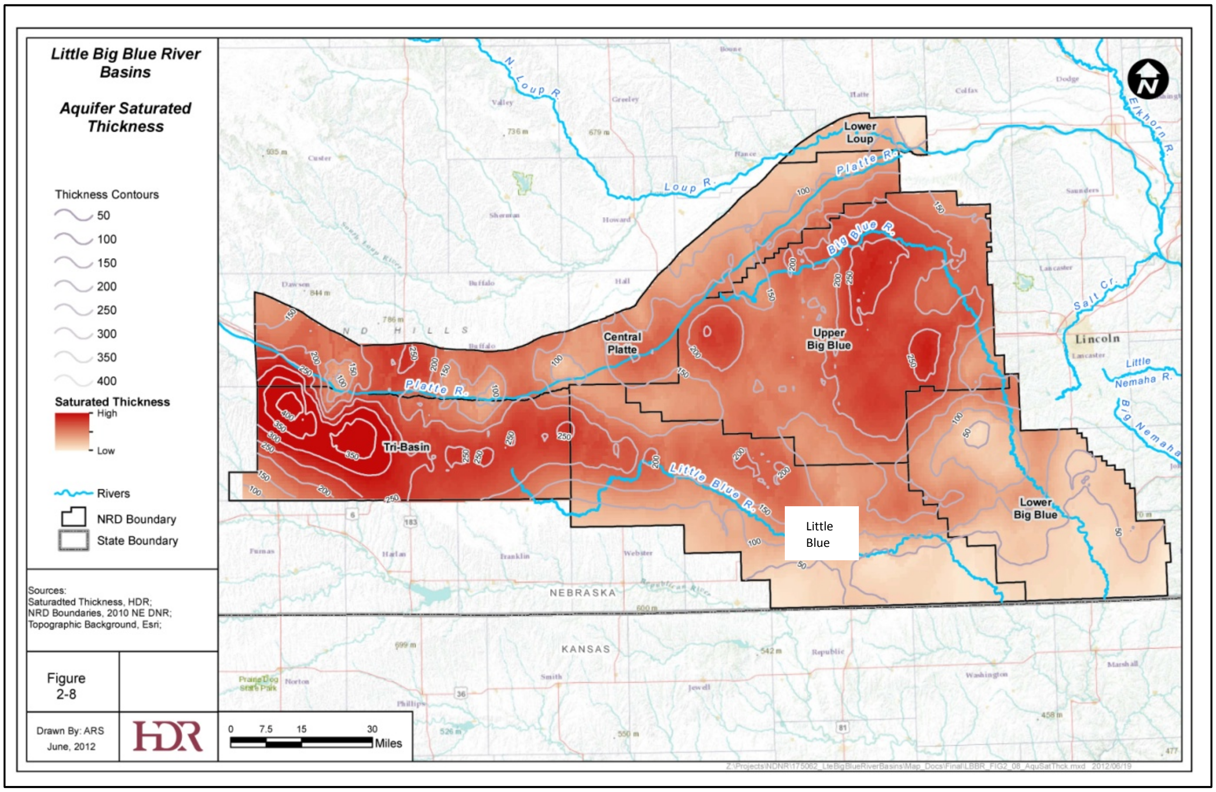


Figure 2-9a –Aquifer Transmissivity (in ft2/day)

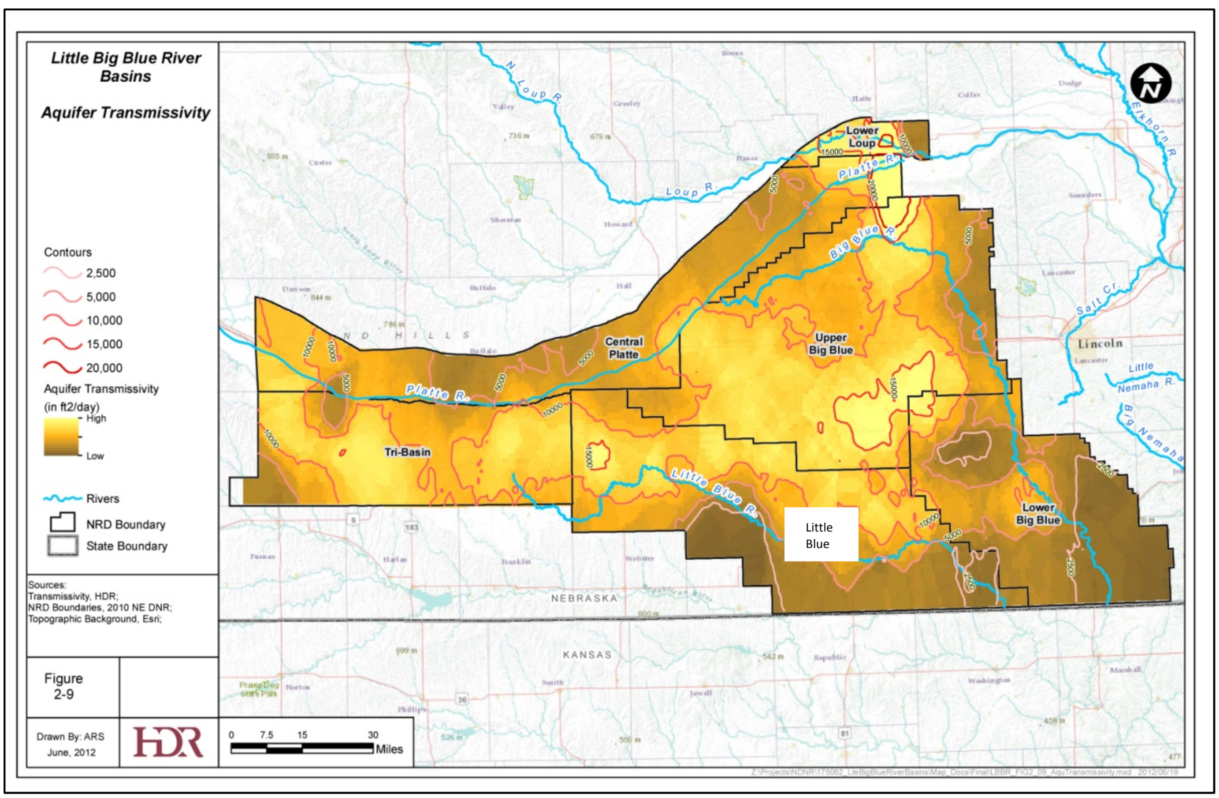
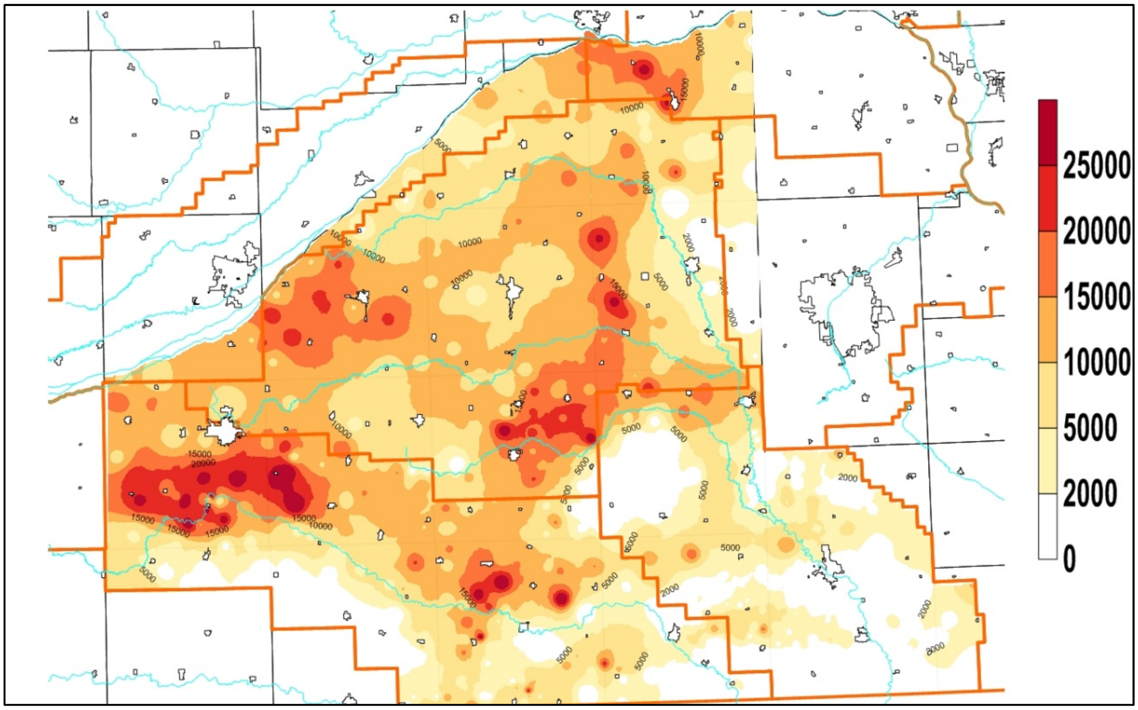


Figure 2-9b –Aquifer Transmissivity from UBBNRD Model (in ft2/day)



2.5 Streambed Conductance

Characterization of degree of interconnection between a stream and an aquifer requires knowledge of streambed conductance parameter. The following data sources are available to help define and calibrate the streambed conductance term in the groundwater model of the Basin.

2.5.1 Streambed Sampling

Streambed conductivity sampling within the Basin has been conducted as part of other groundwater studies. The objective of this sampling is to collect information on the thickness and vertical hydraulic conductivity of the streambed sediments, which are both important parameters in defining the degree of stream-aquifer connections. Sediment and soil samples are collected using direct-push techniques. The methods used in these investigations generally consist of performing an electrical conductivity log of streambed sediments, coring streambed/aquifer sediments, conducting in-situ permeameter tests of the shallow sediments, and performing laboratory permeameter tests on sediment cores collected from deeper sediments. Sediment and soil samples are collected using direct-push techniques.

The primary objective of these tests is to develop estimates of the vertical hydraulic conductivity (K_v) of the streambed. In shallow sediments (generally less than 5 feet), in-situ permeameter tests were conducted to determine the hydraulic conductivity of streambed in the upper part of the channel sediments. In deeper sediments, soil cores were collected using the Geoprobe™ direct-push technique. These soil cores were analyzed in a laboratory, using falling or constant head methods, for determination of the vertical hydraulic conductivity. The following studies have been performed and are available for use in the construction and calibration of the groundwater flow model:

- Determination of Streambed Hydraulic Properties in Tributaries of the Platte River between Gothenburg and Alda in Central Nebraska (Xun-Hong Chen, 2011).
- Determination of Streambed Hydraulic Properties in Tributaries of the Platte River Between Columbus and Alda in South-Central to Eastern Nebraska (Xun-Hong Chen, 2011).

The studies listed above focused on collection of streambed sampling data from the Platte River. In addition to these studies, 19 streambed locations from major rivers and tributaries located within the Basin were tested as part of the UBBNRD 2008 modeling effort. The locations of these tests are shown on Figure 2-10 and the results are summarized in Table 2-2.

Figure 2-10 –Location of Streambed Conductivity Tests Performed in Blue Basin

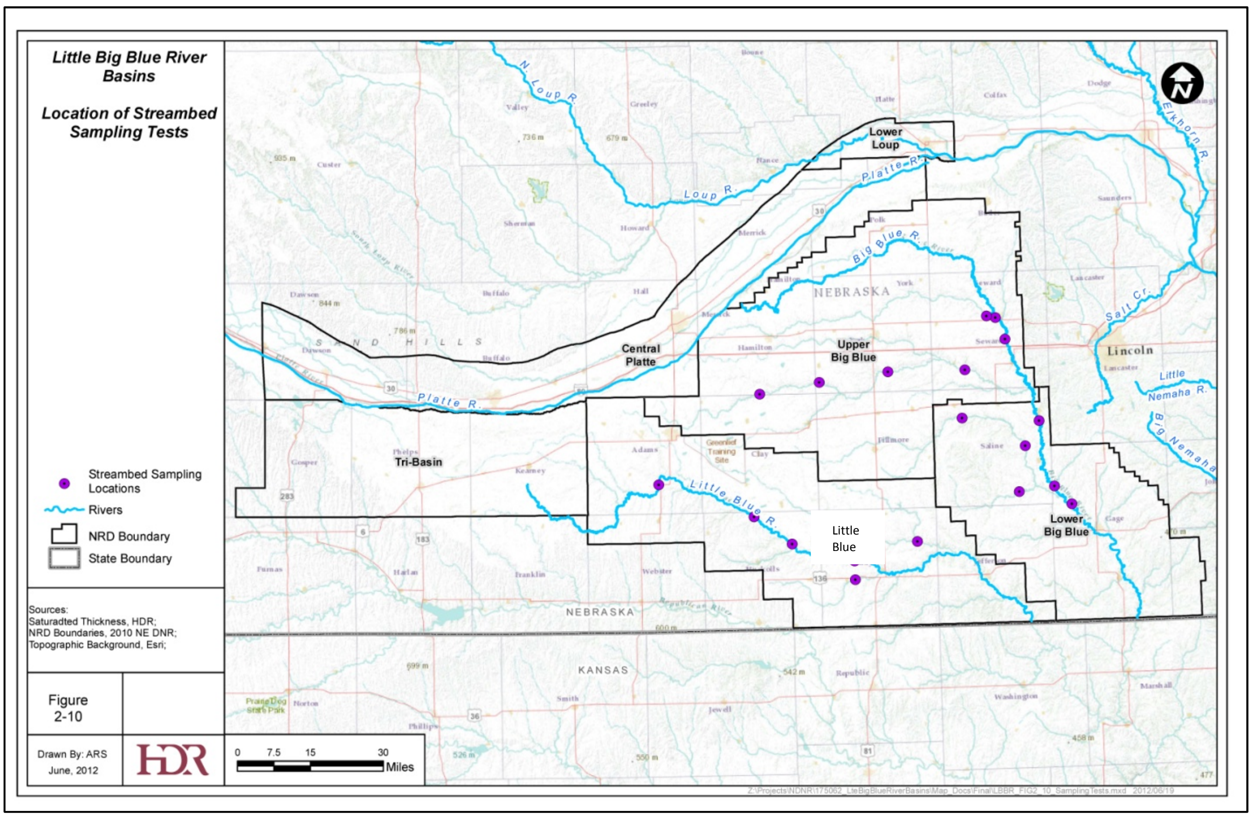


Table 2.2 –Summary of Streambed Conductivity Tests Performed in Blue Basin

Site_Name	Legal Location	Channel Width (feet)	Bed Thickness (feet)	Streambed Kv (feet)	Streambed Conductance (feet)
Little Blue River near Ayr	T5N, R10W, Northern Border of Section 4	40	28	0.0090	0.0130
West Fork, near Henderson	T9N, R4W, SE of Section 19	17	10	0.0317	0.0531
West Fork, near Beaver Crossing	T9N, R2E, southern border of Section 7	39	13	0.0259	0.0780
West Fork, near McCool Junction	T9N, R2W, Se of Section 9	26	35	0.0316	0.0238
Big Blue River, near Ruby	T10N, R3E, SW of Section 10	45	40	0.0076	0.0085
Big Blue River, west of Seward	T11N, R3E, Center of Section 20	35	30	0.0059	0.0059
Lincoln Creek	T11N, R2E, Northern Border of Section 24	30	45	0.0084	0.0056
West Fork, south of Aurora	T9N, R6W, SE of Section 21	10	12	0.0095	0.0079
Little Blue River near Deweese	T4N, R7W, SW of Section 2	61	45	0.0032	0.0040
Little Blue River near Oak	T3N, R5W, SW of Section 6	58	60	0.0114	0.0110
Little Blue River near Hebron	T3N, R3W, NE of Section 30	55	15	0.0187	0.0690
Spring Creek near Deshler	T2N, R3W, NE of Section 18	5	9	0.0168	0.0090
Big Sandy Creek near Alex	T3N, R1W, SE of Section 5	37	20	0.0848	0.1560
Turkey Creek, West	T8N, R1E, SE of Section 36	11	28	0.1840	0.0724
Turkey Creek, South	T7N, R4E, SE of Section 31	22	25	0.0264	0.0233
Big Blue River, near DeWitt	T5N, R5E, Center of Section 18	67	15	0.0353	0.1580
Big Blue River, Beatrice Well Field	T4N, R5E, NW of Section 2	88	20	0.1260	0.5550
Big Blue River, south of Crete	T7N, R4E, SE of Section 3	52	30	0.1000	0.1740
Swan Creek	T5N, R3E, NW of Section 24	32	23	0.1231	0.1710

The K_v values obtained from the streambed sampling within the Basin are low, with ranging from 0.003 ft/day to 0.18 ft/day, with an average value of 0.045 ft/day. The streambed sampling data presented in the studies referenced above could be used in the groundwater model as a method to provide a relative comparison of the permeability of streambeds within the study area.

2.5.2 Streambed Conductivity - Elkhorn Loup Model

The calibrated streambed hydraulic conductivity values developed by the USGS for the Elkhorn Loup Model (USGS, 2010) ranged from 0.1 to 6.0 ft/day. Streambed conductivity values for large rivers such as the Loup and the Elkhorn were generally more than 1 ft/day. These values were obtained through the model calibration process. The procedure to define these values is summarized below (from USGS, 2010):

> "Streambed conductance was calculated separately for each stream cell using width, length, streambed hydraulic conductivity, and thickness terms. Width: determined from low-flow streamflow measurements. Length: calculated using GIS. Streambed hydraulic conductivity: assigned using aquifer hydraulic conductivity adjacent to simulated stream and then adjusted during the manual trial-and-error calibration to improve simulation results. Streambed thickness (m) equaled one(1) foot. "

2.5.3 Streambed Leakance from Aquifer Tests

A nonlinear regression method was used to calculate the hydraulic parameters of a stream-aquifer system using a pumping test performed within the City of Kearney, NE well field. Although Kearney, NE may be outside of the boundaries of the groundwater flow model, the analysis of this test could provide valuable information for the streambed conditions within the Platte River. This method is applicable to other rivers, provided additional pumping tests with monitoring wells are identified.

The results of this study are presented in *Sensitivity Analysis and Determination of Streambed Leakance and Aquifer Hydraulic Properties* (Xun -Hong Chen, 2003). The well field is located on an island of the Platte River, which is a braided sand bar of the river. Streambed sediments of the channels are characterized as sand and gravel with local silt and clay layers. The pumping test was conducted by the Layne-Western Company (1983) and was re-interpreted in an attempt to better understand the stream aquifer interaction in this area. Four observation wells were available for this analysis.

The results of this study indicated the streambed leakance (K_V/m) ranged from 0.5 to 4.5 days^{-1} (Xun - Hong Chen, 2003). These values correspond to a hydraulic resistance (m/K_V) value of 0.2 to 2 days. These values are in general agreement with guidance from Dr. Mary P. Anderson (Anderson, 2007), who provided some “rules of thumb” in selecting the flow resistance of m/K_V, as follows:

- River with sandy bottom – m/K_V - 1 day or less;
- Small stream with silty bottom – m/K_V should be 1 - 10 days.

2.5.4 Streambed Conductivity Recommendations

The streambed sampling data presented in Section 2.5.1 produced conductance values that are significantly smaller than is customarily used in groundwater modeling studies. These values can likely be used to provide relative comparisons of the permeability of streambeds within the study area. However, because the hydraulic conductivity values obtained from these tests are extremely low, it is recommended that streambed conductivity values be developed through the model calibration process. The methodology adopted by the USGS to calibrate the Elkhorn Loup model is consistent with other modeling studies.

3.0 Summary and Conclusions

Several data sources were presented within this Technical Memorandum that can be used to construct or calibrate a groundwater flow model of the Blue River Basin. The data sources and likely uses include:

- Test hole data that was used to develop a starting point for the transmissivity/hydraulic conductivity field
- Mean annual recharge to groundwater that can be used to assign recharge rates for the steady state calibration.
- Predevelopment water level data to perform a steady state calibration.
- Decadal water level changes that can be used to perform a transient water level calibration.
- Long term streamflow data that can be used as part of the transient calibration.
- Streambed hydraulic conductivity testing that can be used as a relative guide of streambed conductivity contrasts within the Basin.
- An aquifer test near Kearney that can be used as a basis for assigning streambed conductivity values for the Platte River.
- Modeled streambed conductivity values from a USGS modeling study with a similar objective.

The datasets listed above will be included in the Model Development Plan. The Model Development Plan will provide additional detail on how these datasets will be used to construct and calibrate the Blue River Basin groundwater flow model and will include general recommendations for the model construction and calibration strategies.

4.0 References

Anderson, M.P. 2007. Week 9 Boundary Conditions Lecture. Online Data File. Accessesed 8/11/2012. http://www.geology.wisc.edu/~andy/g724/

Burbach, 2006. University of Nebraska-Lincoln Statewide Groundwater-Level Monitoring Program. Prepared by Mark E. Burbach, PhD Assistant Geoscientist, UNL.

Layne-Western Company, 1983. Hydrologic Engineering Investigation,City of Kearney, Kearney, Nebraska.

Summerside, S. A., Olafsen-Lackey, S., Goeke, J., Myers, W. 2005. Mapping of Aquifer Properties - Transmissivity and Specific Yield - for Selected River Basins in Central and Eastern Nebraska (OFR-71)

Szilagyi, J. Harvey, F.E. Ayers, J.F. 2003. Regional Estimation of Base Recharge to Ground Water Using Water Balance and a Base-Flow Index. Ground Water, Vol. 41, No. 4, p 504-513.

USGS, 2010. Simulation of Groundwater Flow and Effects of Groundwater Irrigation on Stream Base Flow in the Elkhorn and Loup River Basins, Nebraska, 1895–2055—Phase Two. Scientific Investigations Report 2010–5149.

Xun-Hong Chen, 2003. Sensitivity Analysis and Determination of Streambed Leakance and Aquifer Hydraulic Properties. Journal of Hydrology 284 (2003) 270–284.

Xun-Hong Chen, 2011.Determination of Streambed Hydraulic Properties in Tributaries of the Platte River between Columbus and Alda in South-Central to Eastern Nebraska. A Collaborative Study between the School of Natural Resources, University of Nebraska-Lincoln and the Upper Big Blue Natural Resources District, York, Nebraska.

Xun-Hong Chen, 2011. Determination of Streambed Hydraulic Properties in Tributaries of the Platte River between Gothenburg and Alda in Central Nebraska. A Collaborative Study between the School of Natural Resources, University of Nebraska-Lincoln and the Tri-Basin Natural Resources District, York, Nebraska.

Appendix C – Geologic Cross Sections

Appendix C contains geologic cross sections from within the Basin study area. These cross sections have been developed by others.

Little Blue NRD

Little Blue
Natural Resources District

Geologoic Cross Sections

Cross Sections

Test Holes and Select DNR Wells

Cross Section Lines

Extent of Glacial Deposits (USGS)

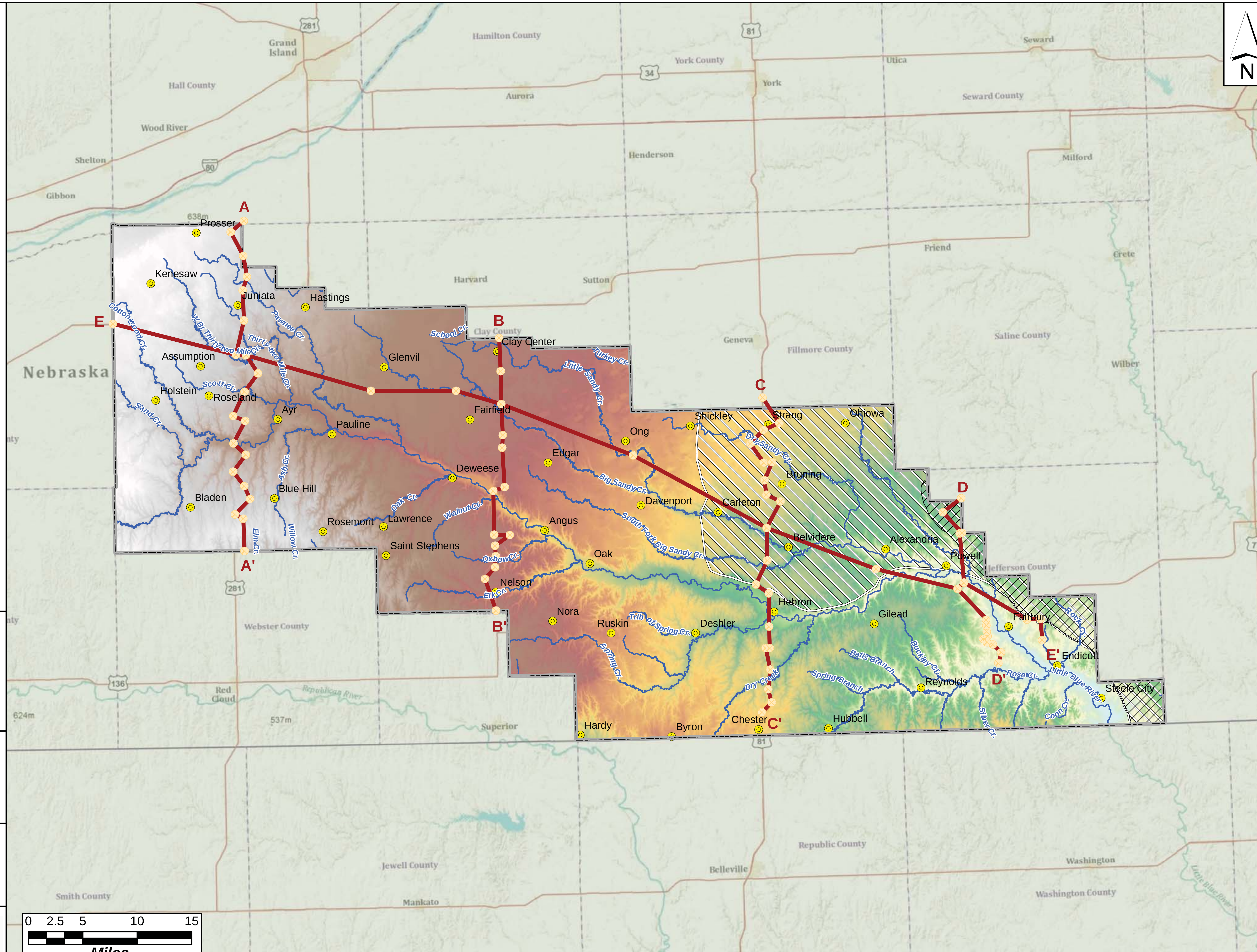
Extent of Glacial Deposits (NDNR)

Base Data Legend

NRD Boundary

Cities/Villages

Streams



Sources:
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Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

Figure: 7.1

Project: R100440

Drawn By: MS

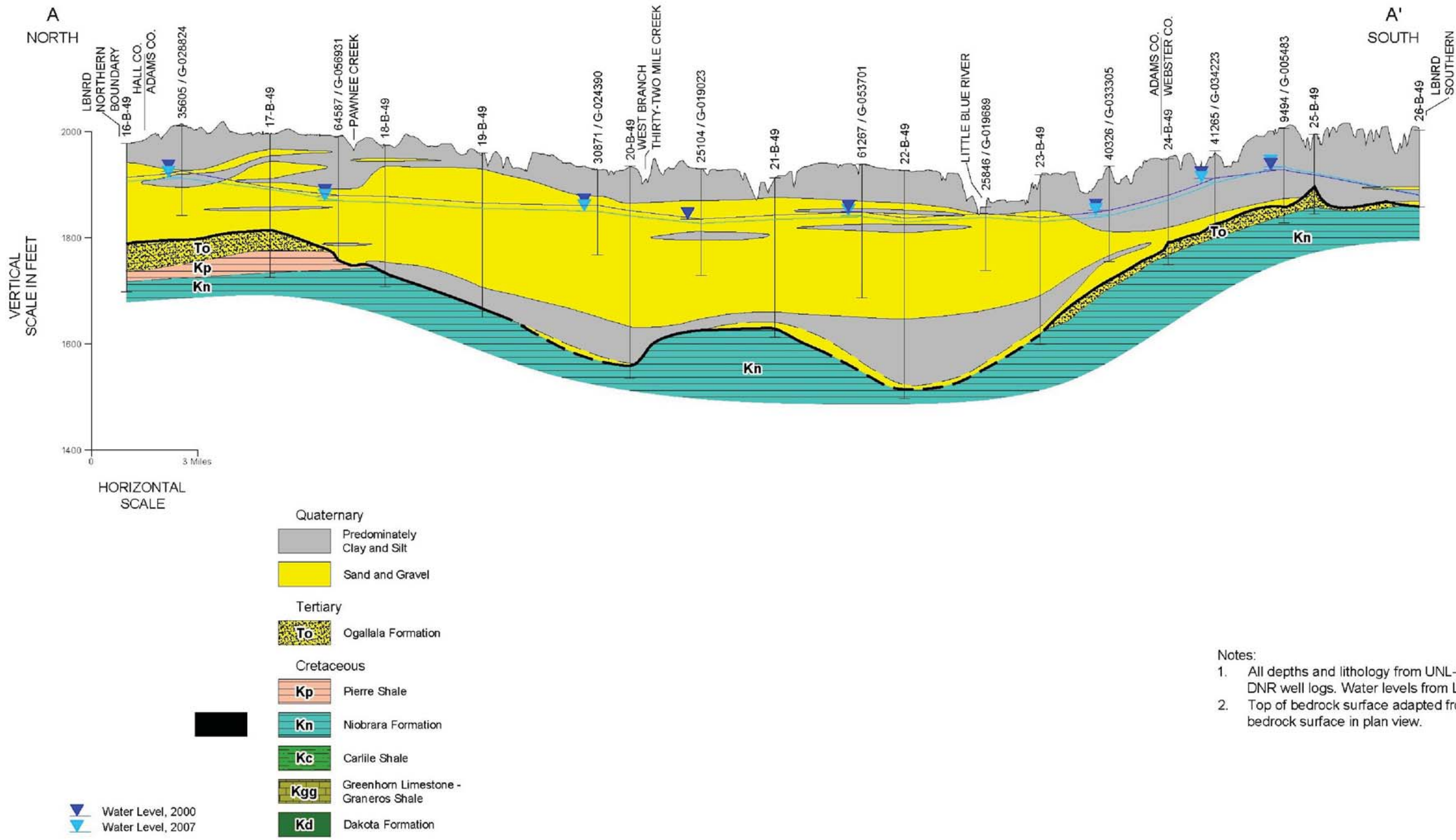
Date: 7/13/2011

LBG

JEO Consulting Group, Inc.

Little Blue Natural Resources District

Geologic Cross Section Section A - A'



Notes:
1. All depths and lithology from UNL-CSD test holes and DNR well logs. Water levels from LBNRD monitoring wells.
2. Top of bedrock surface adapted from the interpolated bedrock surface in plan view.

Sources:

NRD Boundary, 2006, NE DNR:
Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

Figure: 8.1

Project: R100440

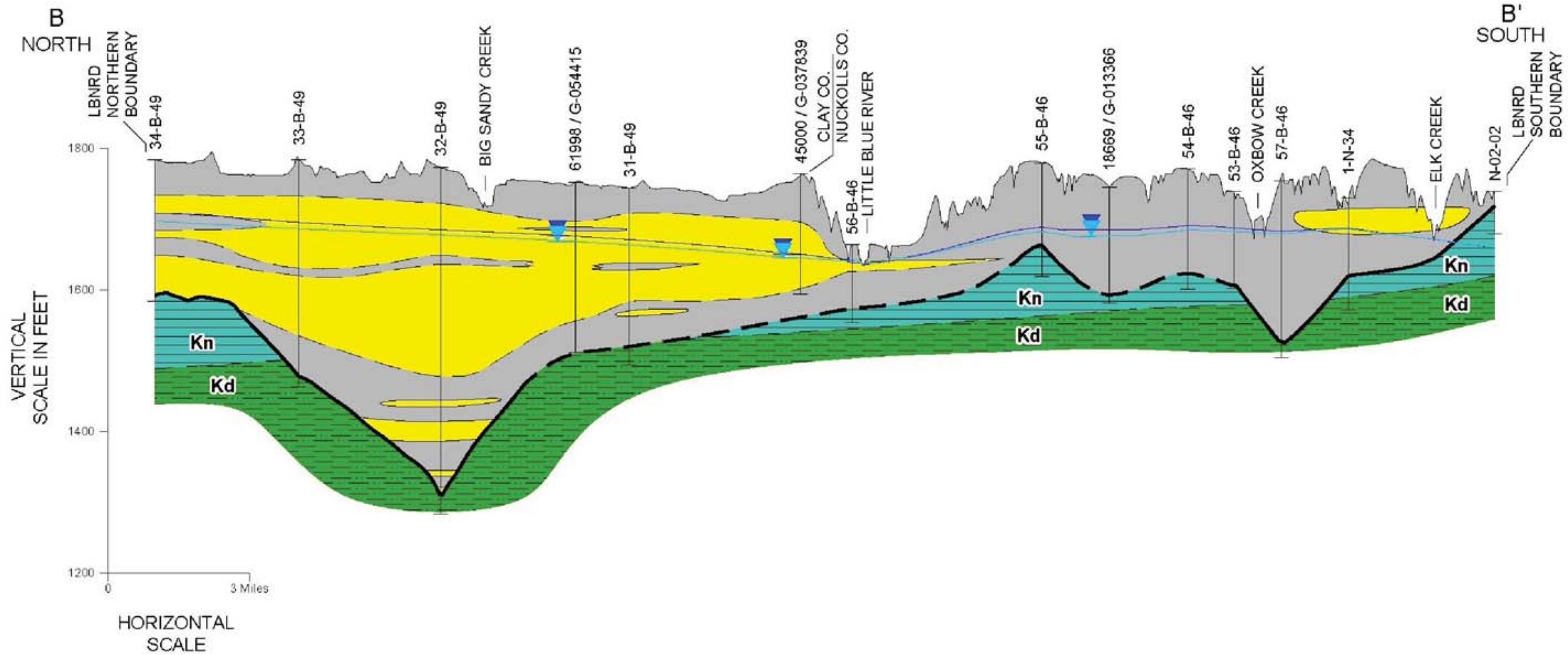
Drawn By: MS

Date: 6/20/2011

JEO Consulting Group, Inc.

Little Blue
Natural Resources District

Geologic Cross Section
Section B - B'



Quaternary
- Predominately Clay and Silt
- Sand and Gravel

Tertiary
- To — Ogallala Formation

Cretaceous
- Kp — Pierre Shale
- Kn — Niobrara Formation
- Kc — Carlile Shale
- Kgg — Greenhorn Limestone - Graneros Shale
- Kd — Dakota Formation

- Water Level, 2000
- Water Level, 2007

Notes:
1. All depths and lithology from UNL-CSD test holes and DNR well logs. Water levels from LBNRD monitoring wells.
2. Top of bedrock surface adapted from the interpolated bedrock surface in plan view.

Sources:
NRD Boundary, 2006, NE DNR:
Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

Figure: 9.1

Project: R100440

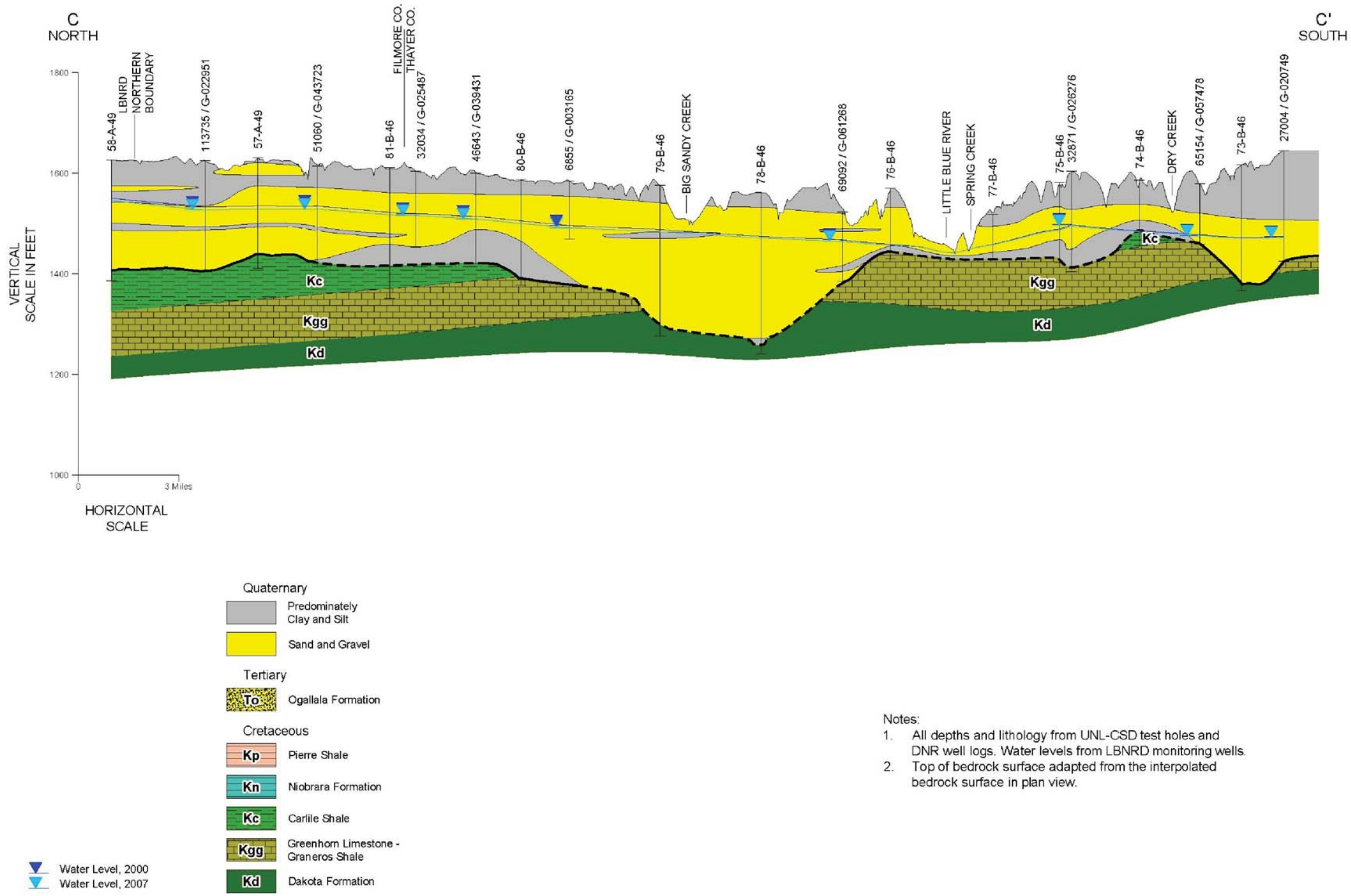
Drawn By: MS

Date: 6/20/2011

JEO Consulting Group, Inc.

Little Blue
Natural Resources District

Geologic Cross Section
Section C - C'



Notes:
1. All depths and lithology from UNL-CSD test holes and DNR well logs. Water levels from LBNRD monitoring wells.
2. Top of bedrock surface adapted from the interpolated bedrock surface in plan view.

Sources:
NRD Boundary, 2006, NE DNR:
Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

Figure: 10.1

Project: R100440

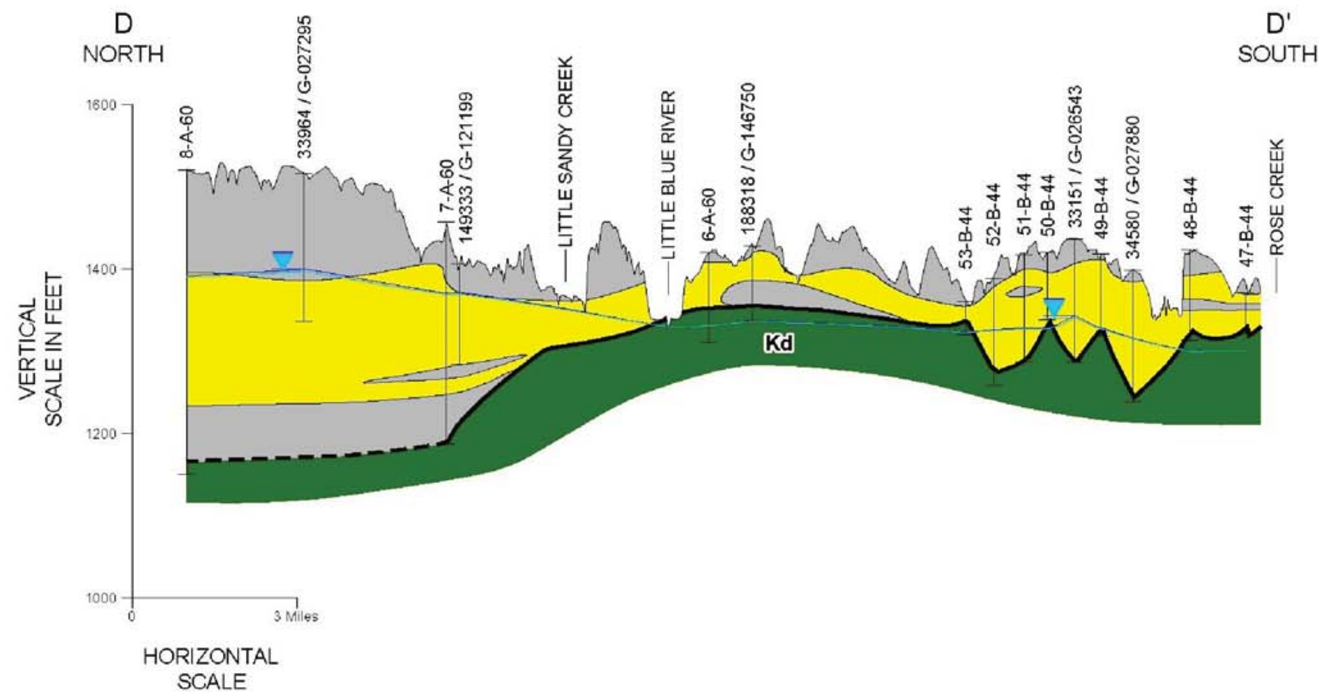
Drawn By: MS

Date: 6/20/2011

JEO Consulting Group, Inc.

Little Blue Natural Resources District

Geologic Cross Section Section D - D'



Quaternary

Predominately Clay and Silt

Sand and Gravel

Tertiary

To Ogallala Formation

Cretaceous

Kp Pierre Shale

Kn Niobrara Formation

Kc Carlile Shale

Kgg Greenhorn Limestone - Graneros Shale

Kd Dakota Formation

Water Level, 2000

Water Level, 2007

Notes:

1. All depths and lithology from UNL-CSD test holes and DNR well logs. Water levels from LBNRD monitoring wells.
2. Top of bedrock surface adapted from the interpolated bedrock surface in plan view.

Sources:

NRD Boundary, 2006, NE DNR:
Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

Figure: 11.1

Project: R100440

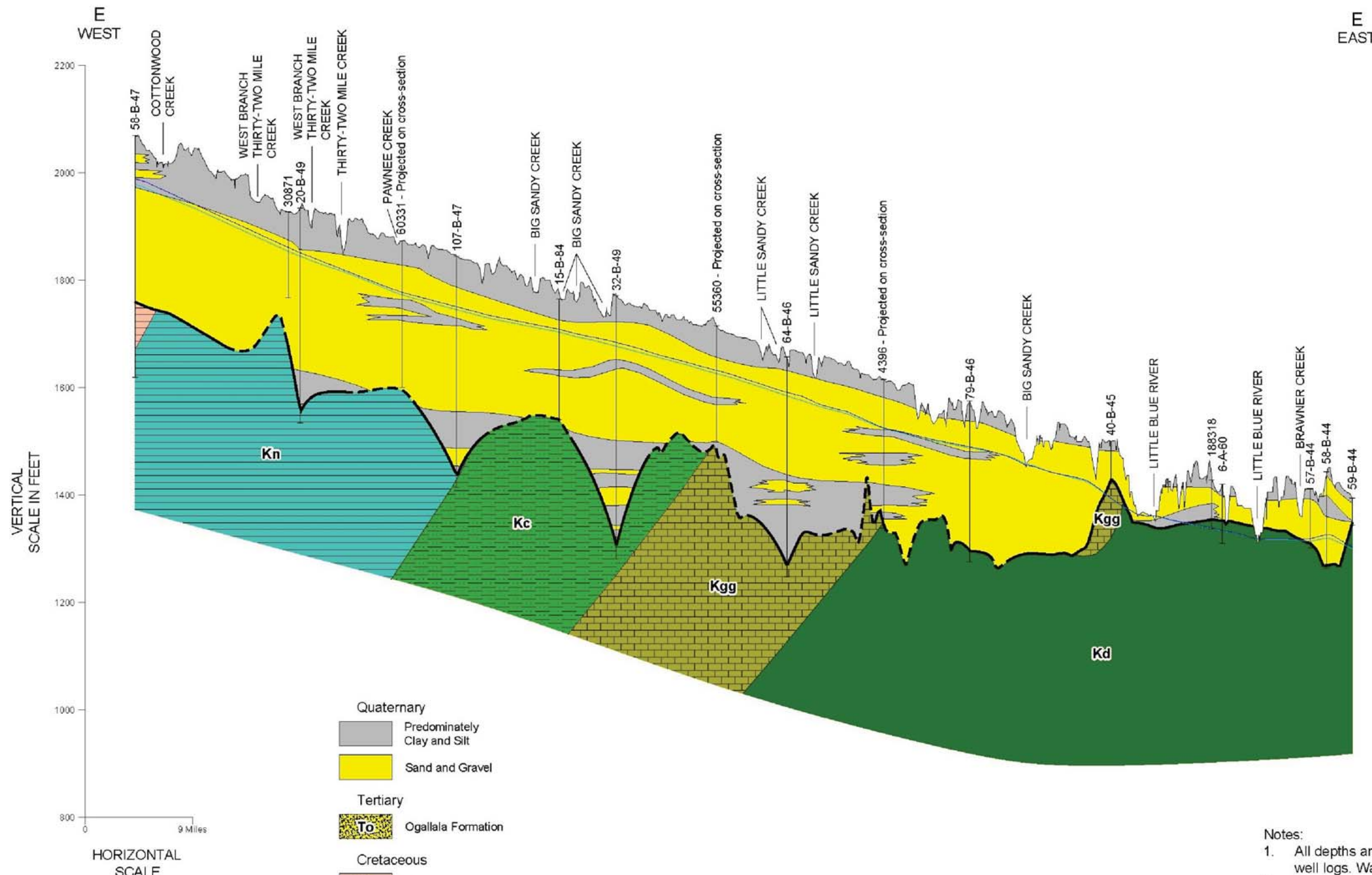
Drawn By: MS

Date: 6/20/2011

JEO Consulting Group, Inc.

Little Blue Natural Resources District

Geologic Cross Section Section E - E'



Quaternary

- Predominately Clay and Silt
- Sand and Gravel

Tertiary

- To — Ogallala Formation

Cretaceous

- Kp — Pierre Shale
- Kn — Niobrara Formation
- Kc — Carlile Shale
- Kgg — Greenhorn Limestone - Graneros Shale
- Kd — Dakota Formation

Water Level, 2000
Water Level, 2007

Notes:
1. All depths and lithology from UNL-CSD test holes and NEDNR well logs. Water levels from LBNRD monitoring wells.
2. Grade interpolated from NEDNR Lidar DEM data.
3. Top of bedrock surface adapted from the interpolated bedrock surface in plan view.

Sources:
NRD Boundary, 2006, NE DNR:
Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

Figure: 12.1

Project: R100440

Drawn By: MS

Date: 6/20/2011

JEO Consulting Group, Inc.

Little Blue Natural Resources District

Geologic Cross Section

Block Diagram Area

Nebraska Bedrock

Tertiary

To Ogallala

Cretaceous

Kp Pierre Shale

Kn Niobrara Formation

Kc Carlile Shale

Kgg Greenhorn-Graneros

Dakota Group

Permian

P Chase Group

Base Data Legend

NRD Boundary

Cities/Villages

Streams

Townships

Sources:
NRD Boundary, 2006, NE DNR:
Perennial Streams, 2006, NE DNR:
City/Village Locations, 2006, NE DNR:
Townships: 2006, NE DNR:
Sections, 2006 NE DNR
Topographic Data, 2010, ESRI:

Note:
Please see Appendix A: Metadata for additional information on data sources and methods used to create the data.

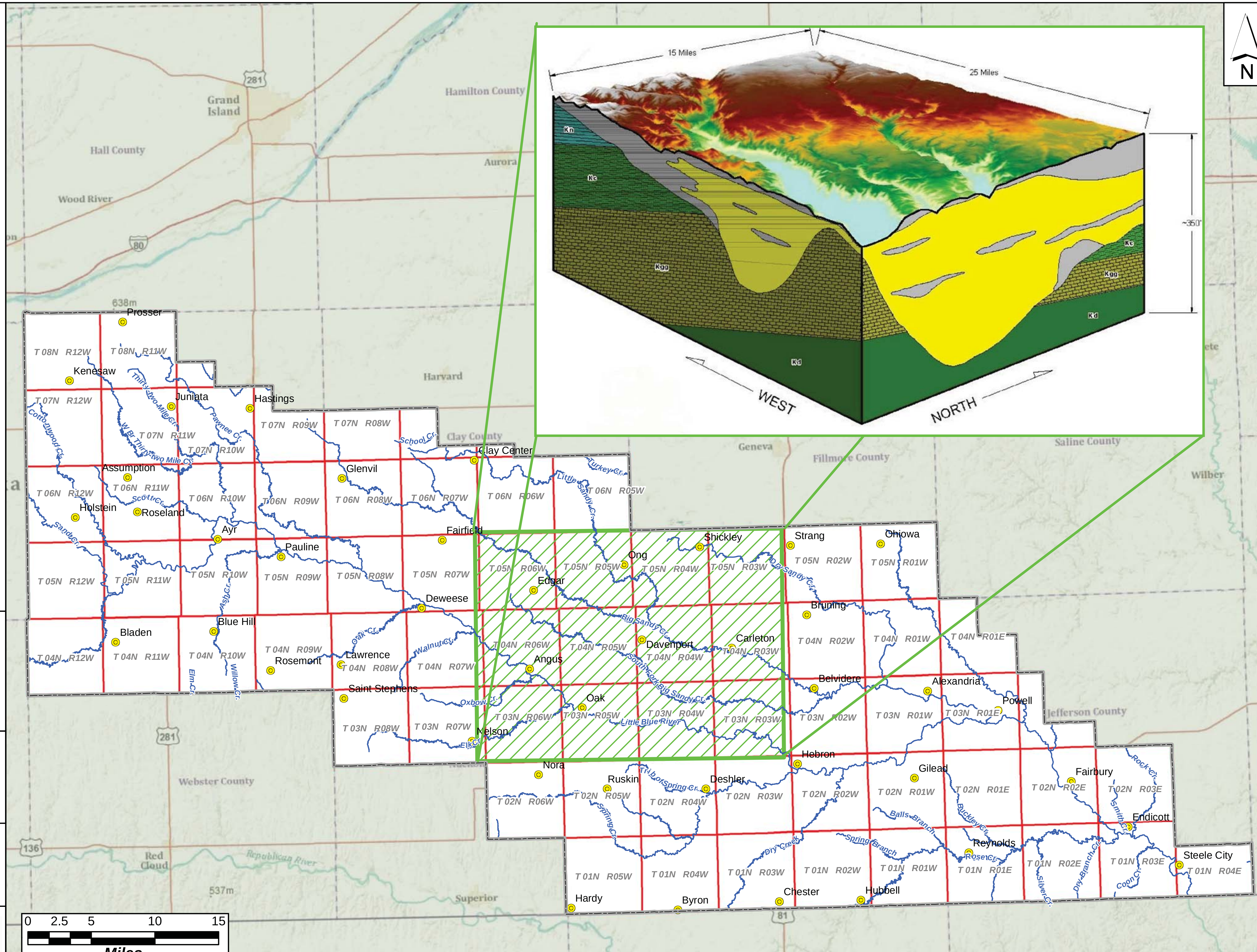
Figure: 13.1

Project: R100440

Drawn By: MS

Date: 6/20/2011

JEO Consulting Group, Inc.



Upper Big Blue NRD

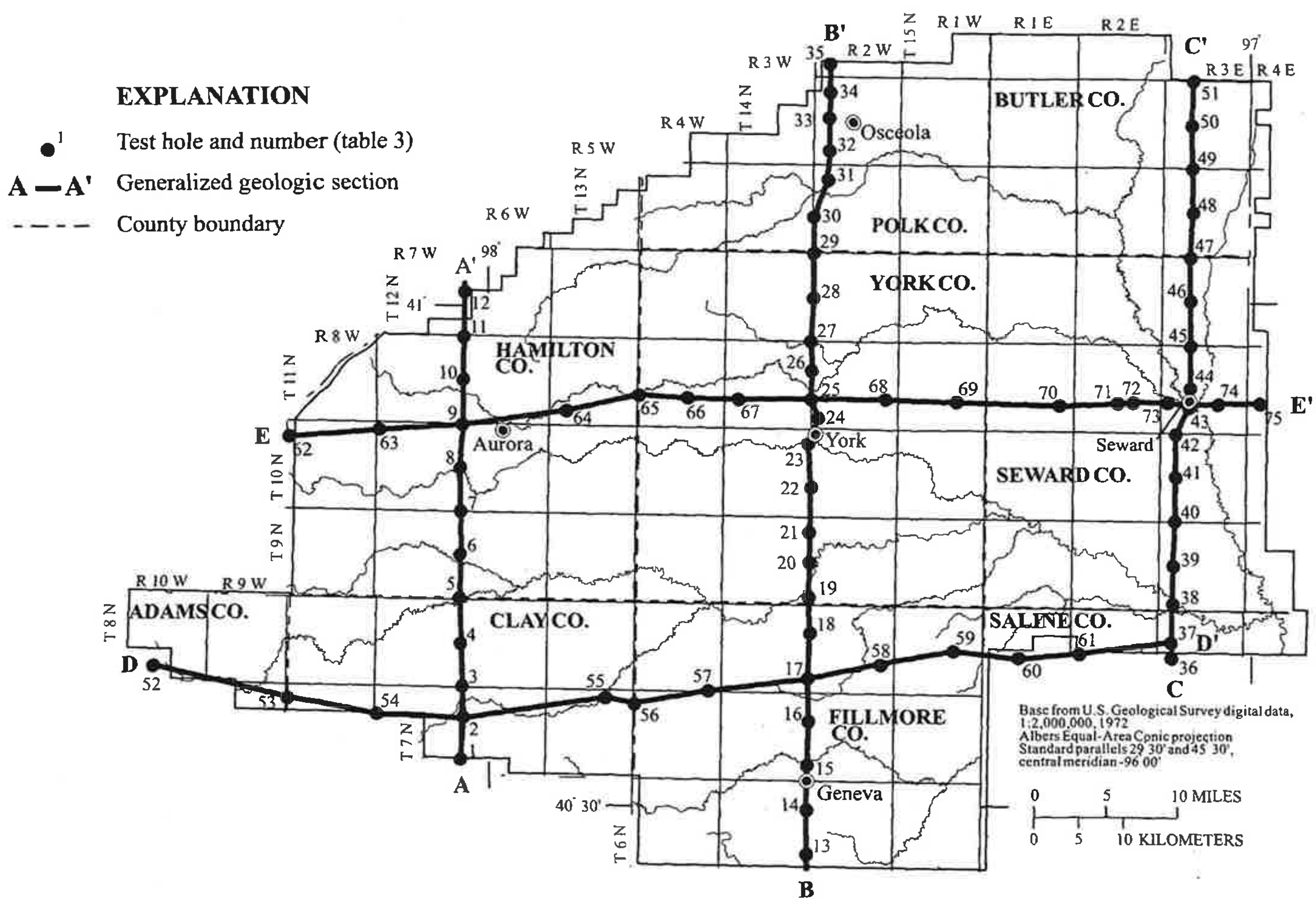


Figure 3. Locations of test holes and generalized geologic sections (figure 4).

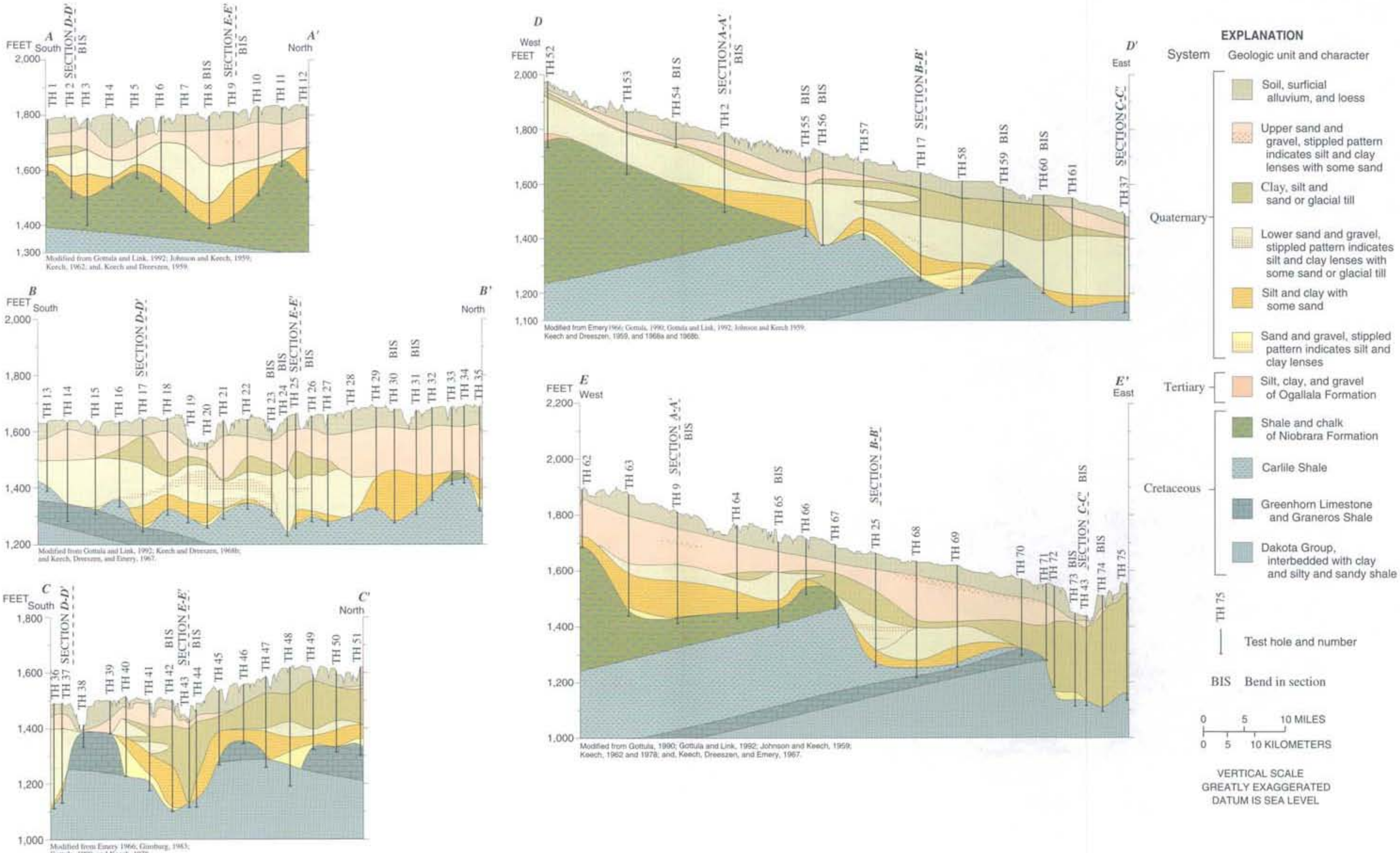
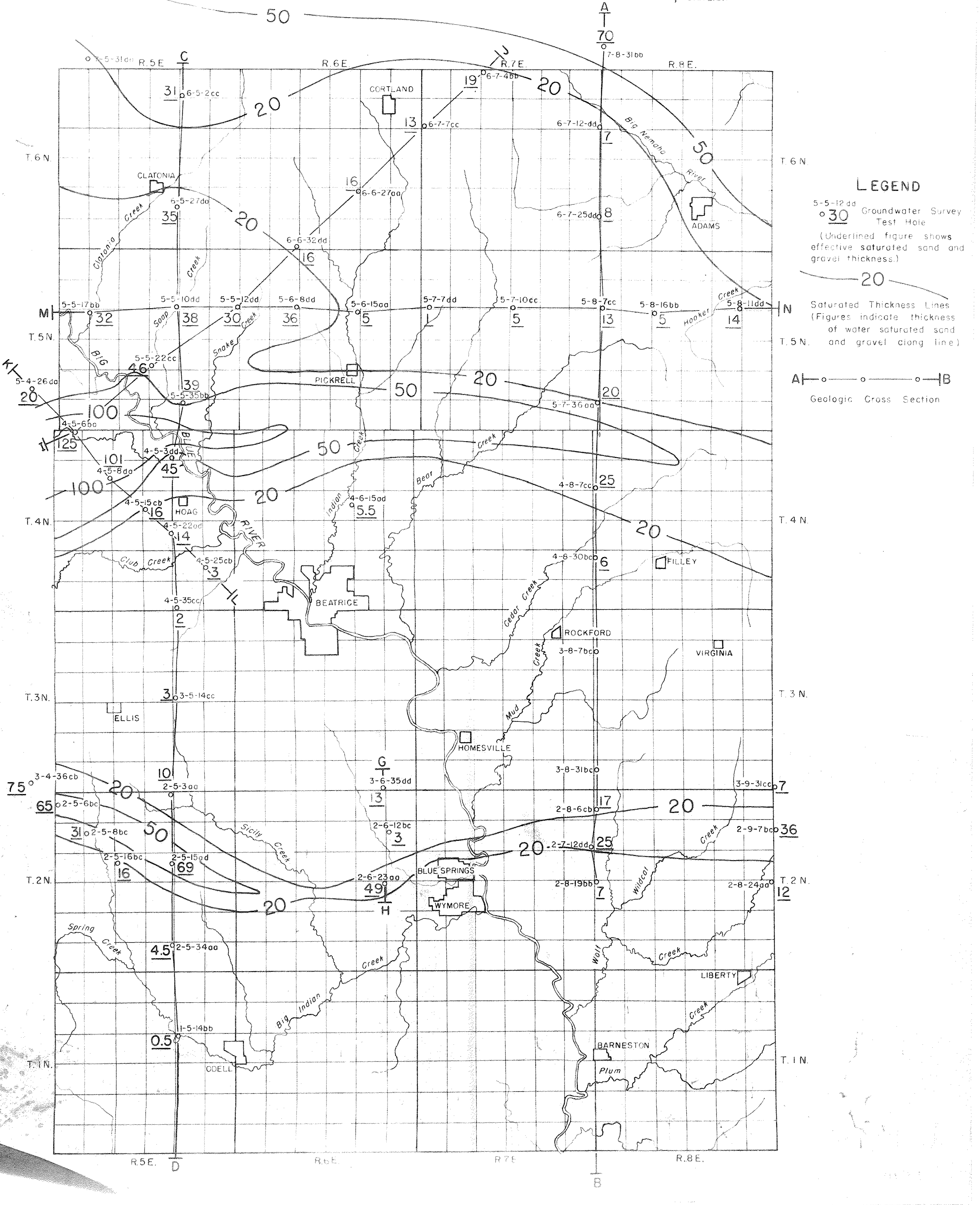


Figure 4. Generalized geologic sections *A-A'* through *E-E'* showing the principal geologic units transected by test holes, Upper Big Blue Natural Resources District, central Nebraska.

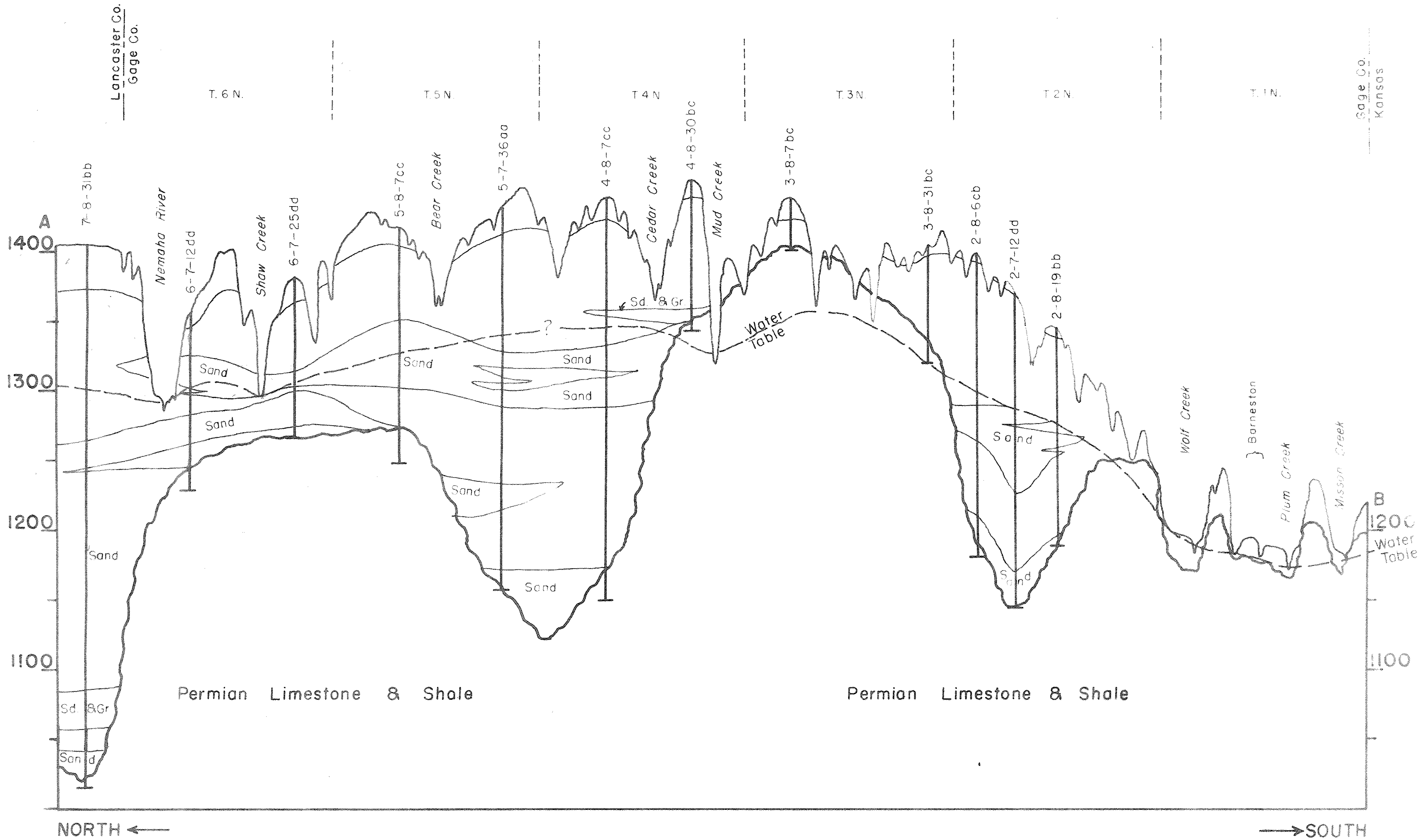
Gage County

Figure

Ground water map showing thickness of water saturated sand and gravel.
(Based on test drilling, Nebr. Water Survey & Ground Water Branch, U.S.G.S.)

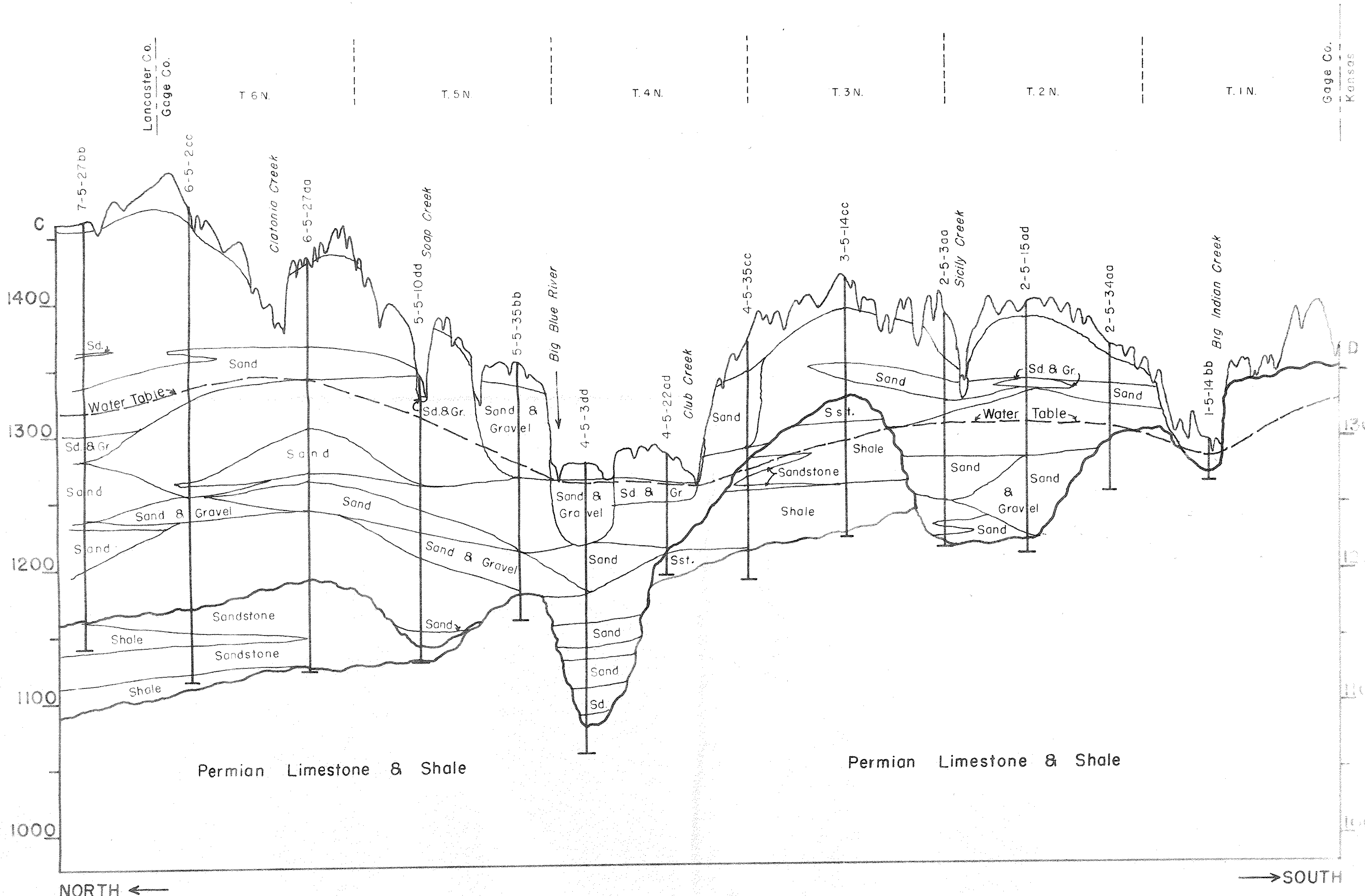


GAGE COUNTY



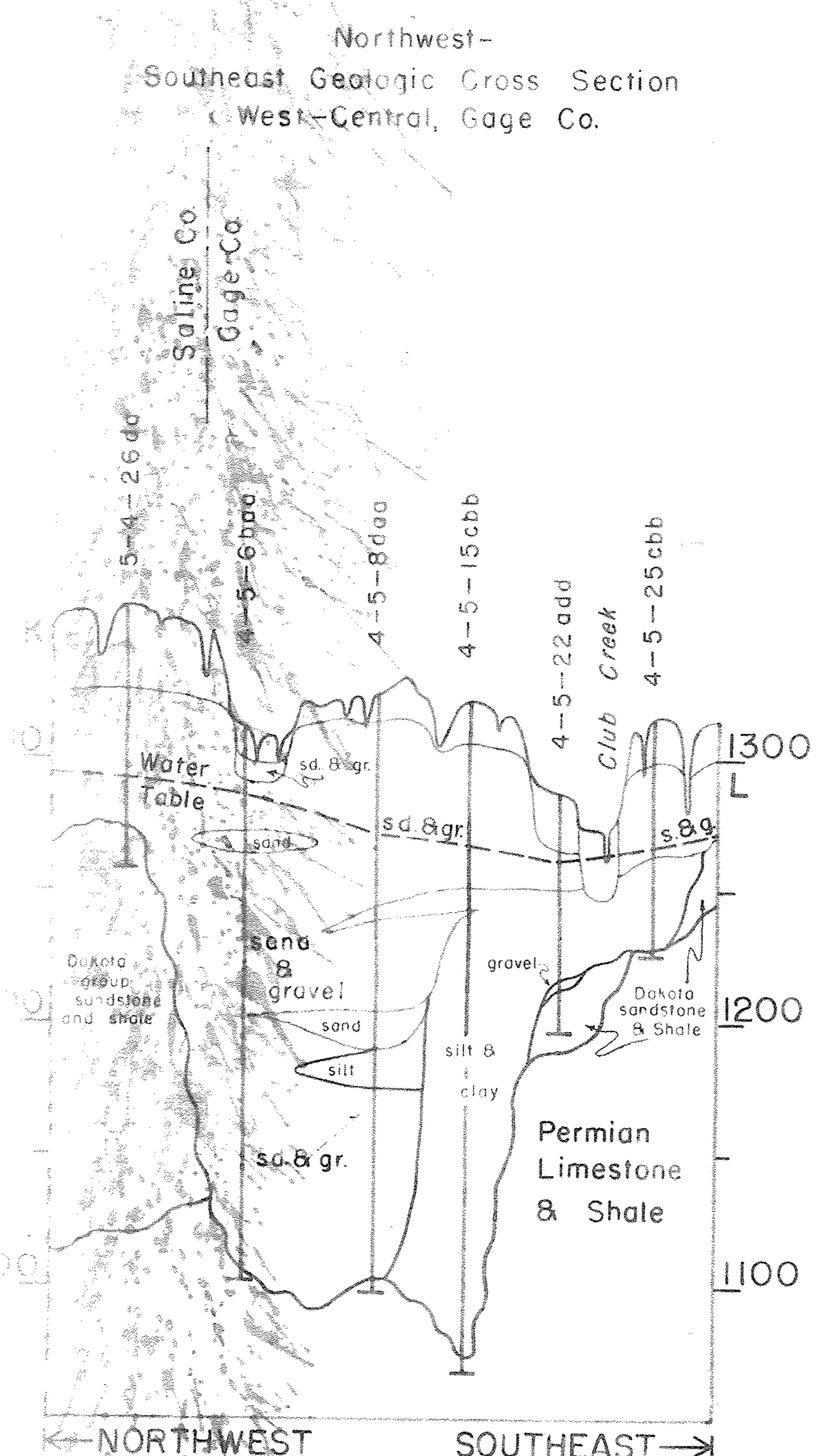
Lancaster Co.
Gage Co.
T. 6 N.
T. 5 N.
T. 4 N.
T. 3 N.
T. 2 N.
T. 1 N.
Gage Co.
Kansas
A
B
1400
1300
1200
1100
7-8-31bb
Nemaha River
6-7-12dd
Shaw Creek
6-7-25dd
5-8-7cc
Bear Creek
5-7-36aa
4-8-7cc
Cedar Creek
4-8-30bc
Mud Creek
3-8-7bc
3-8-31bc
2-8-6cb
2-7-12dd
2-8-19bb
Wolf Creek
Barneston
Plum Creek
Mission Creek
Sd. & Gr.
Sand
Water Table
Sd. &Gr
Permian Limestone & Shale
NORTH
SOUTH

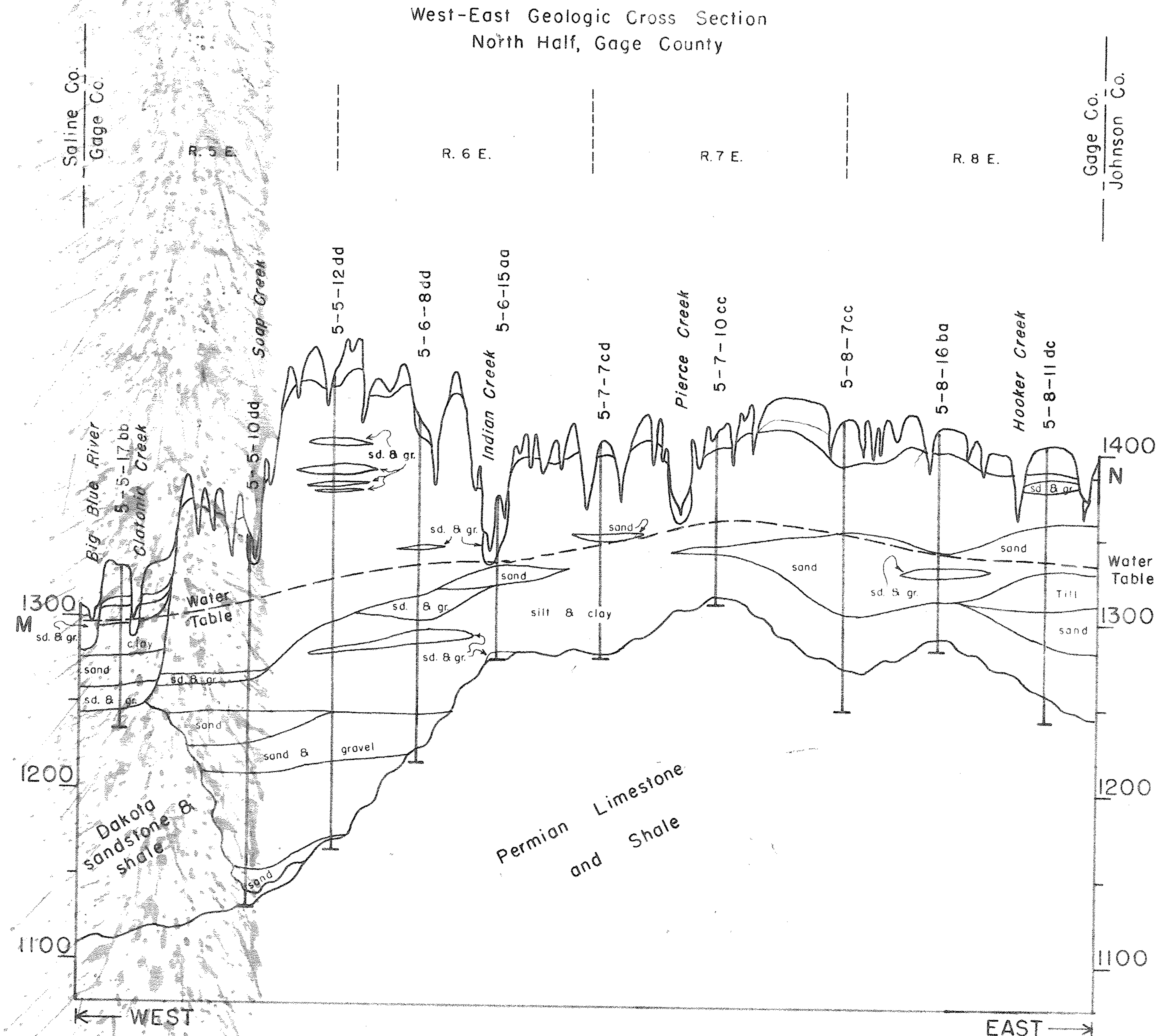
GAGE COUNTY



Lancaster Co.
Gage Co.
T. 6 N.
T. 5 N.
T. 4 N.
T. 3 N.
T. 2 N.
T. 1 N.
Gage Co.
Kansas
C
D
7-5-27bb
6-5-2cc
Clatonia Creek
6-5-27aa
5-5-10dd
Soap Creek
5-5-35bb
Big Blue River
4-5-3dd
4-5-22ad
Club Creek
4-5-35cc
3-5-14cc
2-5-3aa
Sicily Creek
2-5-15ad
2-5-34aa
1-5-14bb
Big Indian Creek
1400
1300
1200
1100
1000
Sd.
Sand
Water Table
Sd. & Gr.
Sand
Sand & Gravel
Sand
Sand
Sand
Sand & Gravel
Sd. & Gr.
Sand & Gravel
Sand & Gravel
Sd. & Gr
Sand
Sand
Sand
Sd.
Sst.
Sand
S st.
Shale
Sandstone
Shale
Sand
Sd. & Gr.
Water Table
Sand
Sand
Sand & Gravel
Sand
Sandstone
Shale
Sandstone
Shale
Sand
Permian Limestone & Shale
Permian Limestone & Shale
NORTH
SOUTH

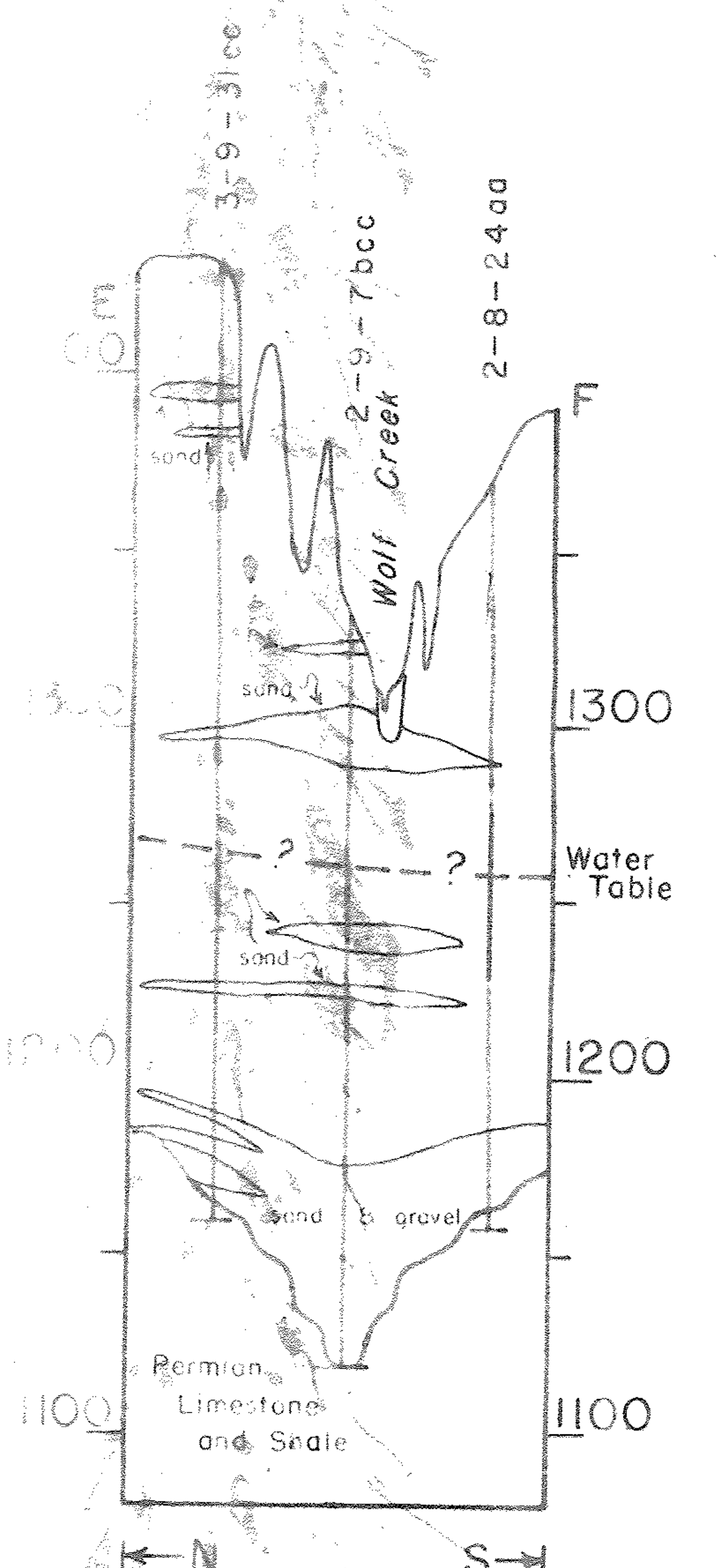
GAGE COUNTY


Northwest-
Southeast Geologic Cross Section
West-Central, Gage Co.
Saline Co.
Gage Co.
5-4-26dd
4-5-6bad
4-5-8daa
4-5-15cbb
4-5-22add
Club Creek
4-5-25cbb
Water Table
sd. & gr.
sand
sd.&gr.
s.&g.
sand & gravel
sand
silt
silt & clay
gravel
Dakota group sandstone and shale
Dakota sandstone & Shale
sd.& gr.
Permian Limestone & Shale
1300
L
1200
1100
NORTHWEST
SOUTHEAST

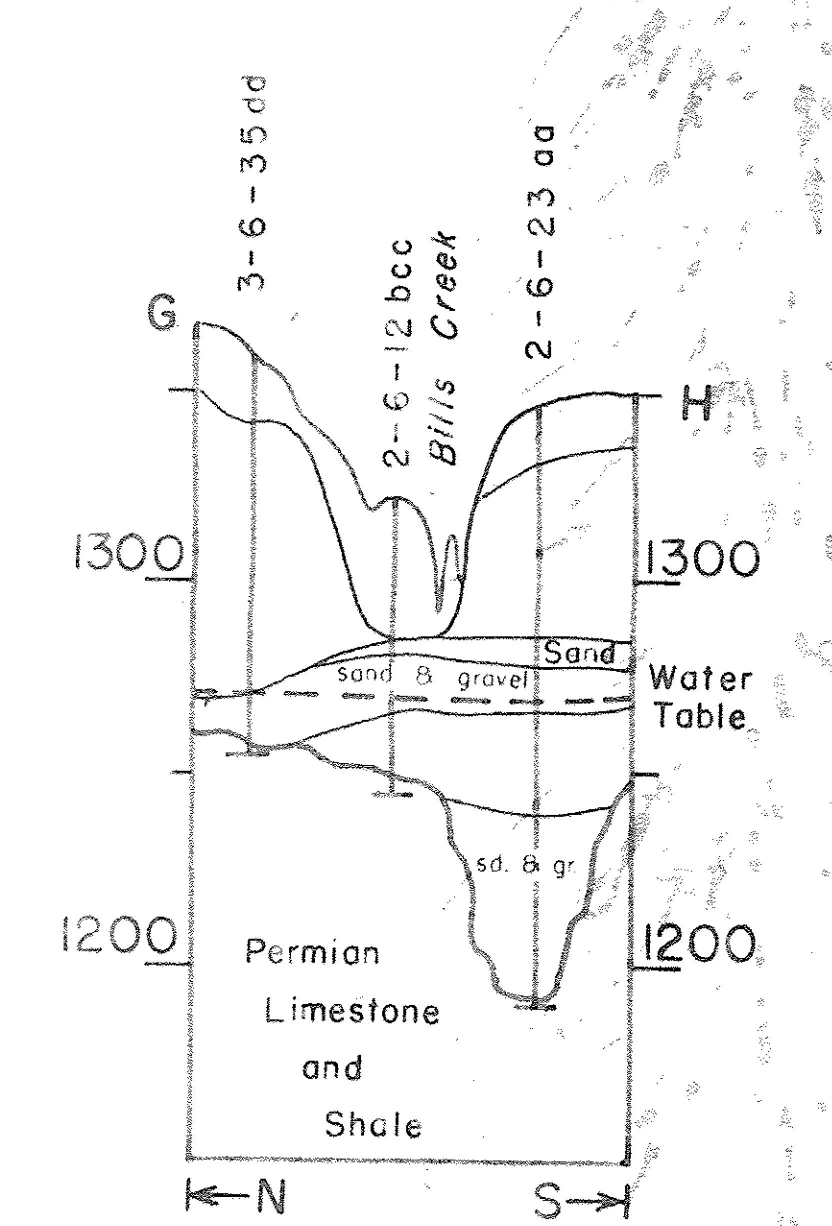

West-East Geologic Cross Section
North Half, Gage County
Saline Co.
Gage Co.
R. 5 E.
R. 6 E.
R. 7 E.
R. 8 E.
Gage Co.
Johnson Co.
Big Blue River
5-5-17bb
Clatonia Creek
5-5-10dd
Soap Creek
5-5-12dd
5-6-8dd
Indian Creek
5-6-15aa
5-7-7cd
Pierce Creek
5-7-10cc
5-8-7cc
5-8-16ba
Hooker Creek
5-8-11dc
1400
N
1300
M
1200
1100
Water Table
sd. & gr.
clay
sand
sd. & gr.
sand
sand & gravel
Dakota sandstone & shale
sand
sd. & gr.
sand
silt & clay
sand
sand
sd. & gr.
Till
sand
Permian Limestone and Shale
WEST
EAST

GAGE COUNTY

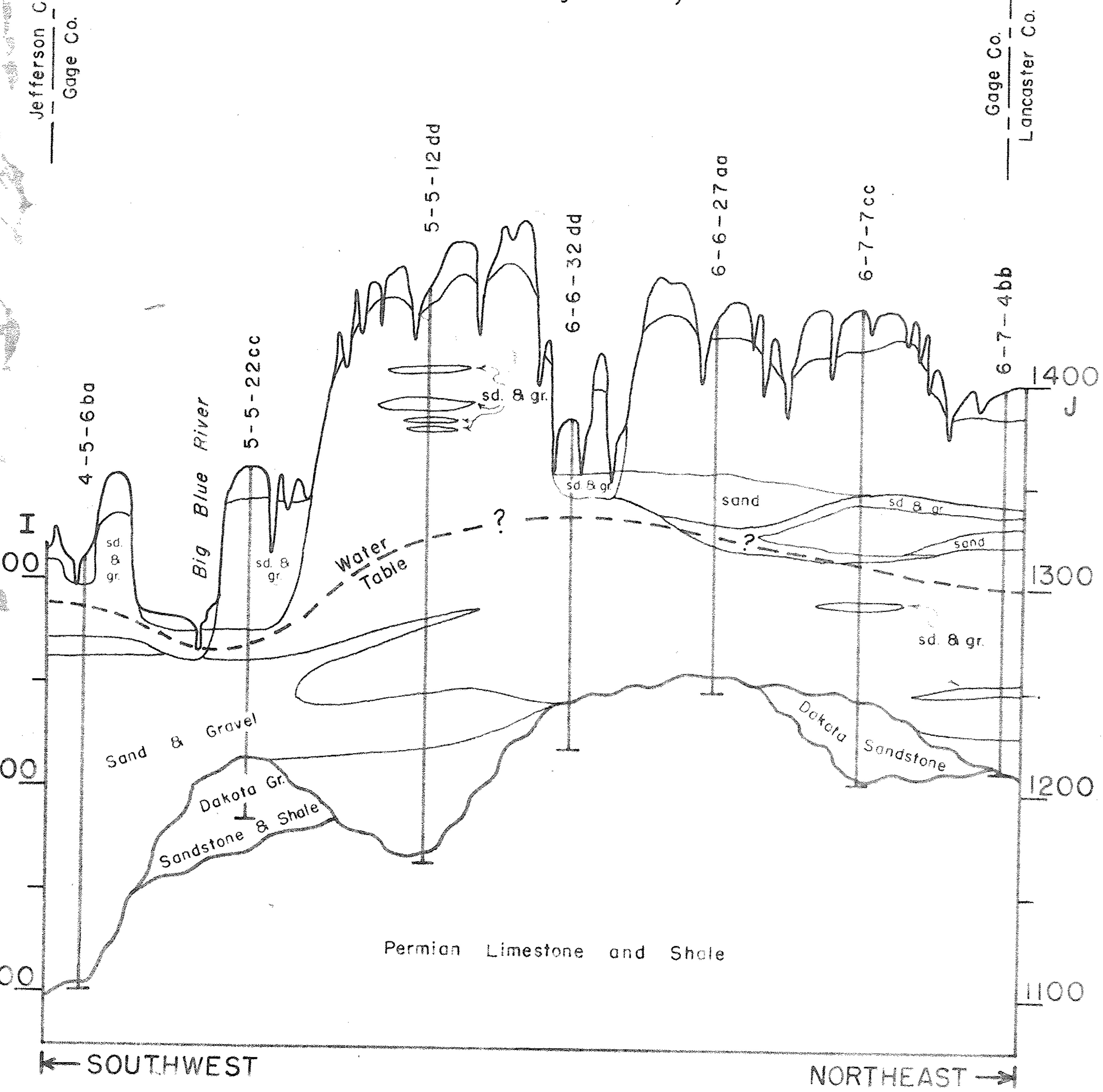
-South Geologic Cross Section
Pawnee County Line, Southern
Gage County



North-South Geologic Cross Section
South-Central Gage County

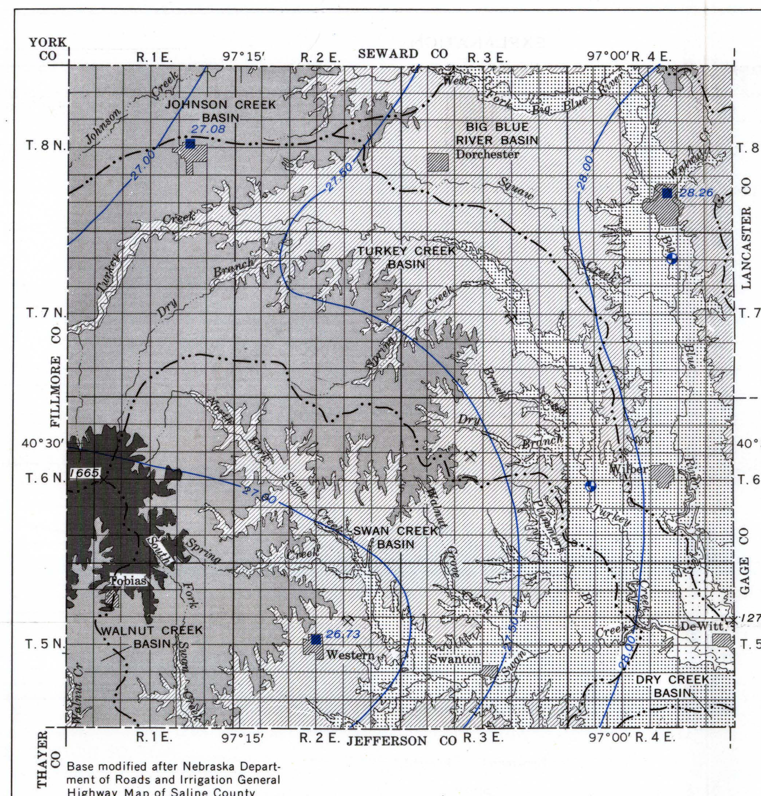


Southwest-Northeast Geologic Cross Section
Northwest Gage County



Saline County

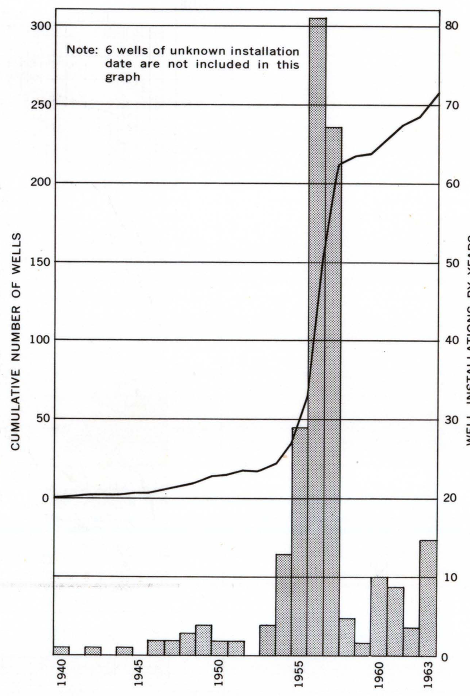
PREPARED AS PART OF THE PROGRAM OF
THE DEPARTMENT OF THE INTERIOR
FOR THE DEVELOPMENT OF THE MISSOURI RIVER BASIN



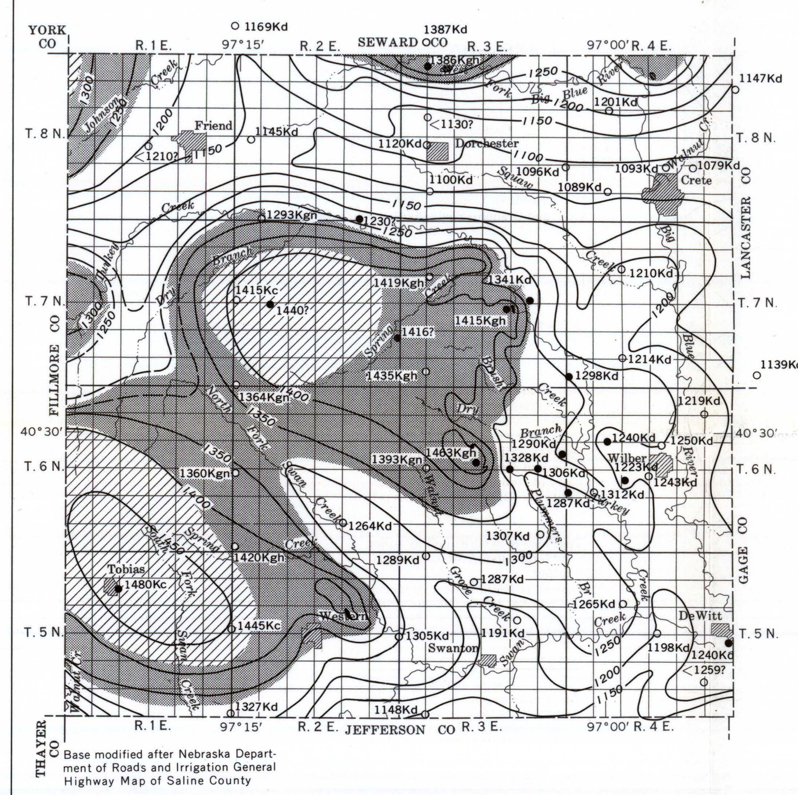
GENERALIZED TOPOGRAPHY, DRAINAGE DIVIDES, AND AVERAGE ANNUAL PRECIPITATION

SCALE 1:250 000

5 0 5 10 MILES



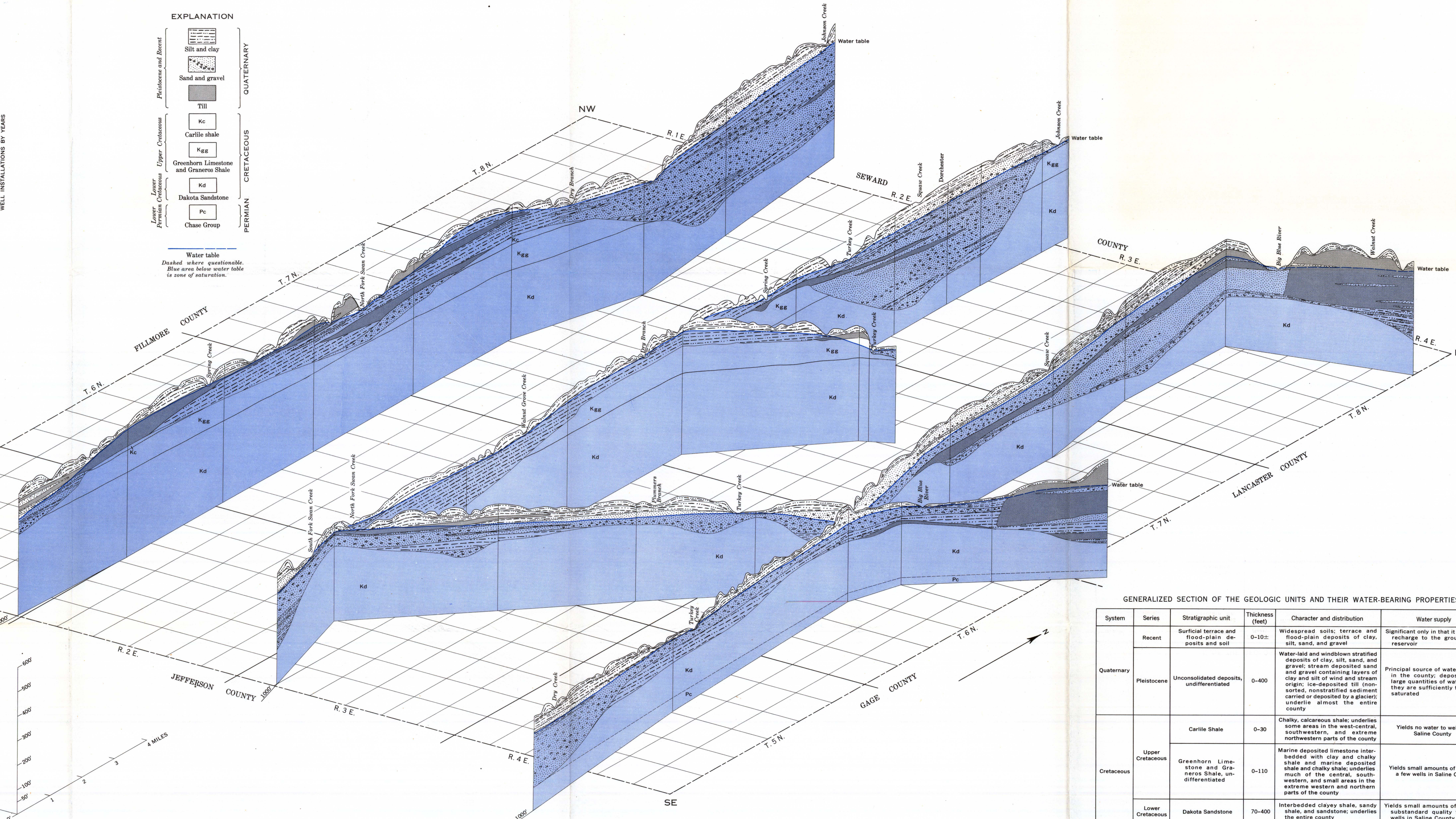
RATE OF INSTALLATION OF IRRIGATION WELLS



AREAL GEOLOGY AND CONFIGURATION OF THE BEDROCK SURFACE

SCALE 1:250 000

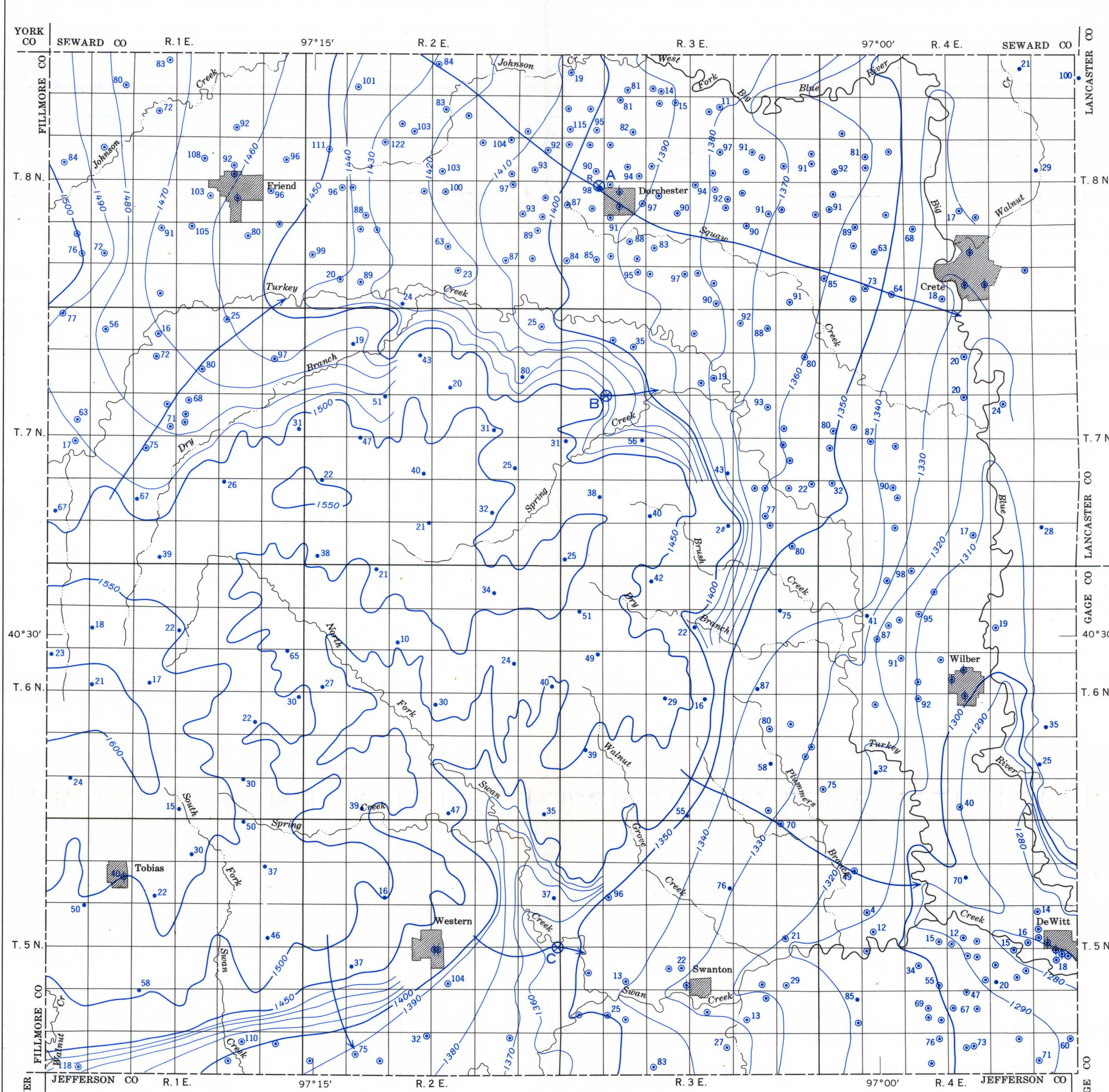
5 0 5 10 MILES



CORRELATION OF STRATIGRAPHY AND ZONE OF SATURATION

GENERALIZED SECTION OF THE GEOLOGIC UNITS AND THEIR WATER-BEARING PROPERTIES

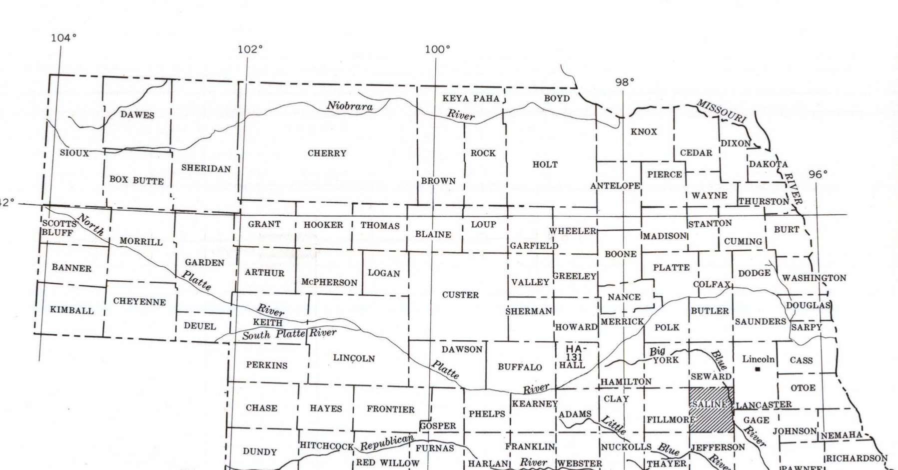
System	Series	Stratigraphic unit	Thickness (feet)	Character and distribution	Water supply
Quaternary	Recent	Surficial terrace and flood-plain deposits and soil	0-10±	Widespread soils; terrace and flood-plain deposits of clay, silt, sand, and gravel	Significant only in that it transmits recharge to the ground-water reservoir
	Pleistocene	Unconsolidated deposits, undifferentiated	0-400	Water-laid and windblown stratified deposits of clay, silt, sand, and gravel; stream deposited sand and gravel containing layers of clay and silt of wind and stream origin; ice-deposited till (nonsorted, nonstratified sediment carried or deposited by a glacier); underlie almost the entire county	Principal source of water to wells in the county; deposits yield large quantities of water where they are sufficiently thick and saturated
Cretaceous	Upper Cretaceous	Carlile Shale	0-30	Chalky, calcareous shale; underlies some areas in the west-central, southwestern, and extreme northwestern parts of the county	Yields no water to wells in Saline County
		Greenhorn Limestone and Graneros Shale, undifferentiated	0-110	Marine deposited limestone interbedded with clay and chalky shale and marine deposited shale and chalky shale; underlies much of the central, southwestern, and small areas in the extreme western and northern parts of the county	Yields small amounts of water to a few wells in Saline County
	Lower Cretaceous	Dakota Sandstone	70-400	Interbedded clayey shale, sandy shale, and sandstone; underlies the entire county	Yields small amounts of water of substandard quality to a few wells in Saline County.
Permian	Lower Permian	Chase Group	?	Limestone, shale sandstone, and siltstone; underlies the entire county	Yields no water to wells in Saline County



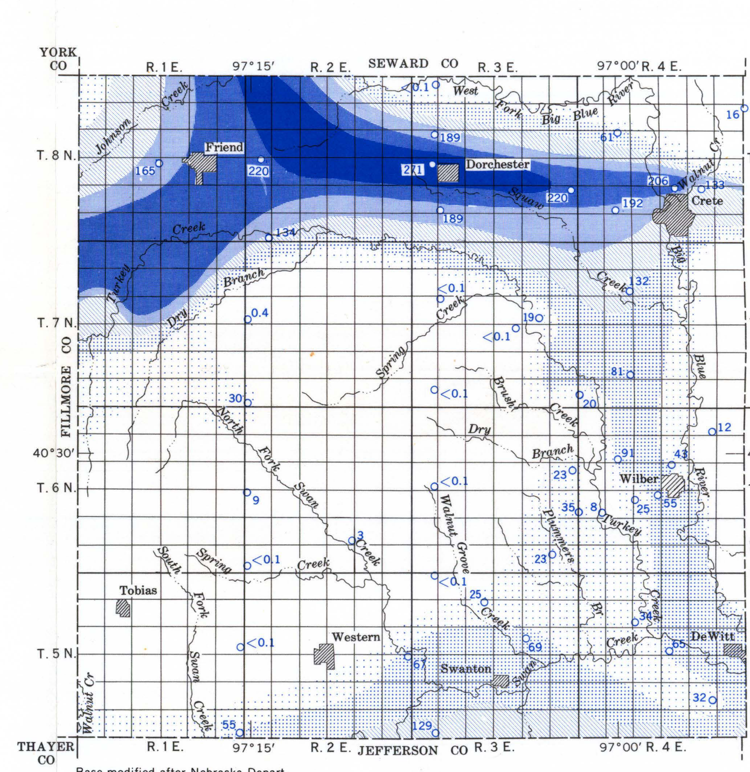
CONFIGURATION OF THE WATER TABLE, DEPTH TO WATER, AND LOCATION OF ALL IRRIGATION WELLS AS OF JANUARY 1, 1964

SCALE 1:125 000

2 0 2 4 6 MILES



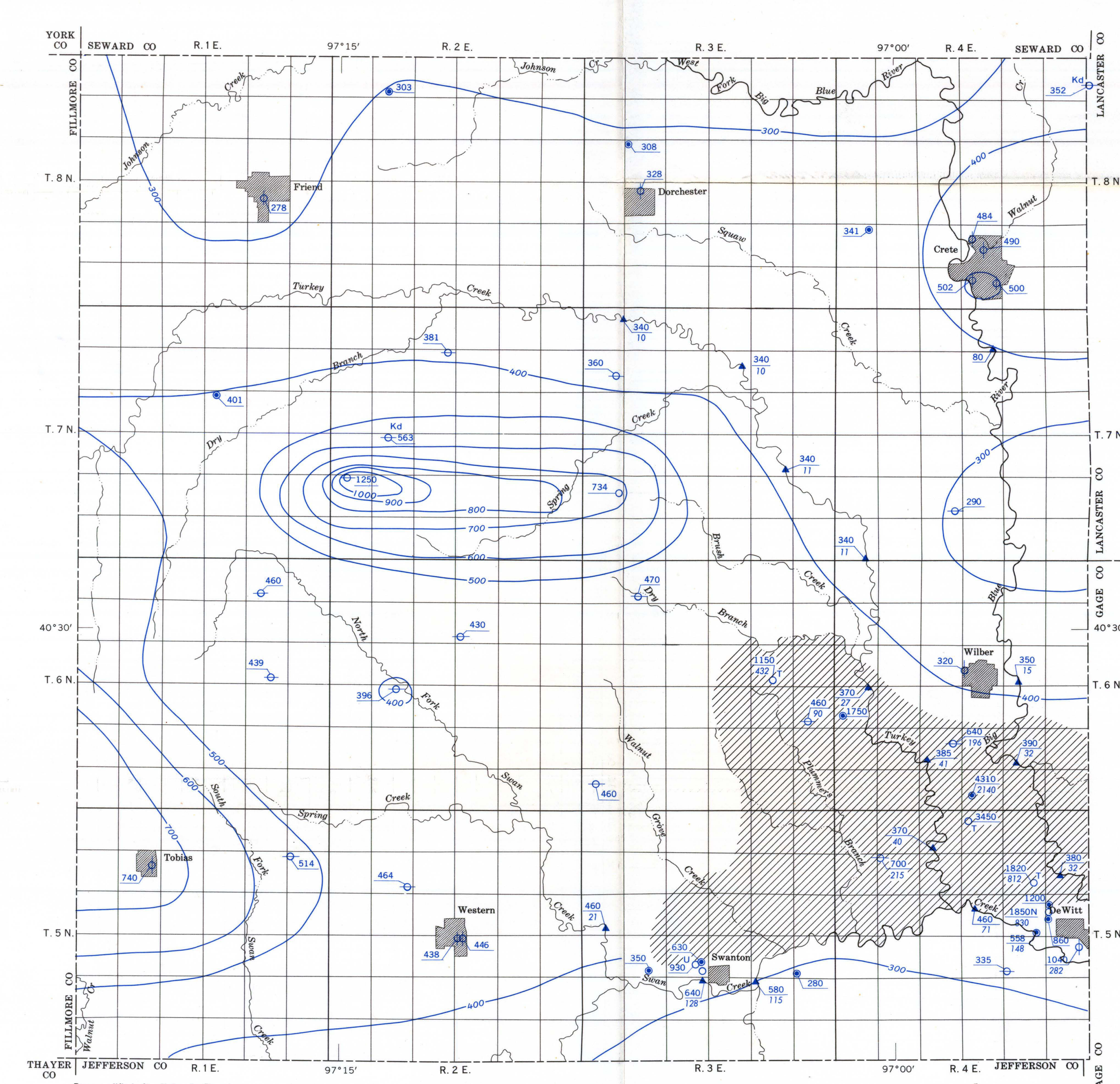
INDEX MAP OF NEBRASKA SHOWING LOCATION OF REPORT AREA



TRANSMISSIBILITY OF THE SATURATED QUATERNARY DEPOSITS

SCALE 1:250 000

5 0 5 10 MILES



DISSOLVED-SOLIDS CONCENTRATION OF THE GROUND AND SURFACE WATER

SCALE 1:125 000

2 0 2 4 6 MILES

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C.—1966—W65413

GEOHYDROLOGY OF SALINE COUNTY, NEBRASKA

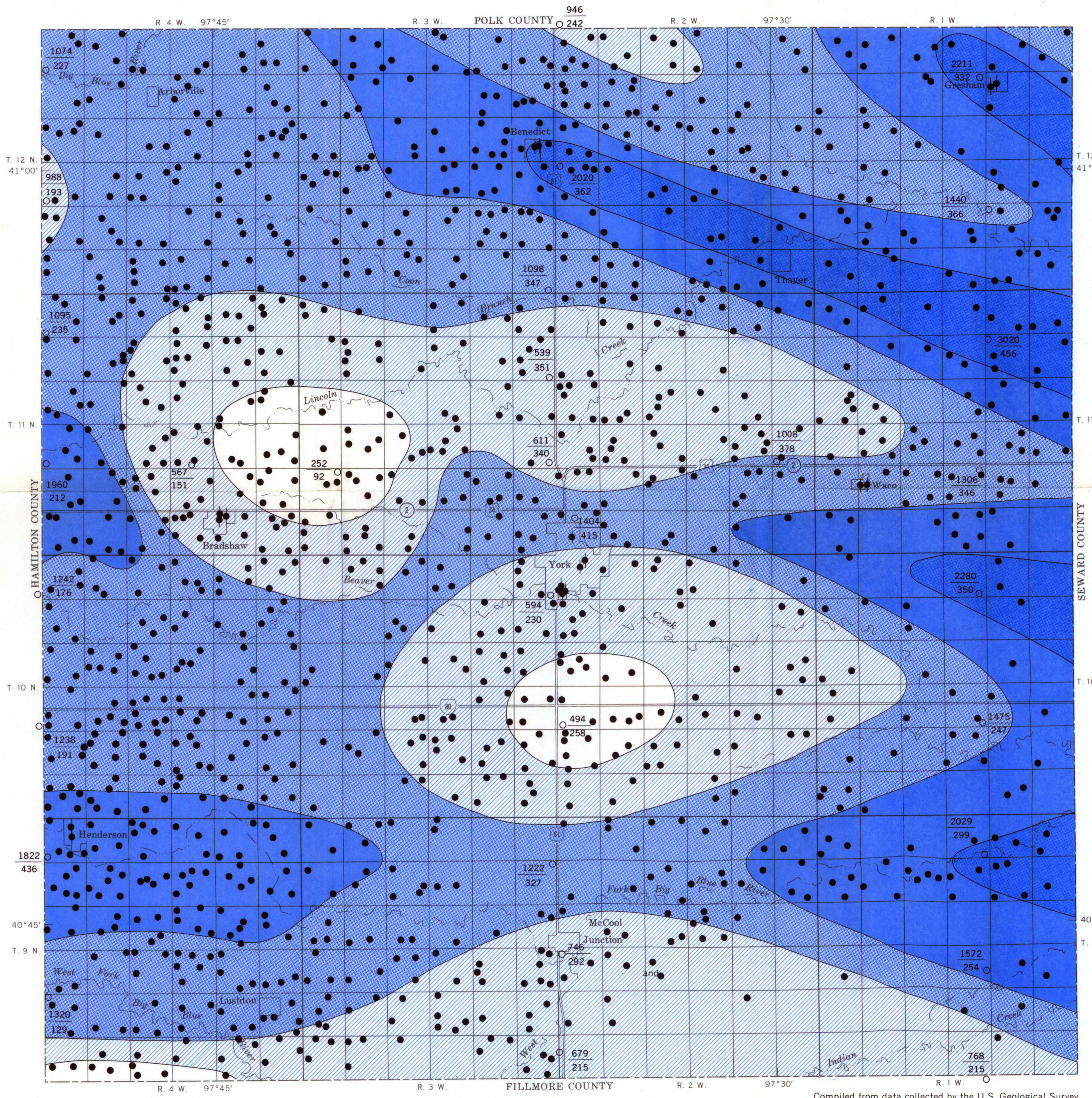
By

Philip A. Emery

1966

York County

PREPARED IN COOPERATION WITH THE
STATE OF NEBRASKA
CONSERVATION AND SURVEY DIVISION
UNIVERSITY OF NEBRASKA



EXPLANATION

Areas of potential yield, in gallons per minute

Less than 500

500–1000

1000–1500

1500–2000

More than 2000

Irrigation well

Municipal well

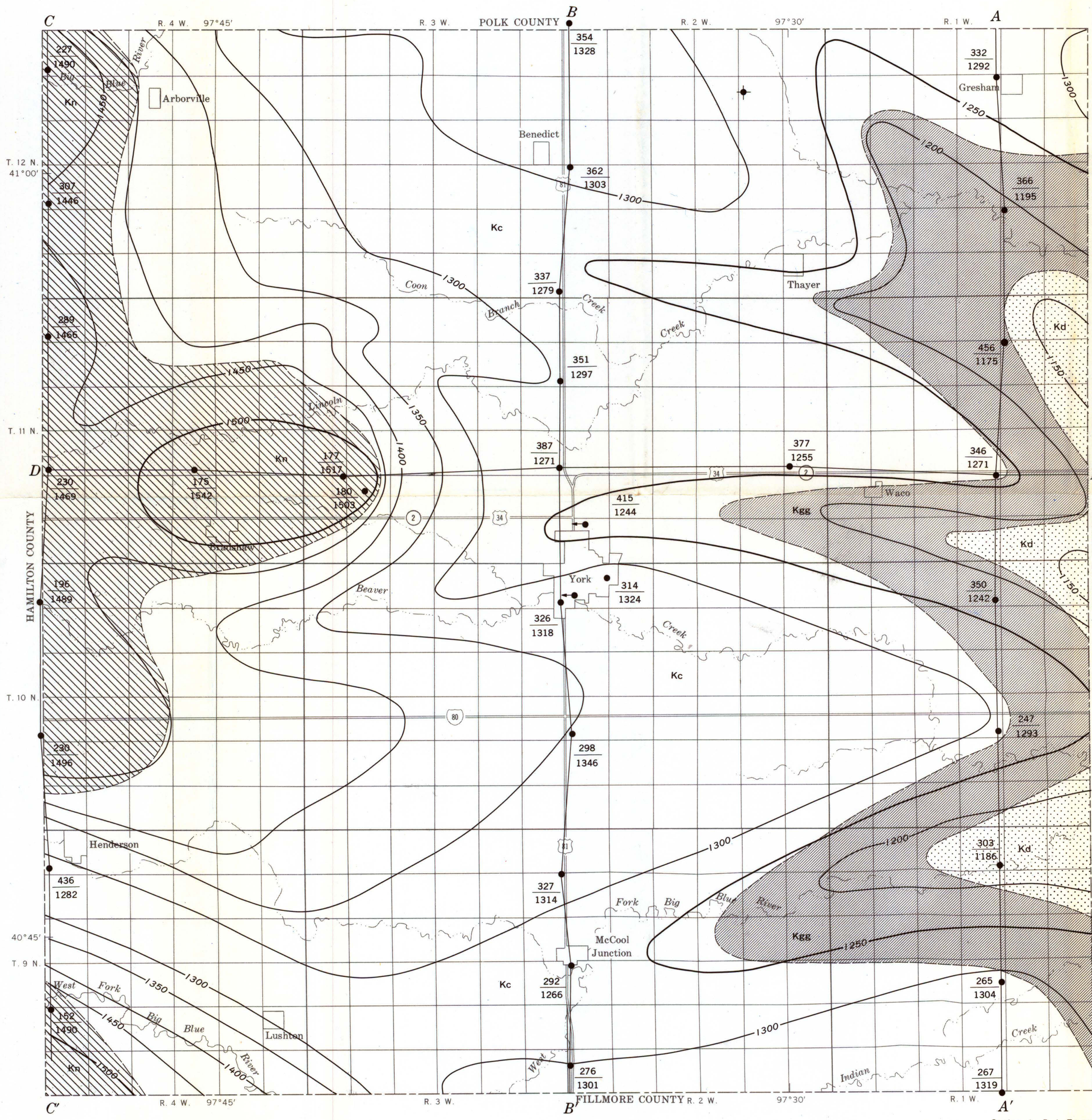
594
230

Test hole

Upper number is estimated coefficient of transmissibility, in hundreds of gallons per day per foot. It is approximately the potential yield of the aquifer to wells, in gallons per minute. Lower number is depth, in feet, to the base of deepest water-yielding material of Quaternary age

Compiled from data collected by the U.S. Geological Survey and the Conservation and Survey Division, University of Nebraska

POTENTIAL YIELD OF QUATERNARY ROCKS AND DISTRIBUTION OF LARGE-CAPACITY WELLS



EXPLANATION

Kn — Niobrara Formation

Kc — Carlile Shale

Kgg — Greenhorn Limestone and Graneros Shale

Upper Cretaceous

Kd — Dakota Sandstone

Lower Cretaceous

CRETACEOUS

Approximate contact

1250
1200

Bedrock contours

Show altitude of bedrock surface. Contour interval 50 feet; datum is mean sea level

415
1244

Test hole

Upper number is depth to bedrock, in feet; lower number is altitude of bedrock surface, in feet

Oil test

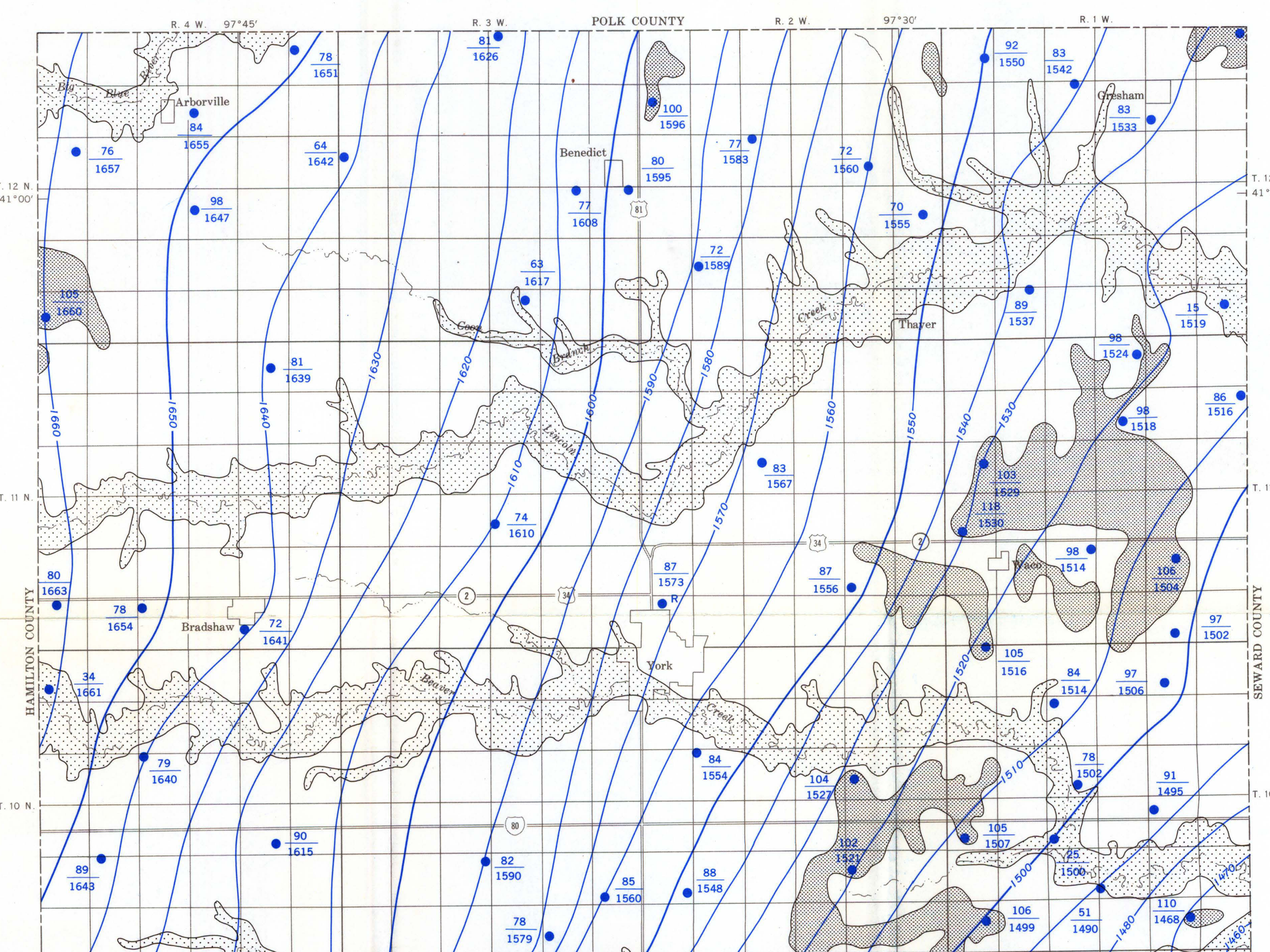
A —— A'

Line of geologic section

Sections shown on plate 2

Geology by P. A. Emery

GEOLOGY AND CONFIGURATION OF THE BEDROCK SURFACE



EXPLANATION

Depth to water, in feet below land surface

Less than 50

50–100

More than 100

1600
1590

Water-table contours

Show altitude of water table. Contour interval 10 feet; datum is mean sea level

R
87
1573

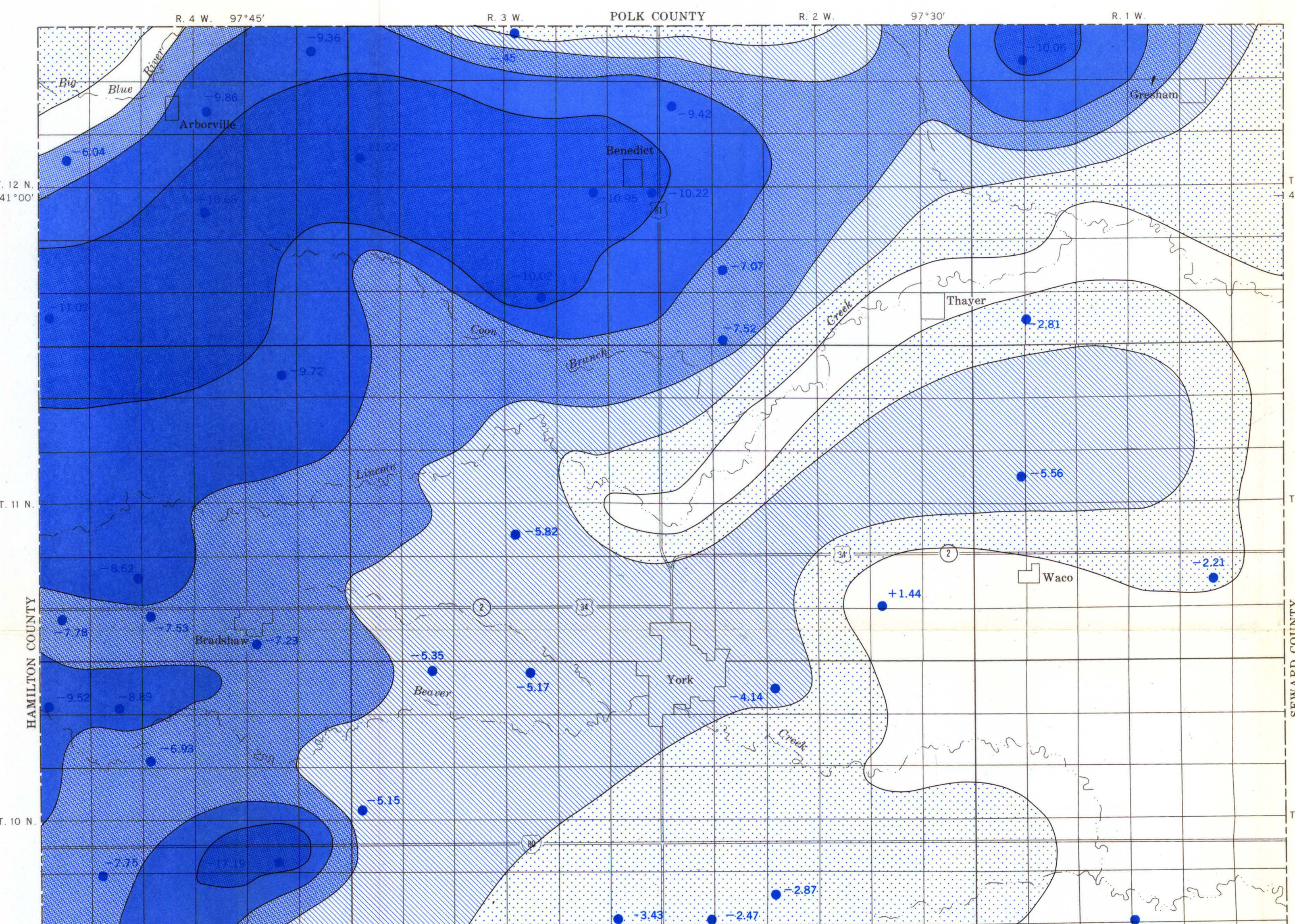
Well

Upper number is depth to water, in feet below land surface; lower number is altitude of water level, in feet above mean sea level. R, *denotes recording gage*

Base modified after Nebraska Department of Roads and Irrigation General Highway Map of York County

Hydrology by P. A. Emery and C. F. Keech

DEPTH TO WATER AND CONFIGURATION OF WATER TABLE, SPRING 1964



EXPLANATION

Water-level decline, in feet

Less than 2

2–4

4–6

6–8

8–10

More than 10

−7.52

Observation well

Number is change in ground-water level, in feet

NET CHANGE IN GROUND-WATER LEVELS, SPRING 1953 TO SPRING 1964

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1967—W66393

HYDROGEOLOGIC MAPS OF YORK COUNTY, NEBRASKA

TRUE NORTH
MAGNETIC NORTH
9½°
APPROXIMATE MEAN DECLINATION, 1967

SCALE 1:125 000

2 0 2 4 6 8 10 MILES

2 0 2 4 6 8 10 KILOMETERS

GEOLOGIC SECTIONS ACROSS YORK COUNTY, NEBRASKA

SCALE 1:125 000

2 0 2 4 6 8 10 MILES

2 0 2 4 6 8 10 KILOMETERS

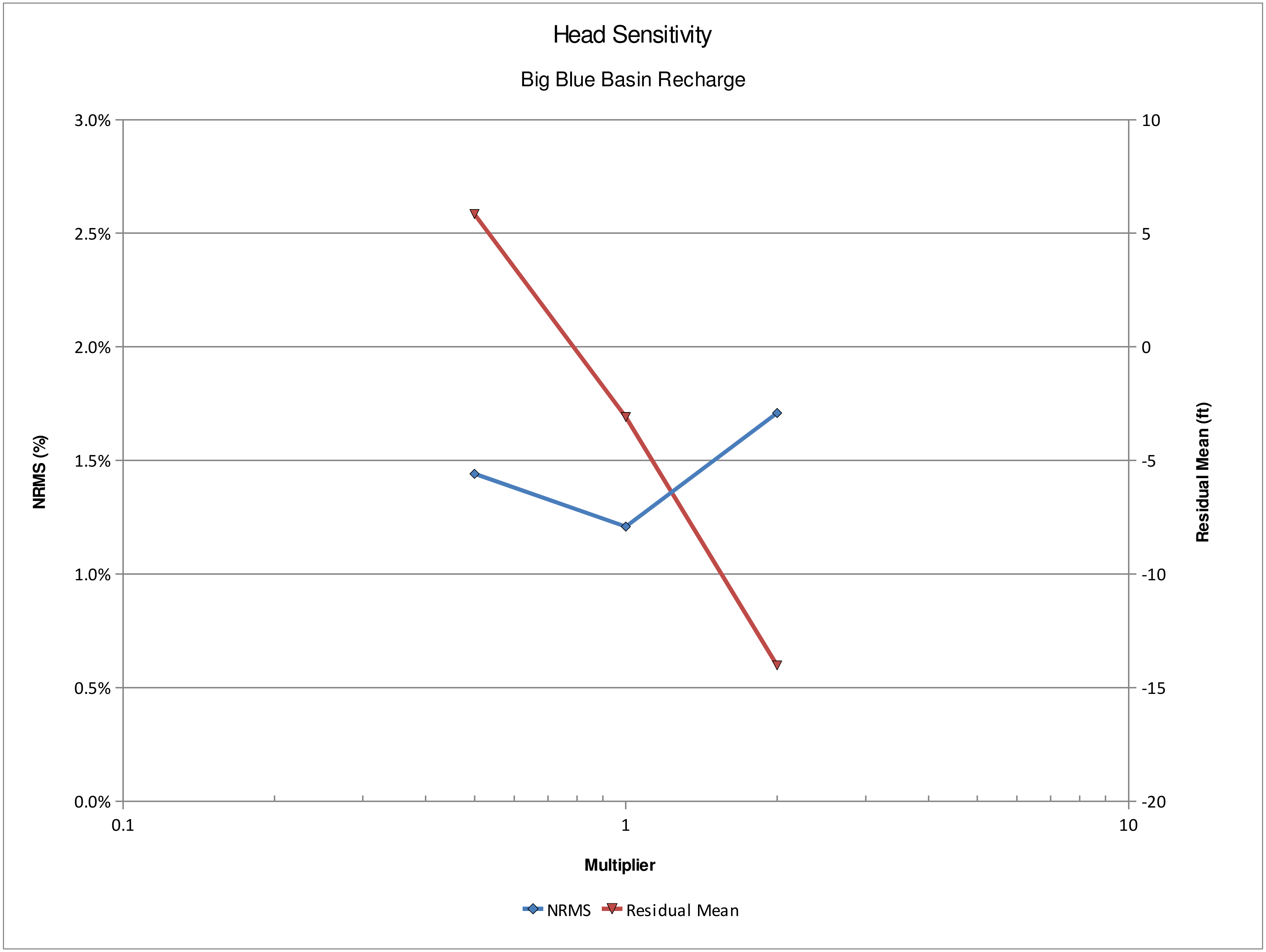
DATUM IS MEAN SEA LEVEL
VERTICAL EXAGGERATION APPROXIMATELY X 53

268-823 O - 67 (In pocket)

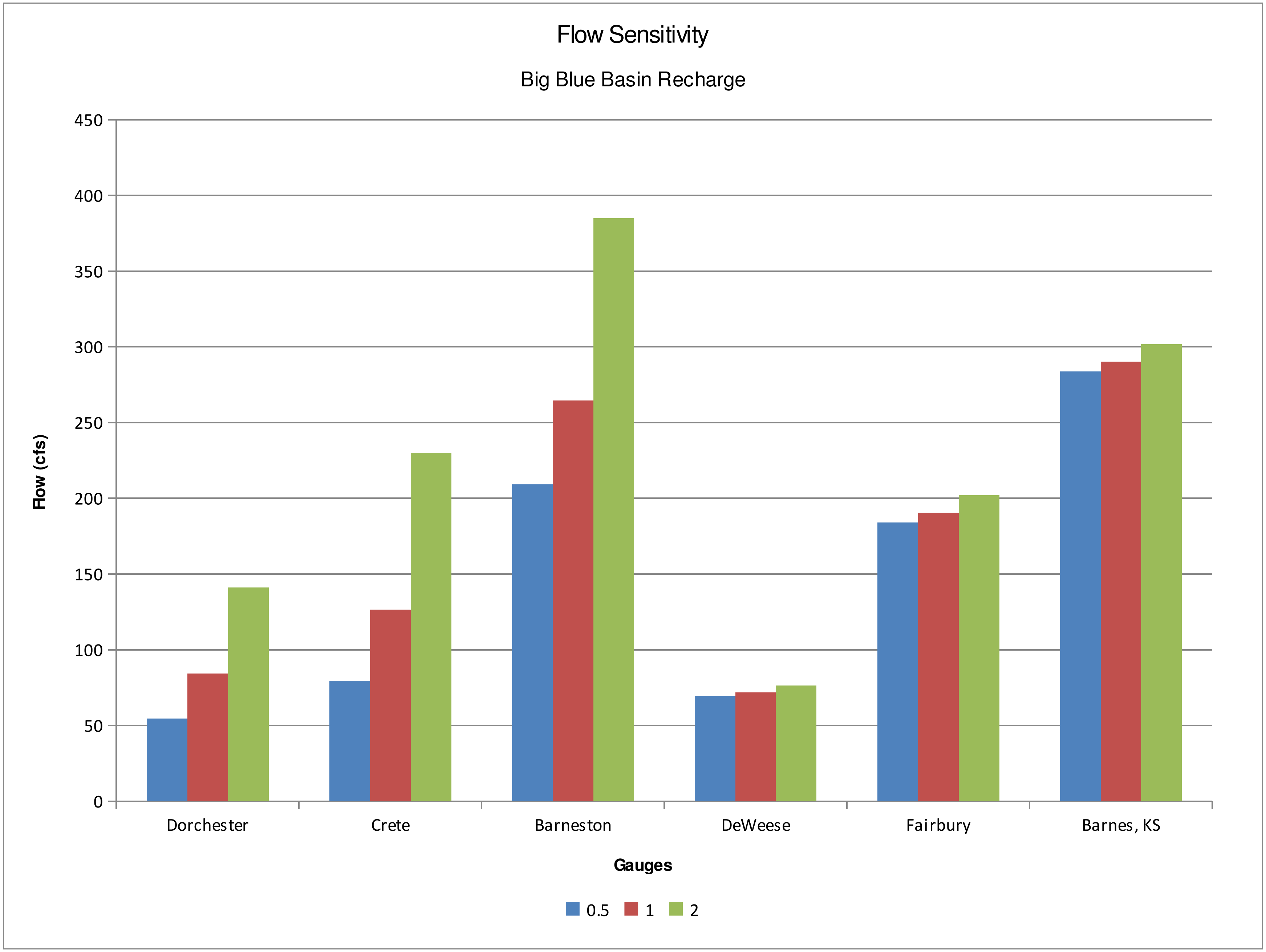
Appendix D – Sensitivity Analyses

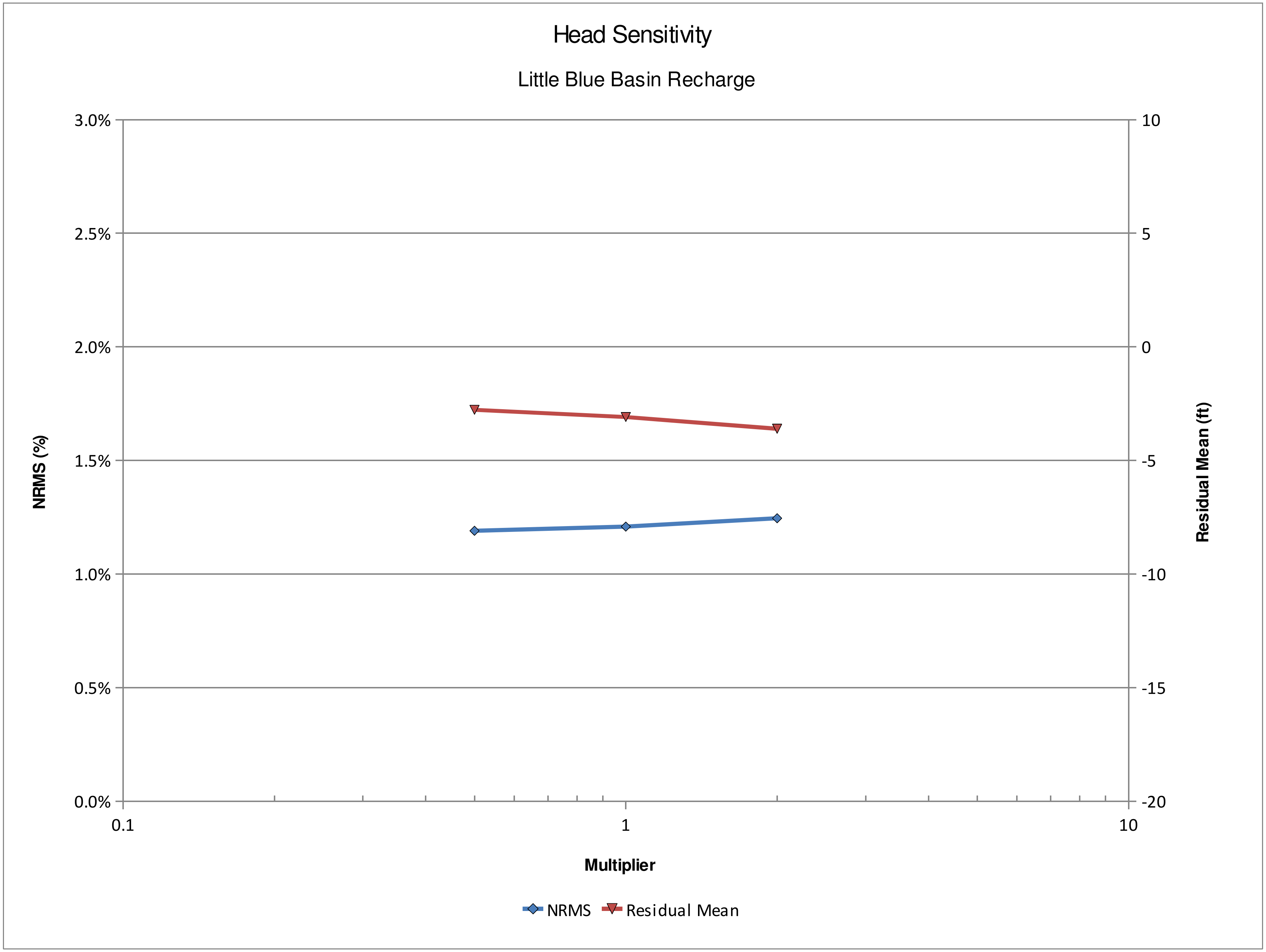
Appendix D contains plots that illustrate the results of the model sensitivity analysis.

Recharge Sensitivity by Basin

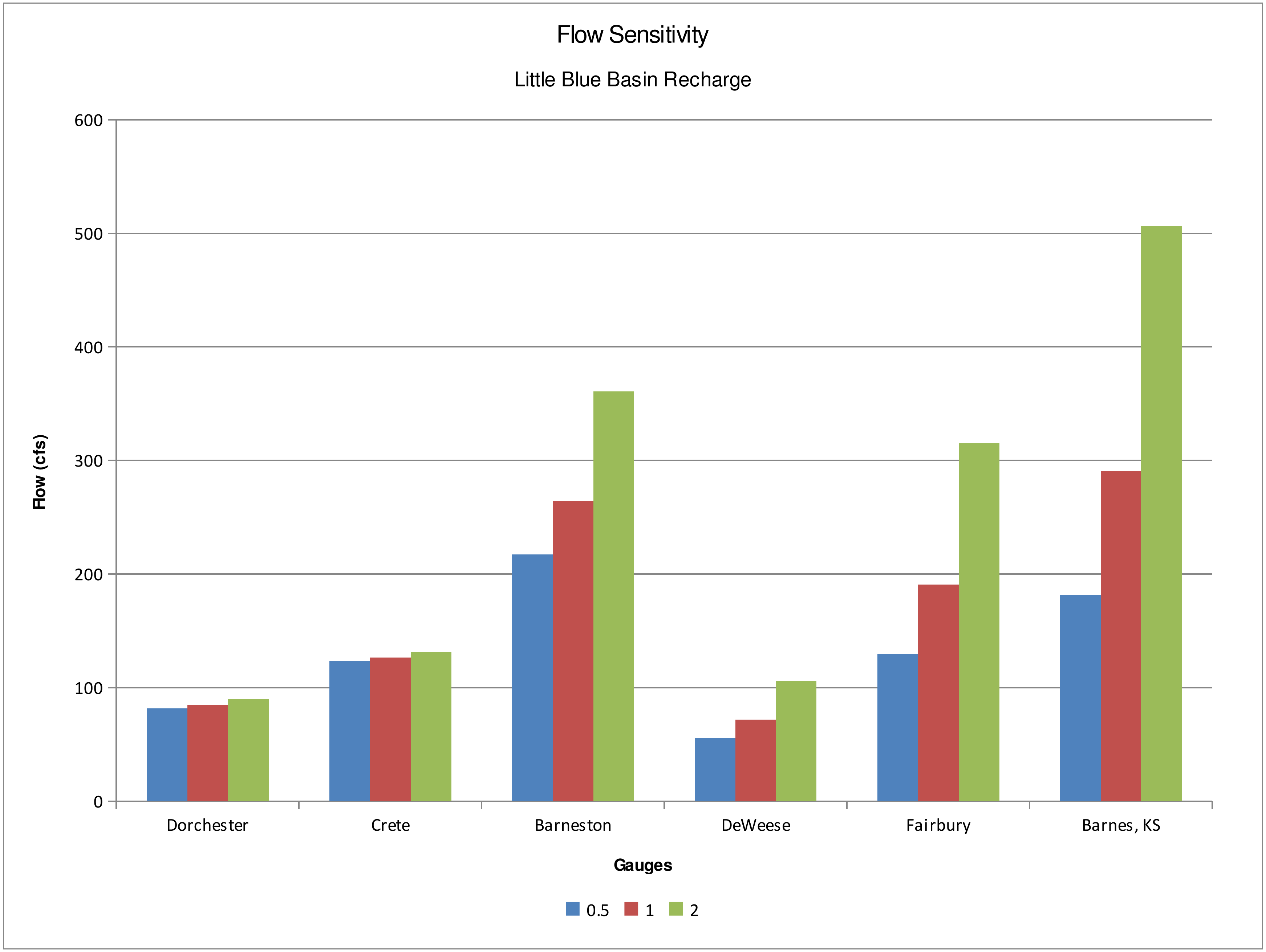


Head Sensitivity
Big Blue Basin Recharge
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
NRMS (%)
10
5
0
-5
-10
-15
-20
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean


Flow Sensitivity
Big Blue Basin Recharge
Flow (cfs)
450
400
350
300
250
200
150
100
50
0
Dorchester
Crete
Barneston
DeWeese
Fairbury
Barnes, KS
Gauges
0.5
1
2

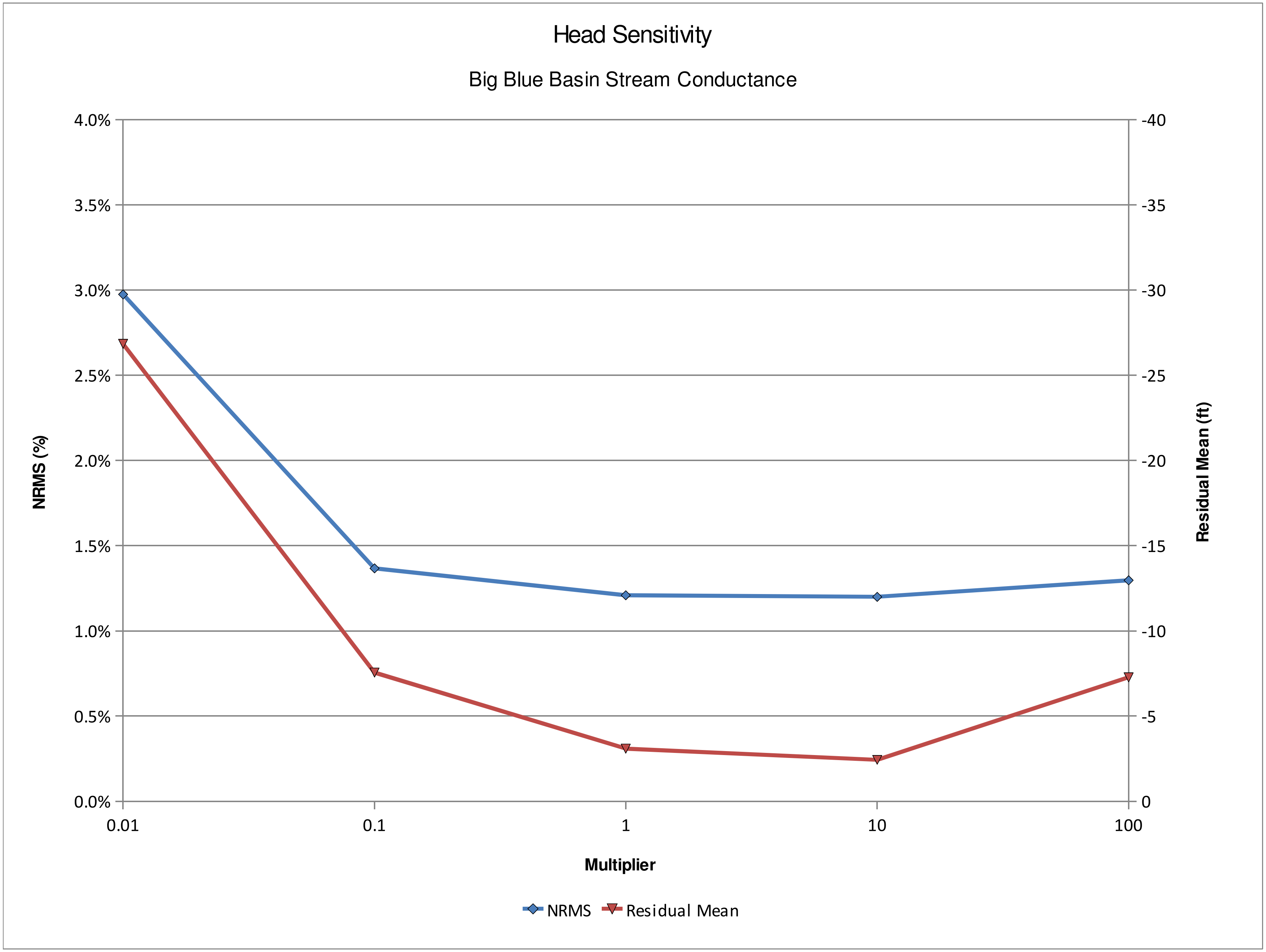


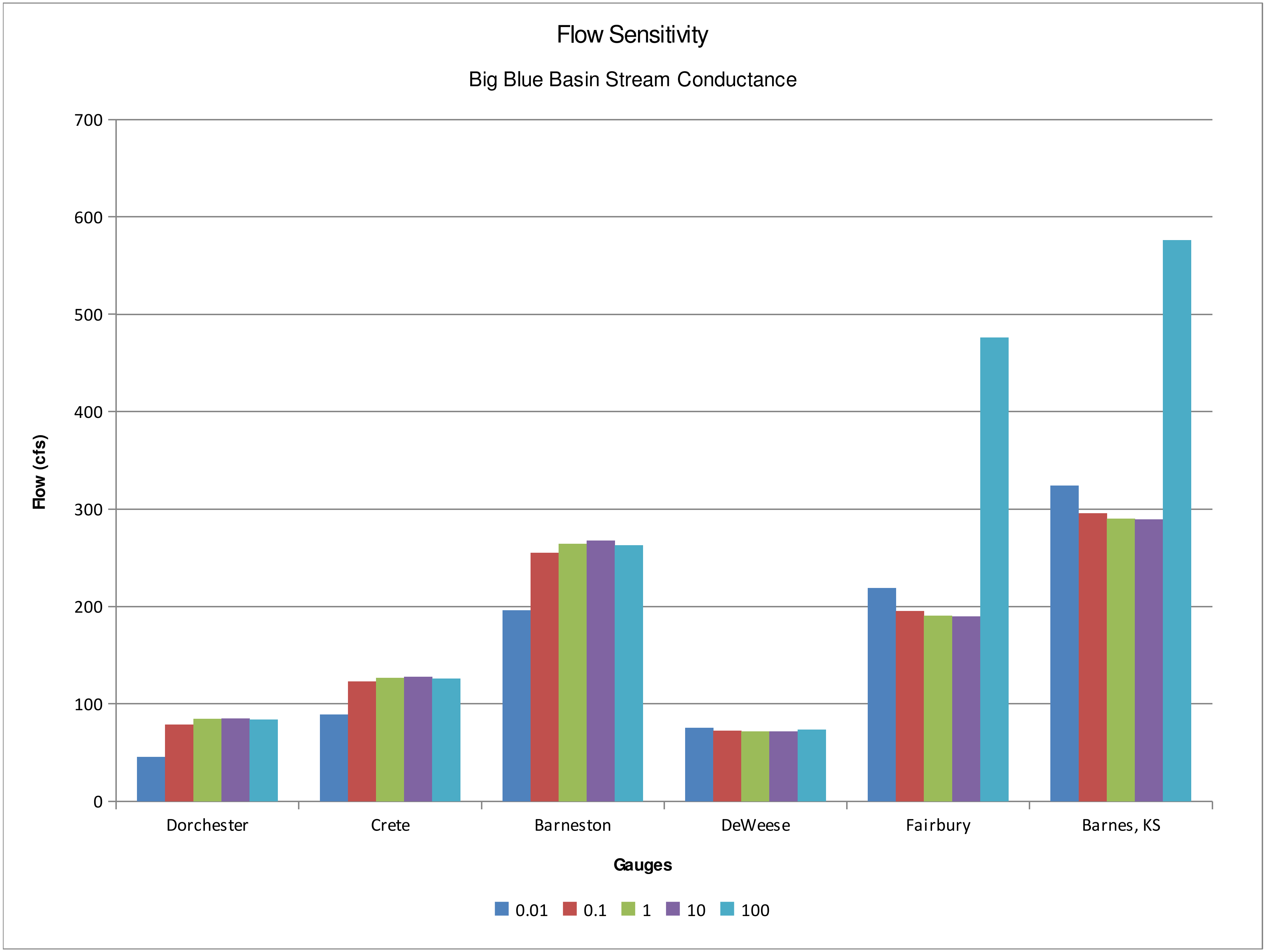
Head Sensitivity
Little Blue Basin Recharge
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
NRMS (%)
10
5
0
-5
-10
-15
-20
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



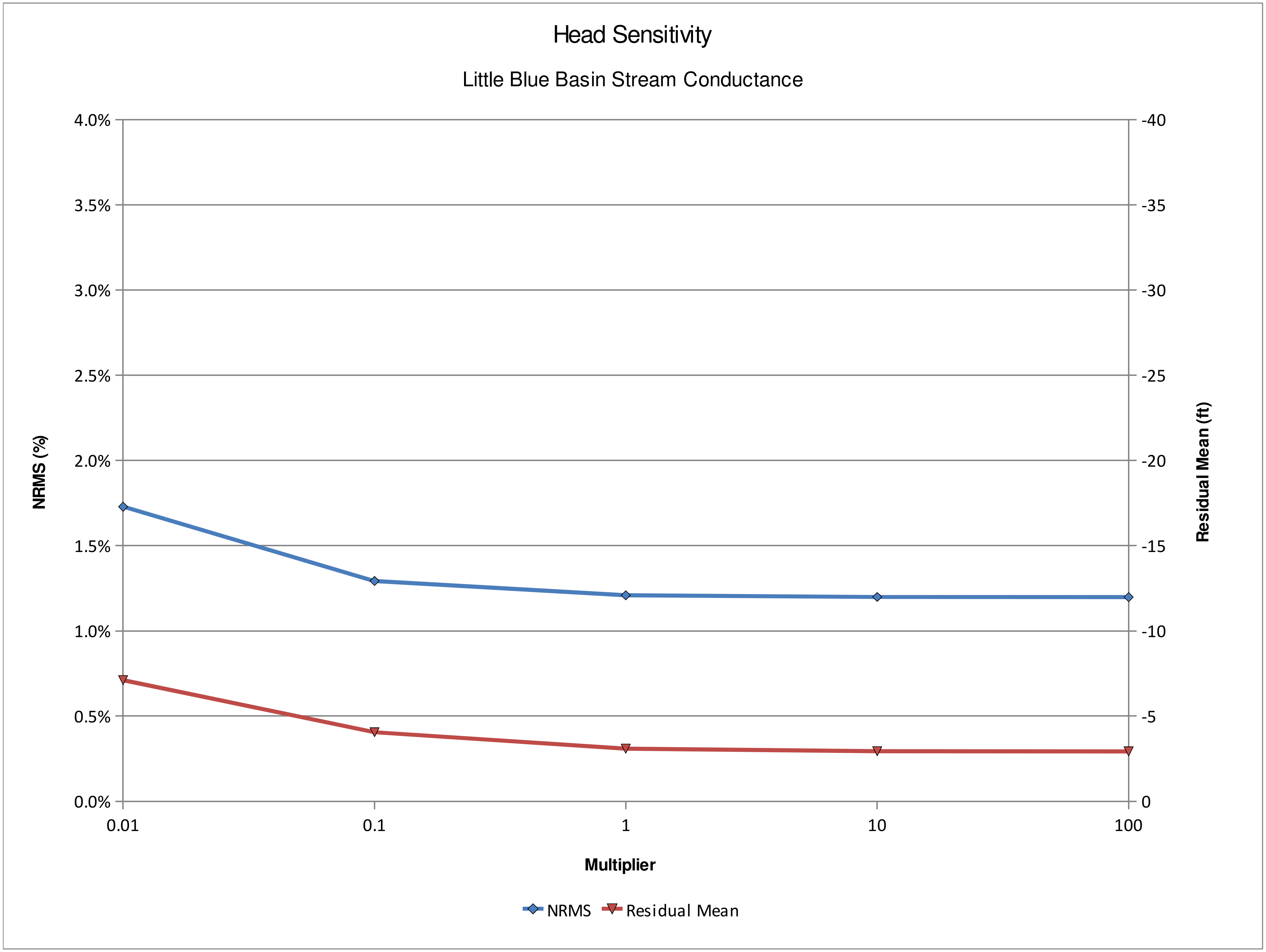
Flow Sensitivity
Little Blue Basin Recharge
600
500
400
300
200
100
0
Flow (cfs)
Dorchester
Crete
Barneston
DeWeese
Fairbury
Barnes, KS
Gauges
0.5
1
2

Streambed Conductance Sensitivity by Basin

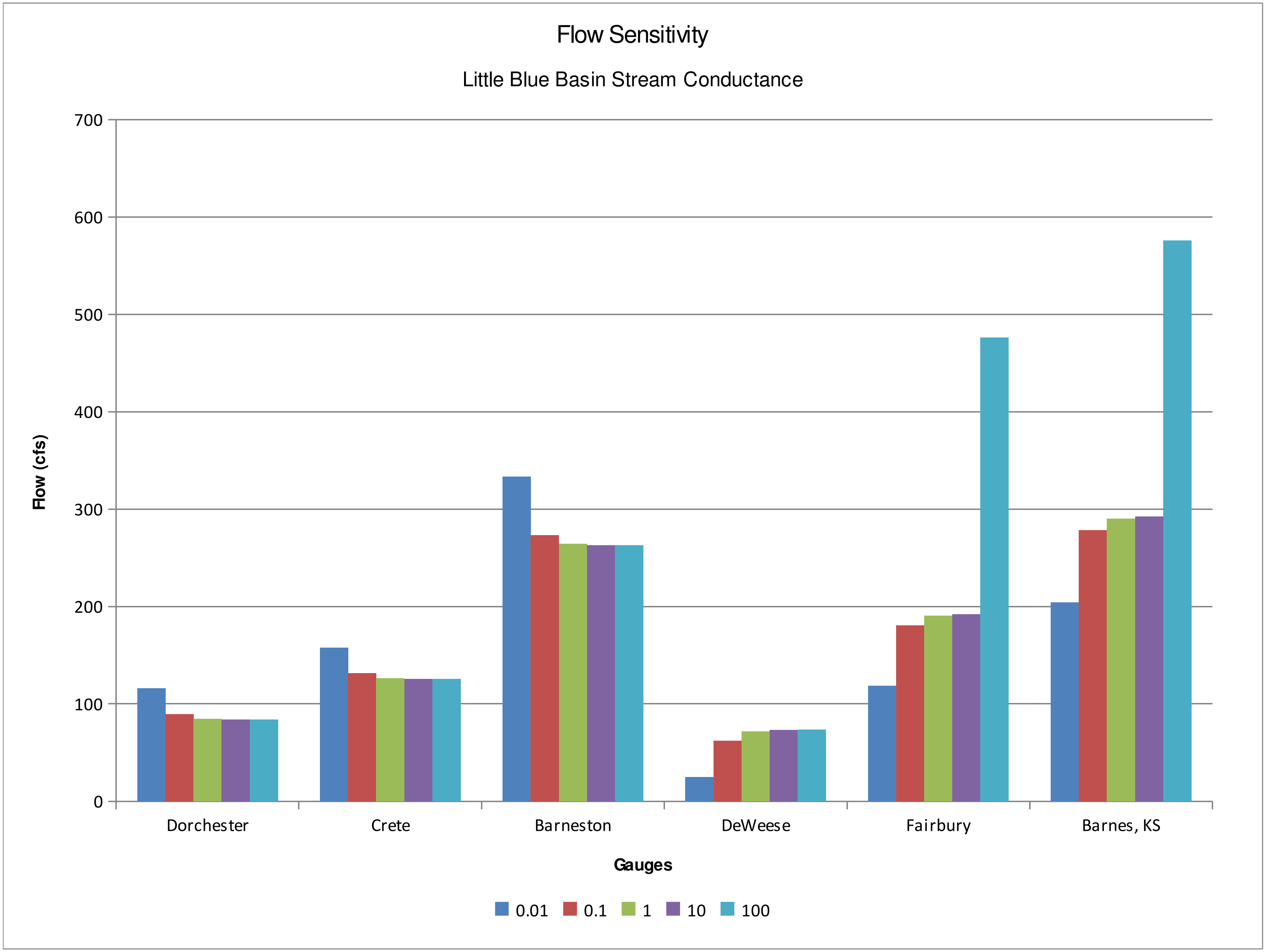

Head Sensitivity
Big Blue Basin Stream Conductance
NRMS (%)
Residual Mean (ft)
Multiplier
4.0%
3.5%
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
-40
-35
-30
-25
-20
-15
-10
-5
0
0.01
0.1
1
10
100
NRMS
Residual Mean



Flow Sensitivity
Big Blue Basin Stream Conductance
Flow (cfs)
0
100
200
300
400
500
600
700
Dorchester
Crete
Barneston
DeWeese
Fairbury
Barnes, KS
Gauges
0.01
0.1
1
10
100

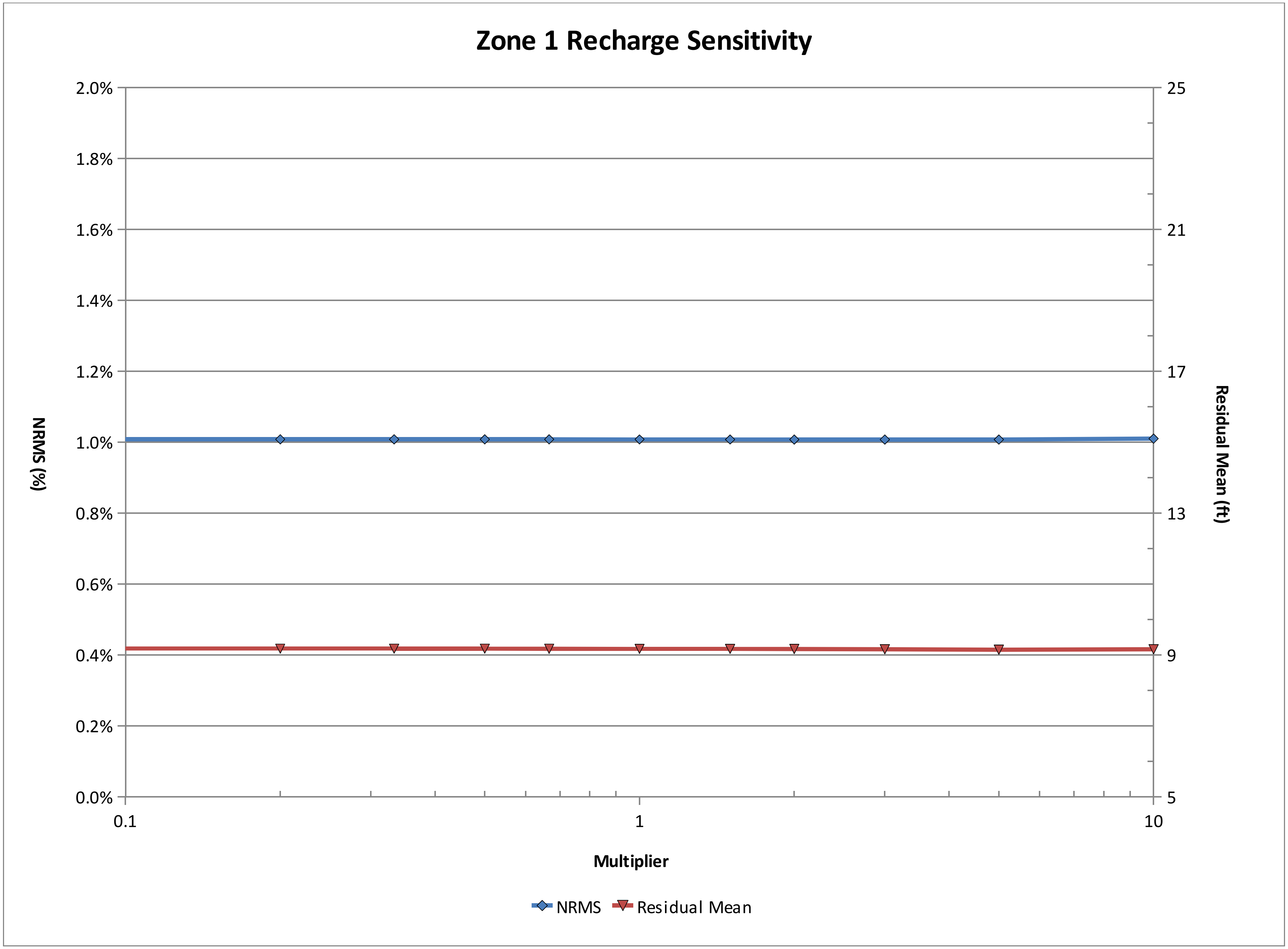


Head Sensitivity
Little Blue Basin Stream Conductance
NRMS (%)
Residual Mean (ft)
4.0%
3.5%
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
-40
-35
-30
-25
-20
-15
-10
-5
0
0.01
0.1
1
10
100
Multiplier
NRMS
Residual Mean

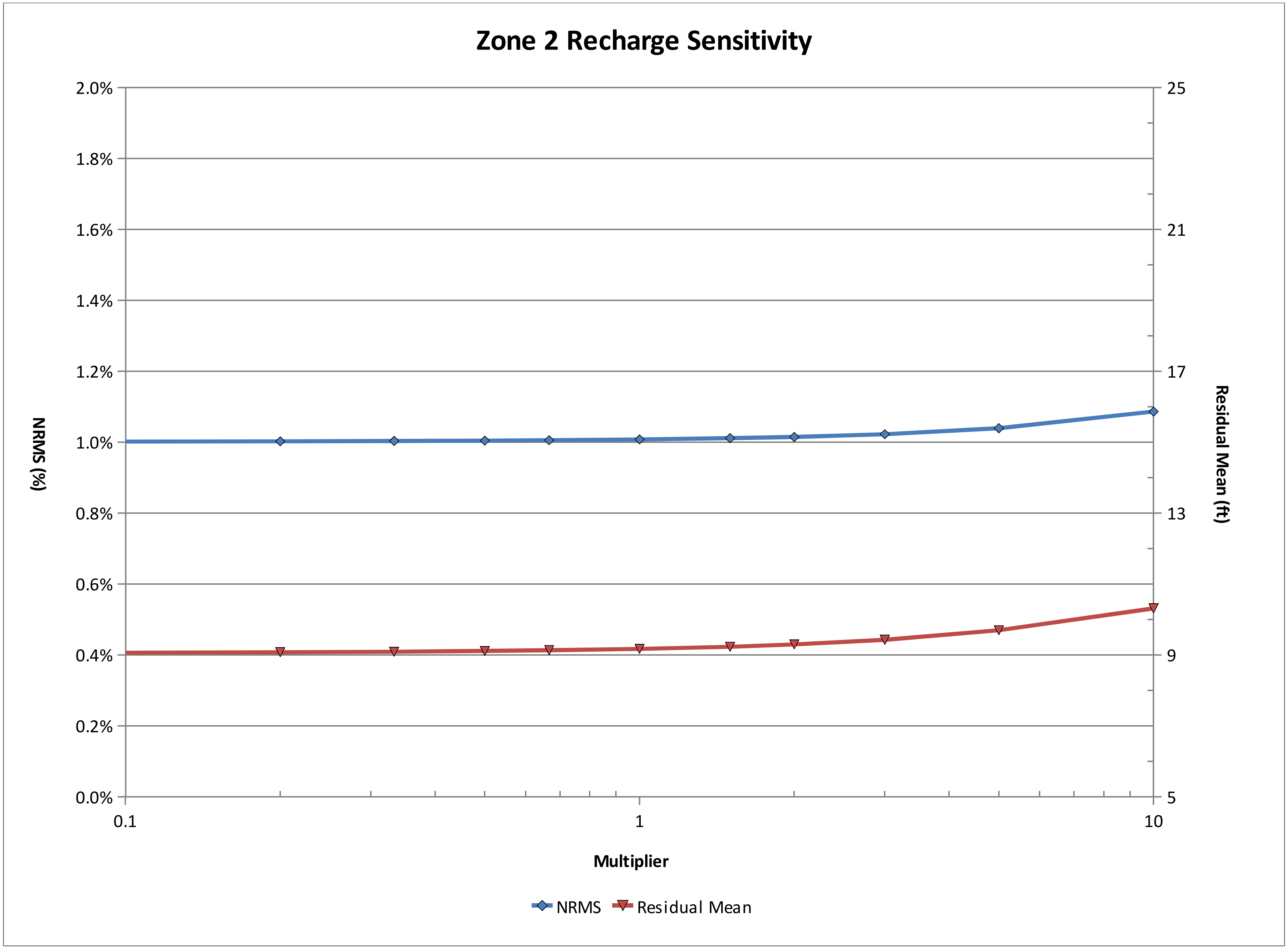


Flow Sensitivity
Little Blue Basin Stream Conductance
Flow (cfs)
700
600
500
400
300
200
100
0
Dorchester
Crete
Barneston
DeWeese
Fairbury
Barnes, KS
Gauges
0.01
0.1
1
10
100

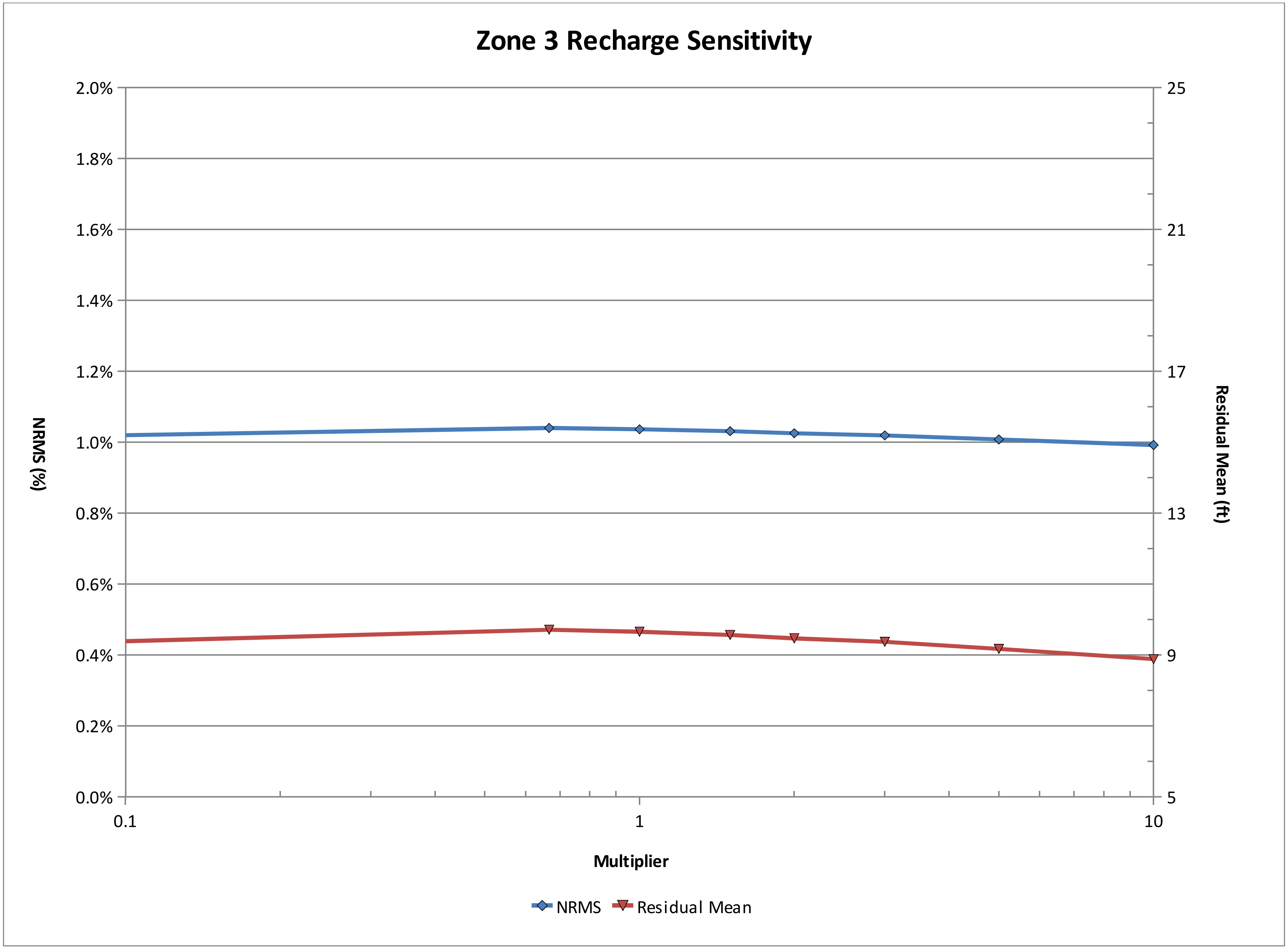
Recharge Sensitivity by Zone



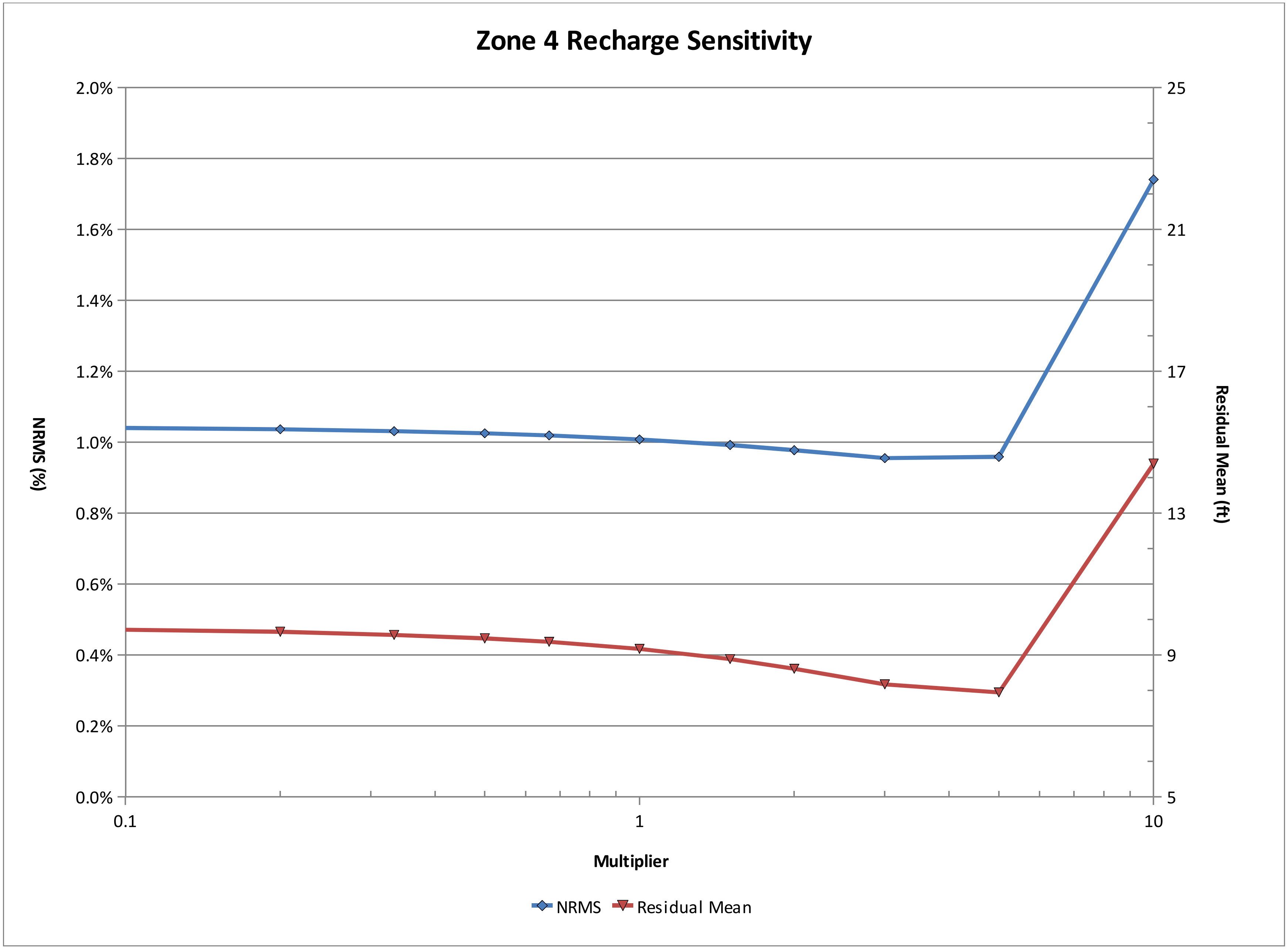
Zone 1 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



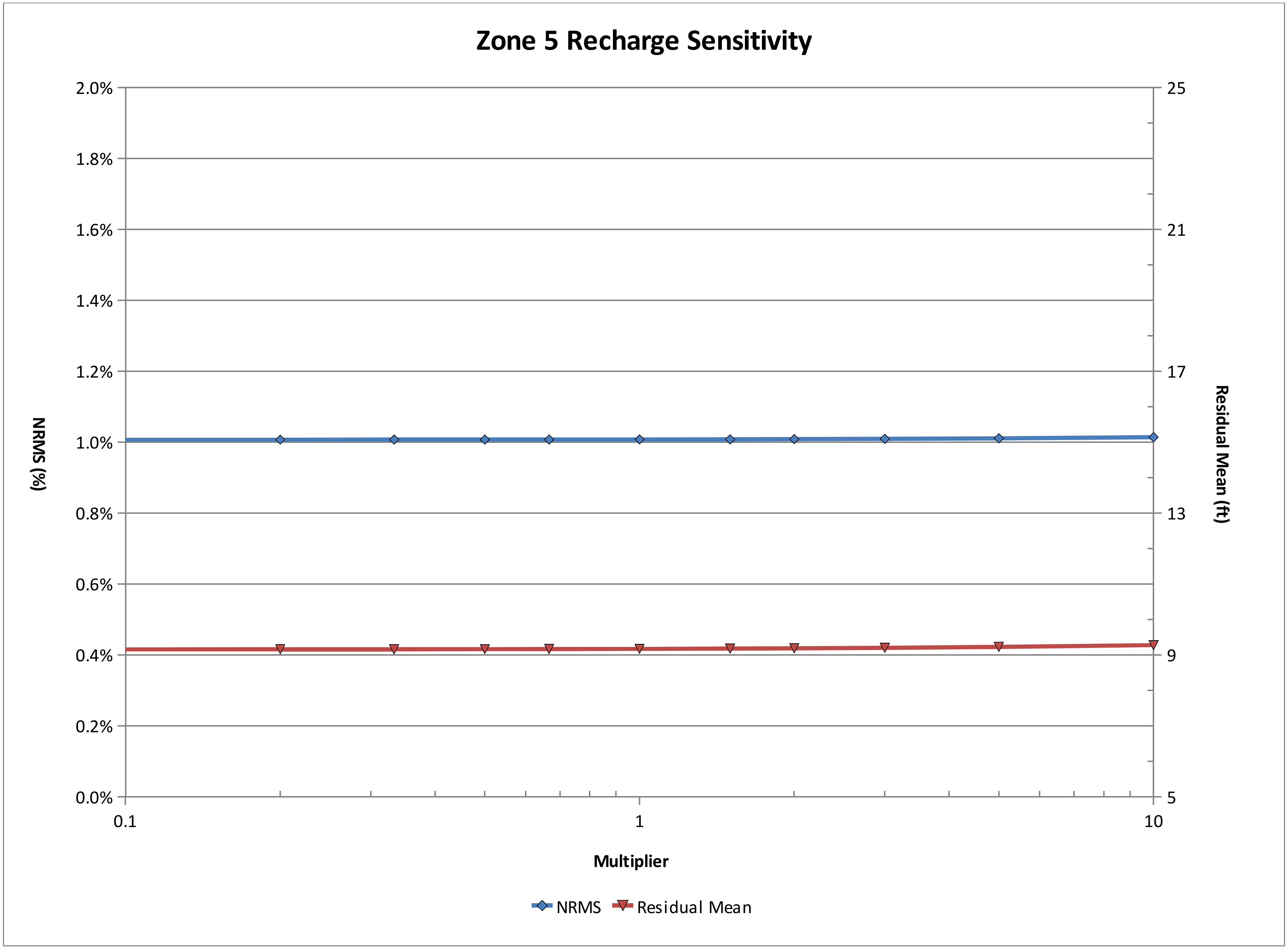
Zone 2 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

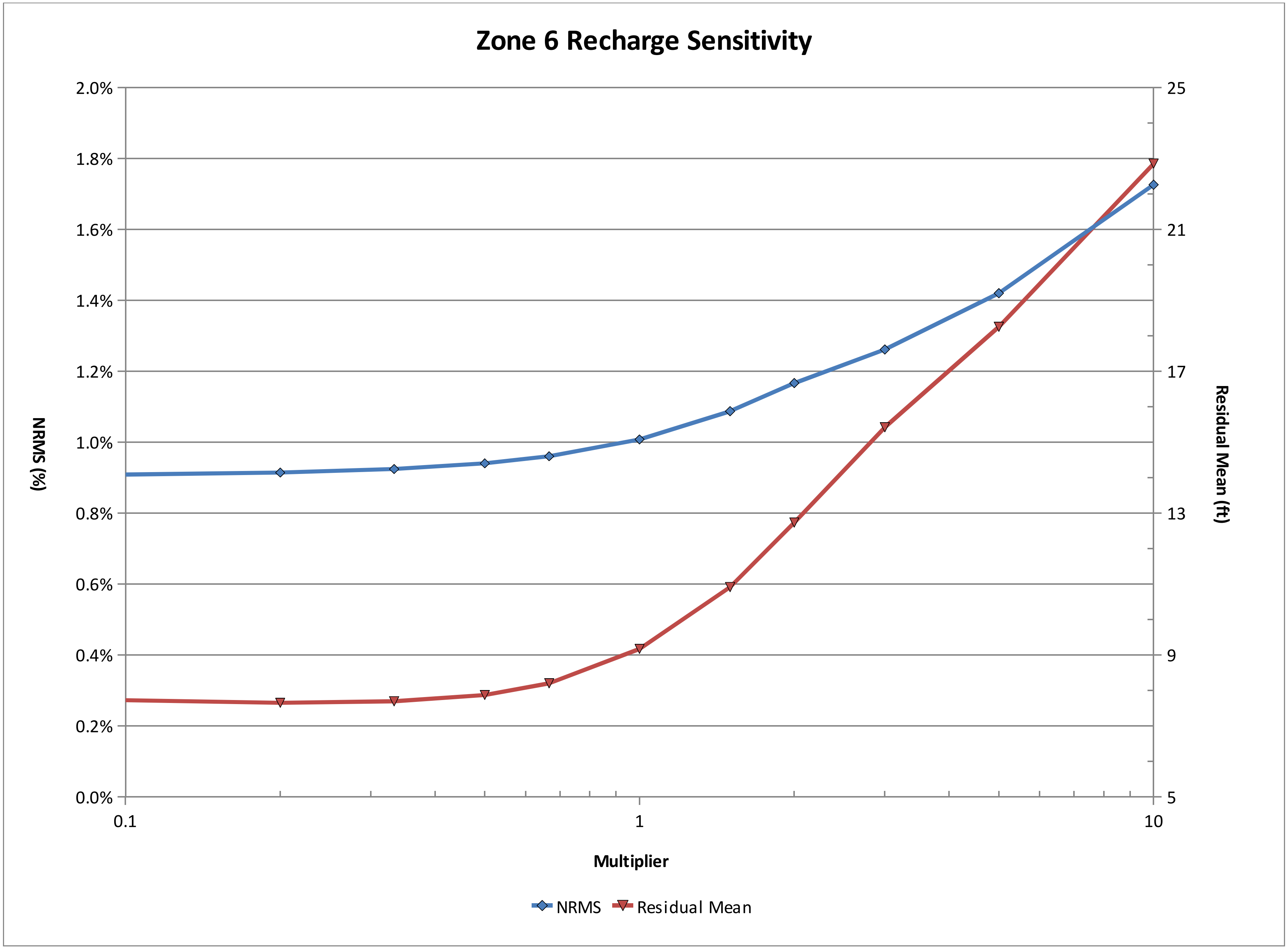


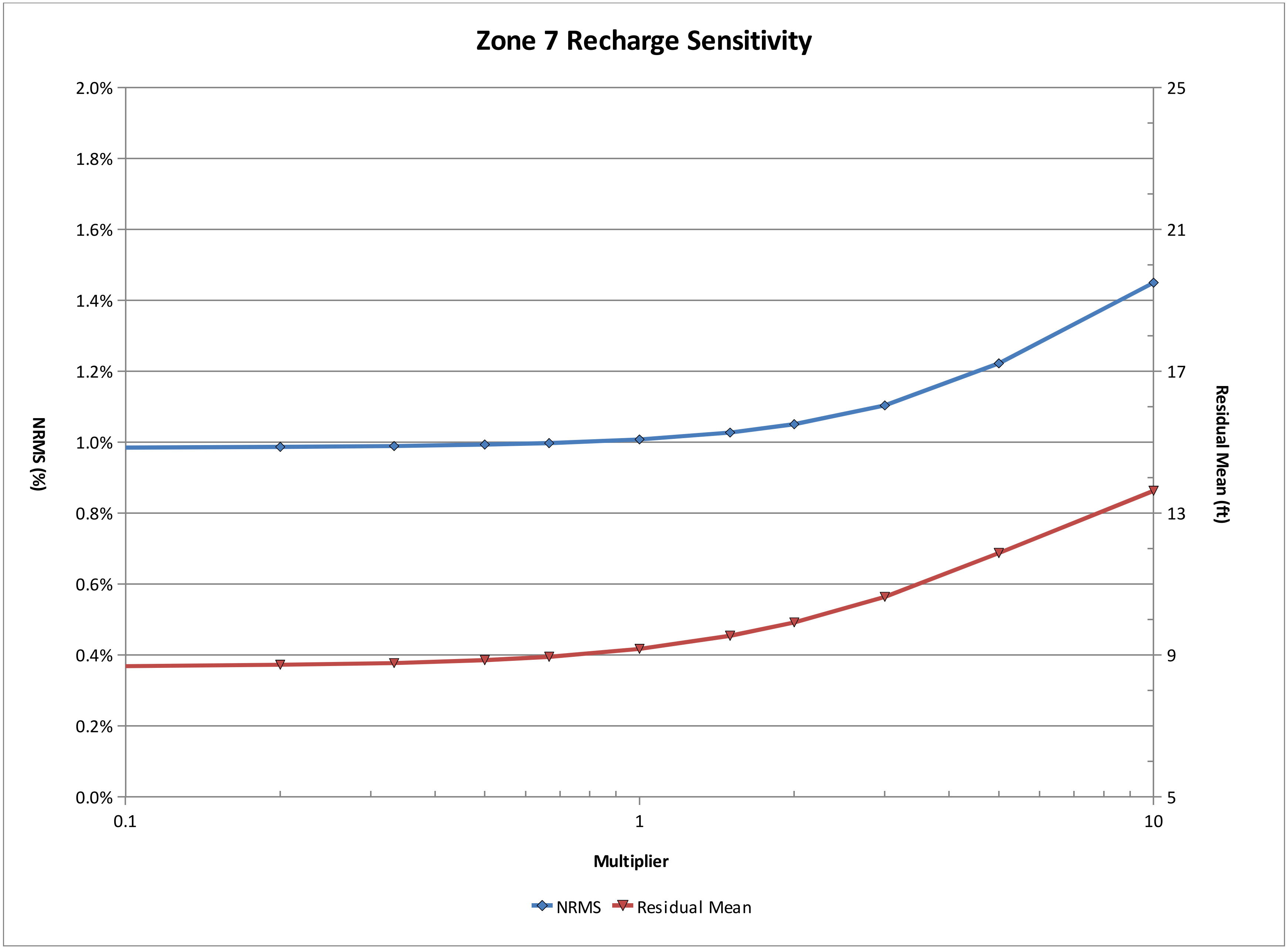
Zone 3 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

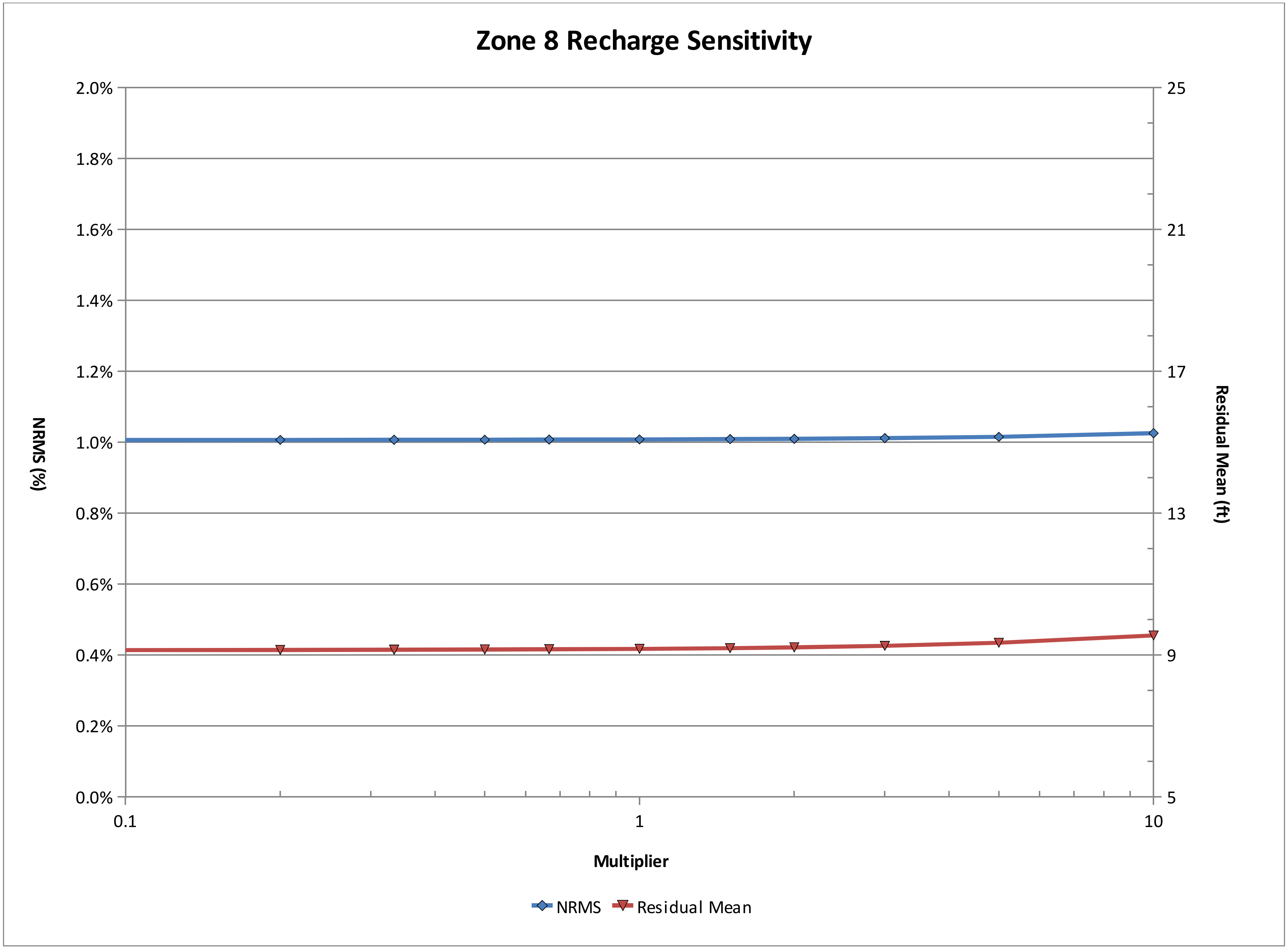


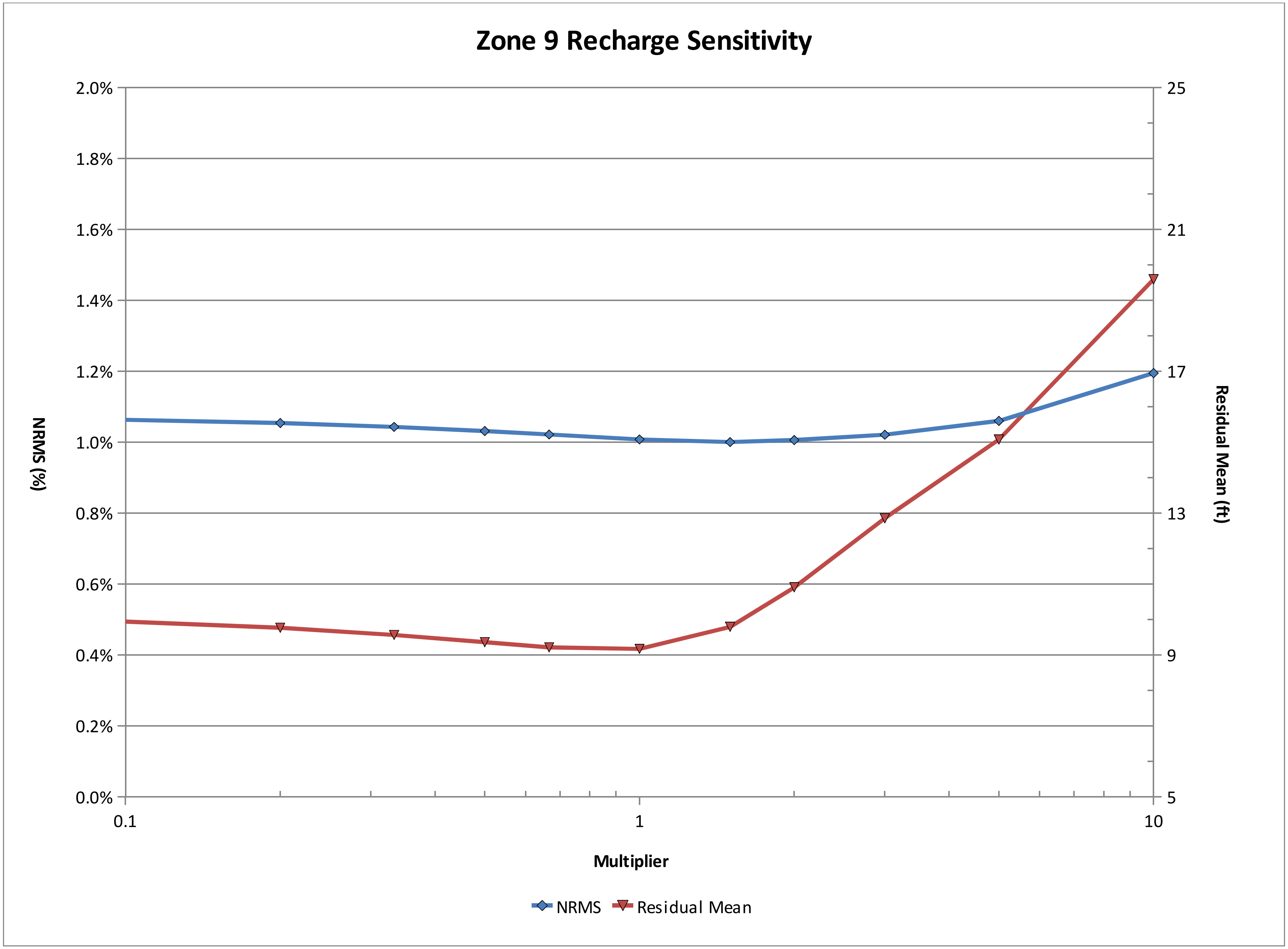
Zone 4 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

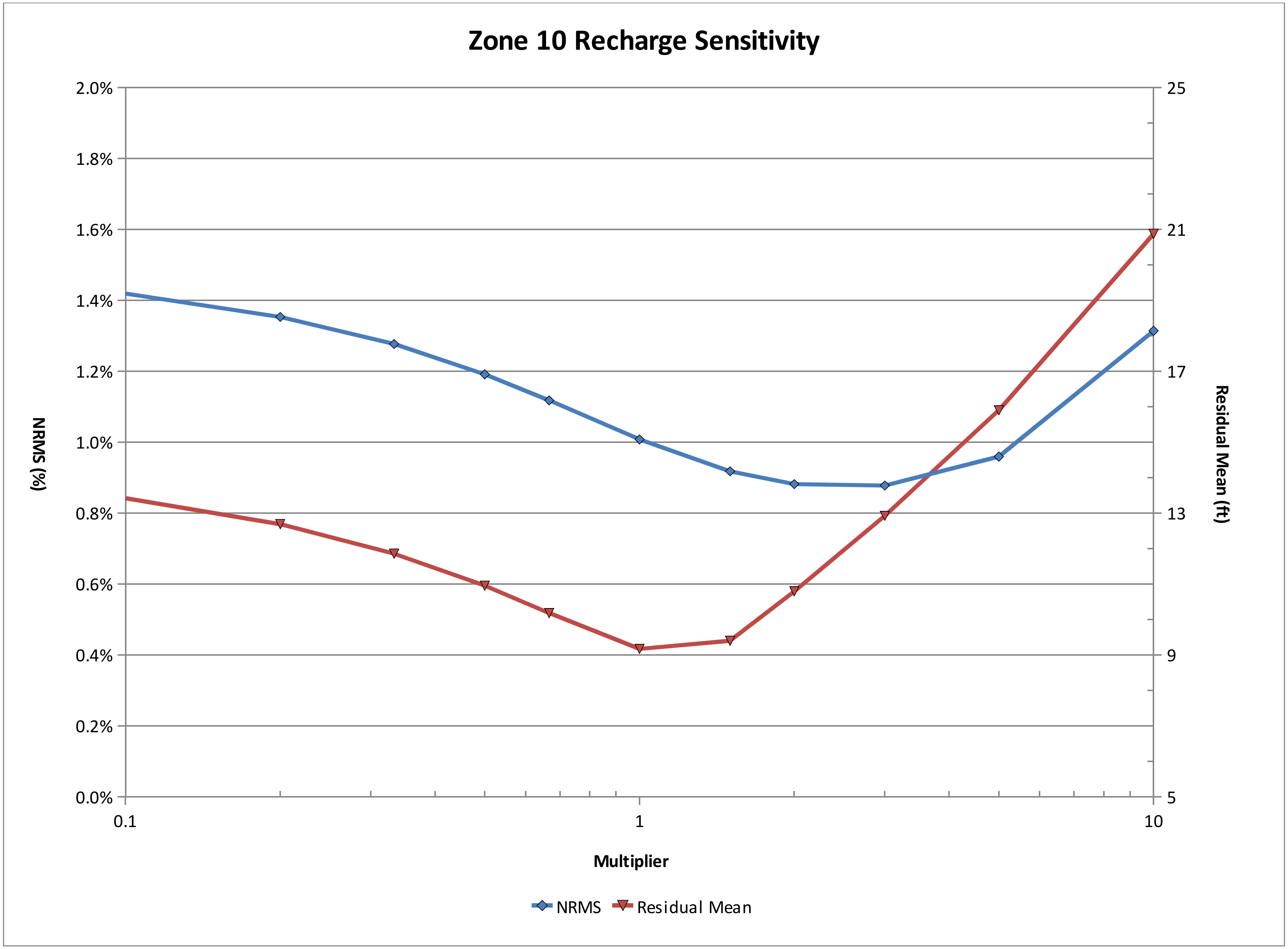

Zone 5 Recharge Sensitivity
NRMS (%)
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
Residual Mean (ft)
25
21
17
13
9
5
0.1
1
10
Multiplier
NRMS
Residual Mean

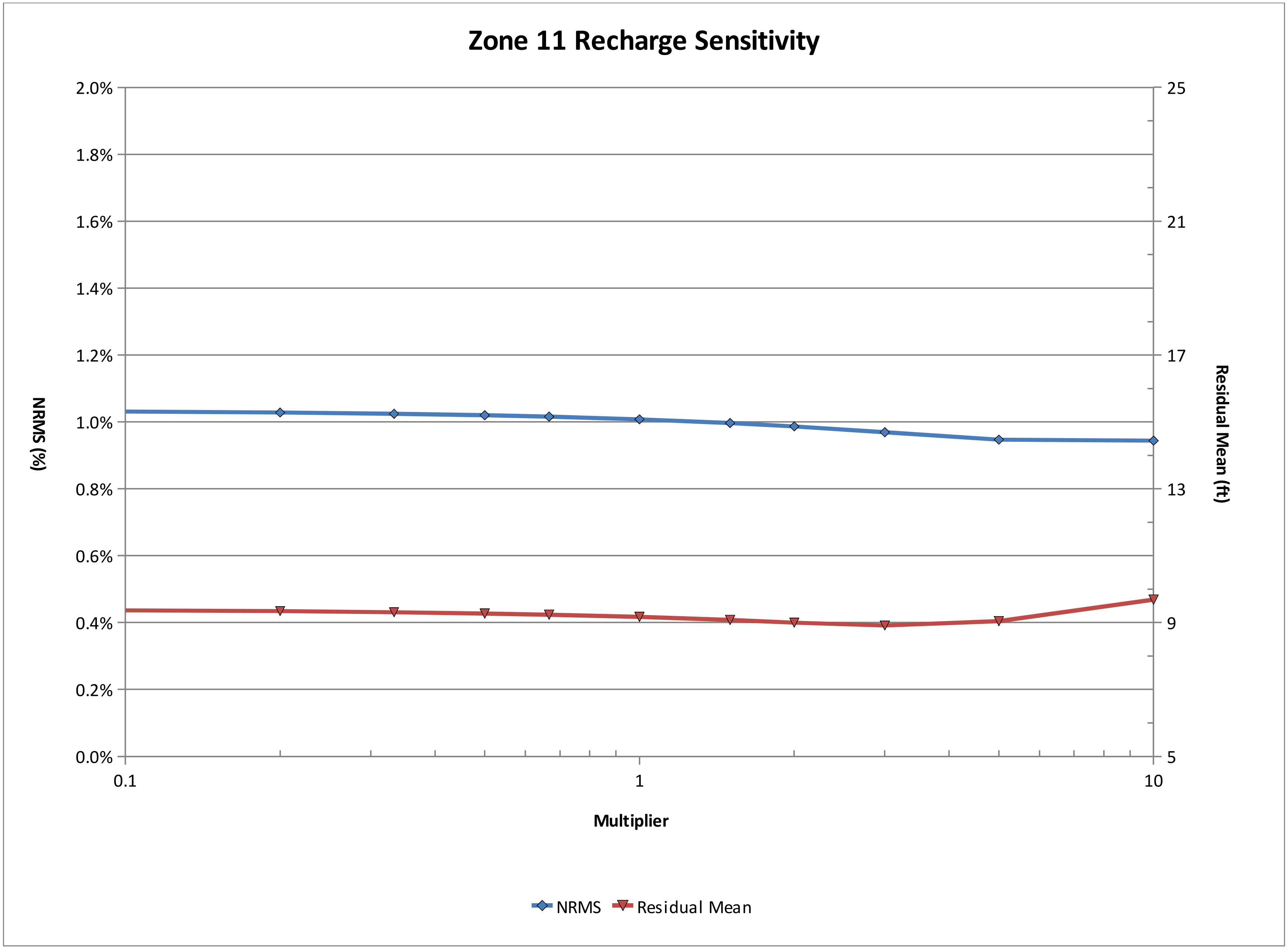

Zone 6 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean


Zone 7 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

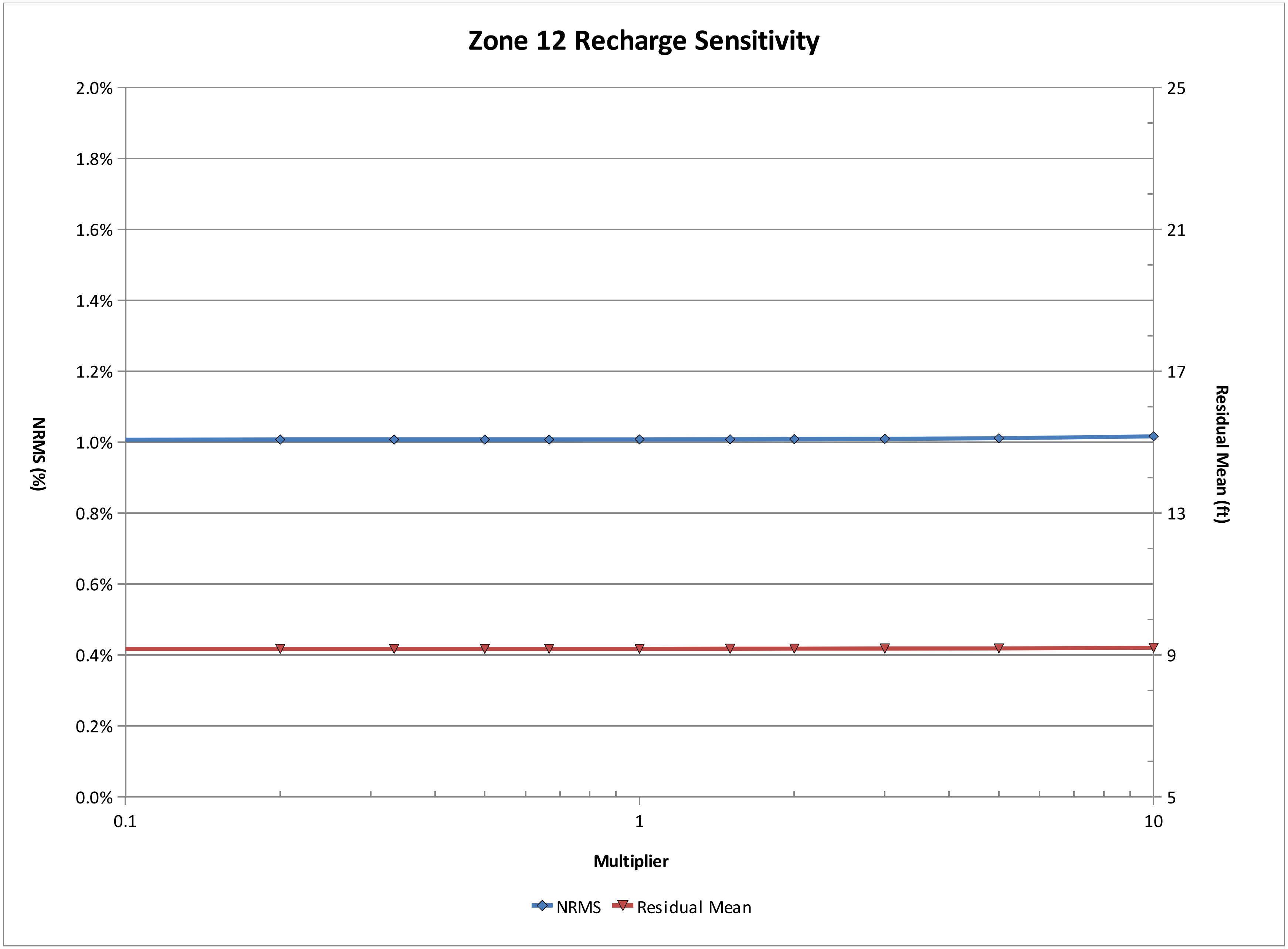

Zone 8 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

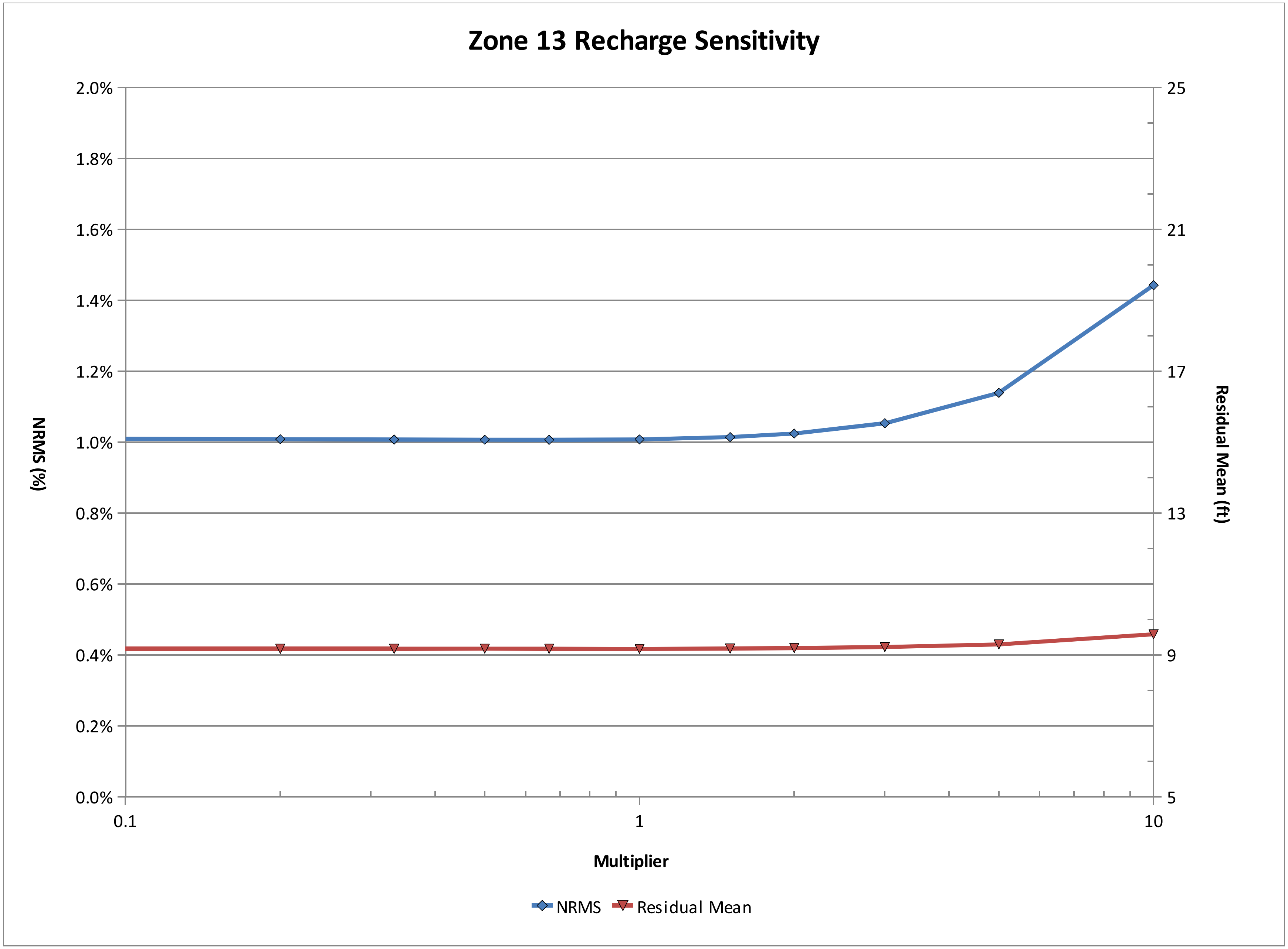

Zone 9 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

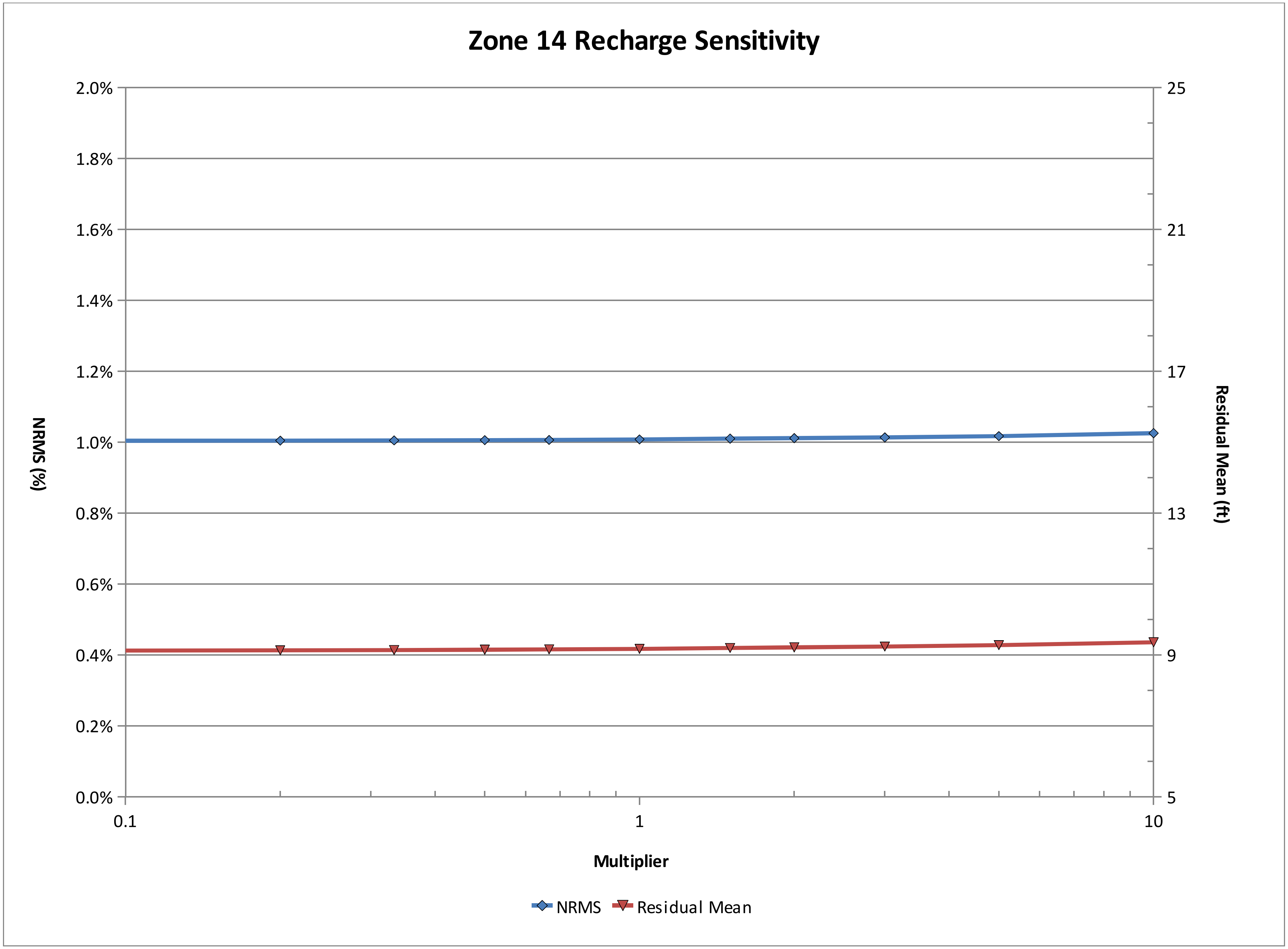

Zone 10 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



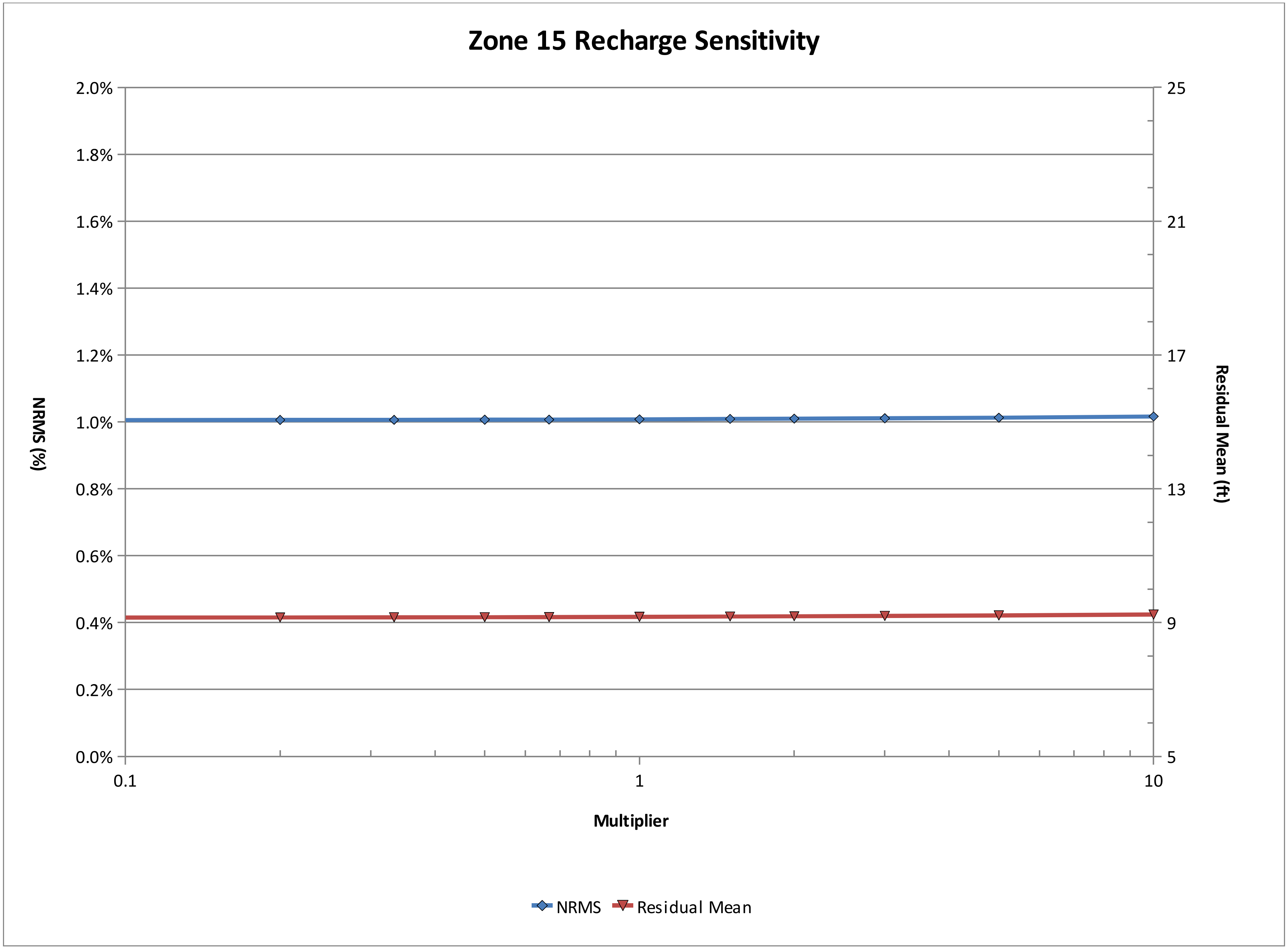
Zone 11 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean


Zone 12 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

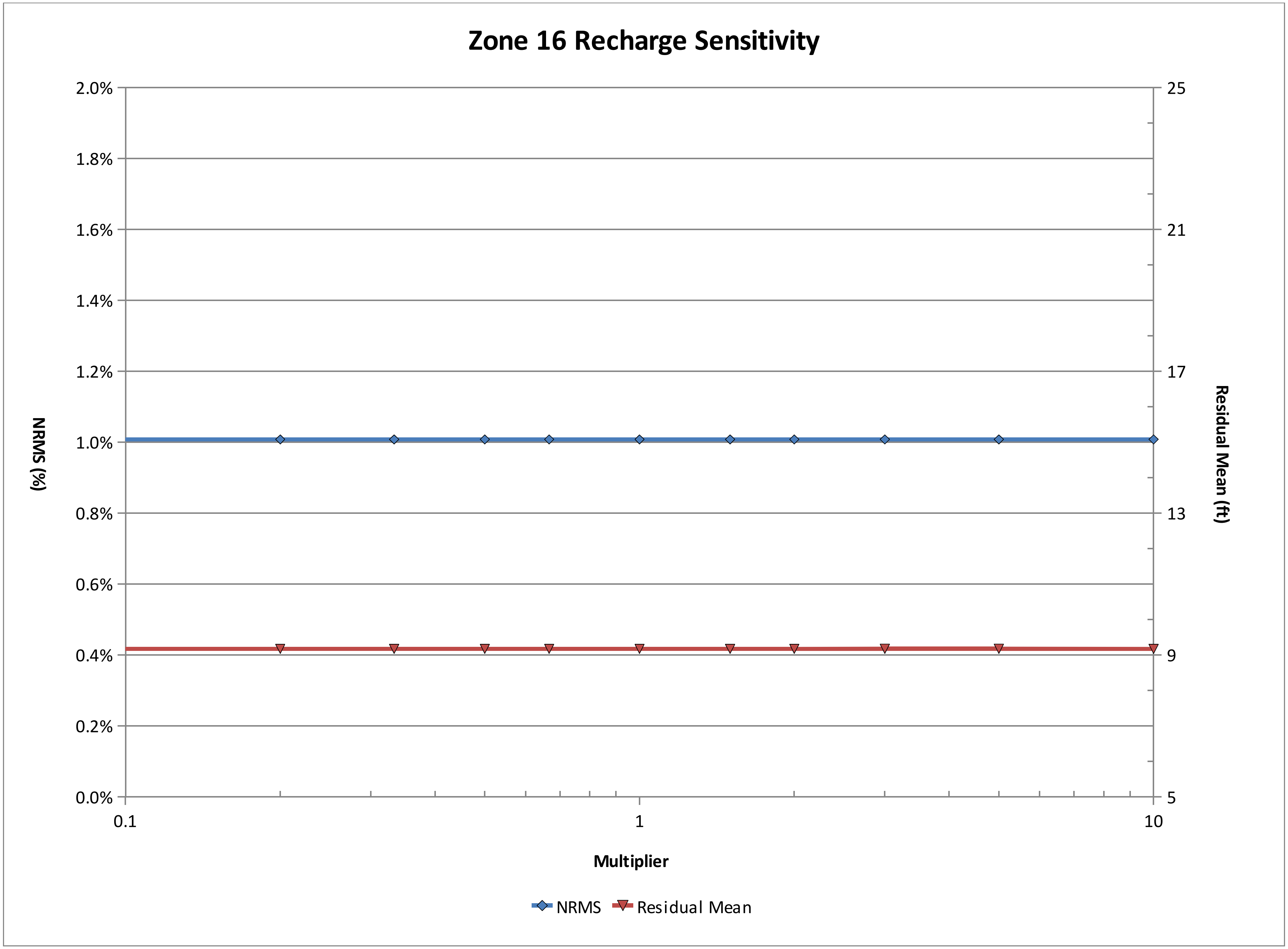

Zone 13 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



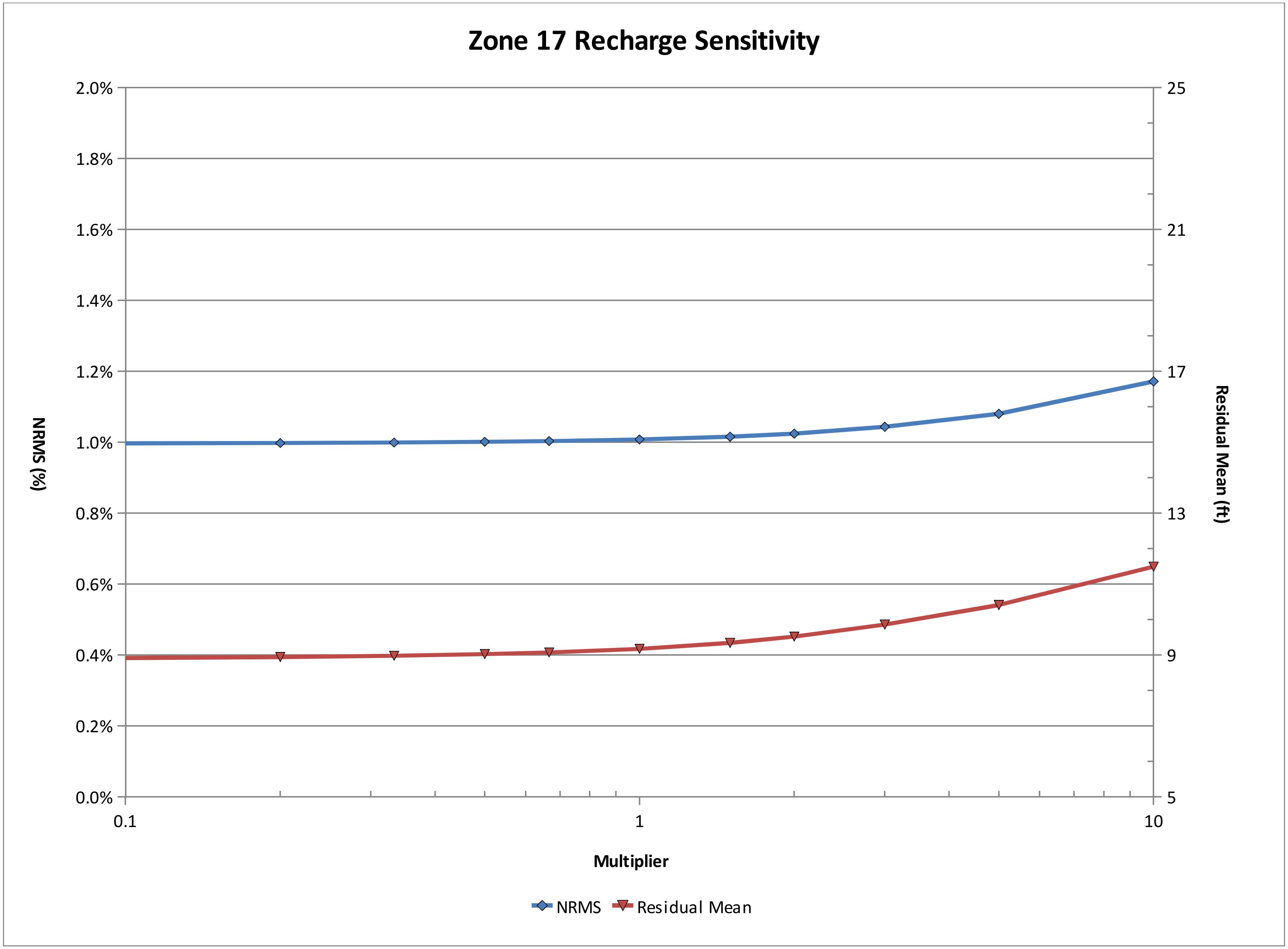
Zone 14 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



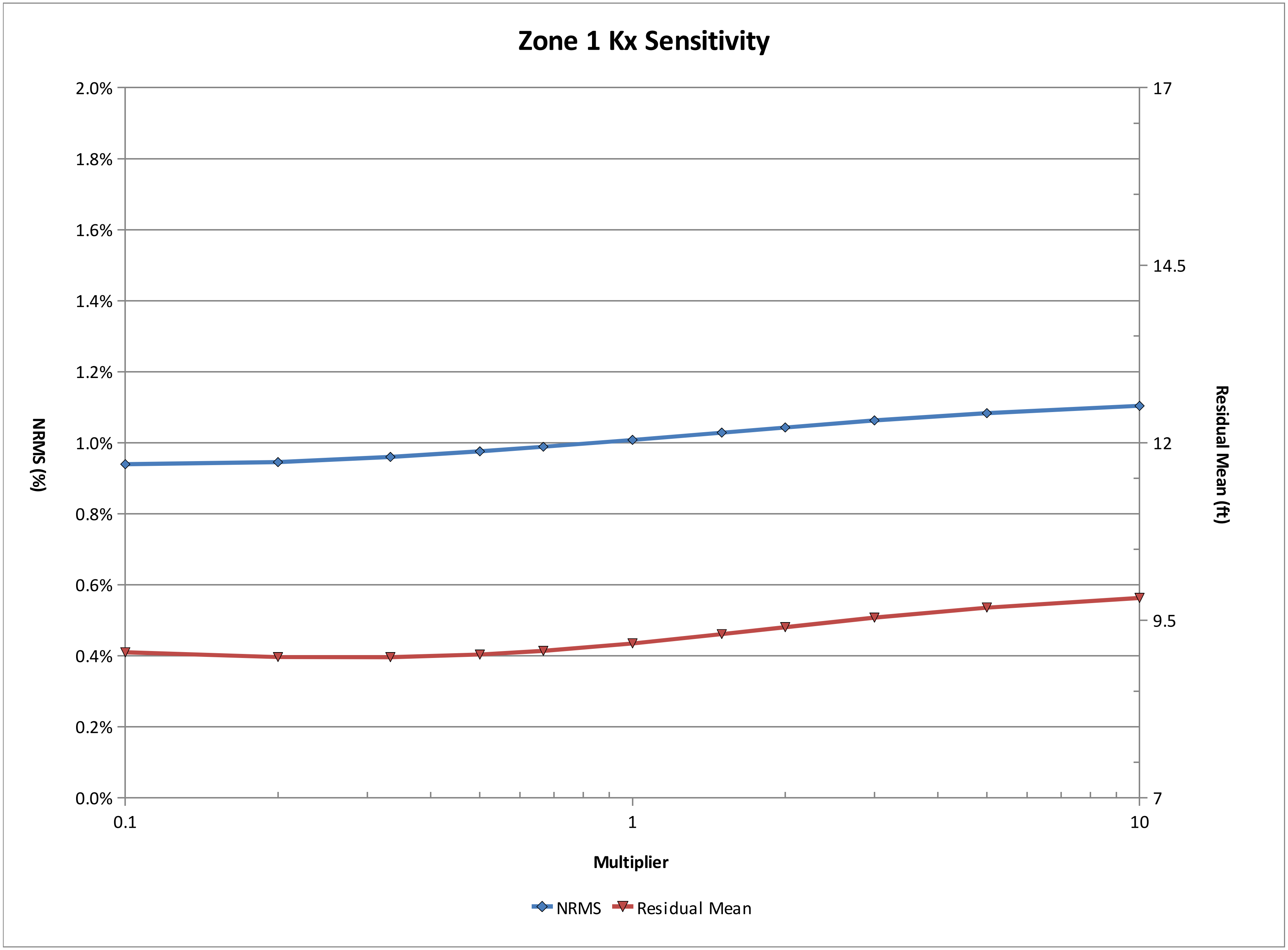
Zone 15 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



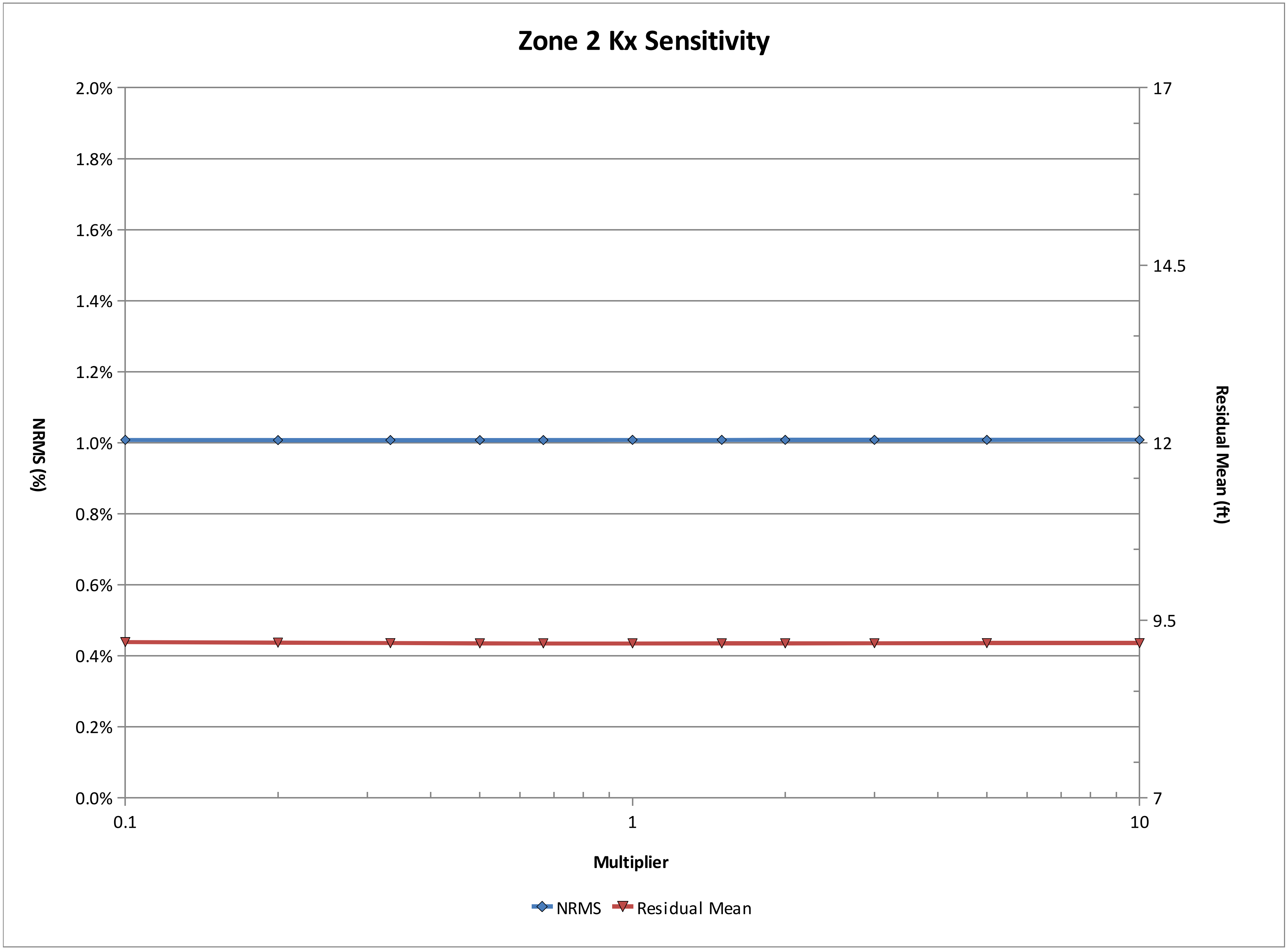
Zone 16 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean


Zone 17 Recharge Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
25
21
17
13
9
5
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

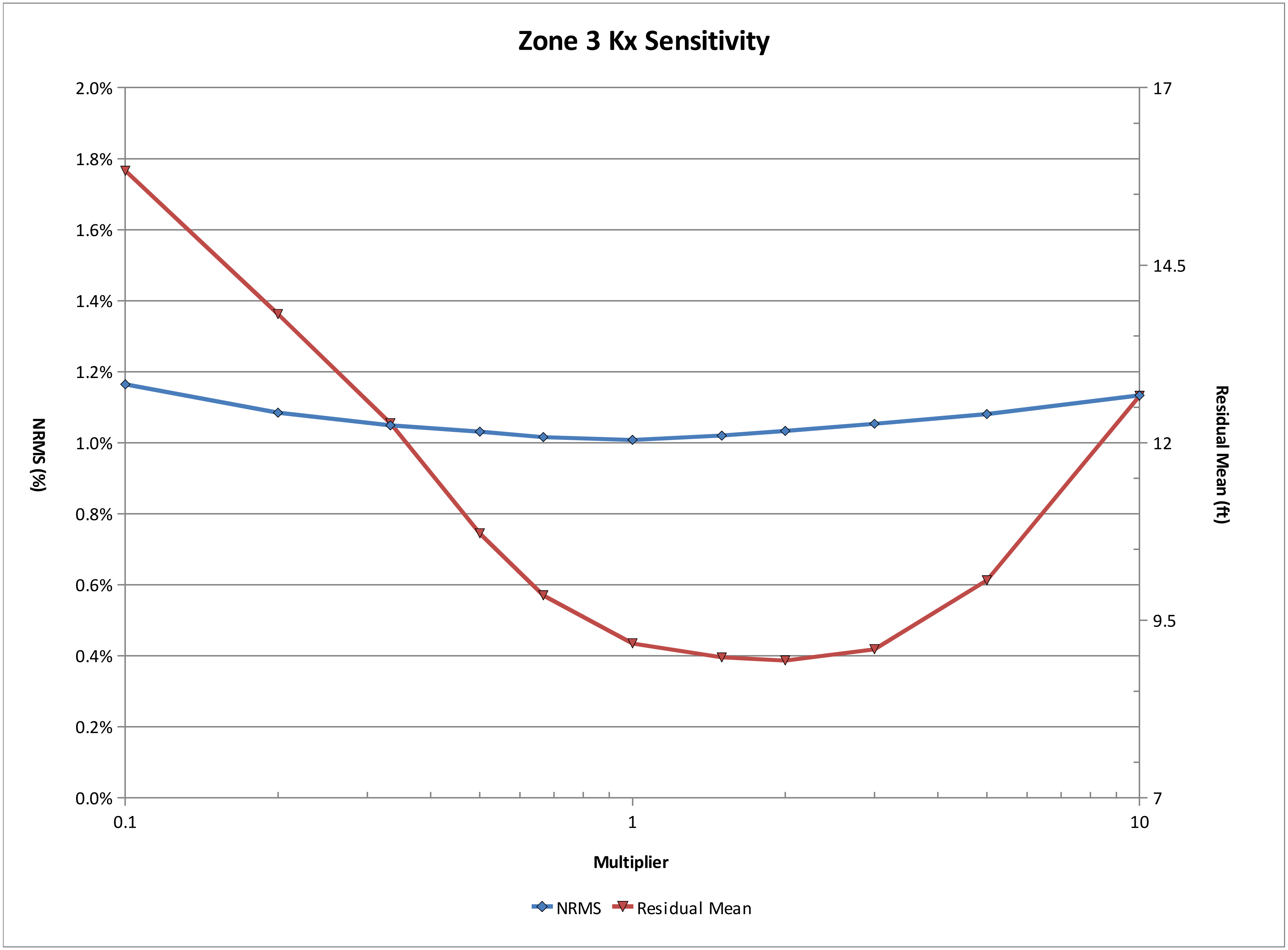
Hydraulic Conductivity Sensitivity by Zone



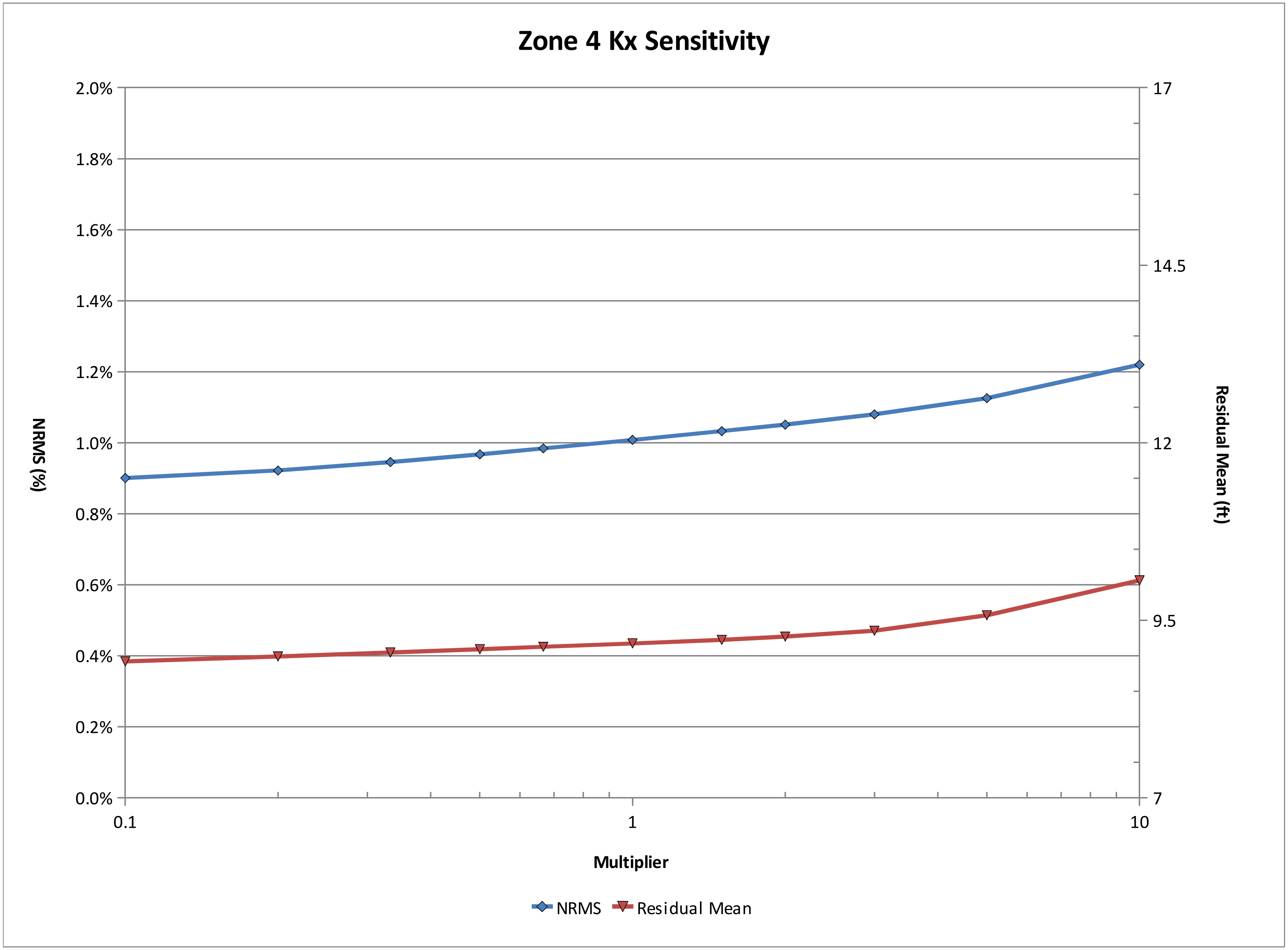
Zone 1 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



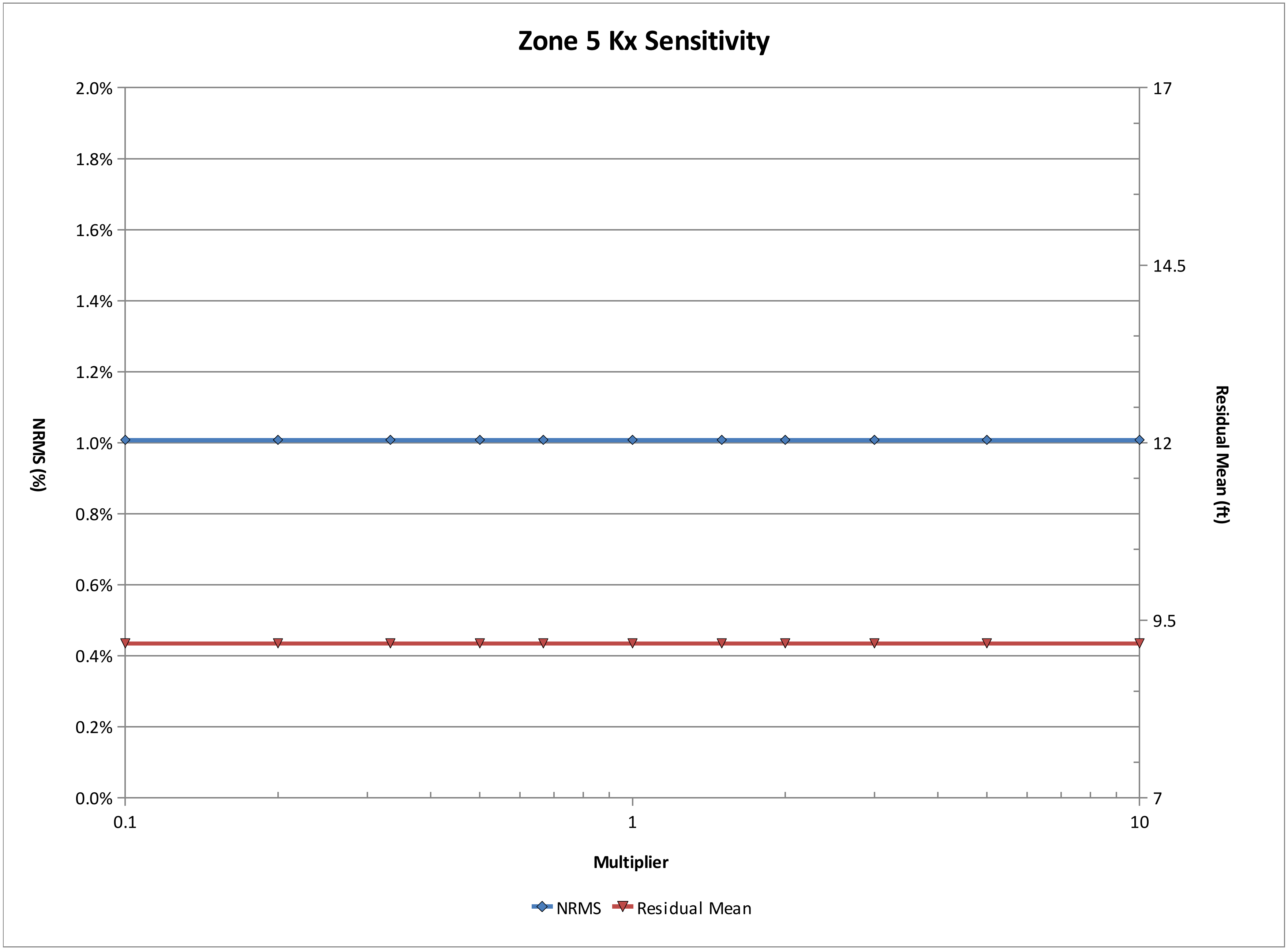
Zone 2 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

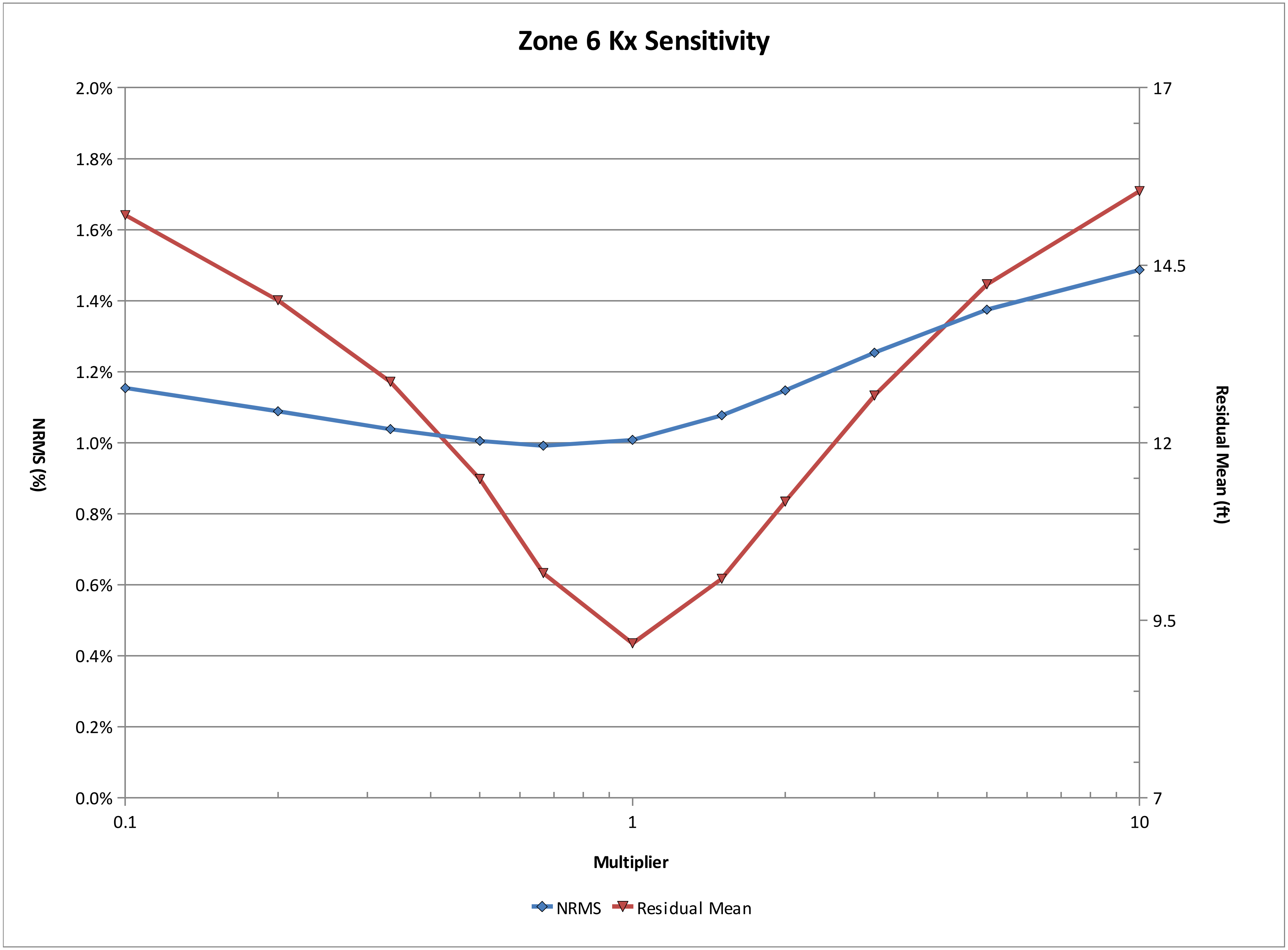


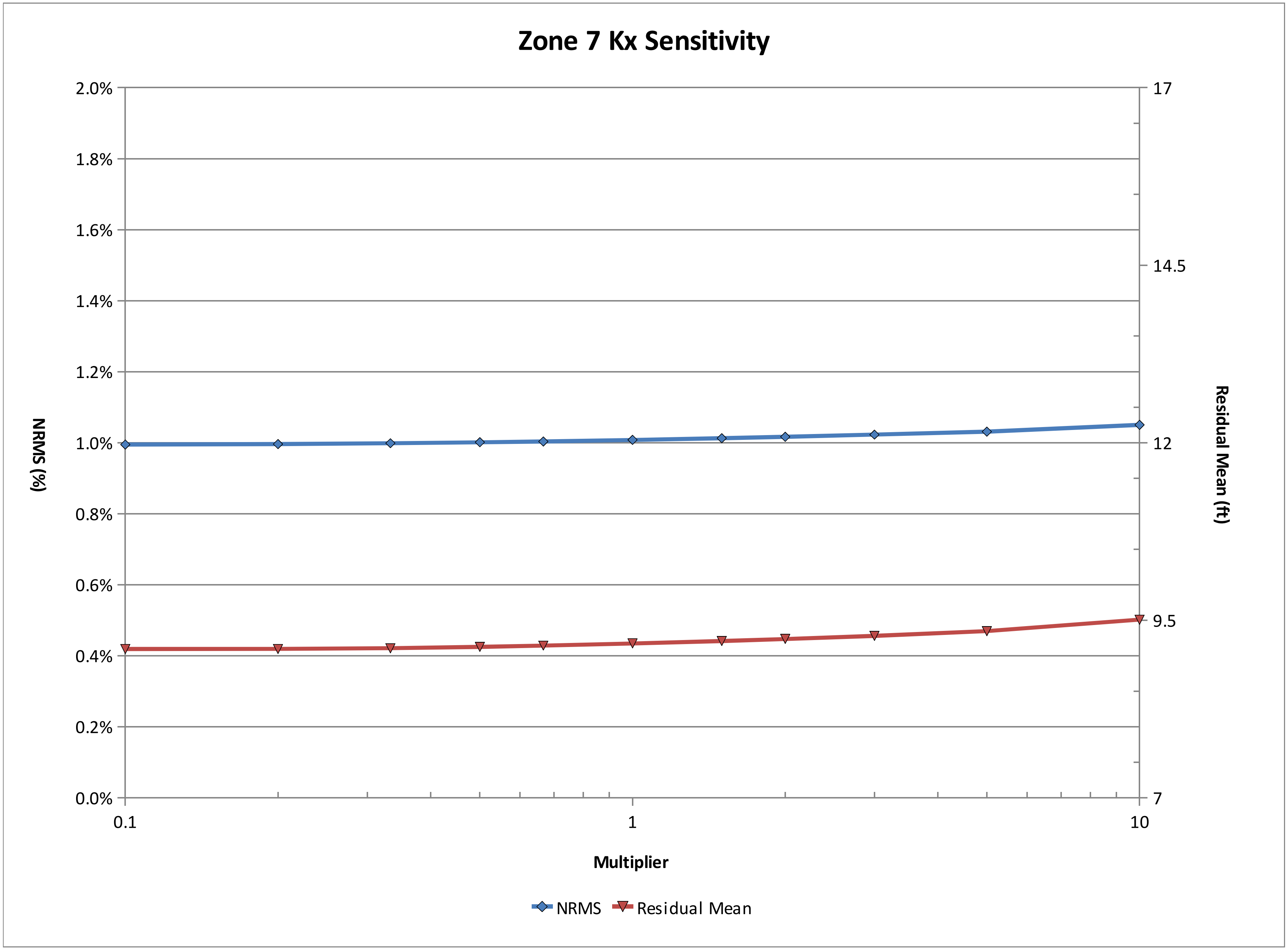
Zone 3 Kx Sensitivity
NRMS (%)
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
Residual Mean (ft)
17
14.5
12
9.5
7
0.1
1
10
Multiplier
NRMS
Residual Mean

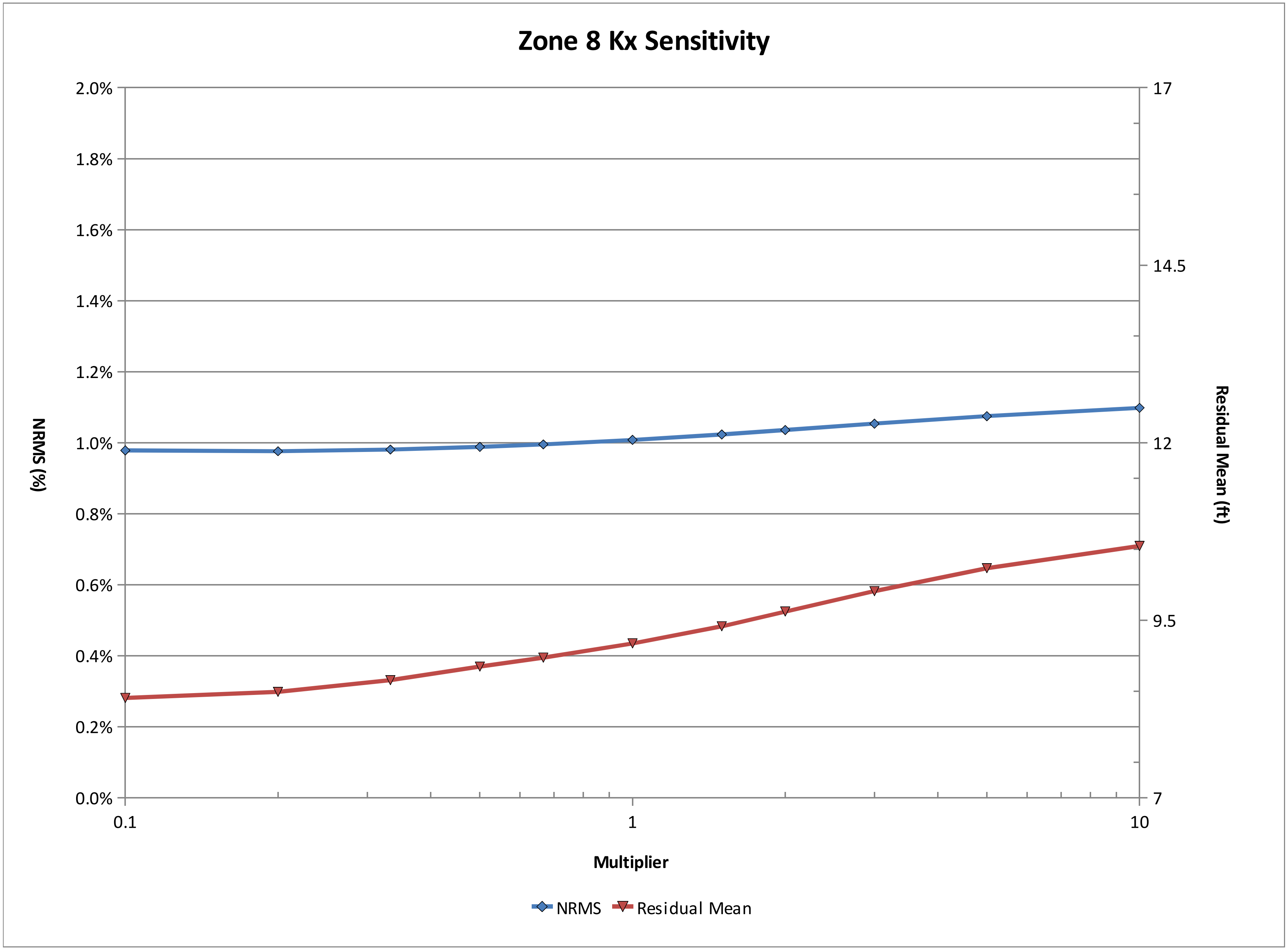


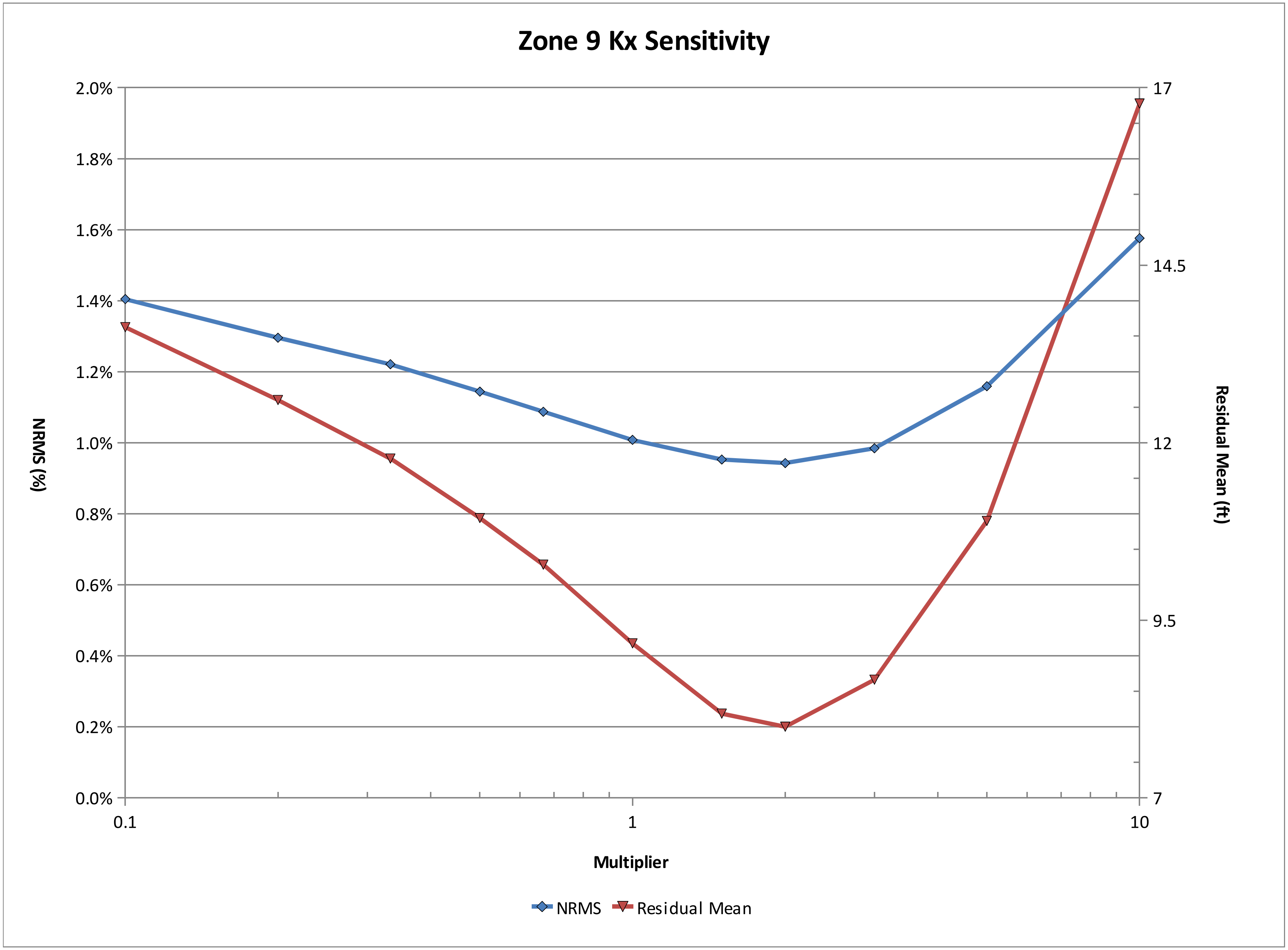
Zone 4 Kx Sensitivity
NRMS (%)
Residual Mean (ft)
Multiplier
0.0%
0.2%
0.4%
0.6%
0.8%
1.0%
1.2%
1.4%
1.6%
1.8%
2.0%
7
9.5
12
14.5
17
0.1
1
10
NRMS
Residual Mean

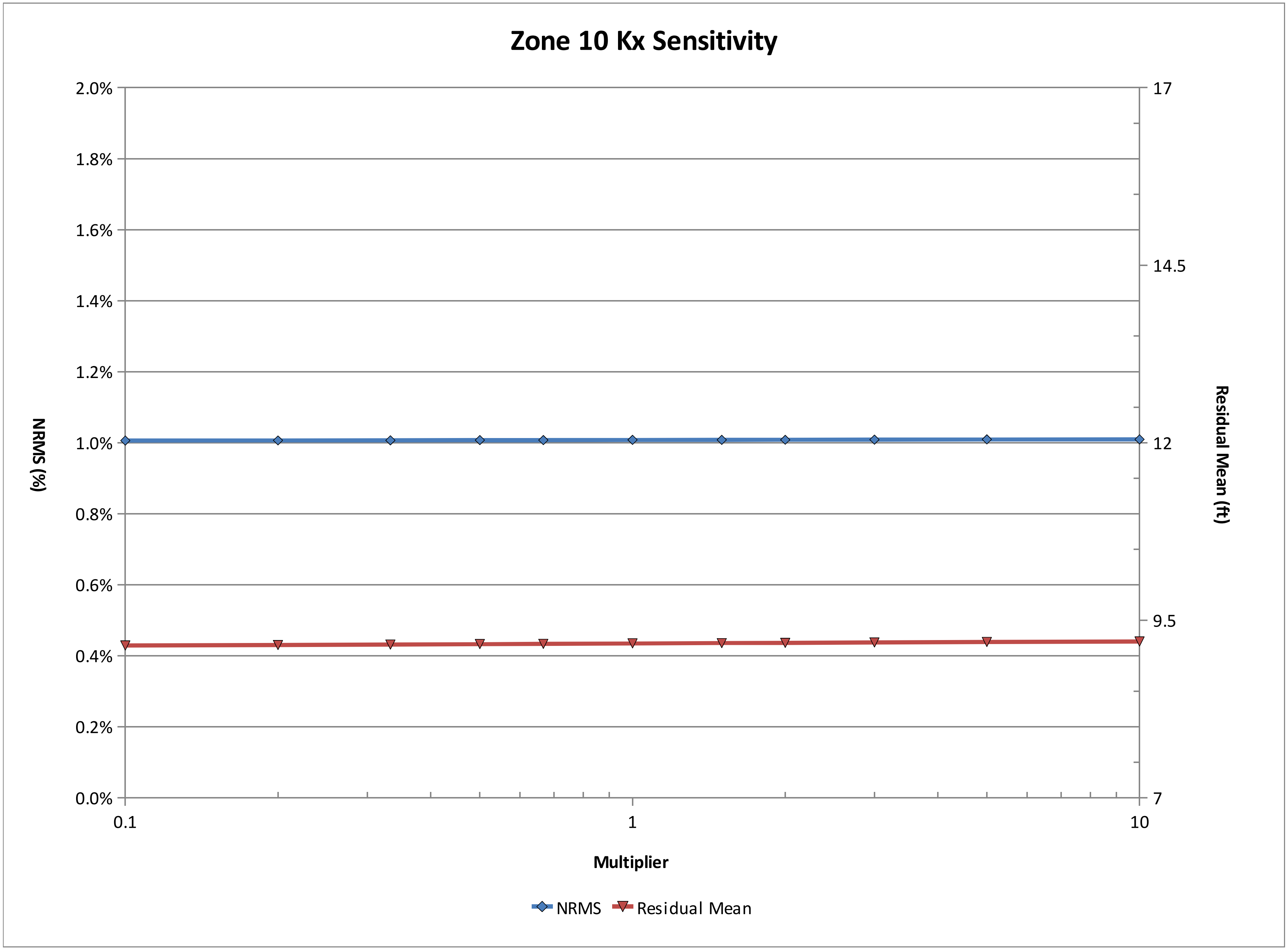

Zone 5 Kx Sensitivity
NRMS (%)
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
Residual Mean (ft)
17
14.5
12
9.5
7
0.1
1
10
Multiplier
NRMS
Residual Mean


Zone 6 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

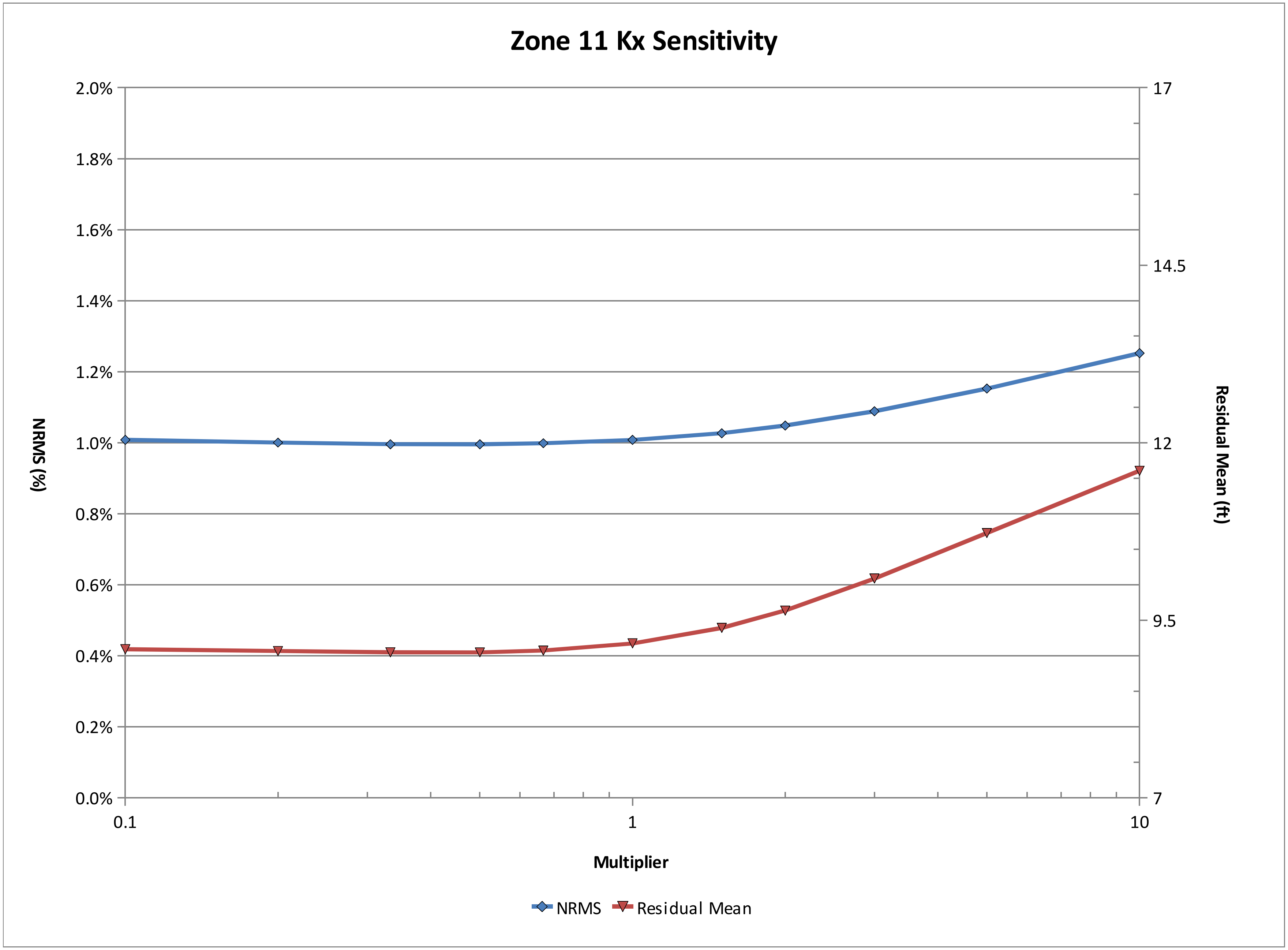

Zone 7 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean


Zone 8 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

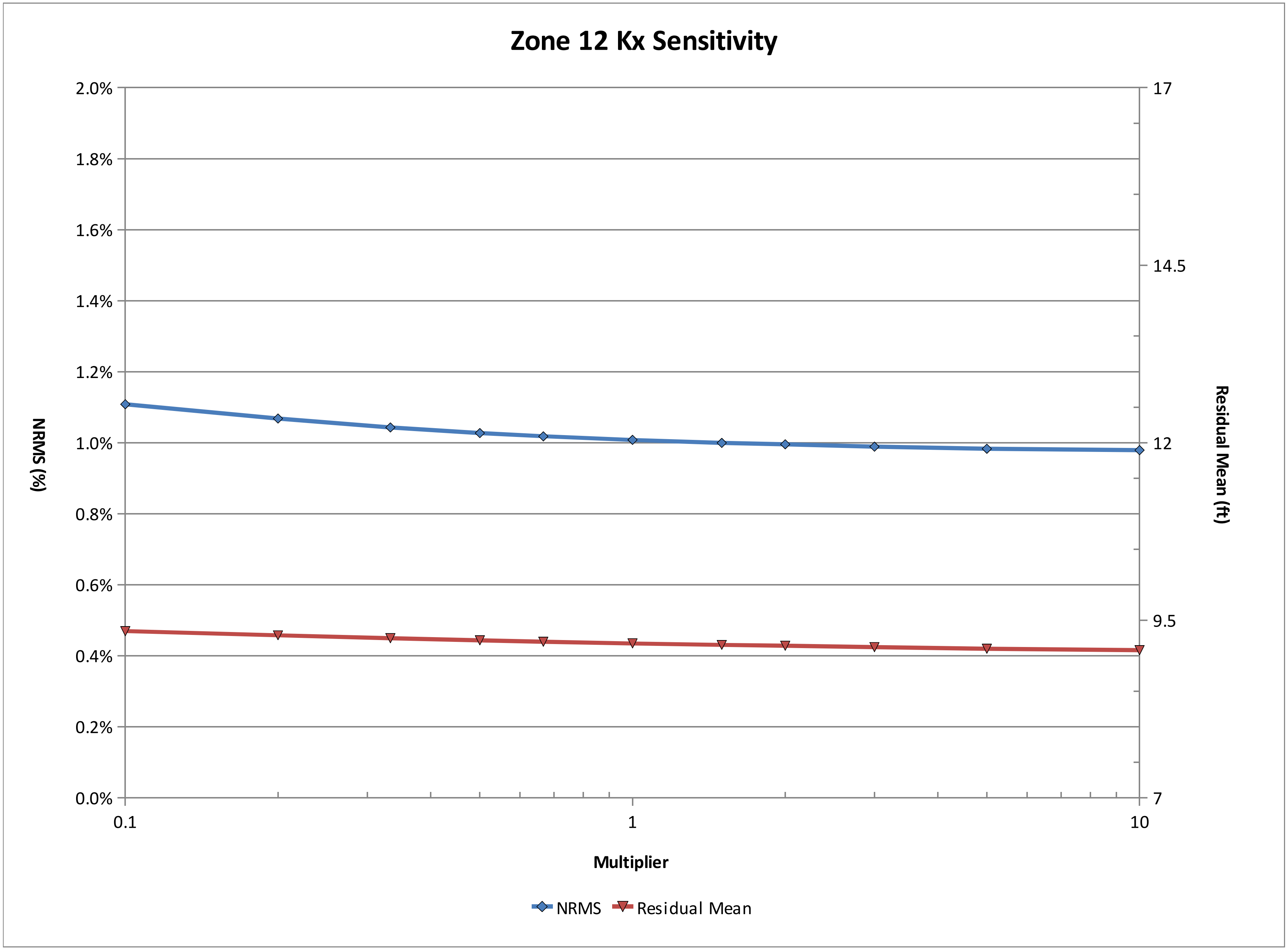

Zone 9 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



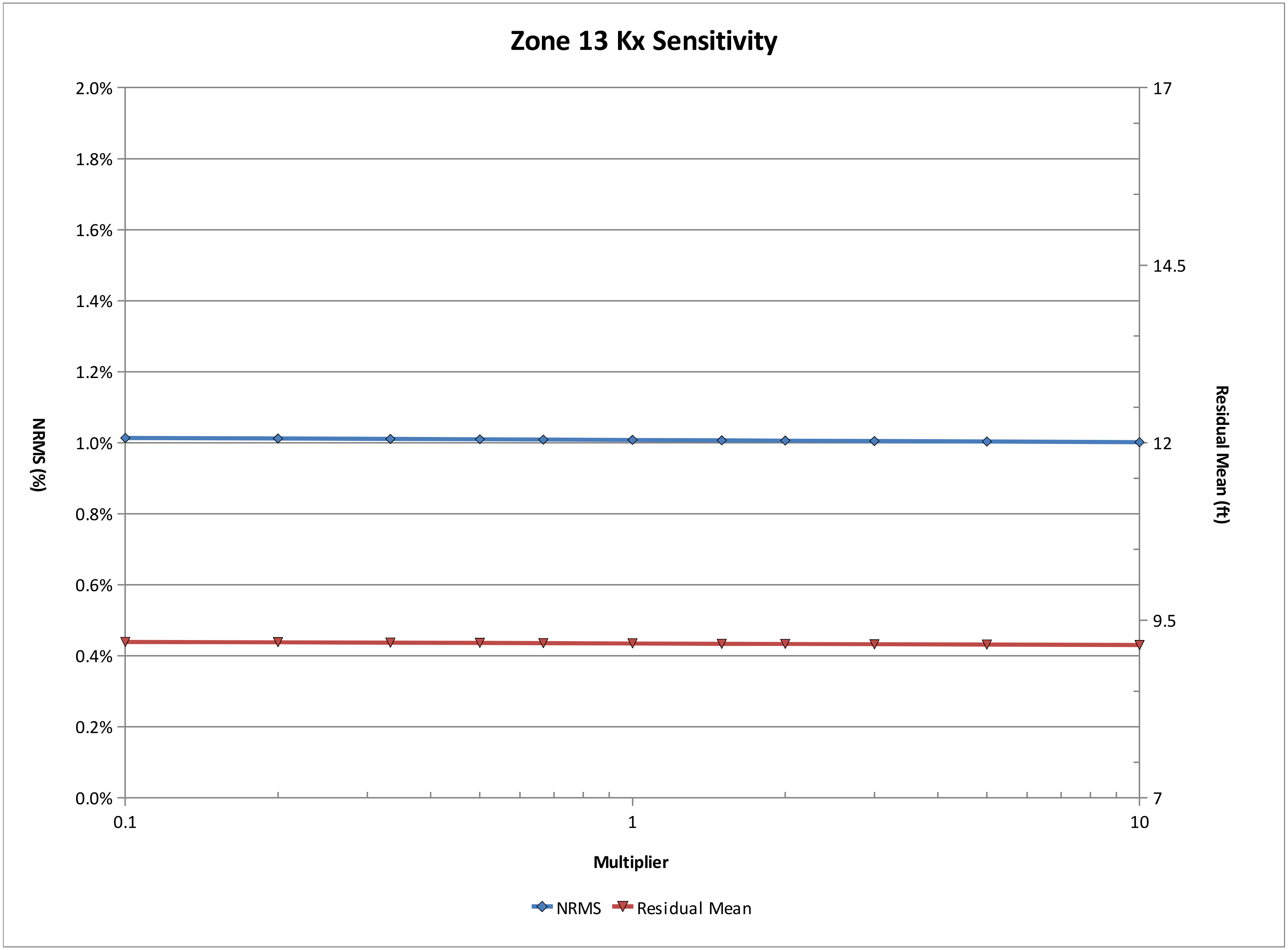
Zone 10 Kx Sensitivity
NRMS (%)
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
Residual Mean (ft)
17
14.5
12
9.5
7
0.1
1
10
Multiplier
NRMS
Residual Mean

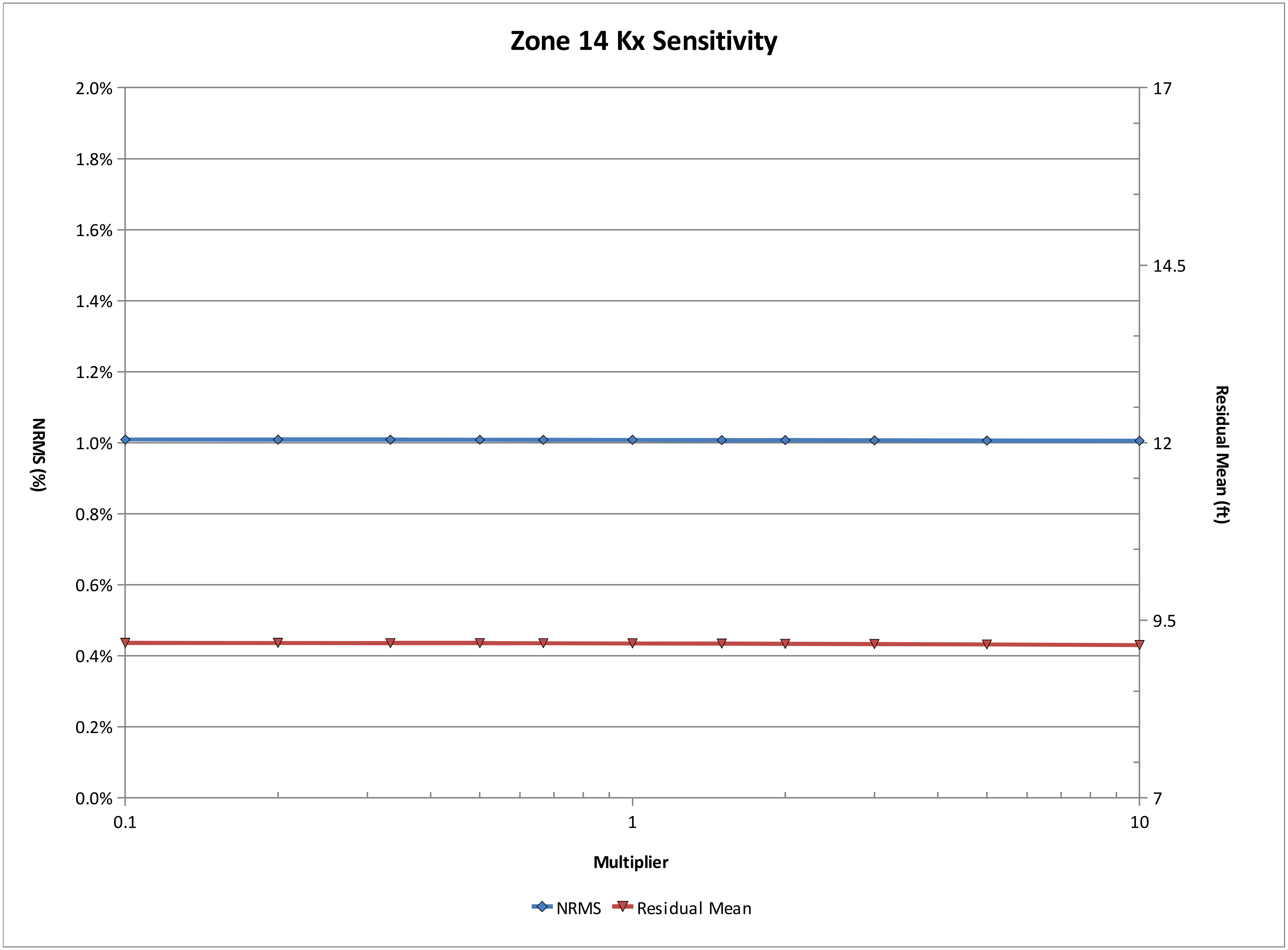


Zone 11 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

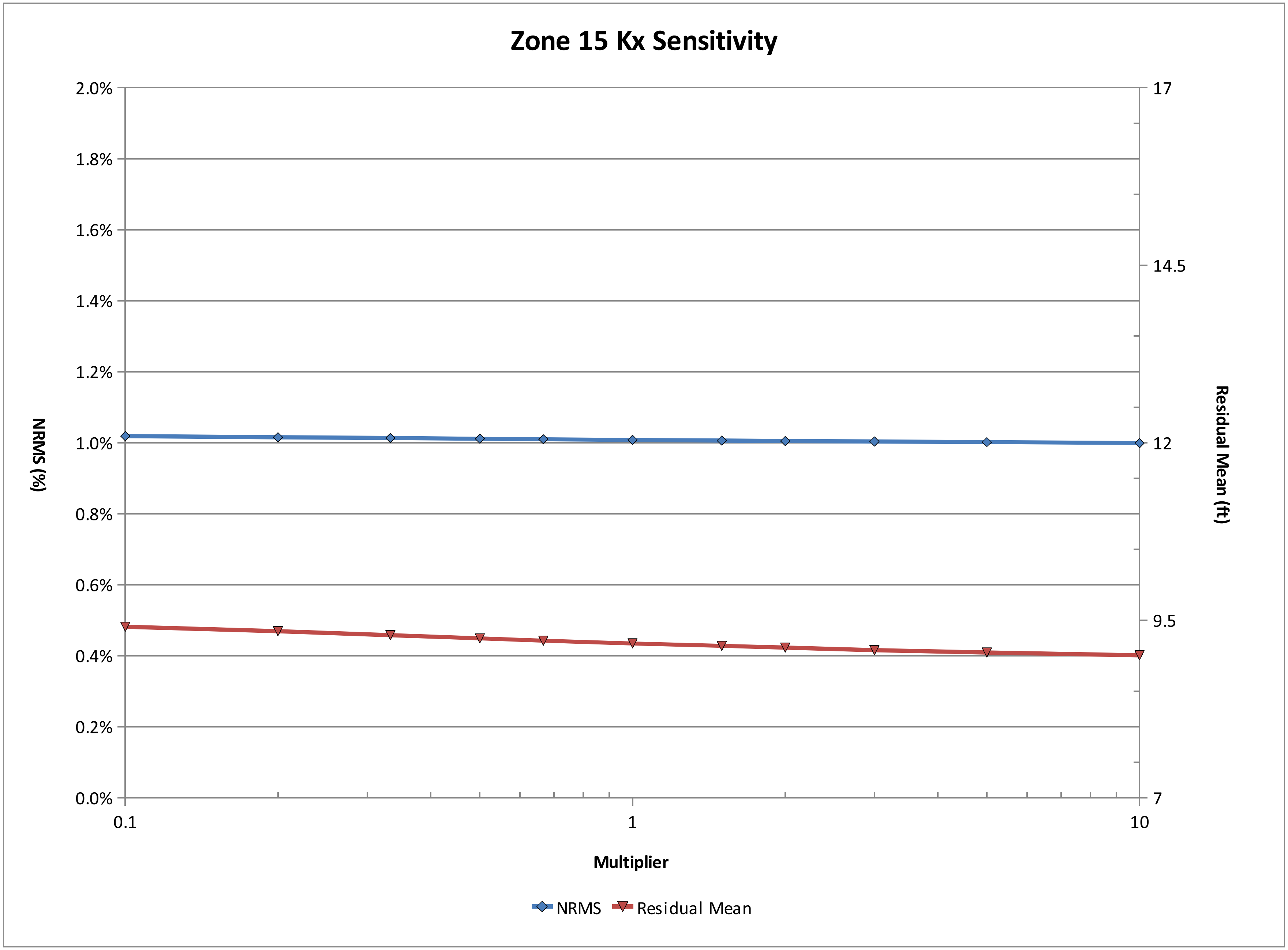


Zone 12 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

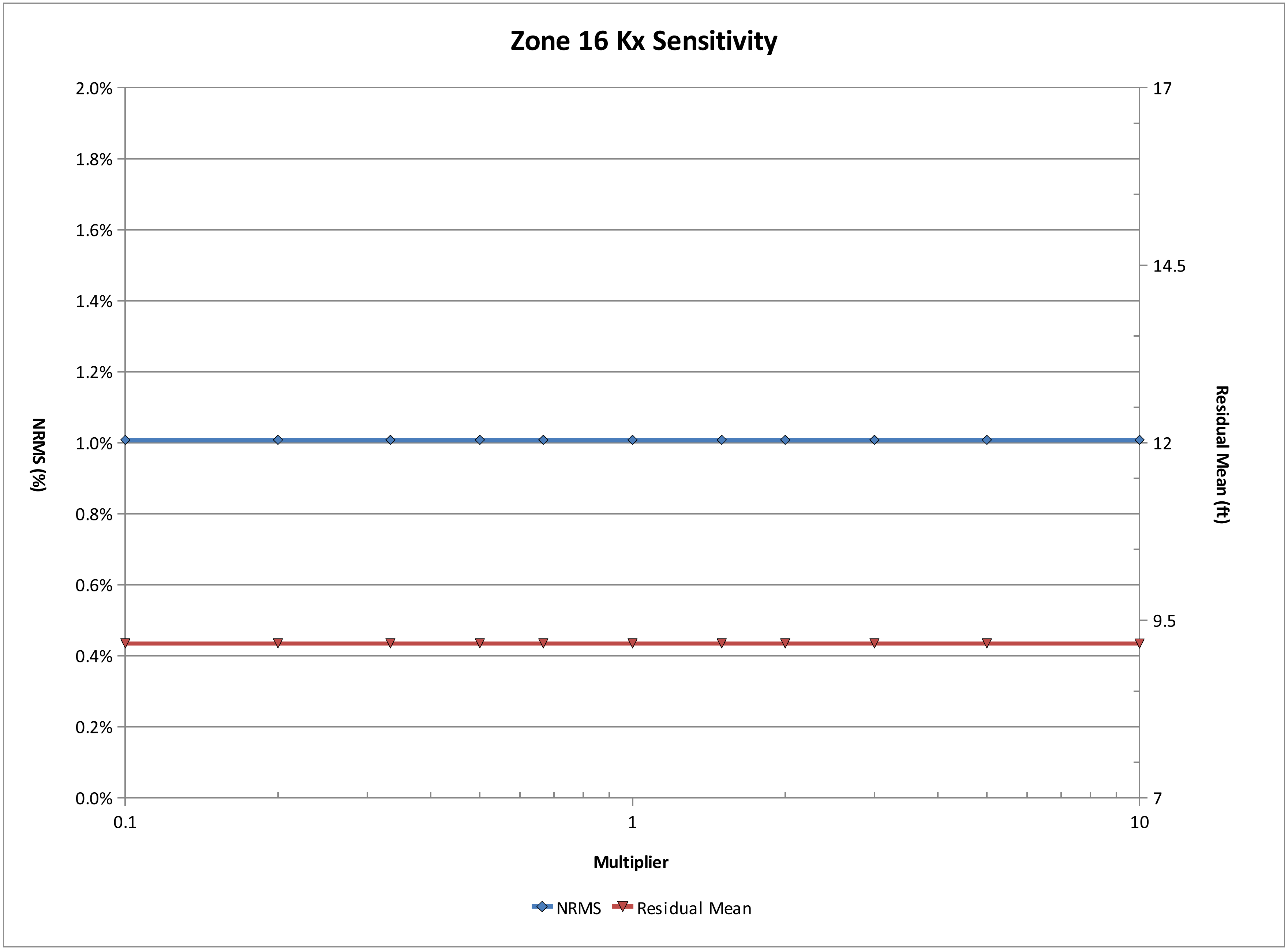

Zone 13 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean



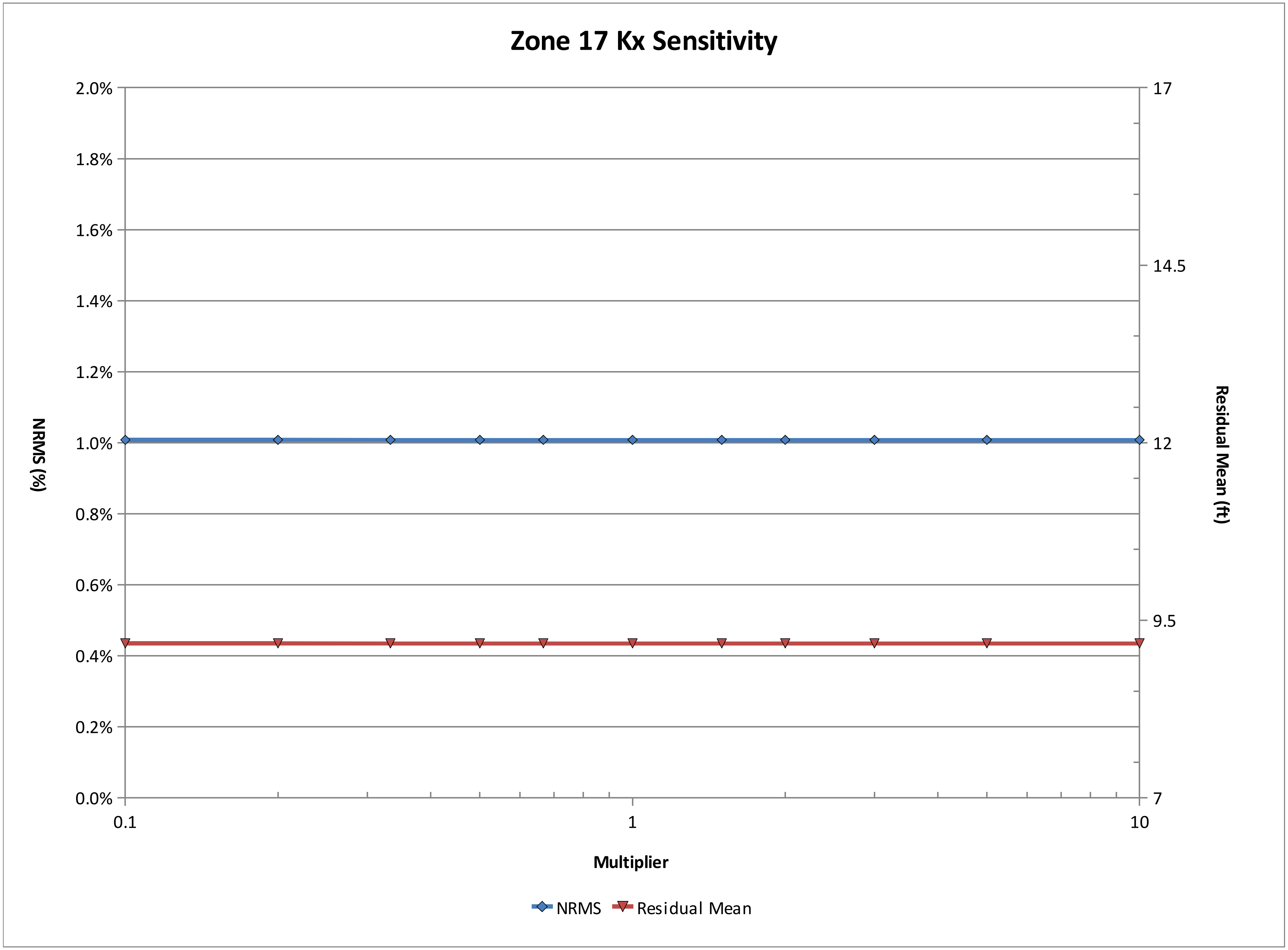
Zone 14 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

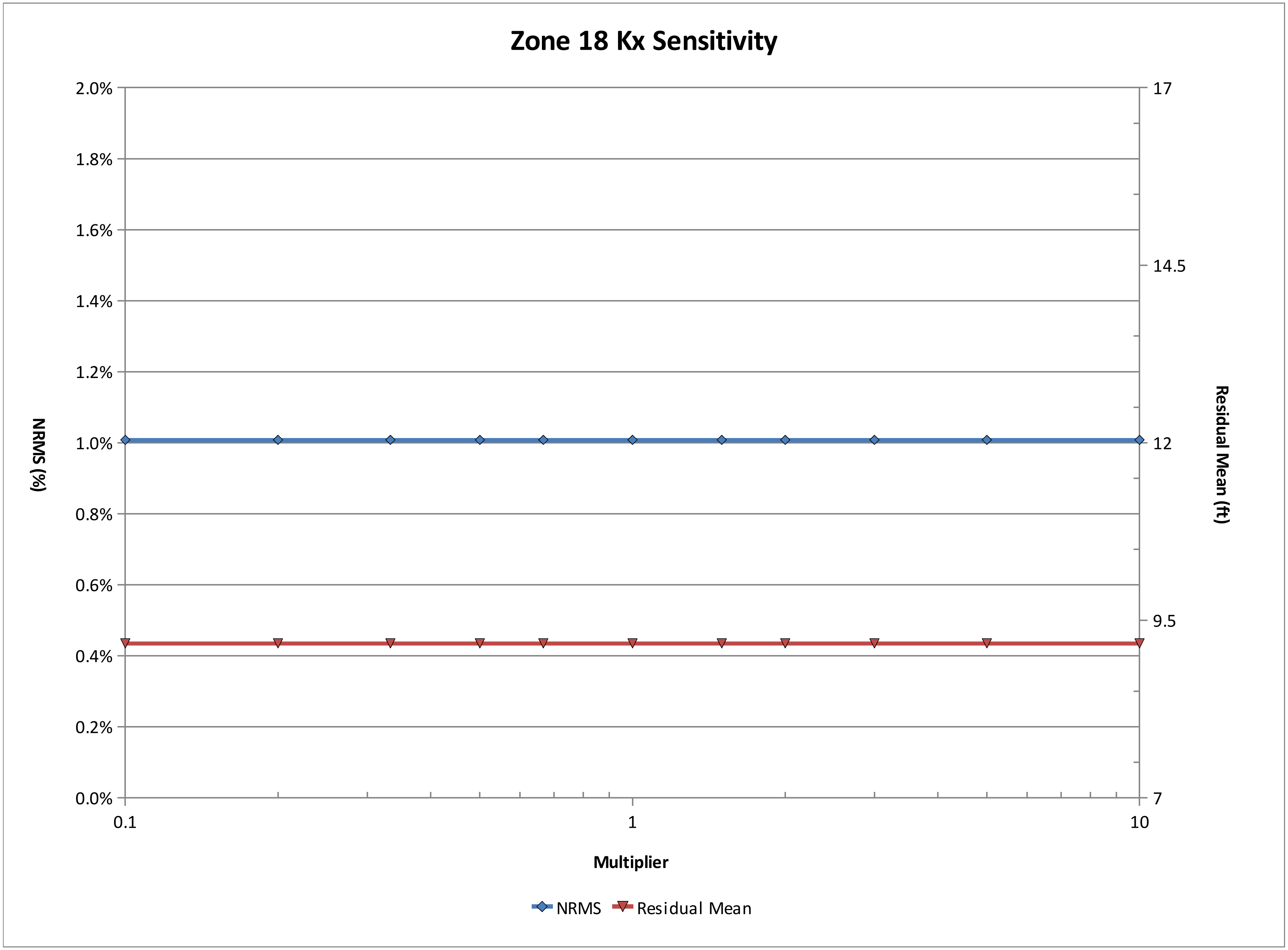


Zone 15 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

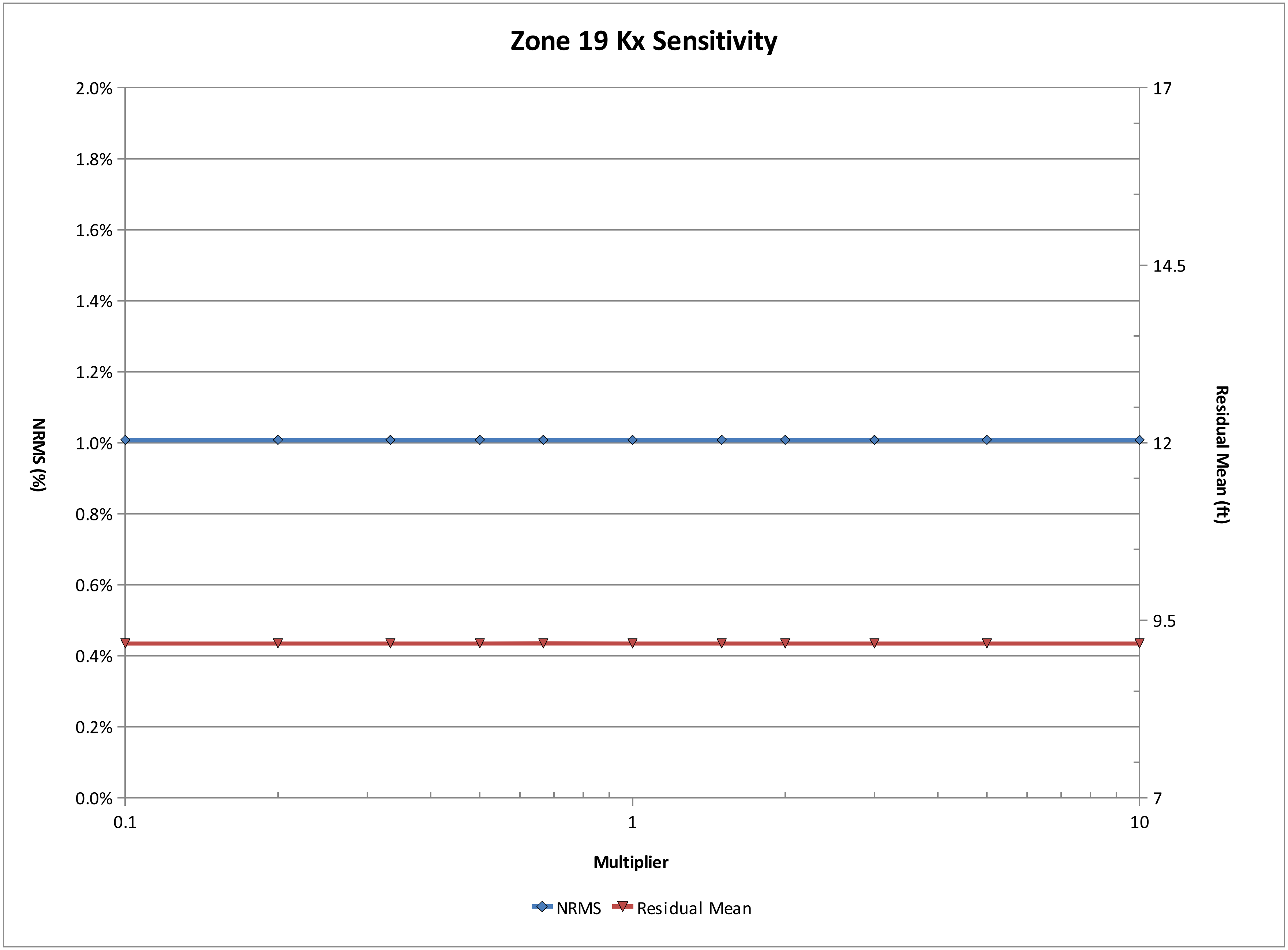


Zone 16 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean


Zone 17 Kx Sensitivity
NRMS (%)
Residual Mean (ft)
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
17
14.5
12
9.5
7
0.1
1
10
Multiplier
NRMS
Residual Mean

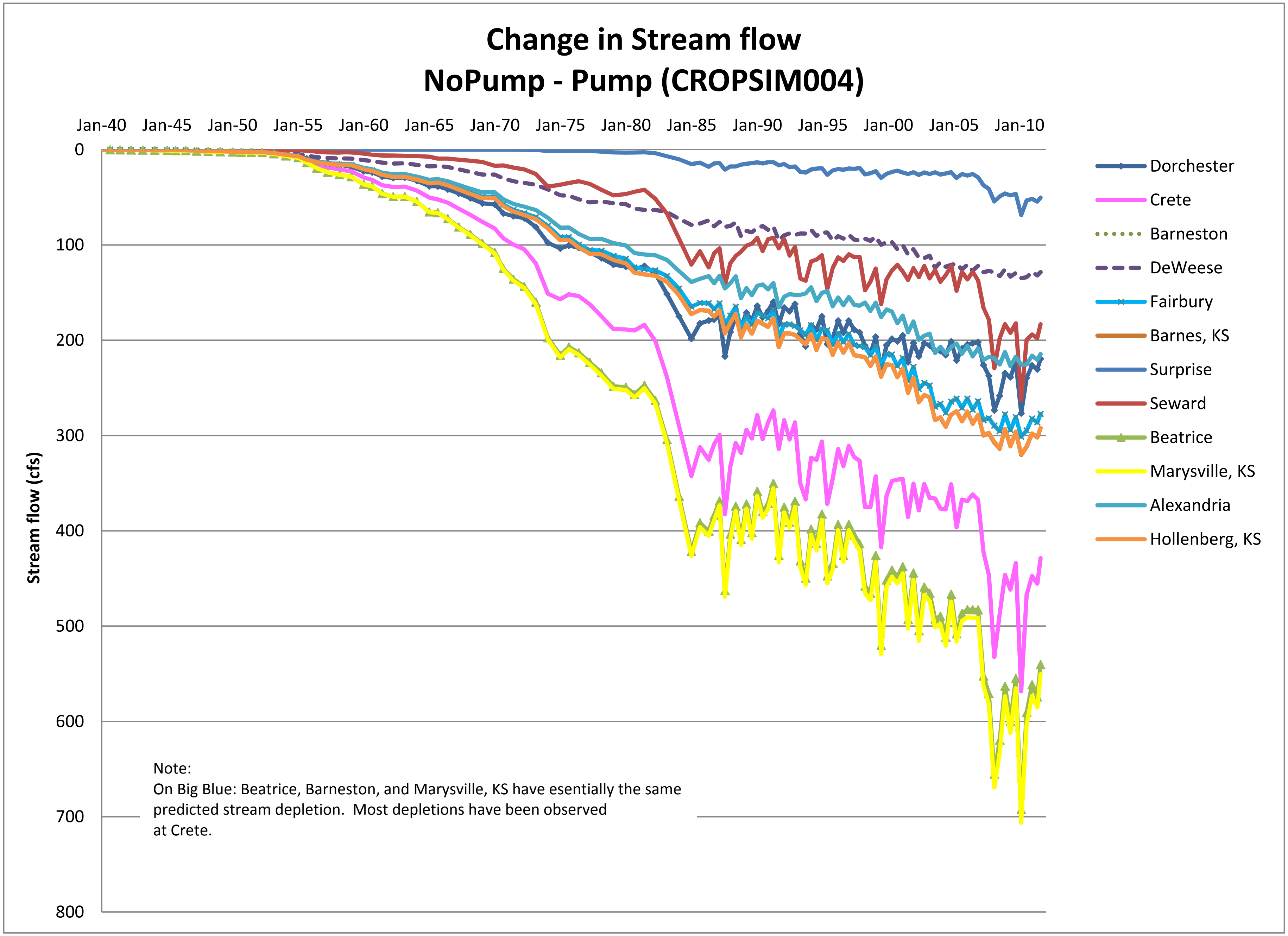


Zone 18 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

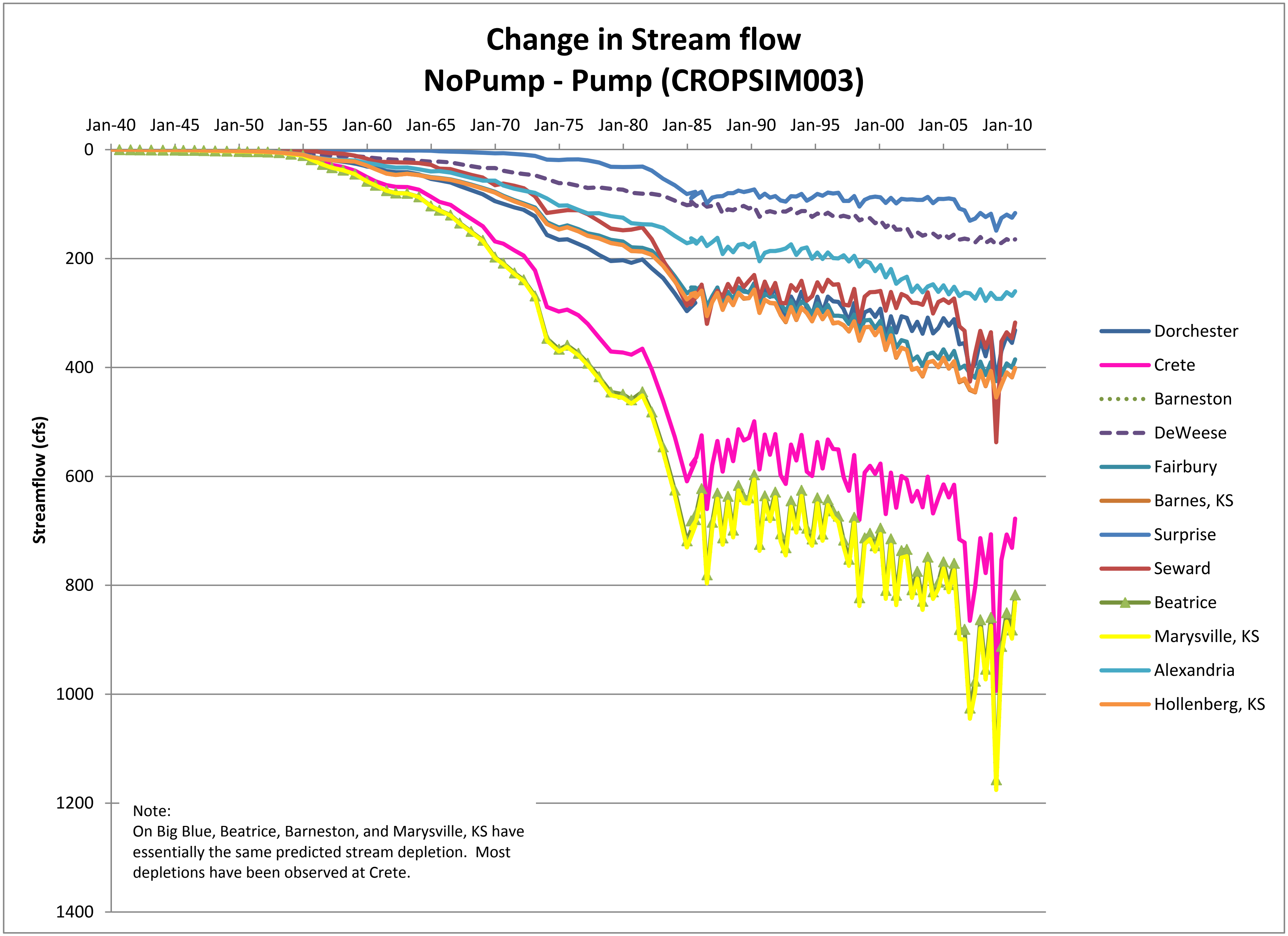

Zone 19 Kx Sensitivity
2.0%
1.8%
1.6%
1.4%
1.2%
1.0%
0.8%
0.6%
0.4%
0.2%
0.0%
NRMS (%)
17
14.5
12
9.5
7
Residual Mean (ft)
0.1
1
10
Multiplier
NRMS
Residual Mean

Appendix E – Comparison between CROPSIM003 and CROPSIM004

Appendix E contains streamflow and groundwater hydrographs that illustrate the results of the model runs performed using the CROPSIM003 and CROPSIM004 pumping and recharge files.



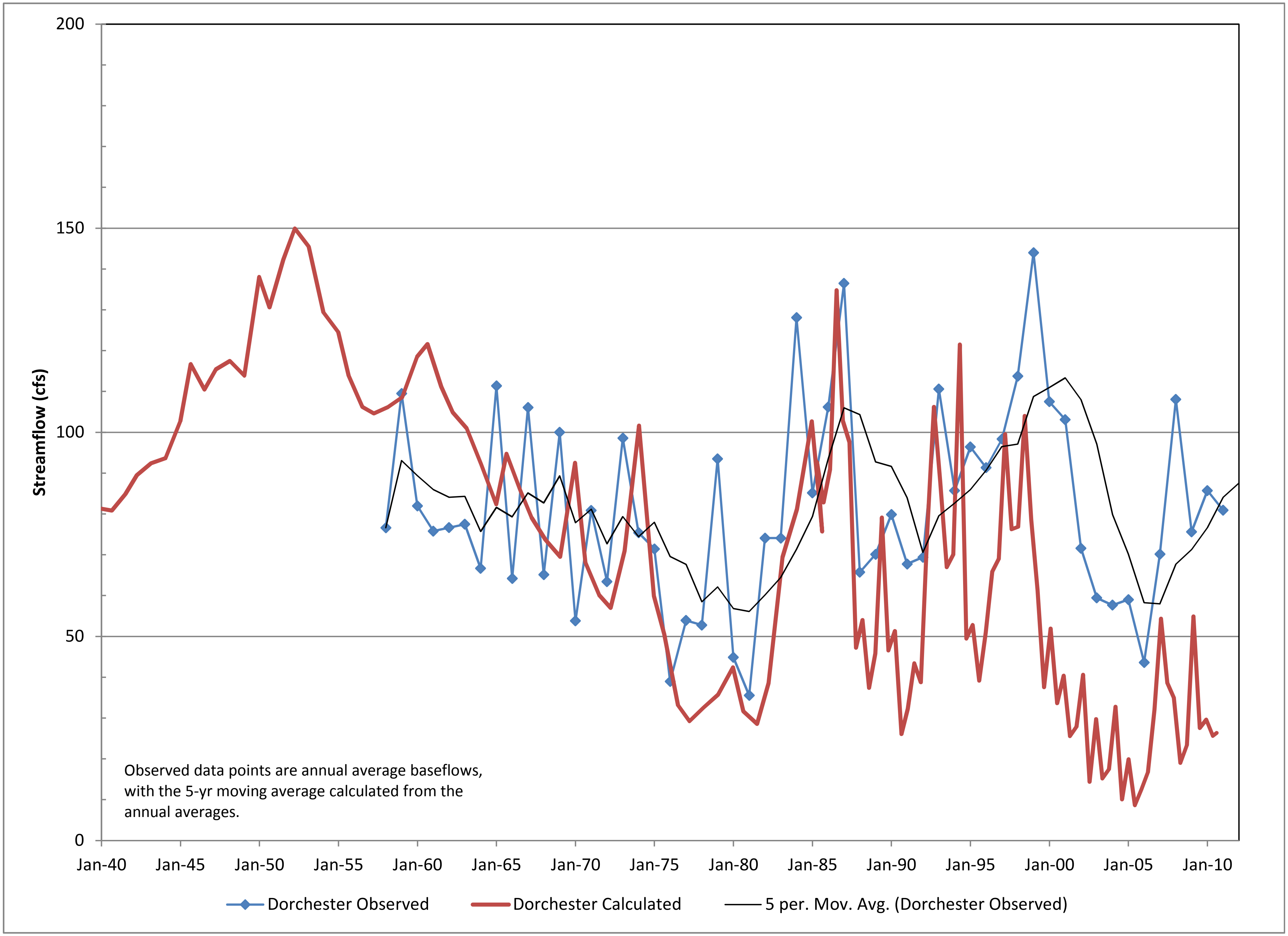
Change in Stream flow
NoPump - Pump (CROPSIM004)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
0
100
200
300
400
500
600
700
800
Stream flow (cfs)
Dorchester
Crete
Barneston
DeWeese
Fairbury
Barnes, KS
Surprise
Seward
Beatrice
Marysville, KS
Alexandria
Hollenberg, KS
Note:
On Big Blue: Beatrice, Barneston, and Marysville, KS have esentially the same predicted stream depletion. Most depletions have been observed at Crete.



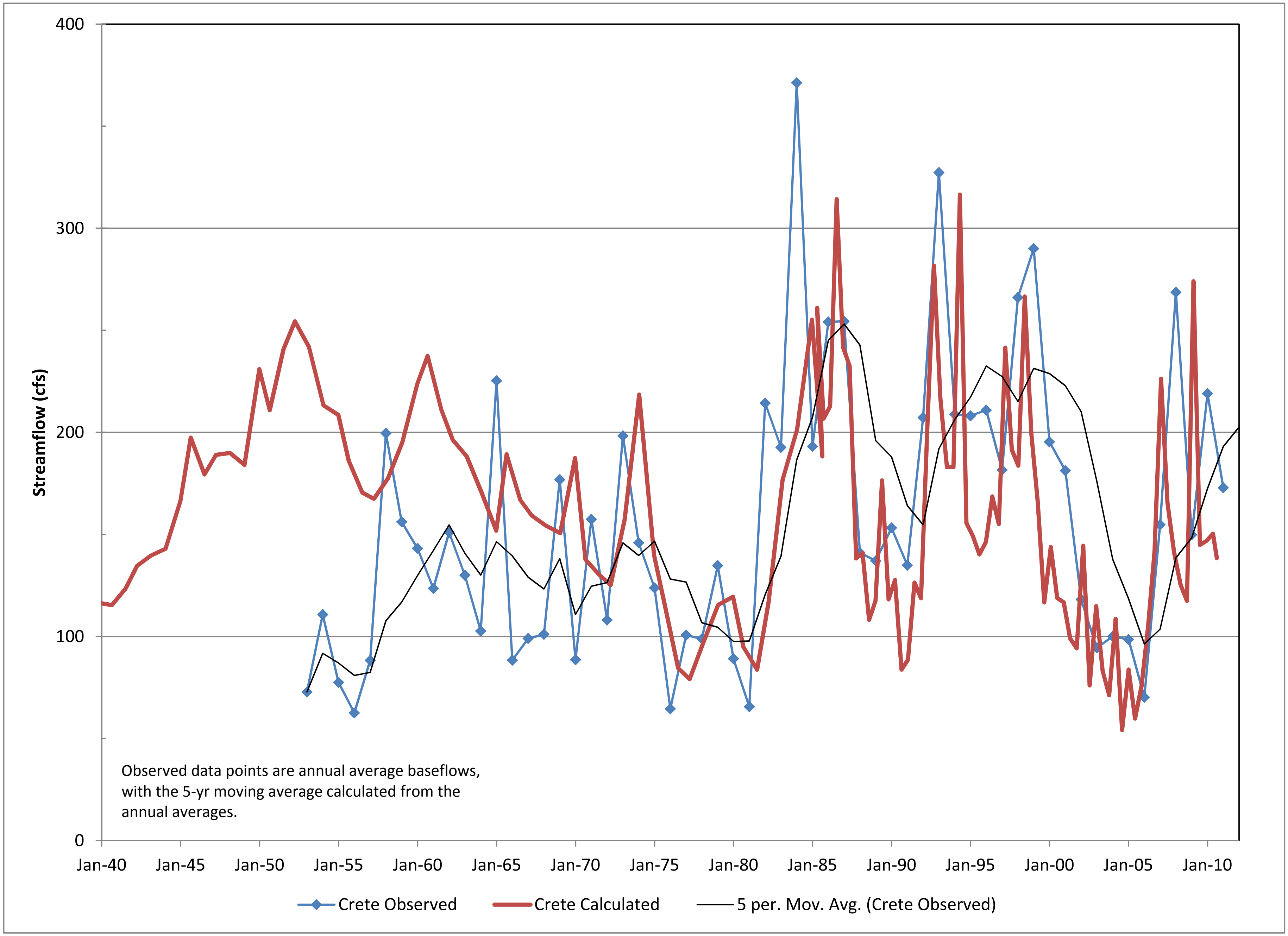
Change in Stream flow
NoPump - Pump (CROPSIM003)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
0
200
400
600
800
1000
1200
1400
Streamflow (cfs)
Dorchester
Crete
Barneston
DeWeese
Fairbury
Barnes, KS
Surprise
Seward
Beatrice
Marysville, KS
Alexandria
Hollenberg, KS
Note:
On Big Blue, Beatrice, Barneston, and Marysville, KS have essentially the same predicted stream depletion. Most depletions have been observed at Crete.

CROPSIM003

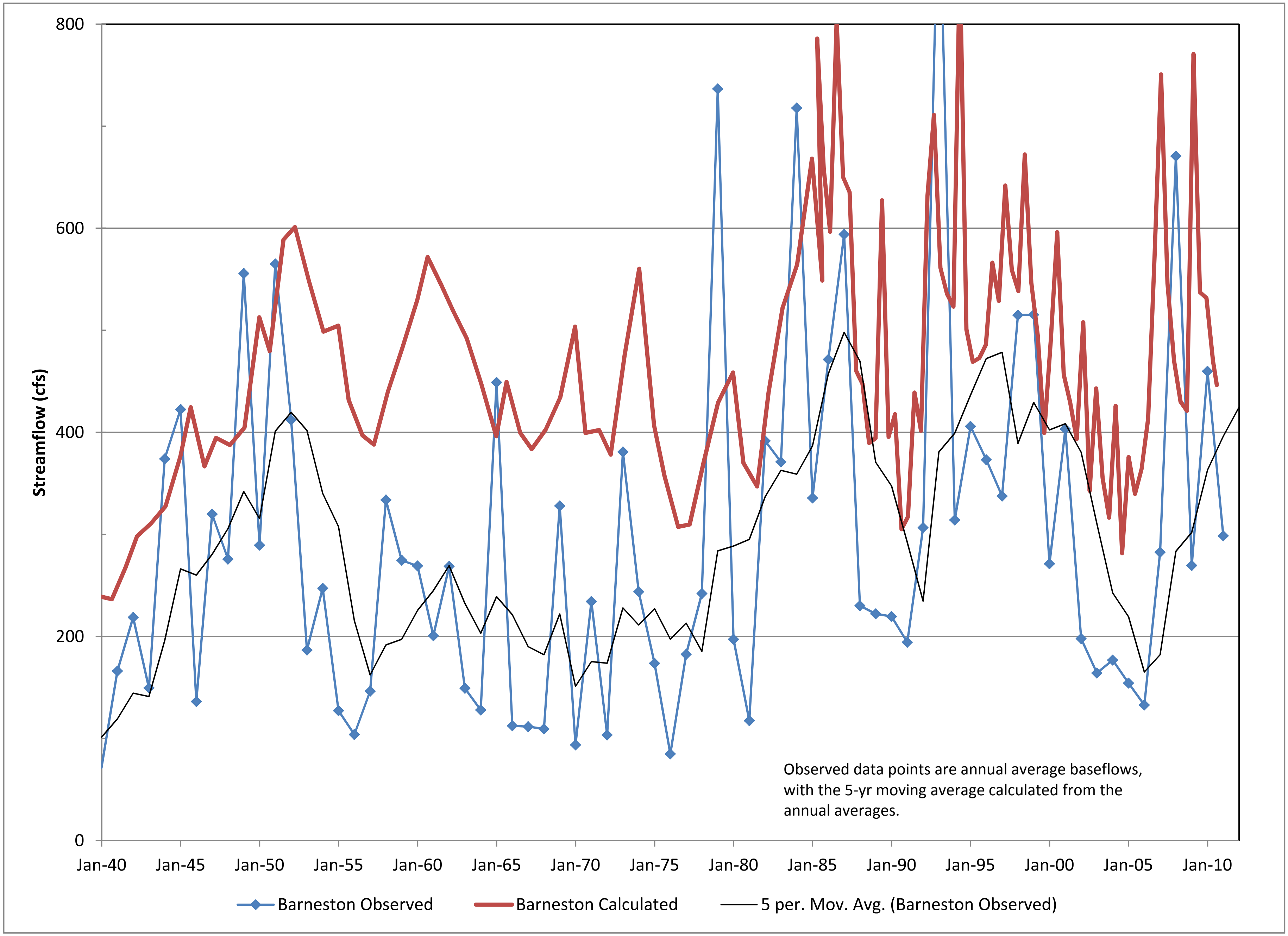
Streamflow Hydrographs



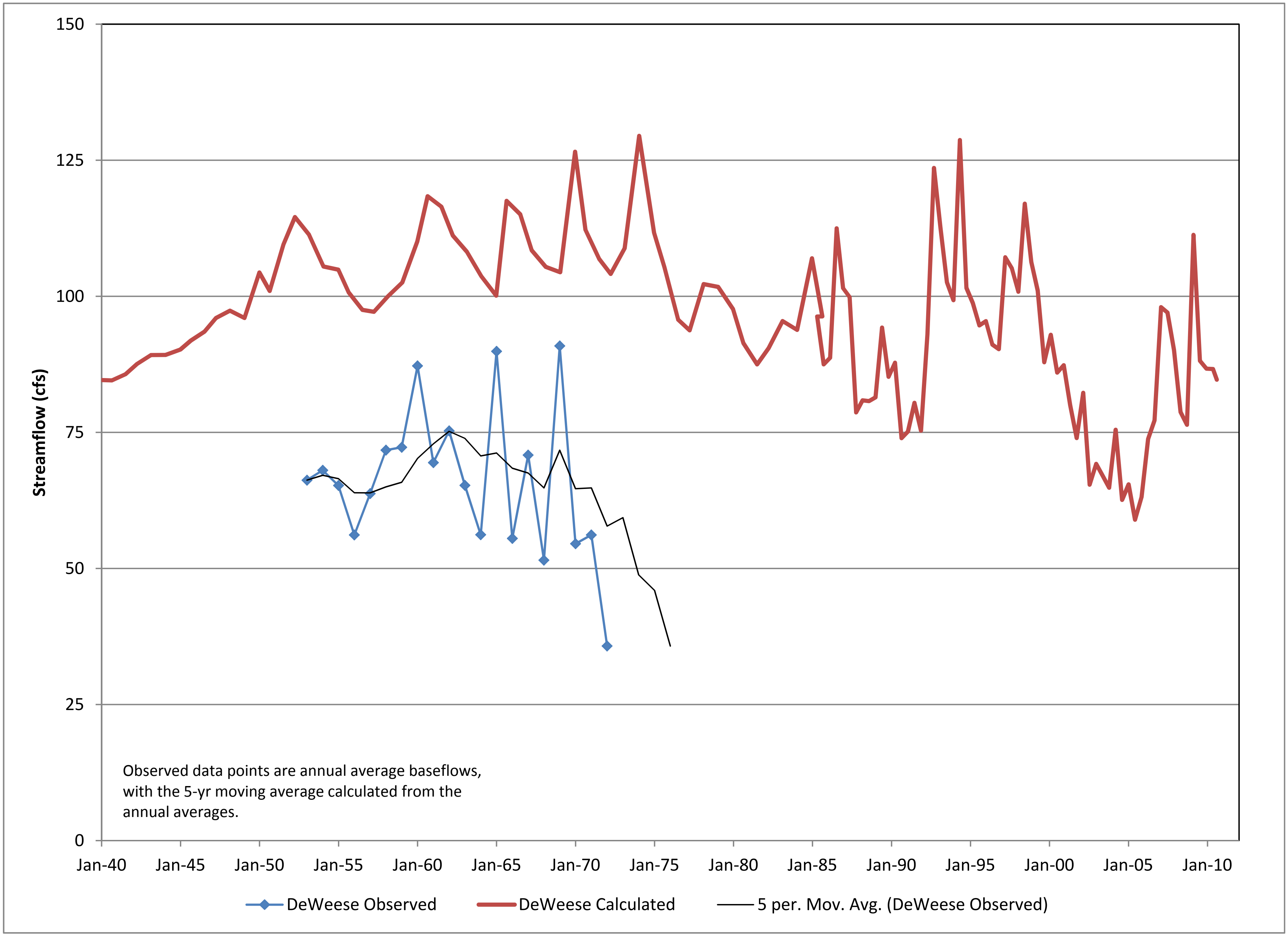
Streamflow (cfs)
200
150
100
50
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Dorchester Observed
Dorchester Calculated
5 per. Mov. Avg. (Dorchester Observed)



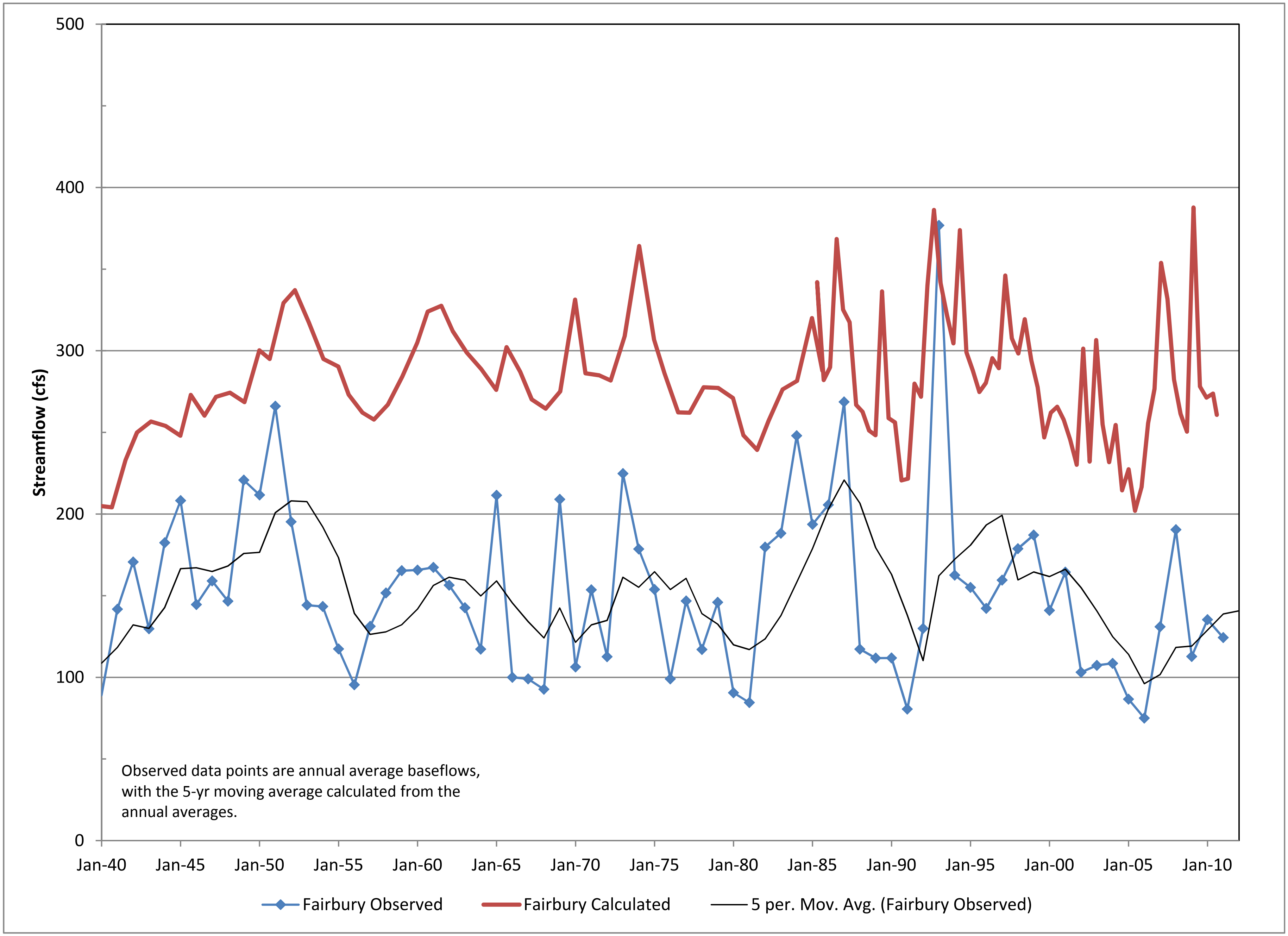
400
300
200
100
0
Streamflow (cfs)
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Crete Observed
Crete Calculated
5 per. Mov. Avg. (Crete Observed)



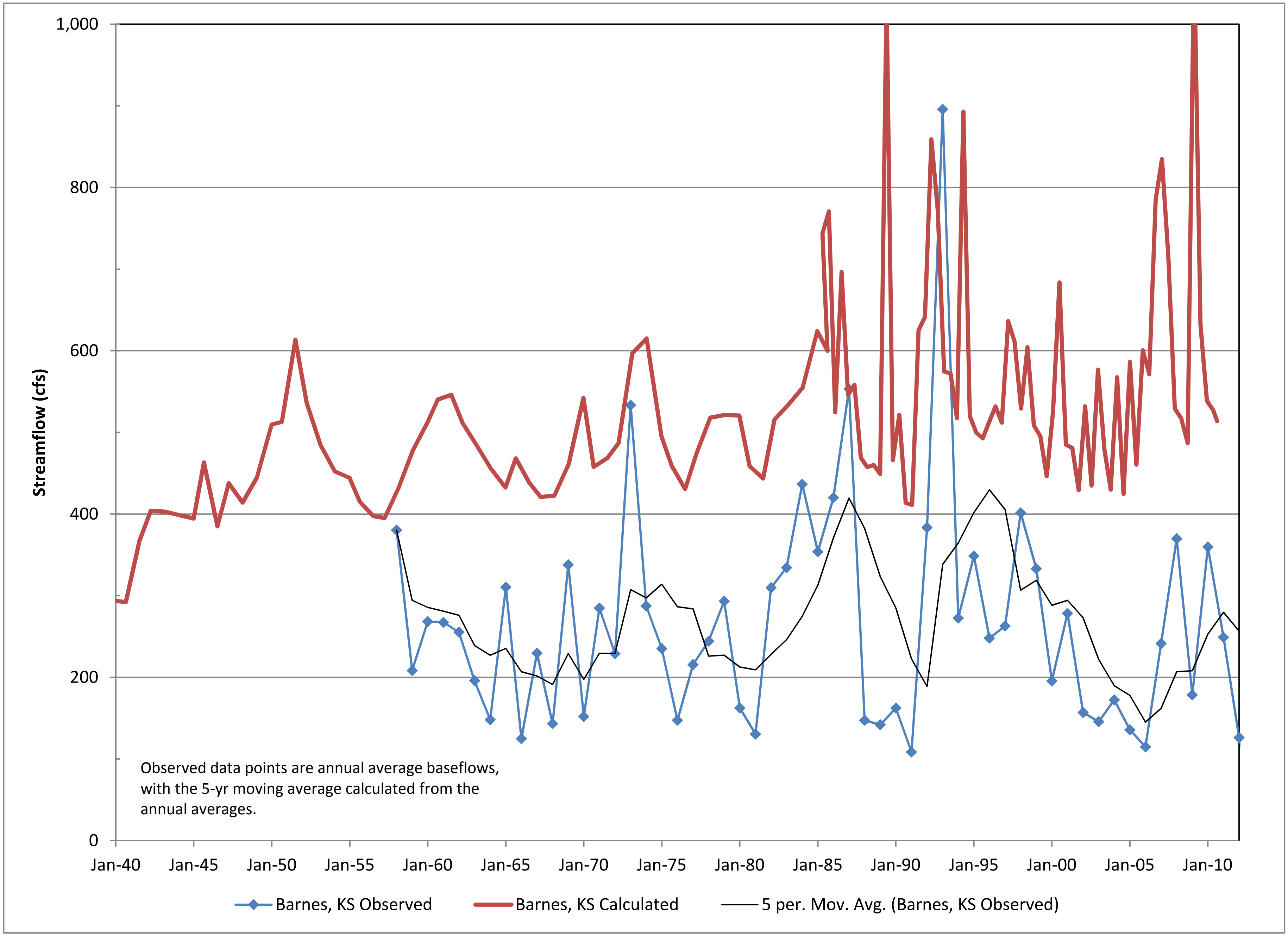
Streamflow (cfs)
800
600
400
200
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Barneston Observed
Barneston Calculated
5 per. Mov. Avg. (Barneston Observed)



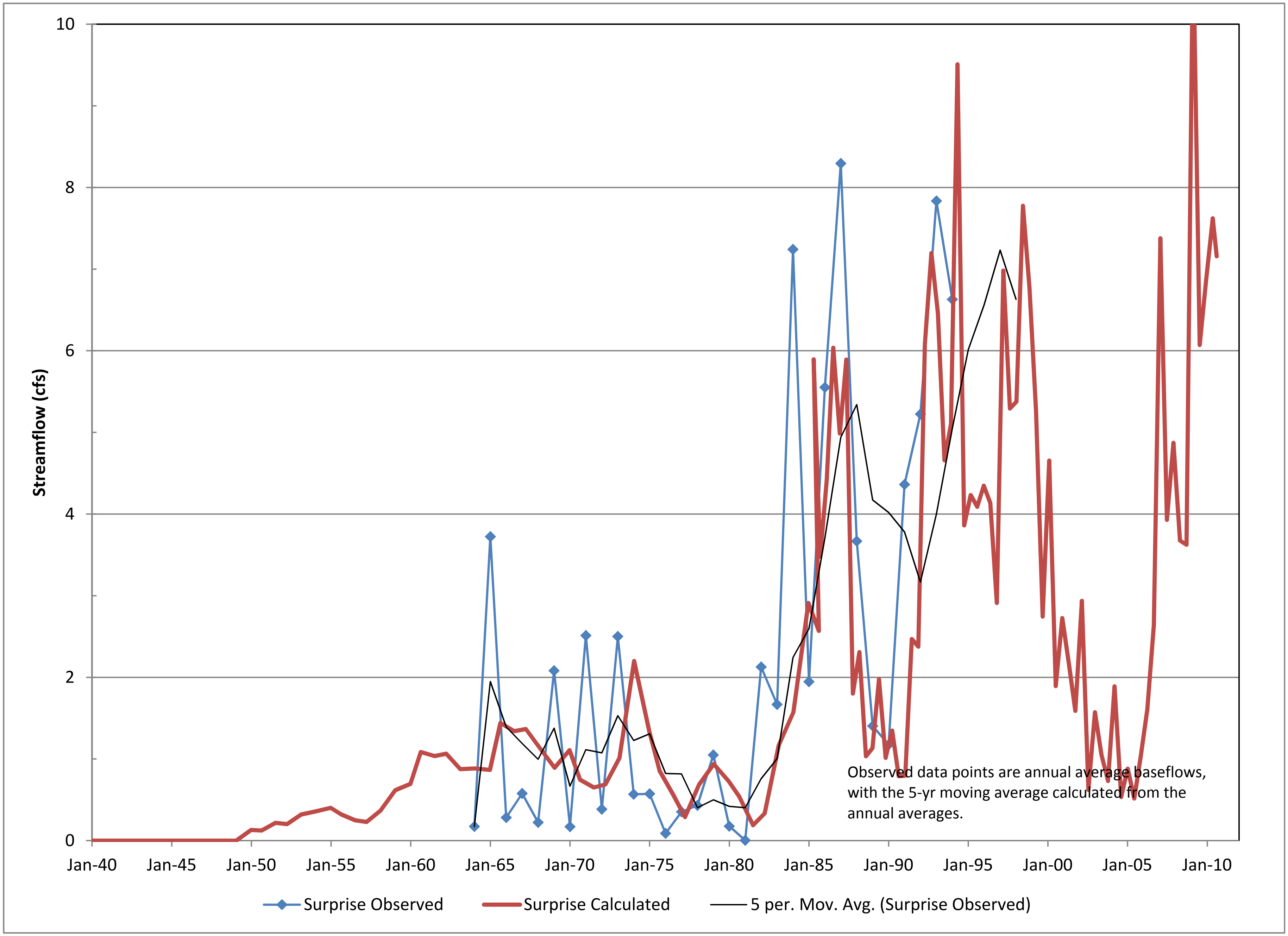
150
125
100
75
50
25
0
Streamflow (cfs)
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
DeWeese Observed
DeWeese Calculated
5 per. Mov. Avg. (DeWeese Observed)

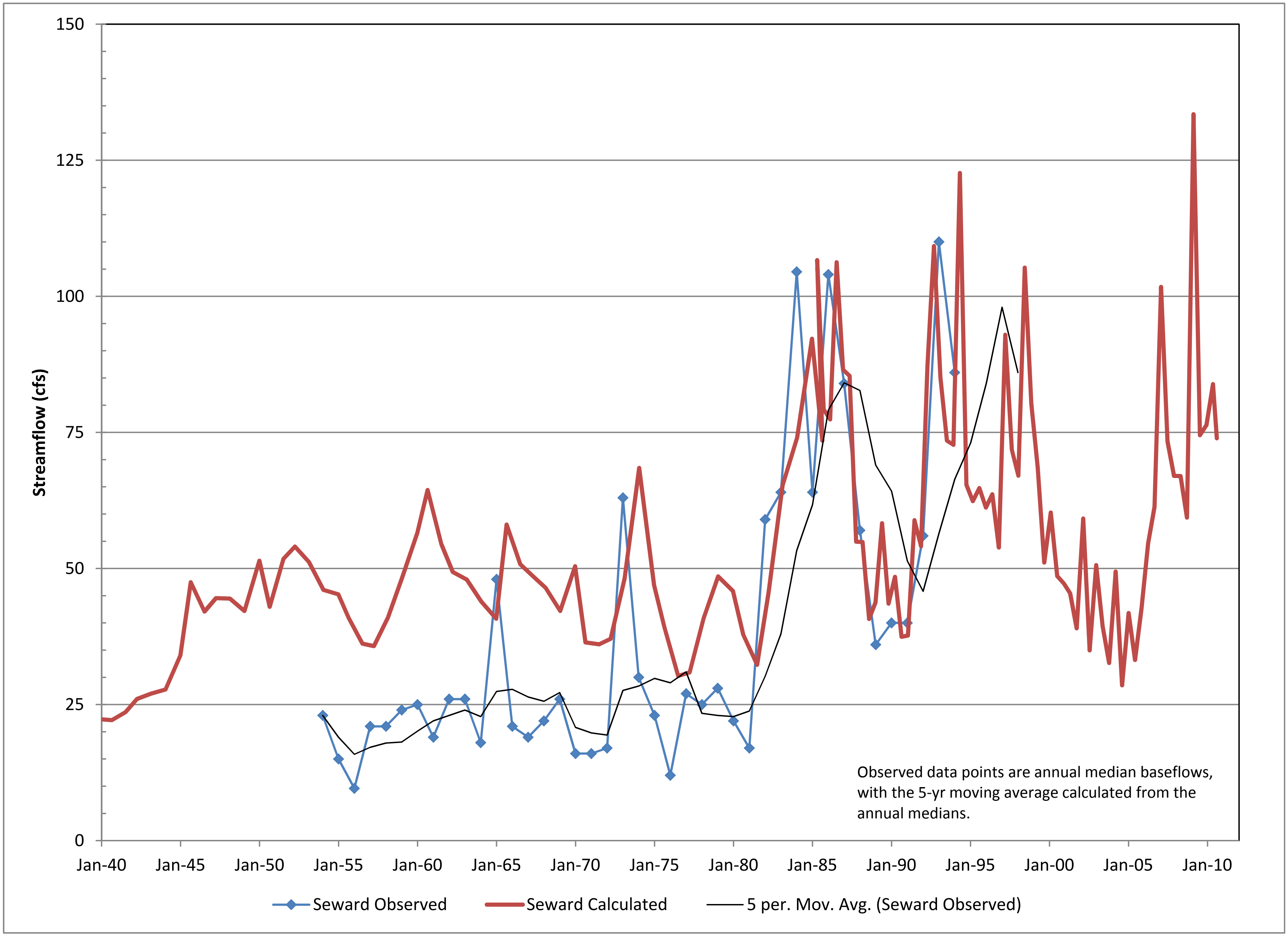


Streamflow (cfs)
500
400
300
200
100
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Fairbury Observed
Fairbury Calculated
5 per. Mov. Avg. (Fairbury Observed)

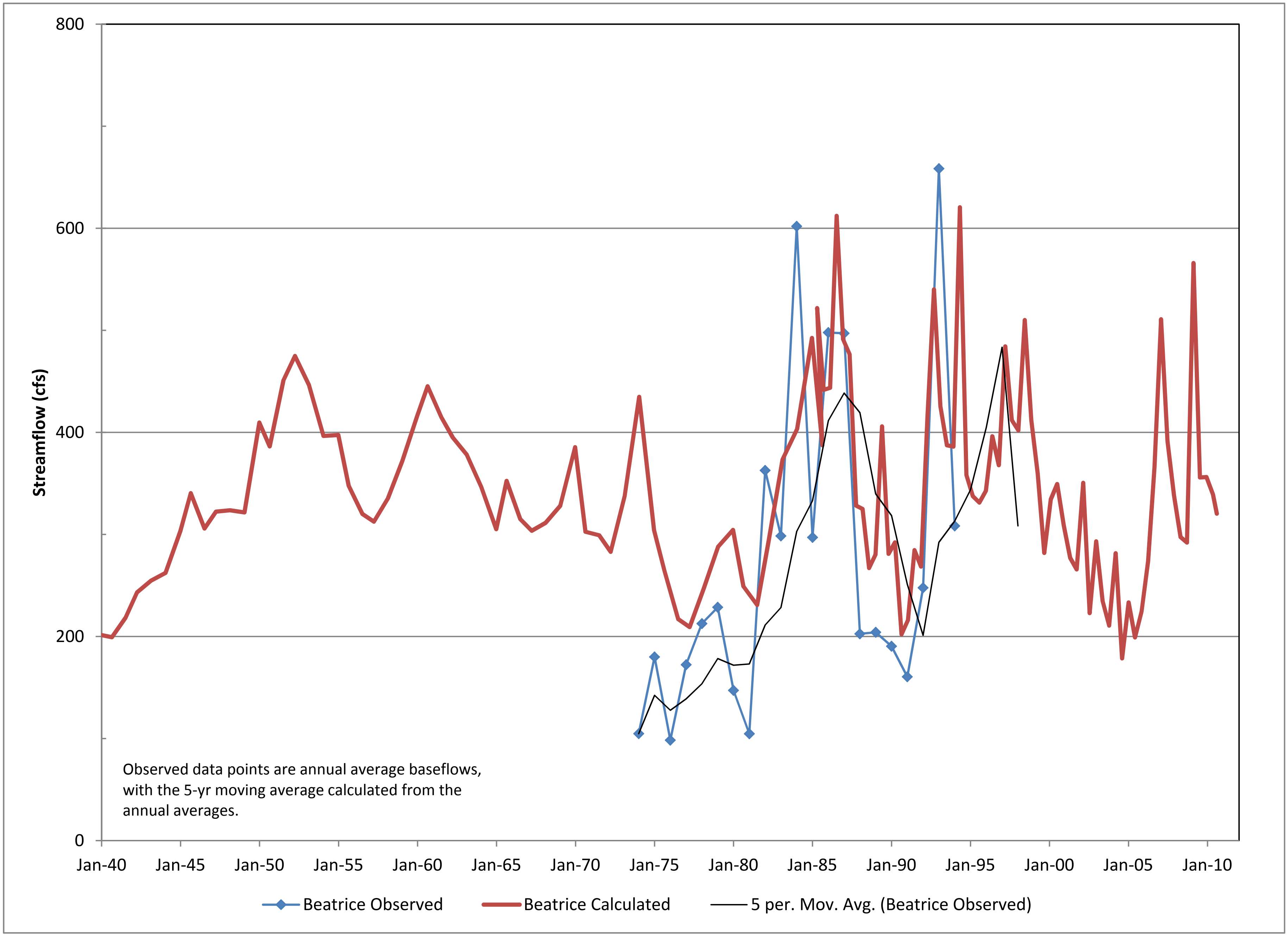


1,000
800
600
400
200
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Barnes, KS Observed
Barnes, KS Calculated
5 per. Mov. Avg. (Barnes, KS Observed)

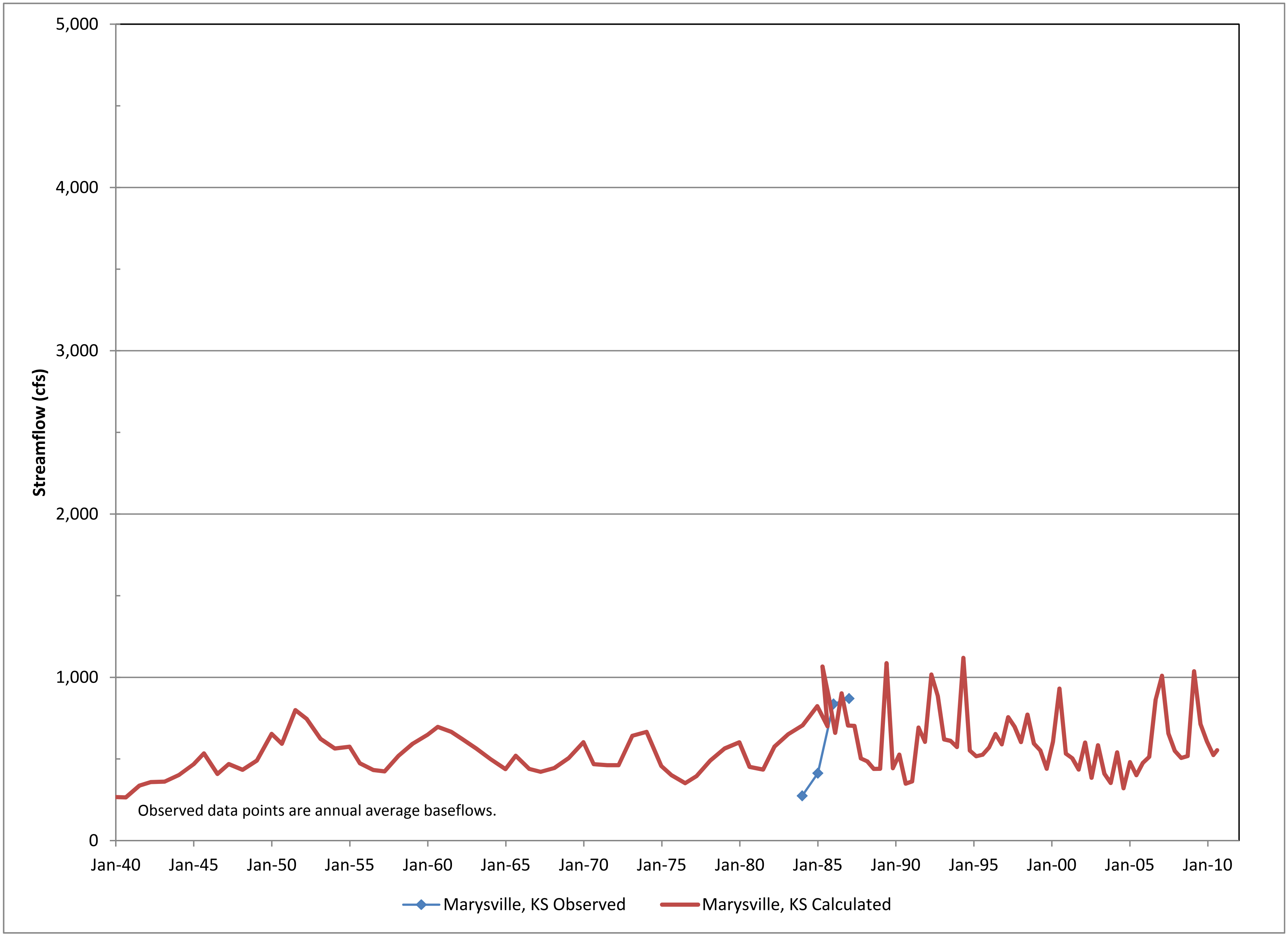

Streamflow (cfs)
10
8
6
4
2
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Surprise Observed
Surprise Calculated
5 per. Mov. Avg. (Surprise Observed)



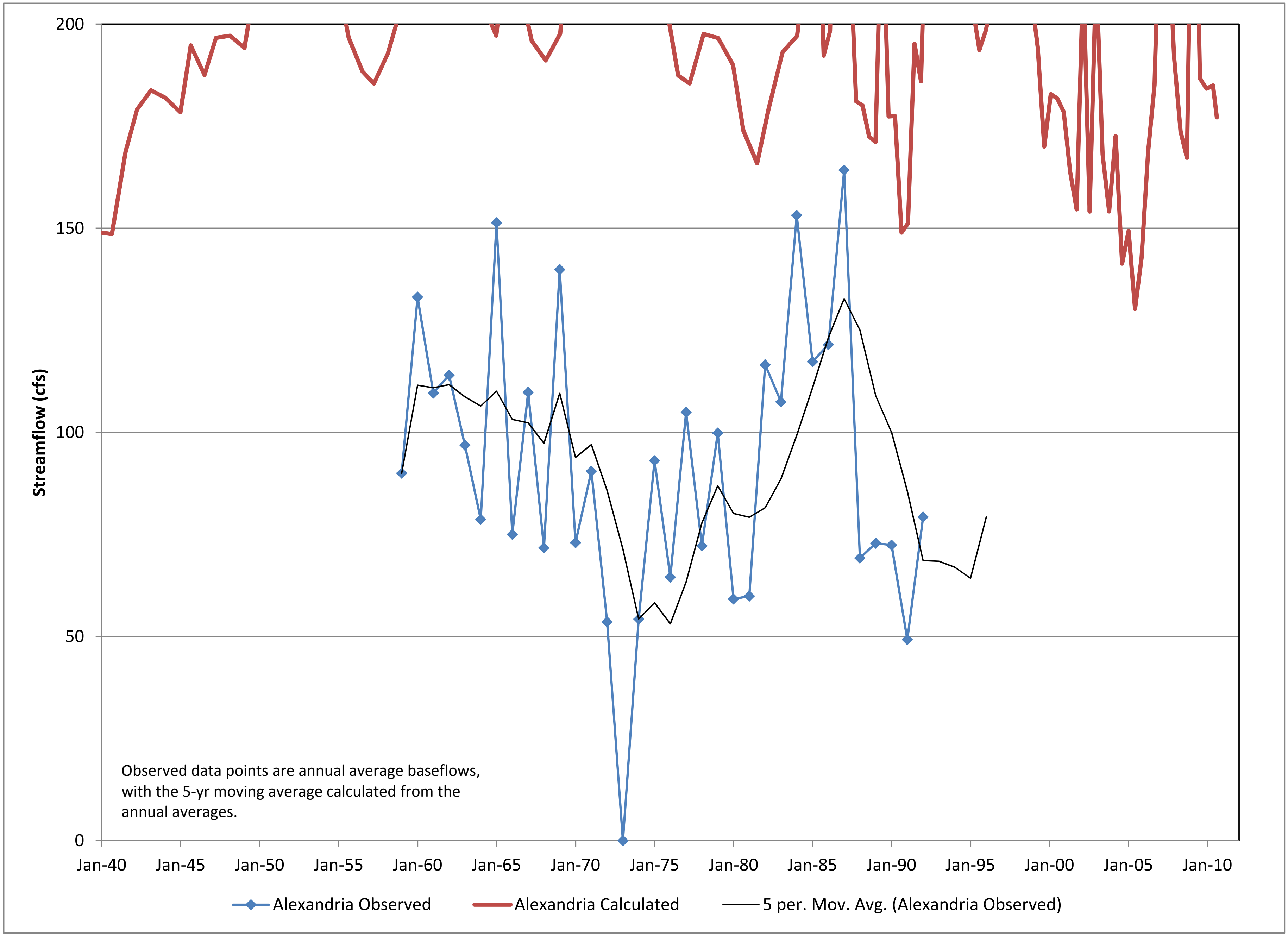
Streamflow (cfs)
150
125
100
75
50
25
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual median baseflows, with the 5-yr moving average calculated from the annual medians.
Seward Observed
Seward Calculated
5 per. Mov. Avg. (Seward Observed)

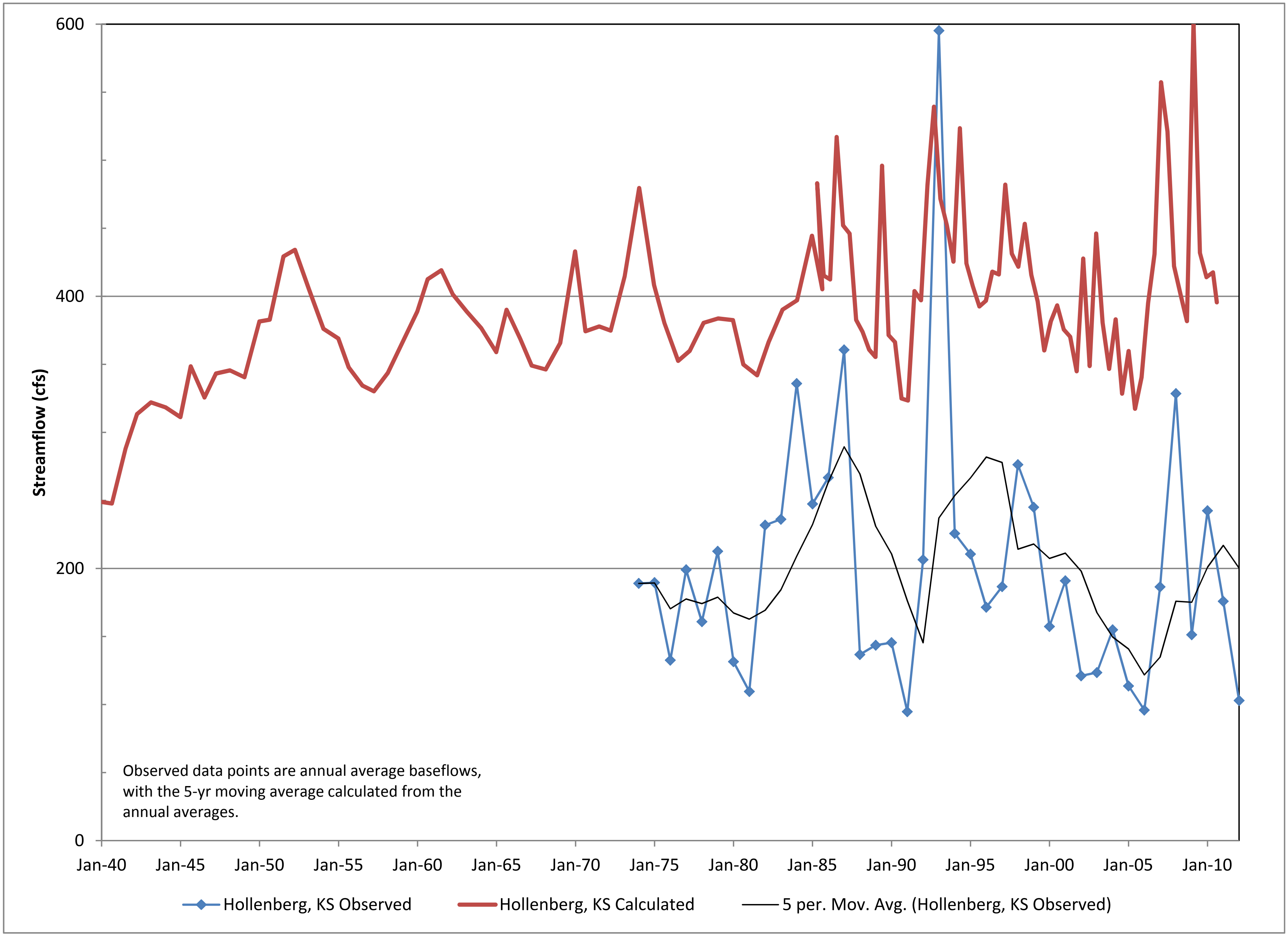


800
600
400
200
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Beatrice Observed
Beatrice Calculated
5 per. Mov. Avg. (Beatrice Observed)



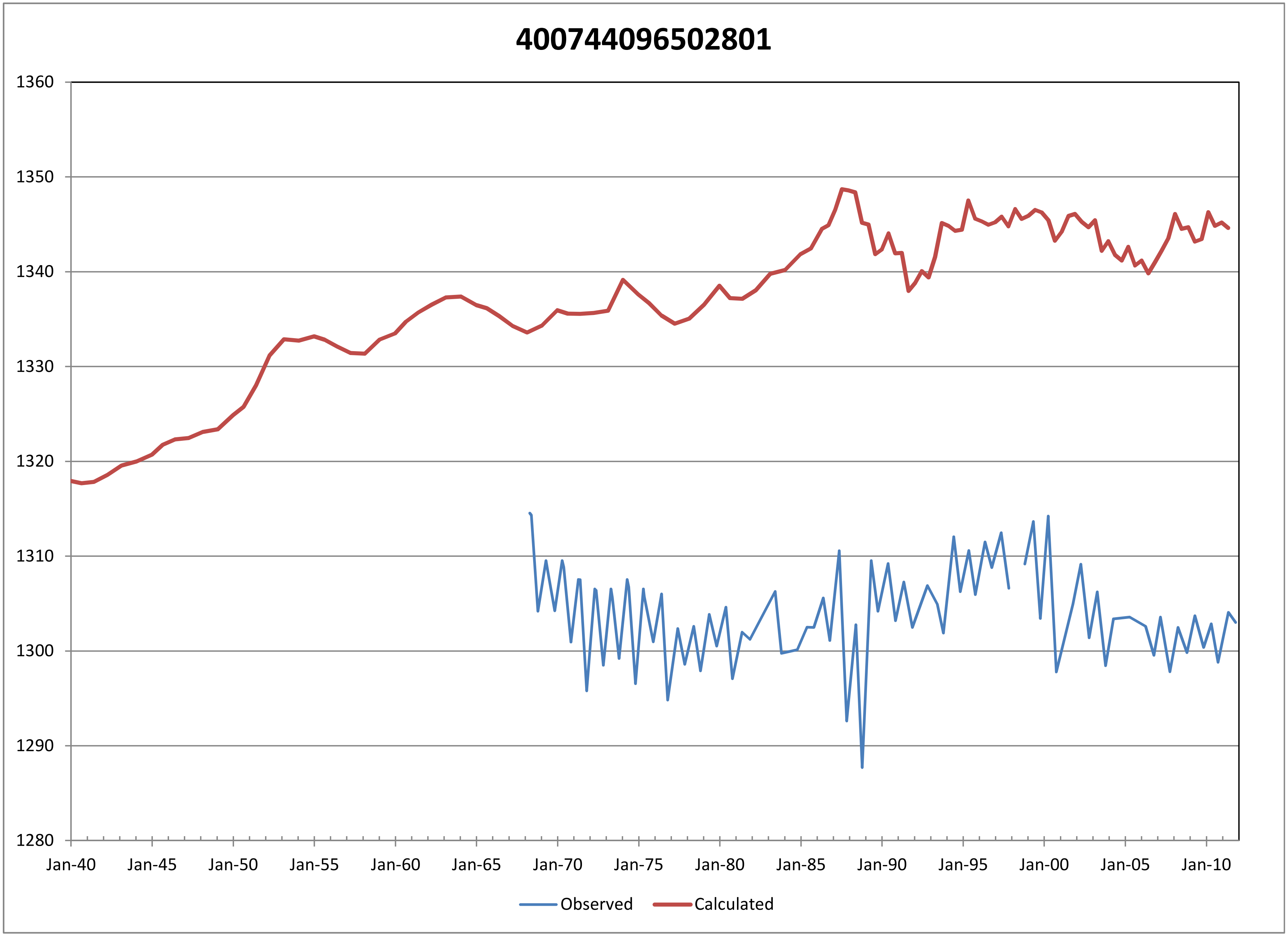
5,000
4,000
3,000
2,000
1,000
0
Streamflow (cfs)
Observed data points are annual average baseflows.
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Marysville, KS Observed
Marysville, KS Calculated


200
150
100
50
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Alexandria Observed
Alexandria Calculated
5 per. Mov. Avg. (Alexandria Observed)

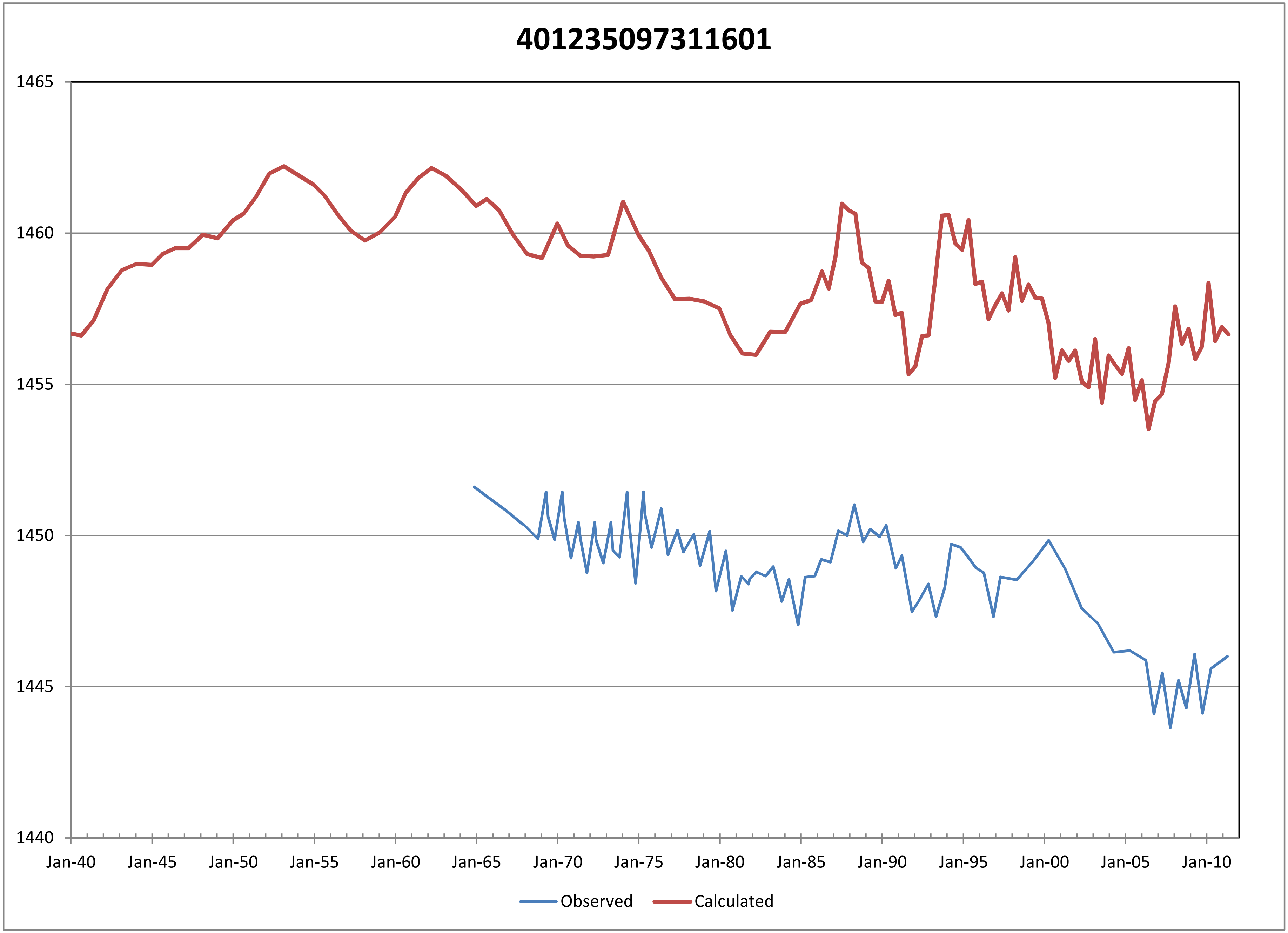


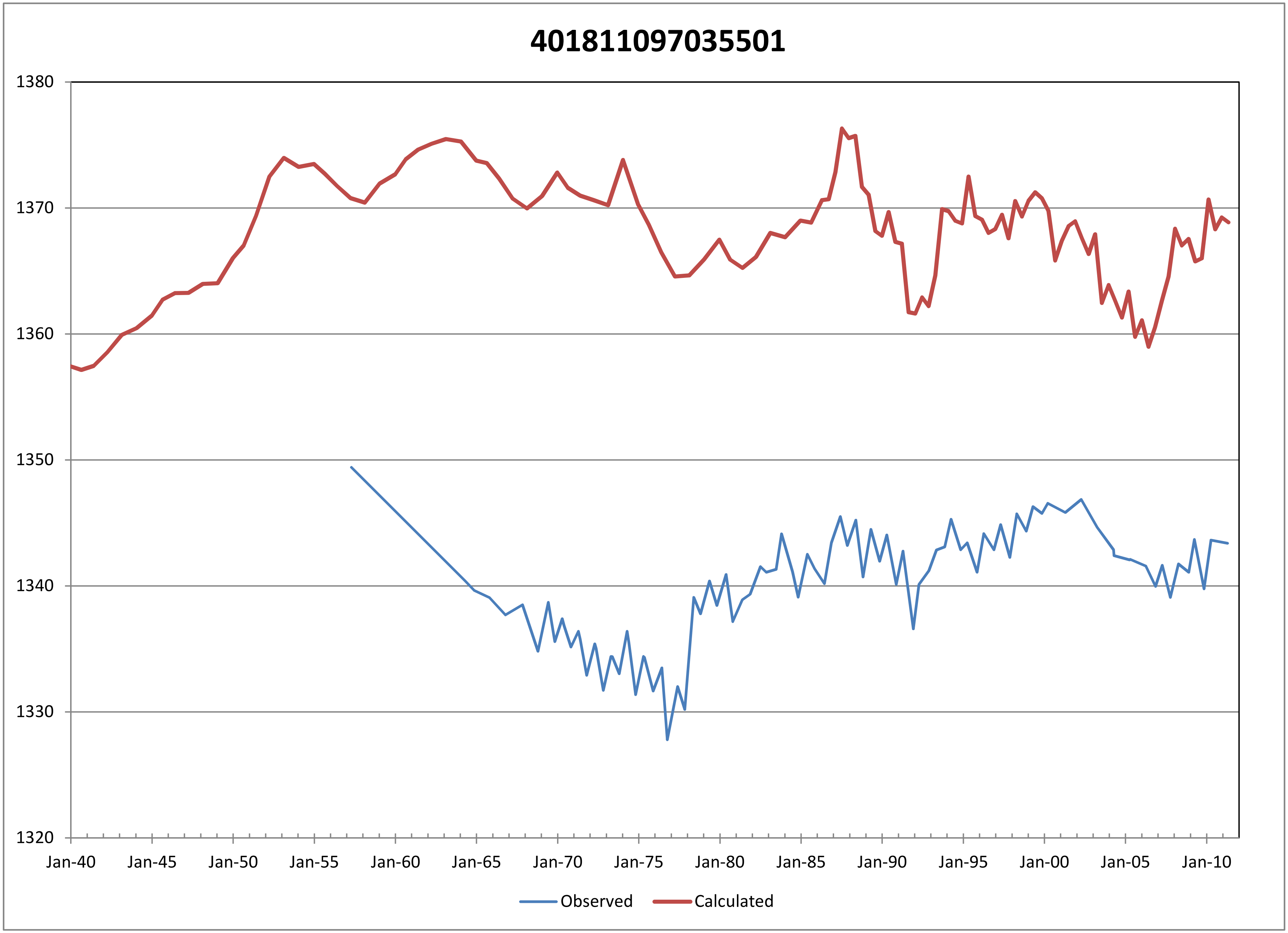
600
400
200
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Hollenberg, KS Observed
Hollenberg, KS Calculated
5 per. Mov. Avg. (Hollenberg, KS Observed)

Well Hydrographs



400744096502801
1360
1350
1340
1330
1320
1310
1300
1290
1280
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed
Calculated


401235097311601
1465
1460
1455
1450
1445
1440
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed
Calculated



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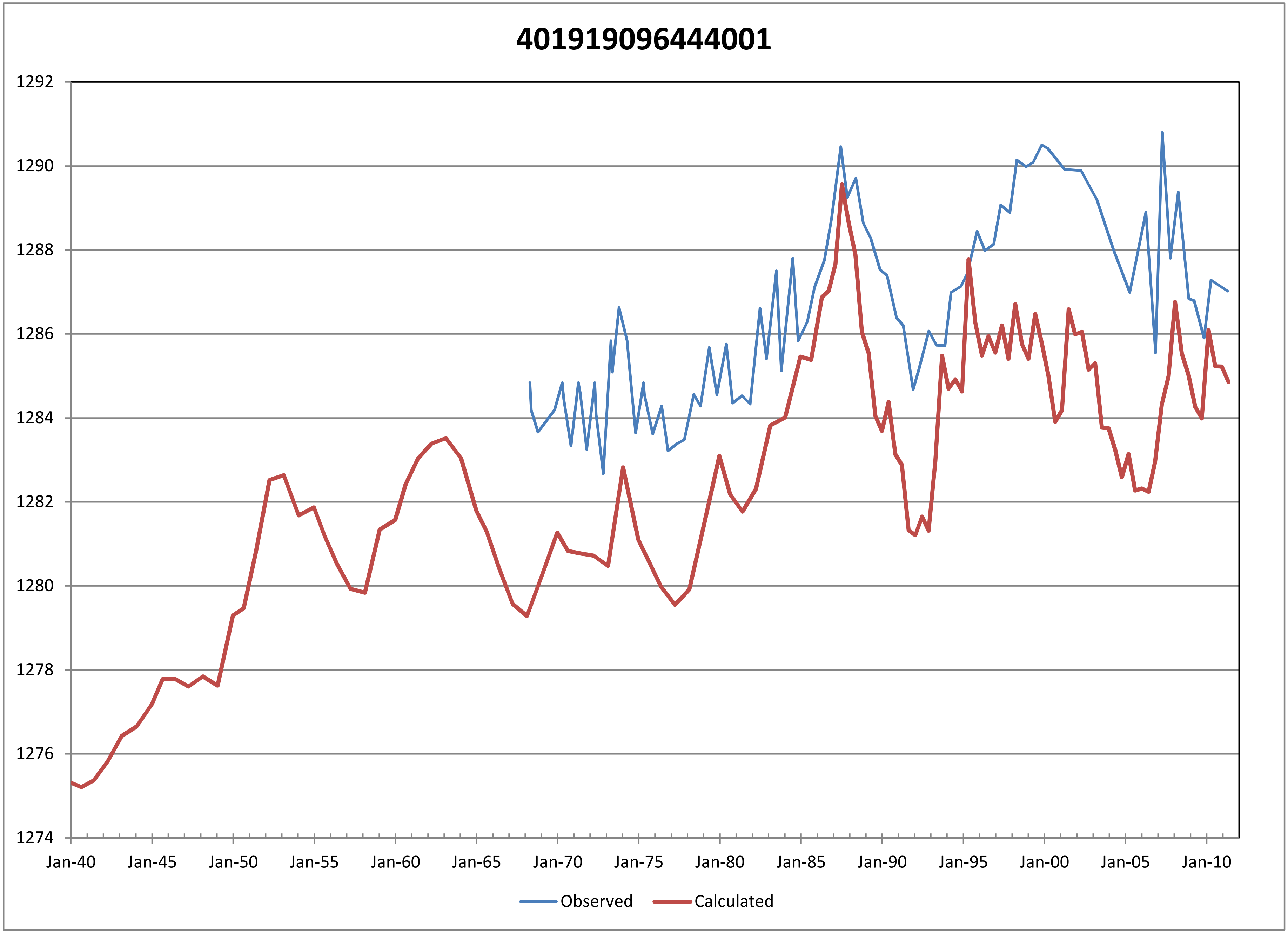

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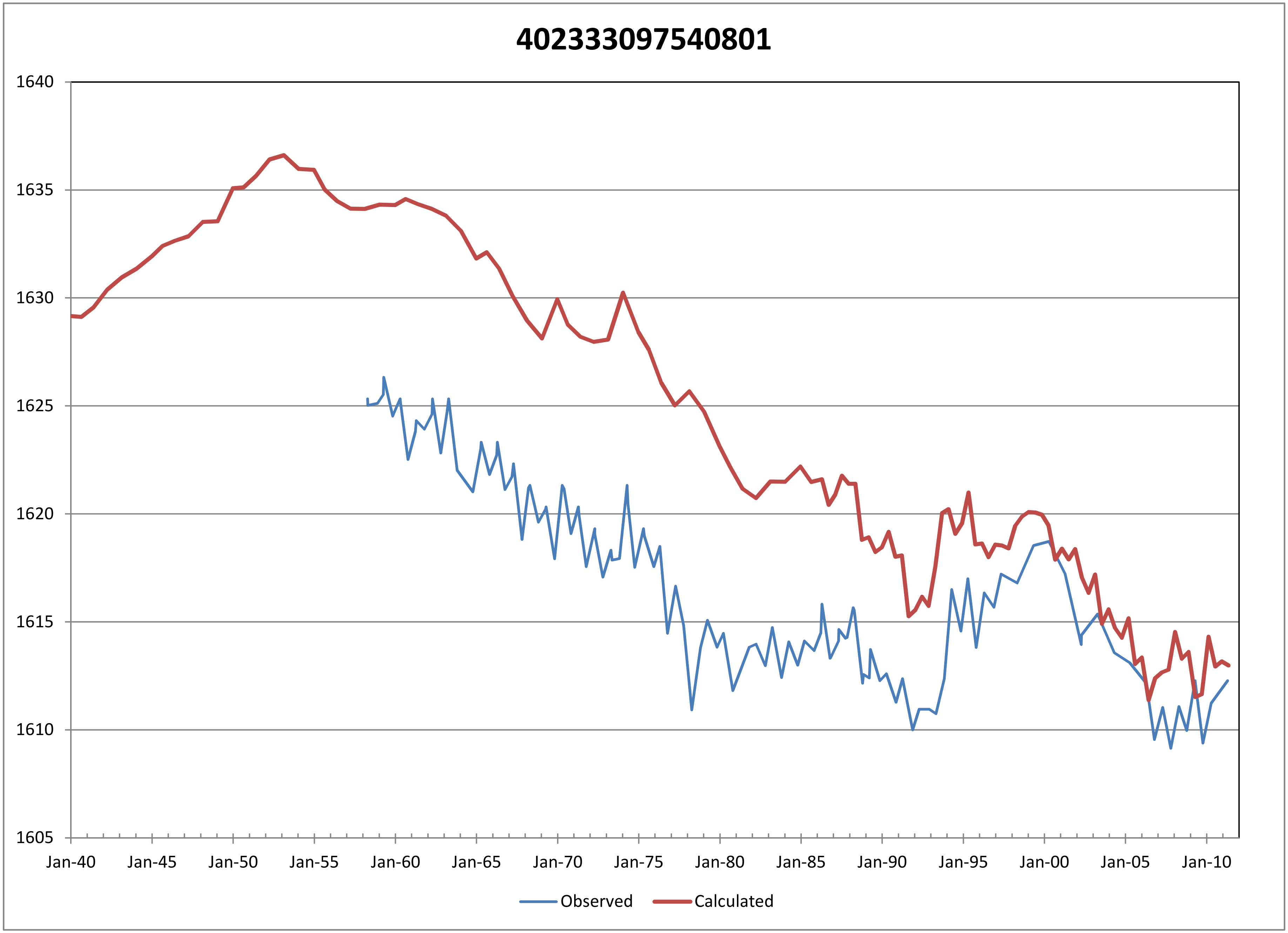

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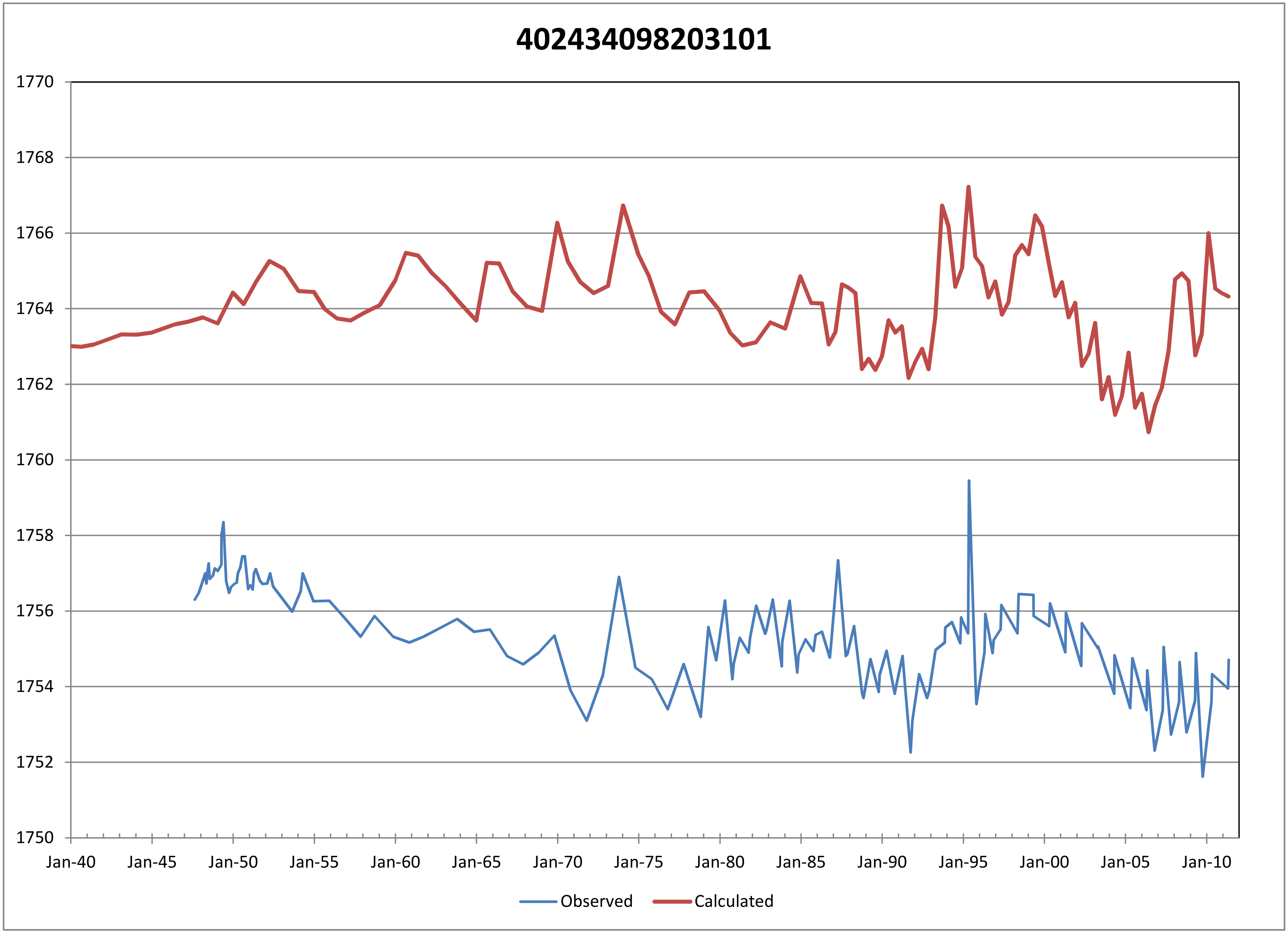
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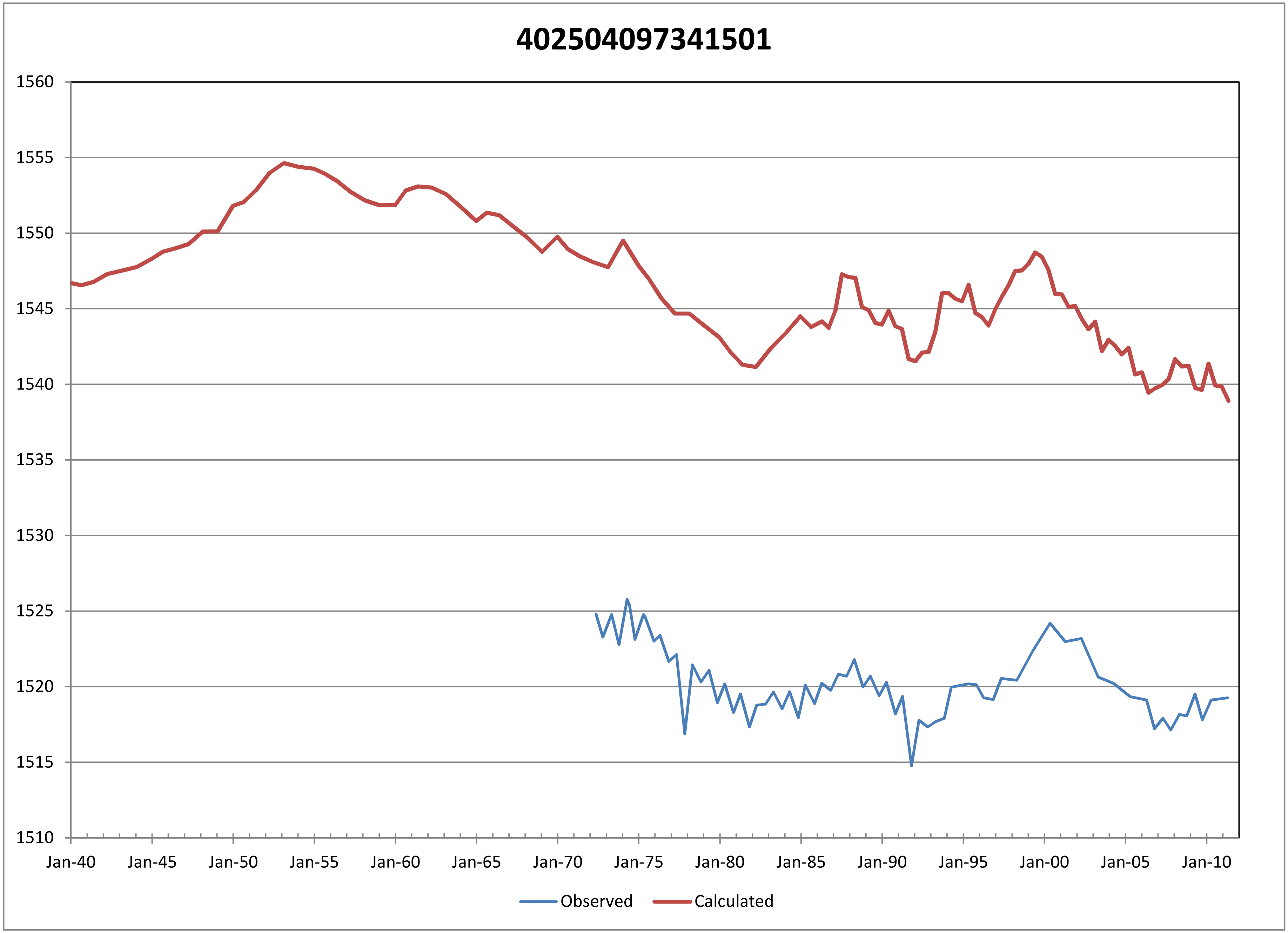
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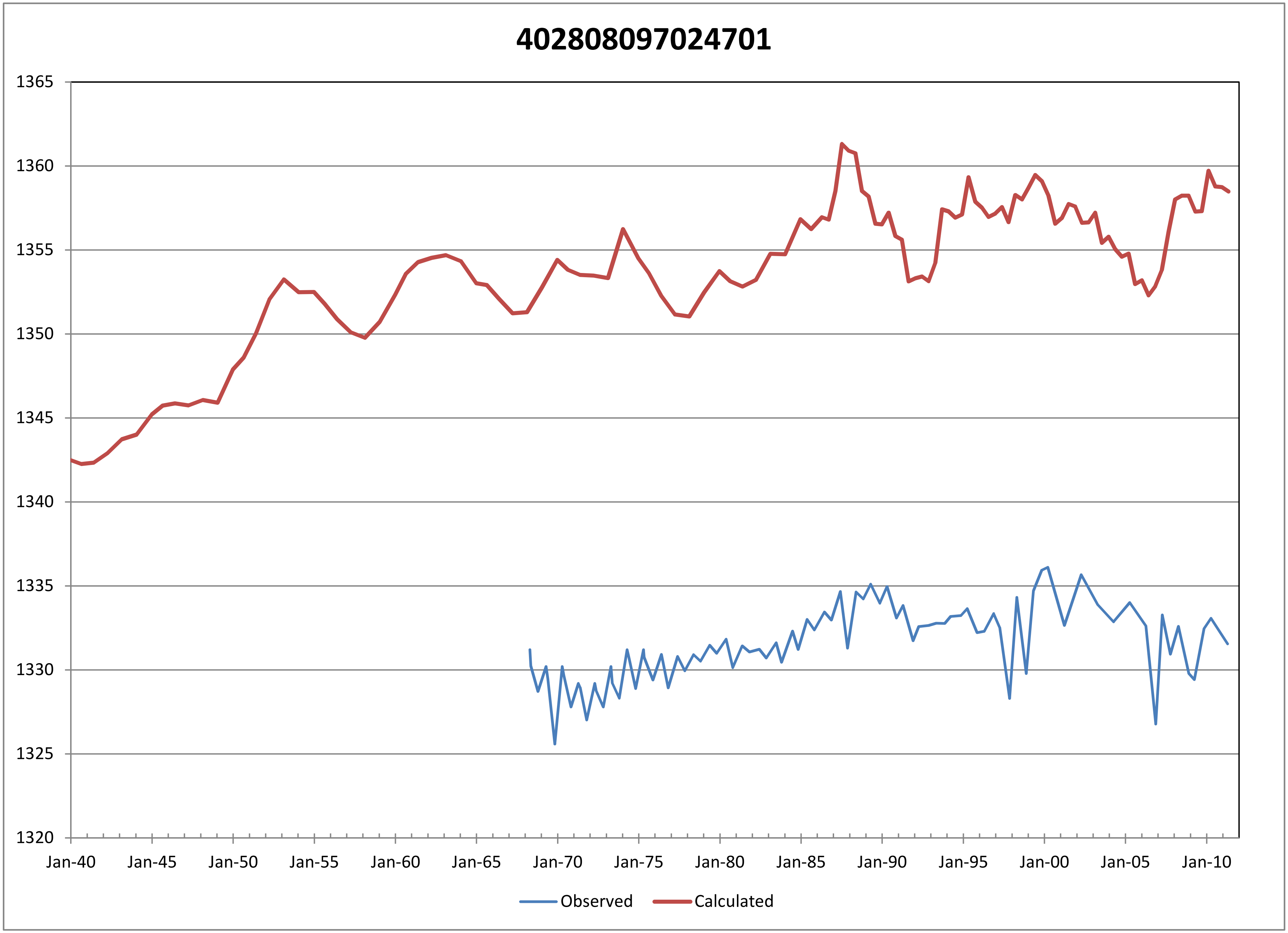
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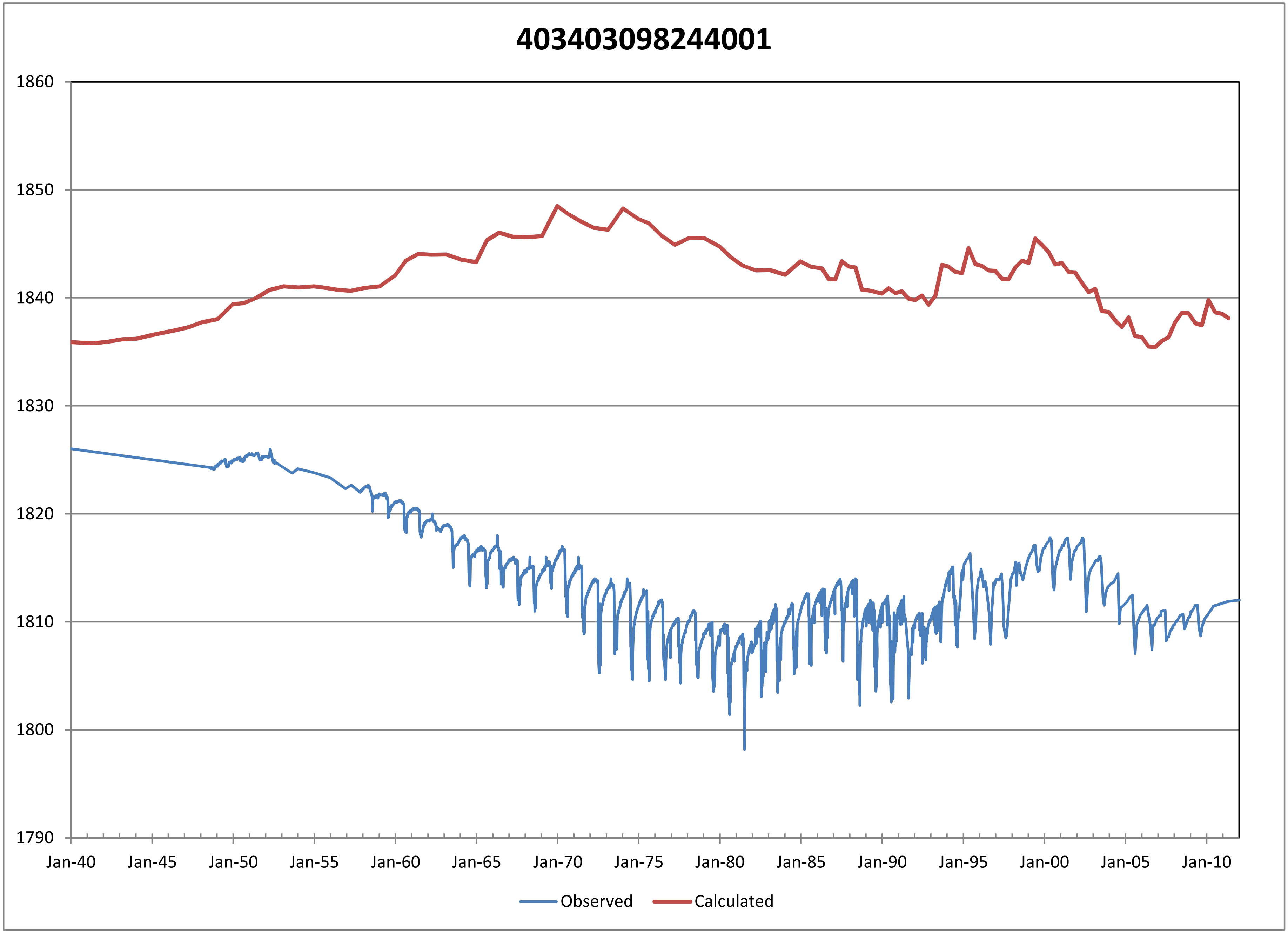

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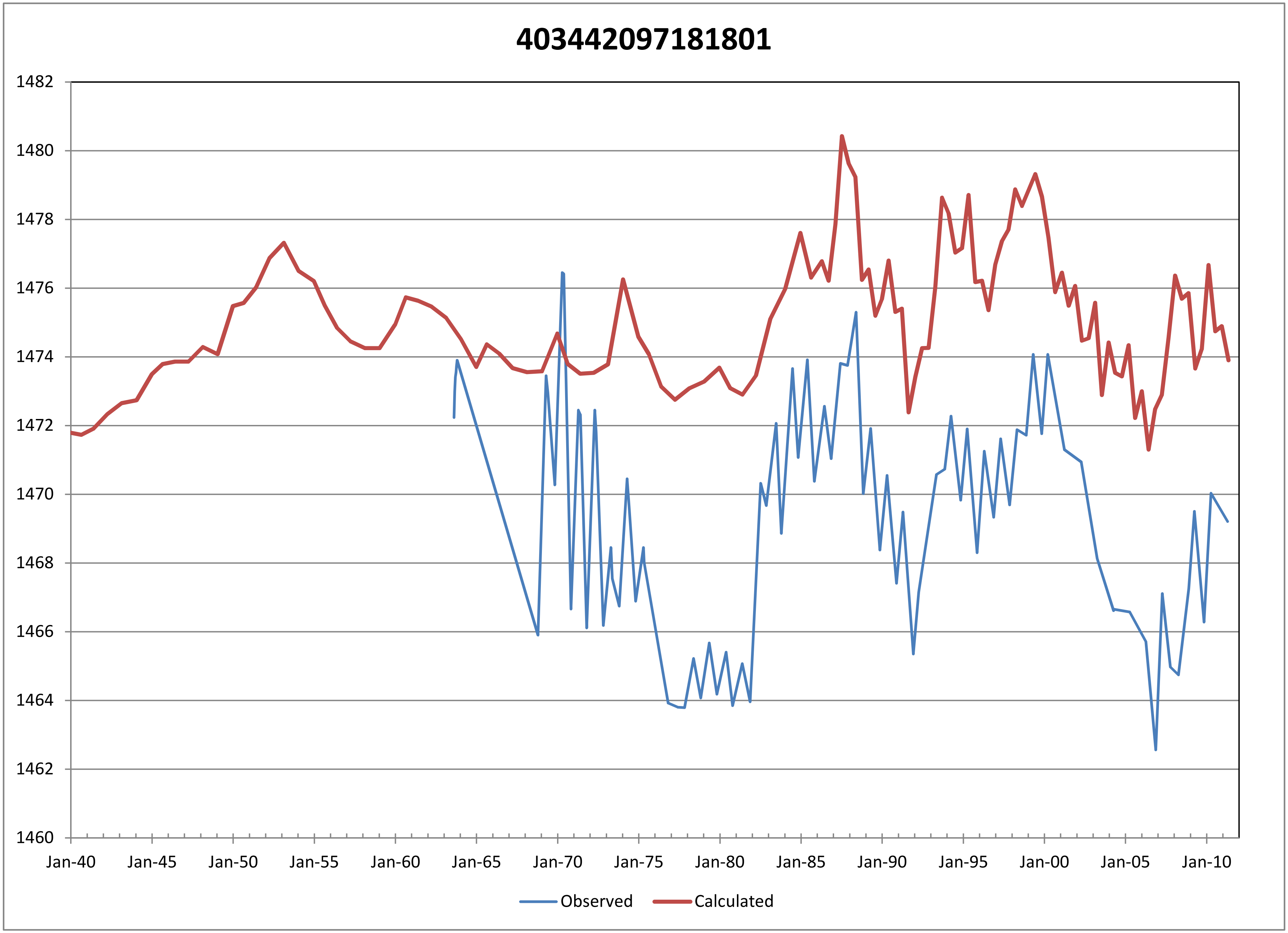

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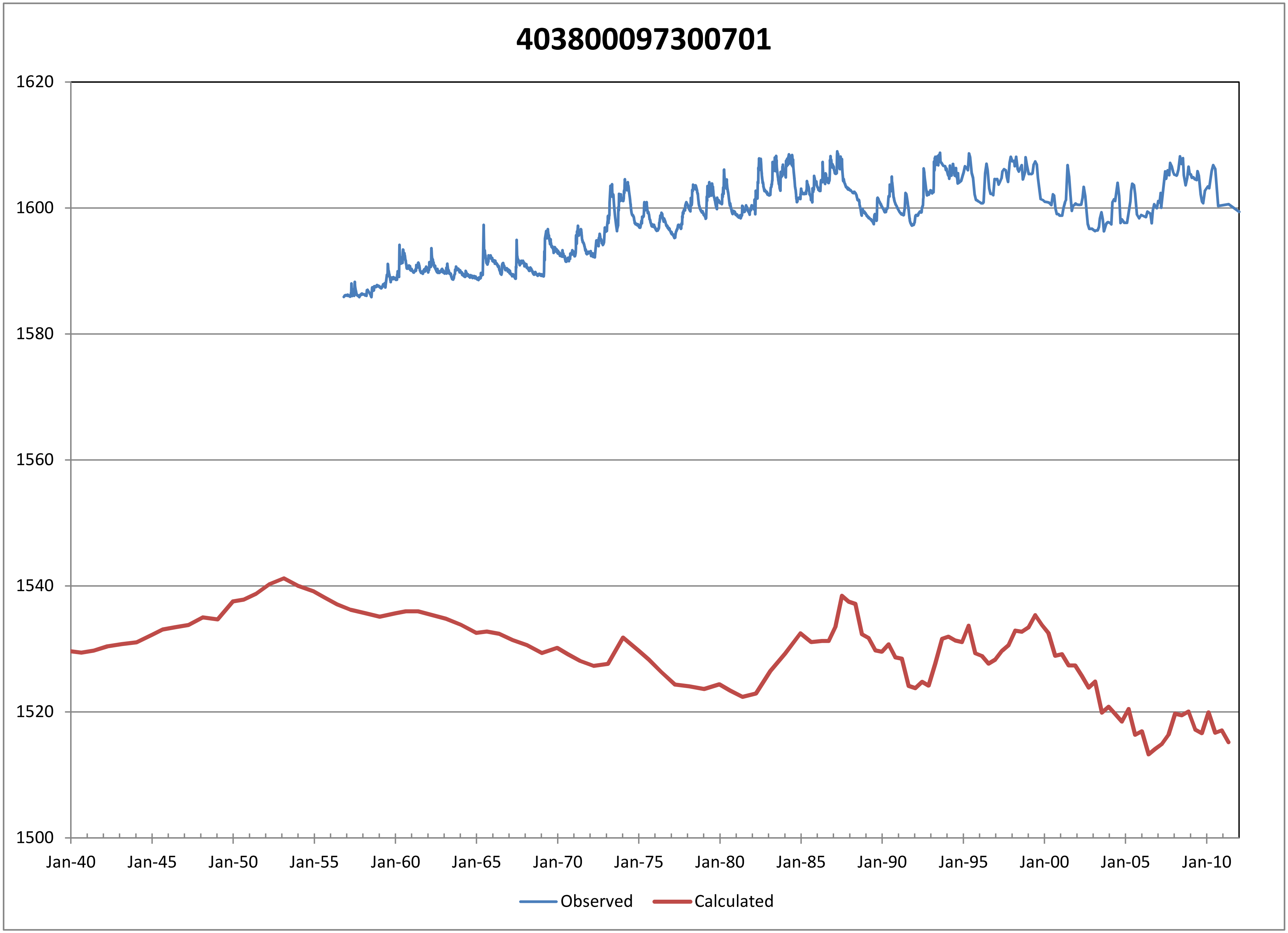

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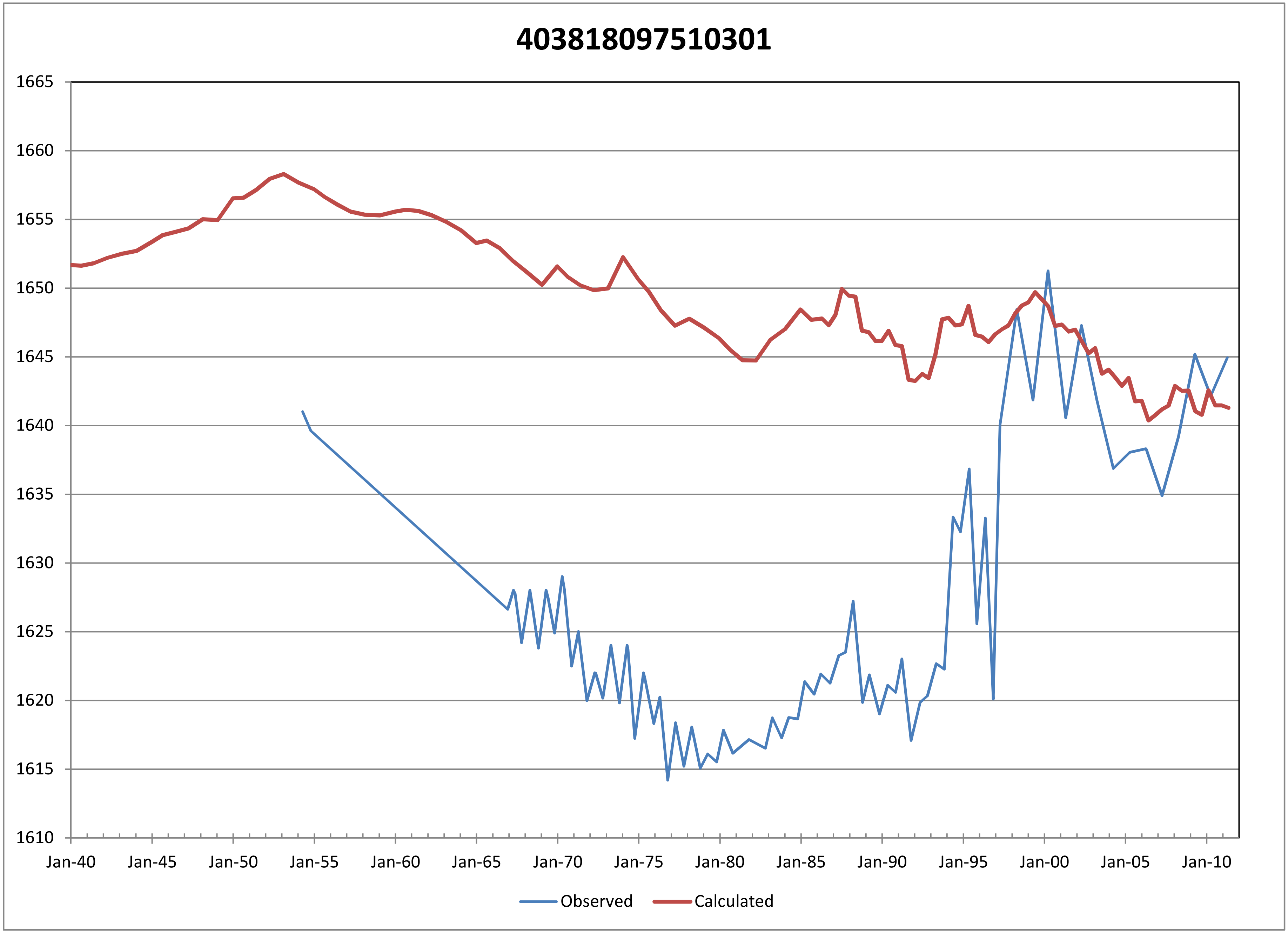
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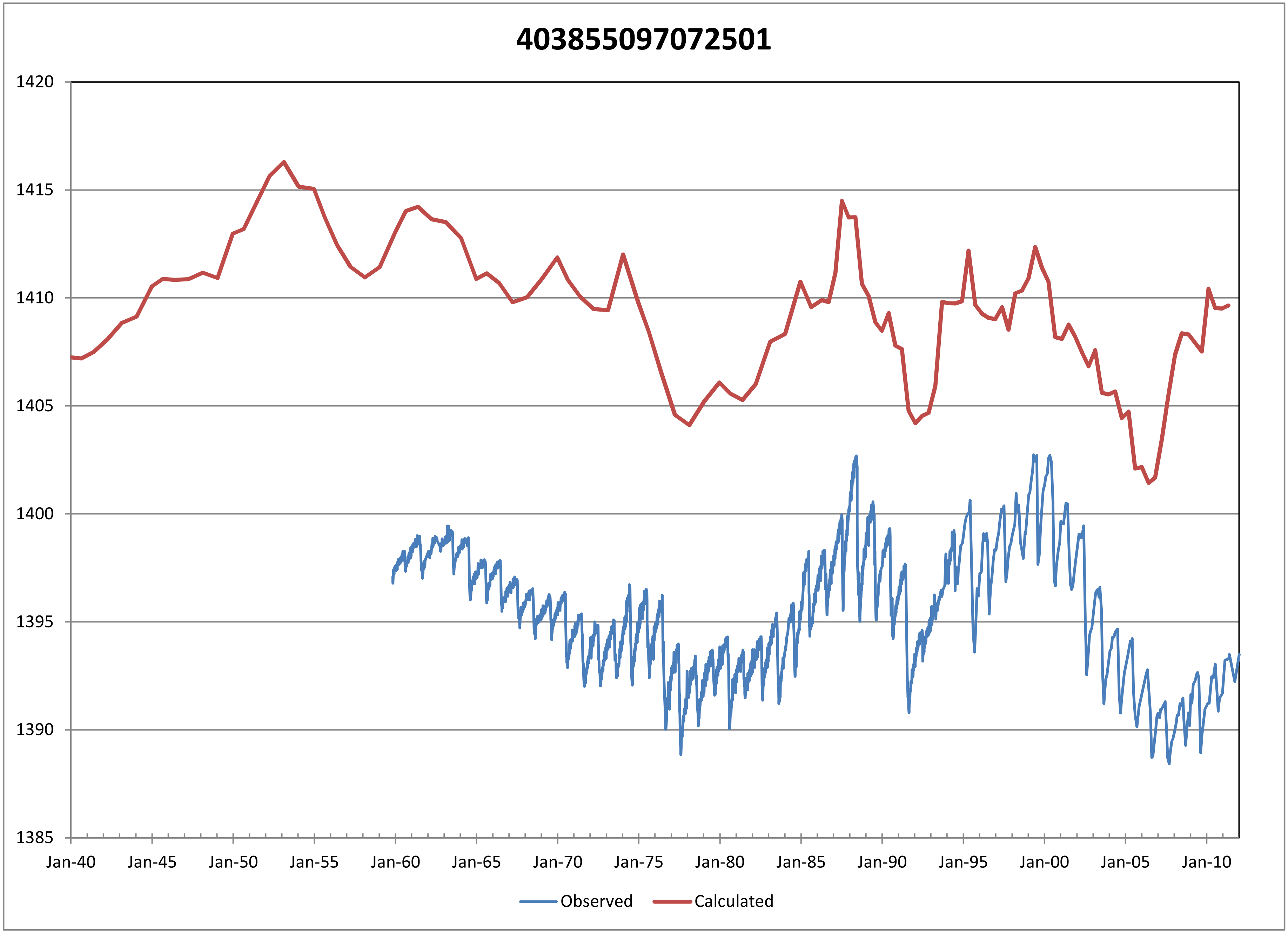

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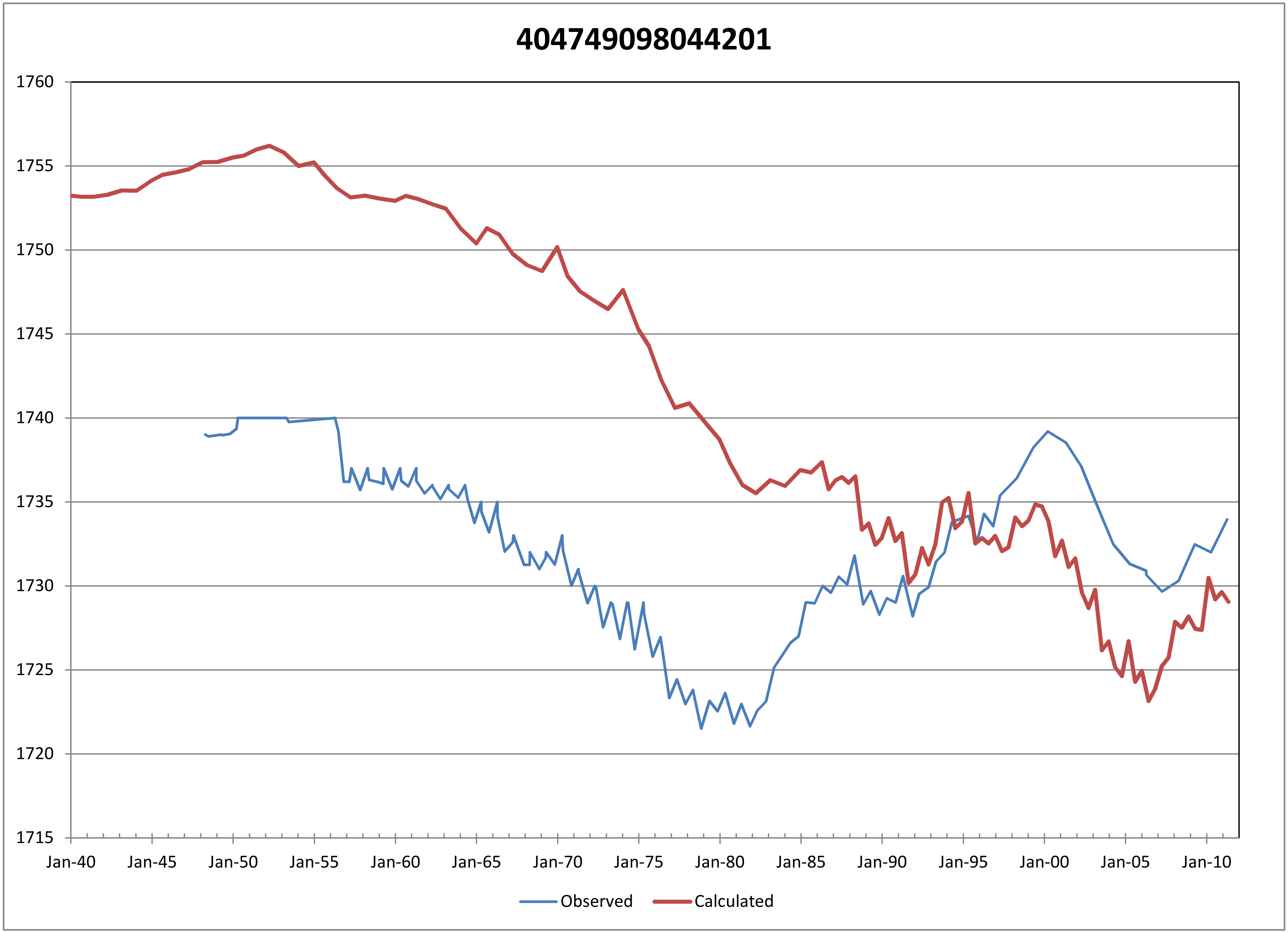
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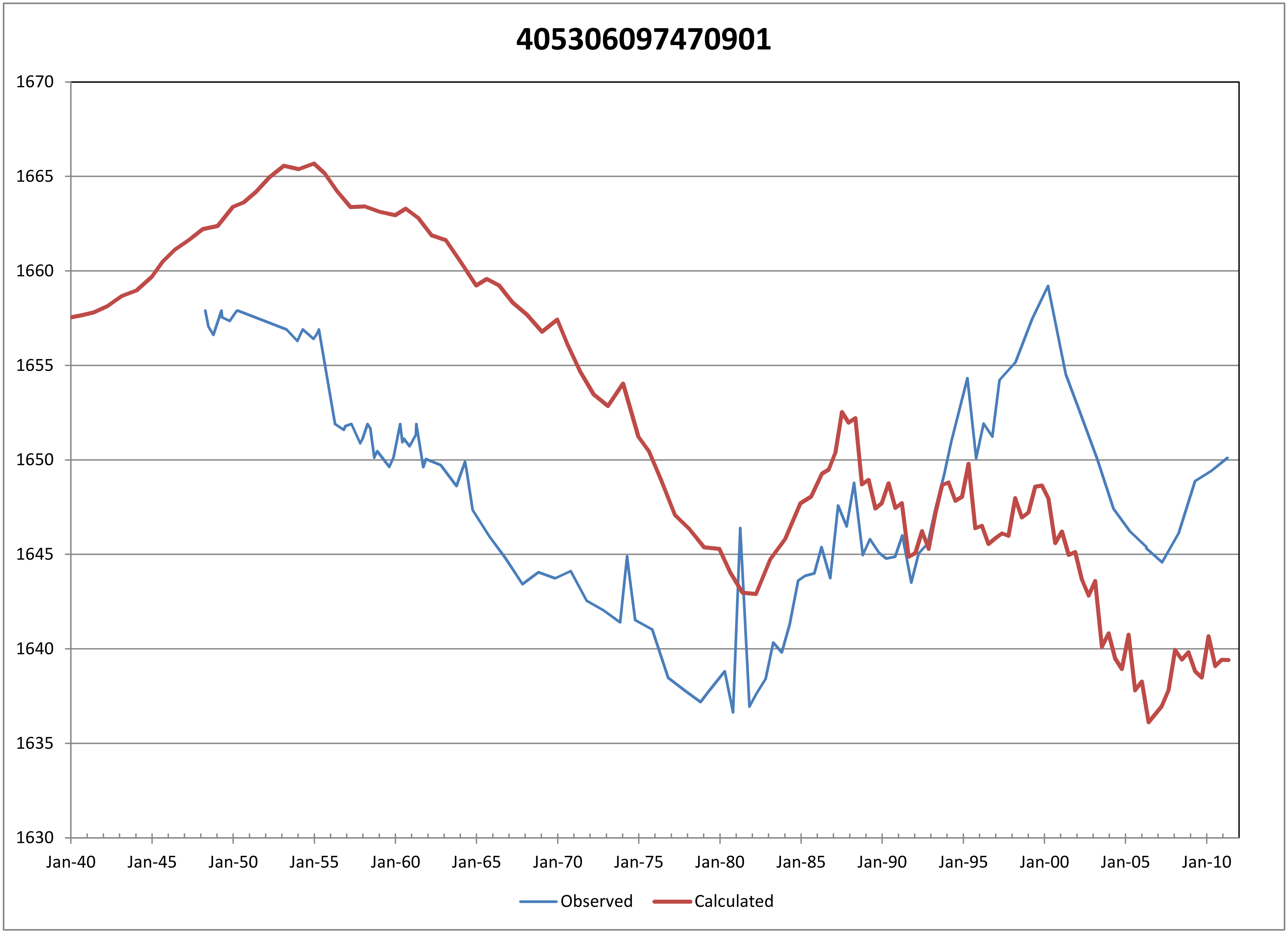
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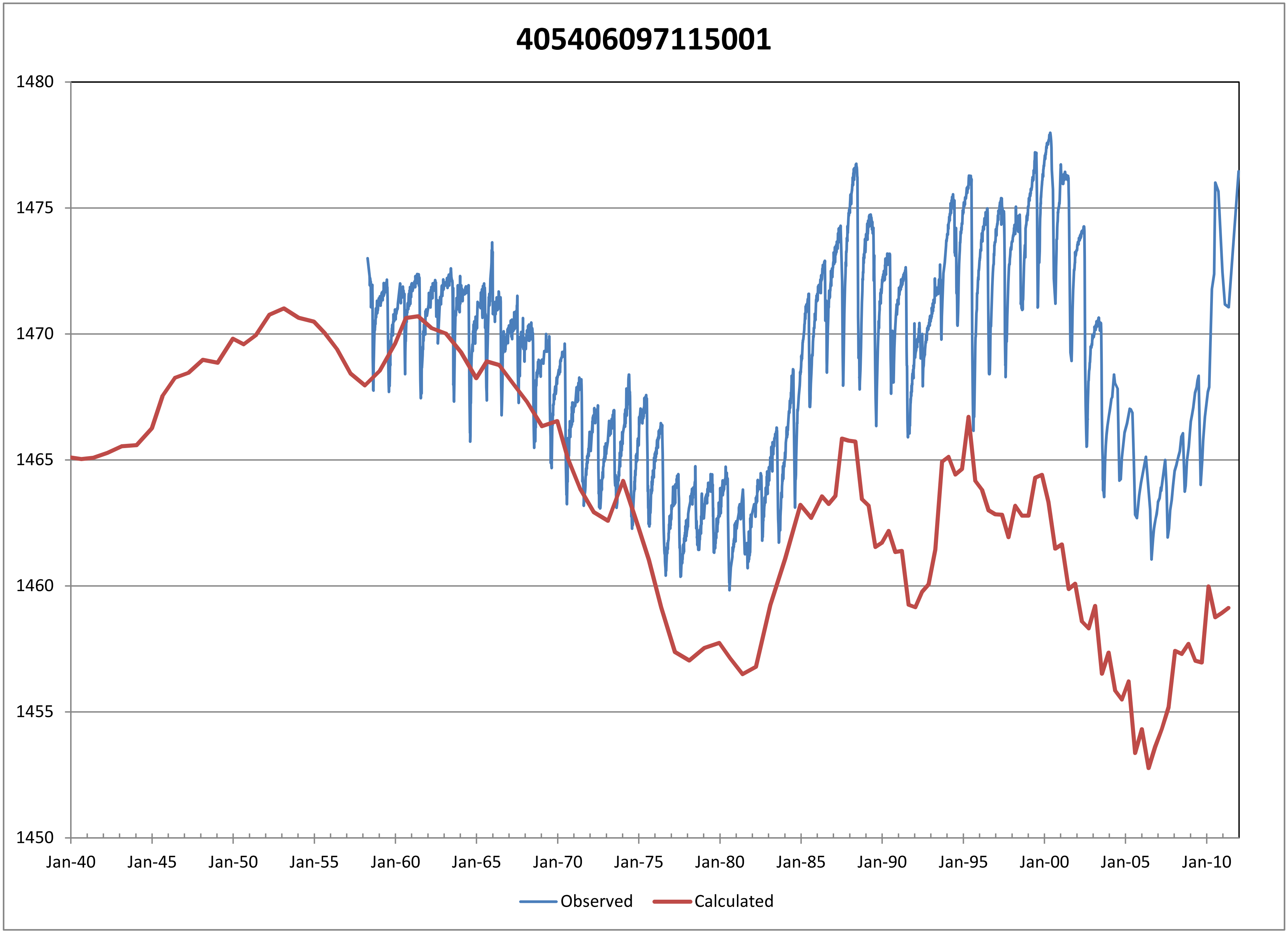

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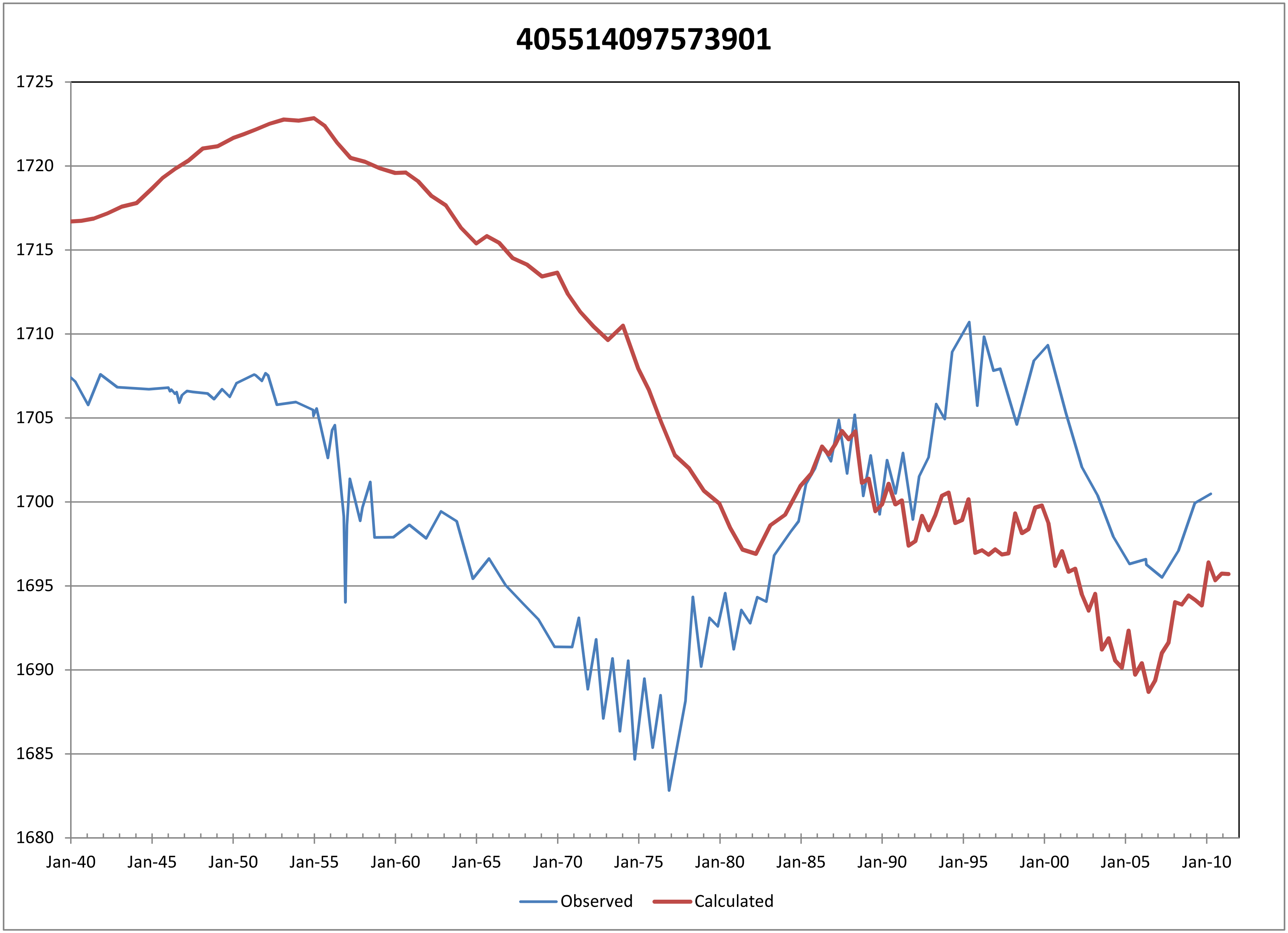
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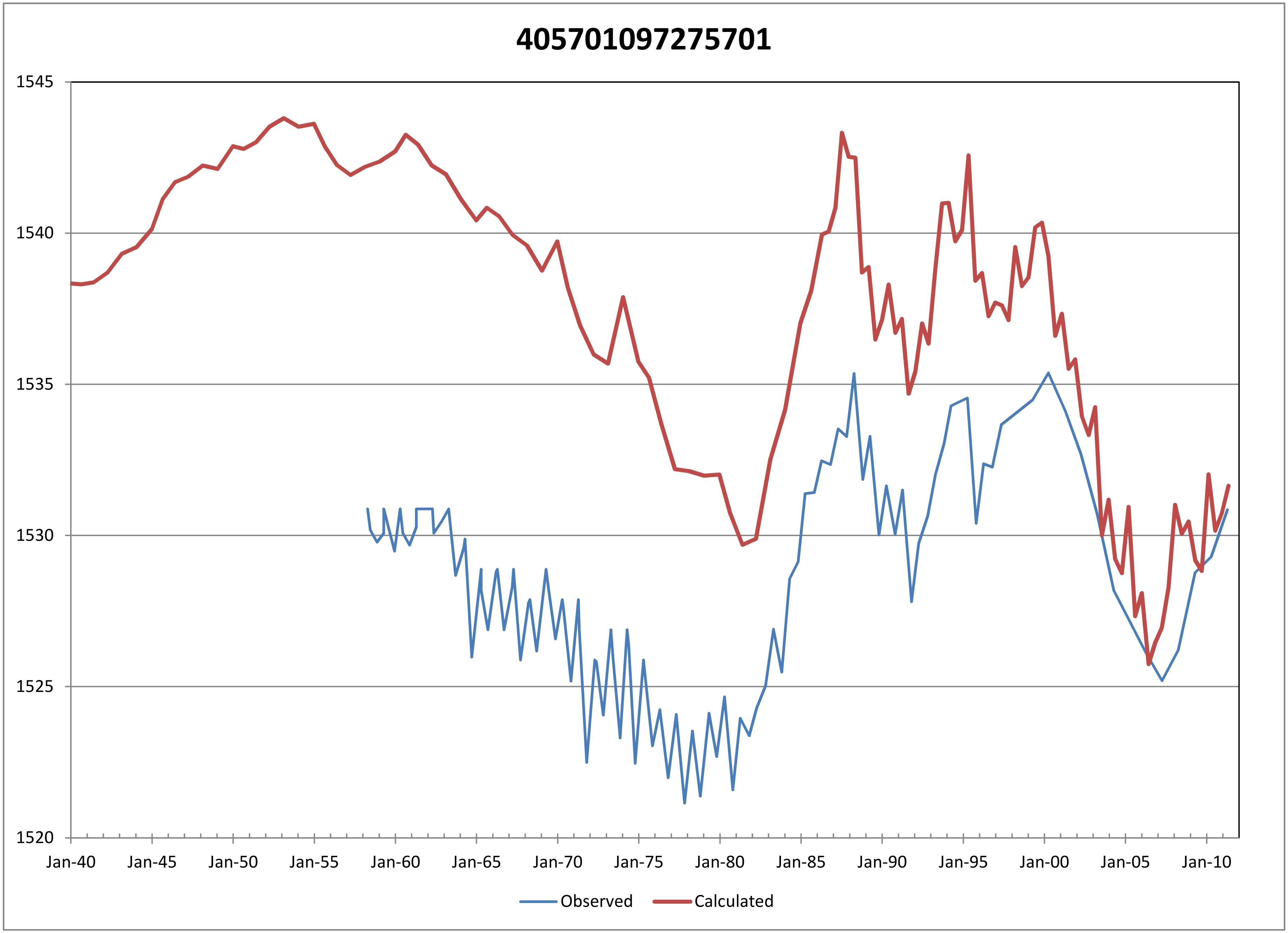

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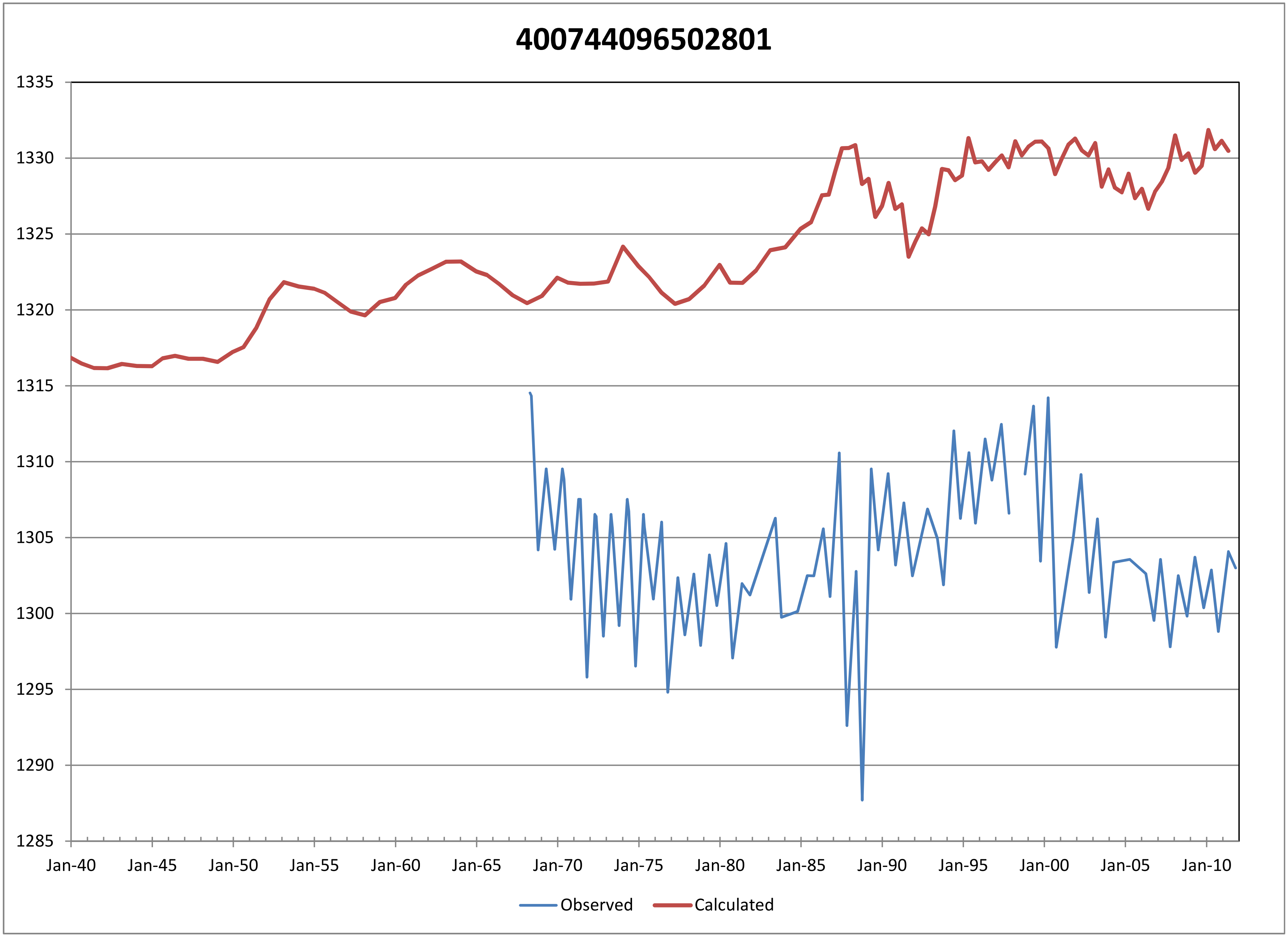
Appendix F – Well Hydrographs

Appendix F contains well hydrographs that illustrate the observed changes in groundwater elevation over time in that well, plus the model predicted groundwater elevation in that well from the transient simulation. Results are representative of CROPSIM004 run.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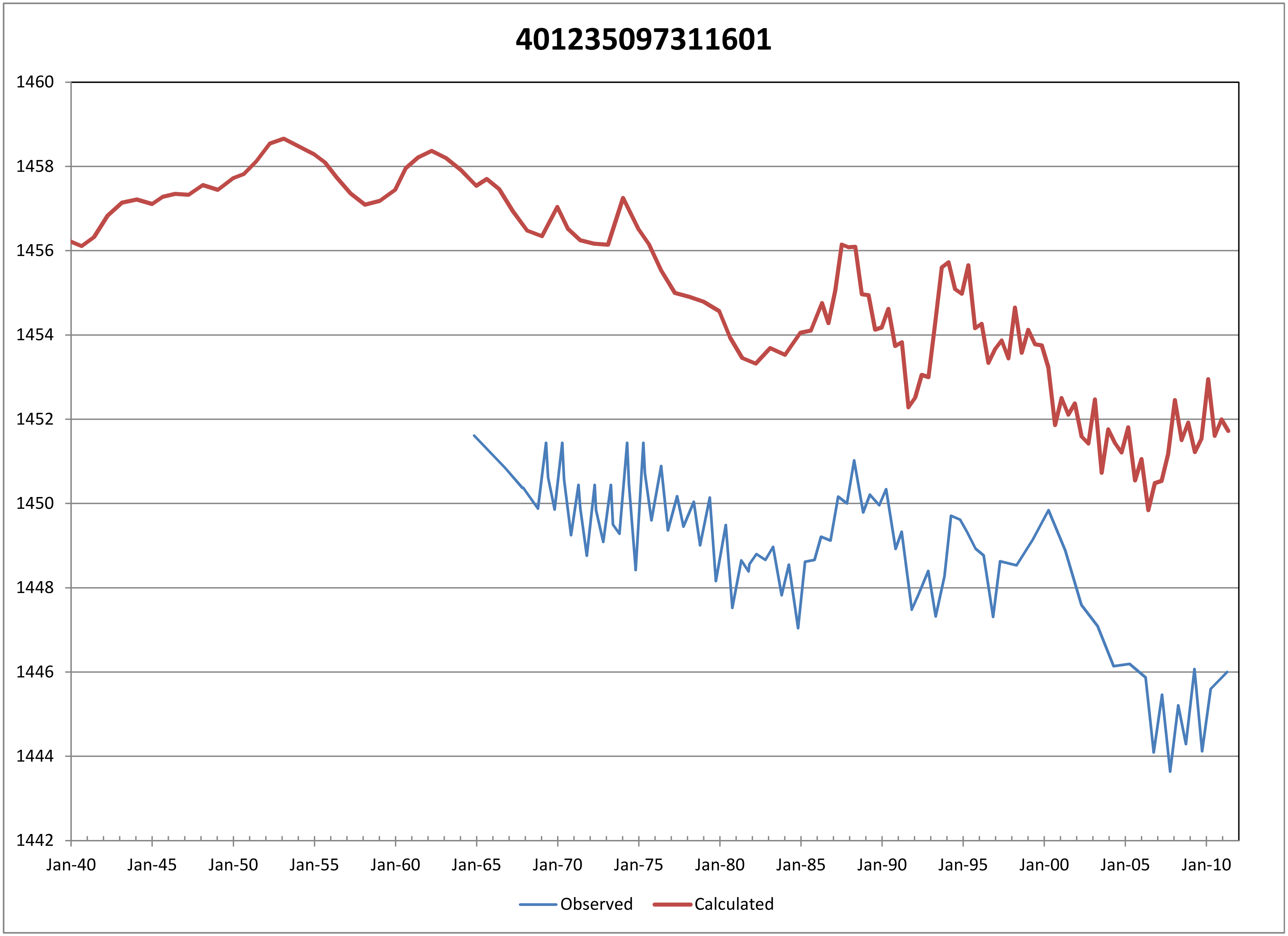
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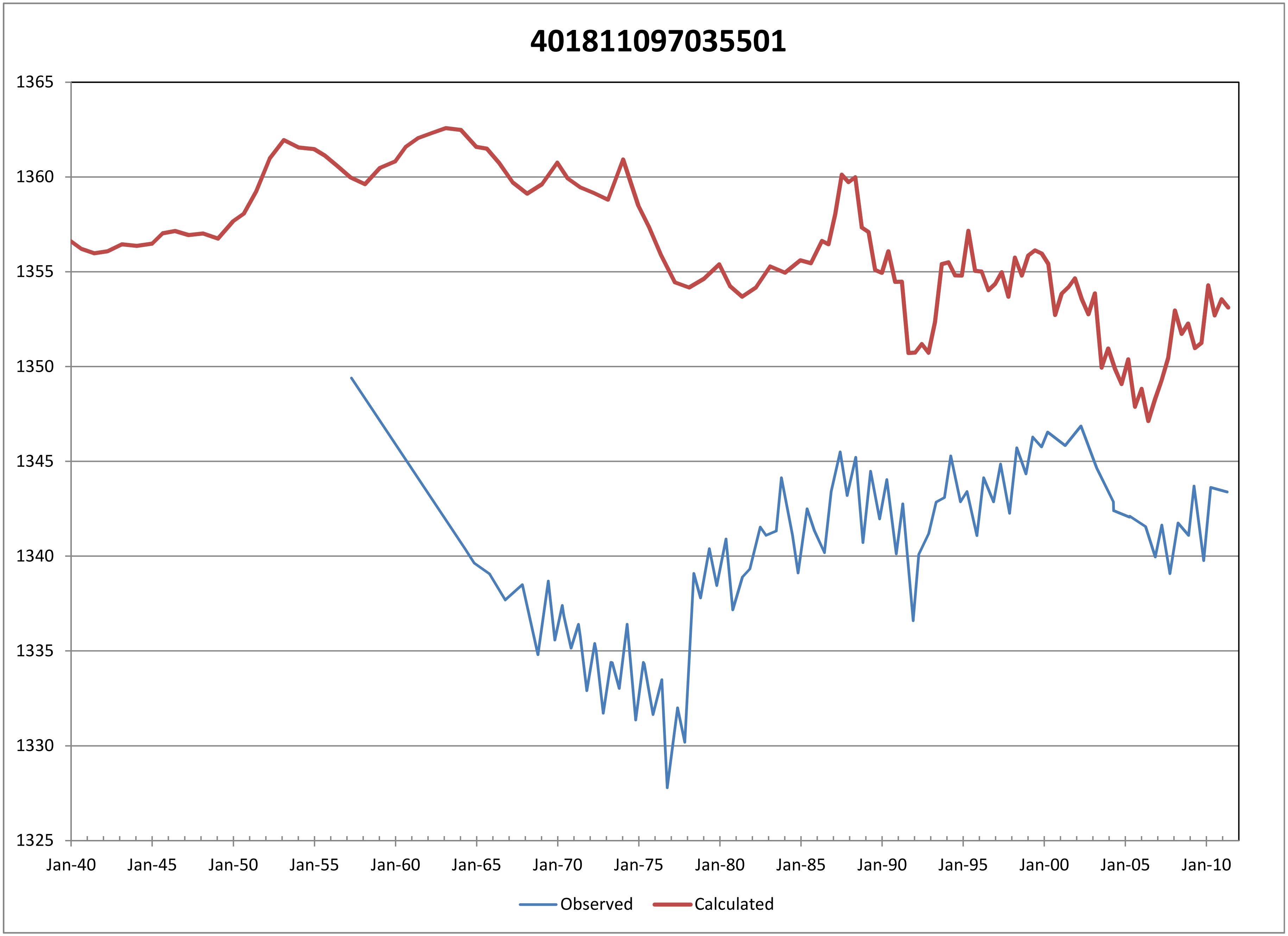
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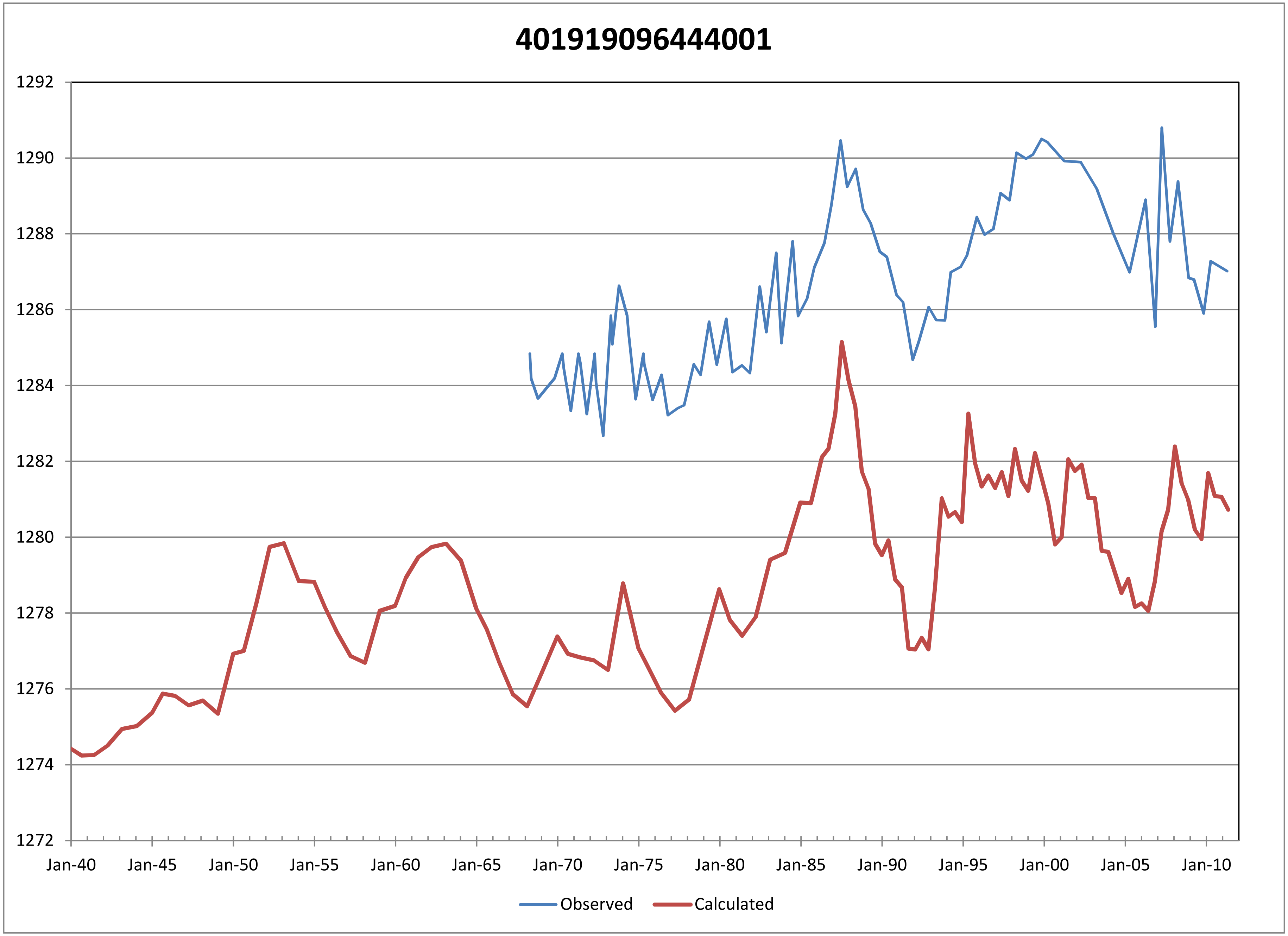
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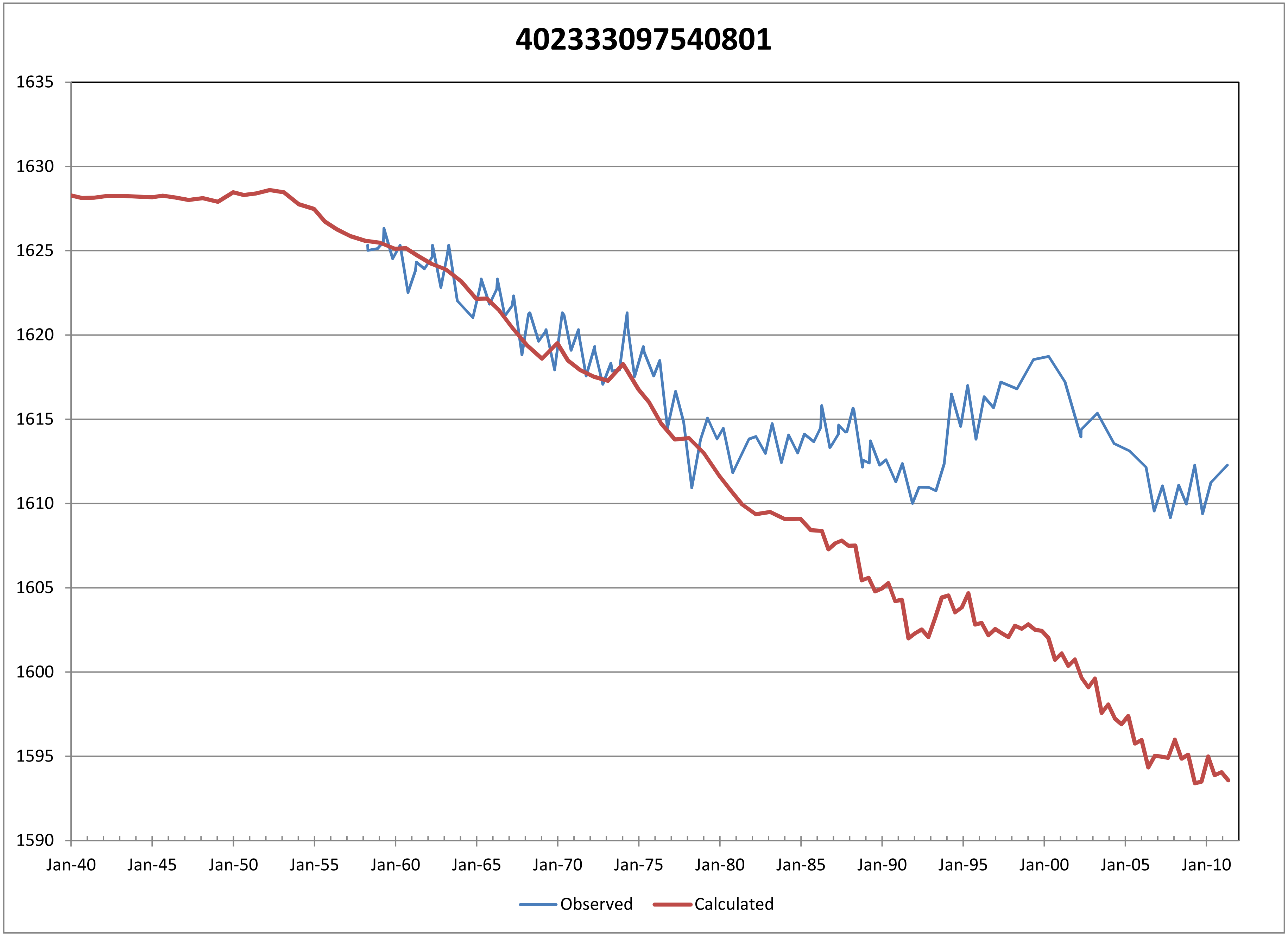

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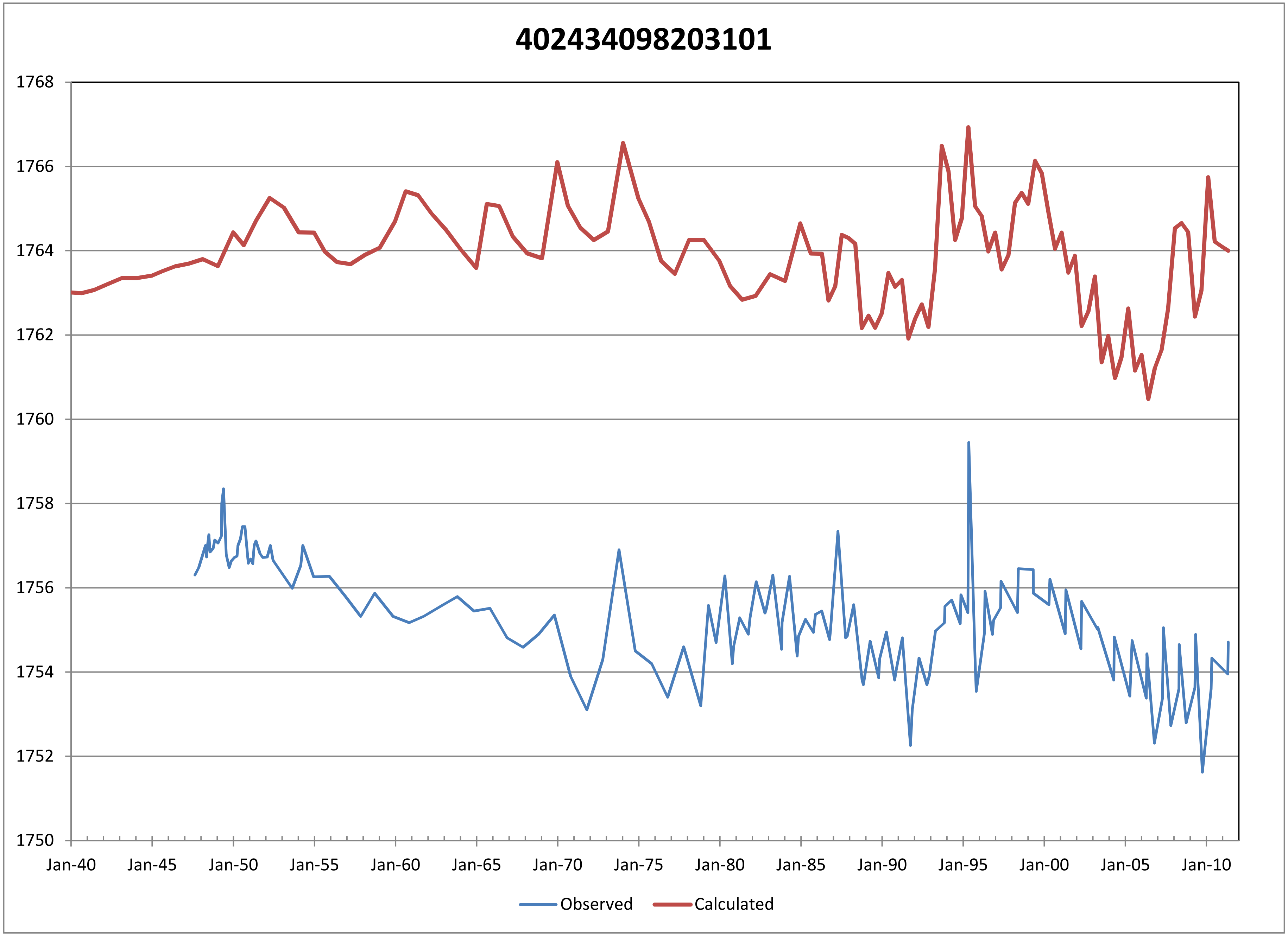
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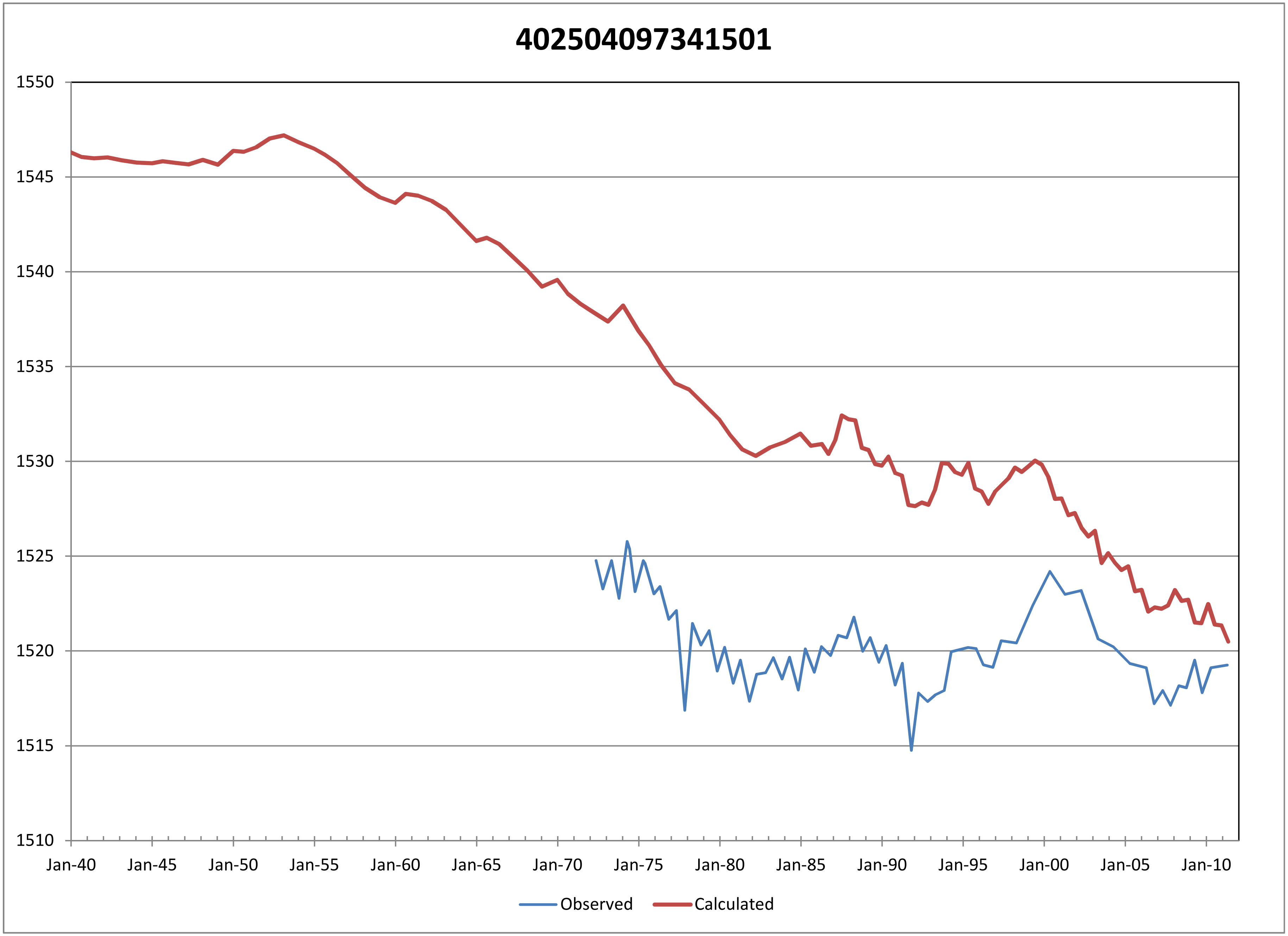
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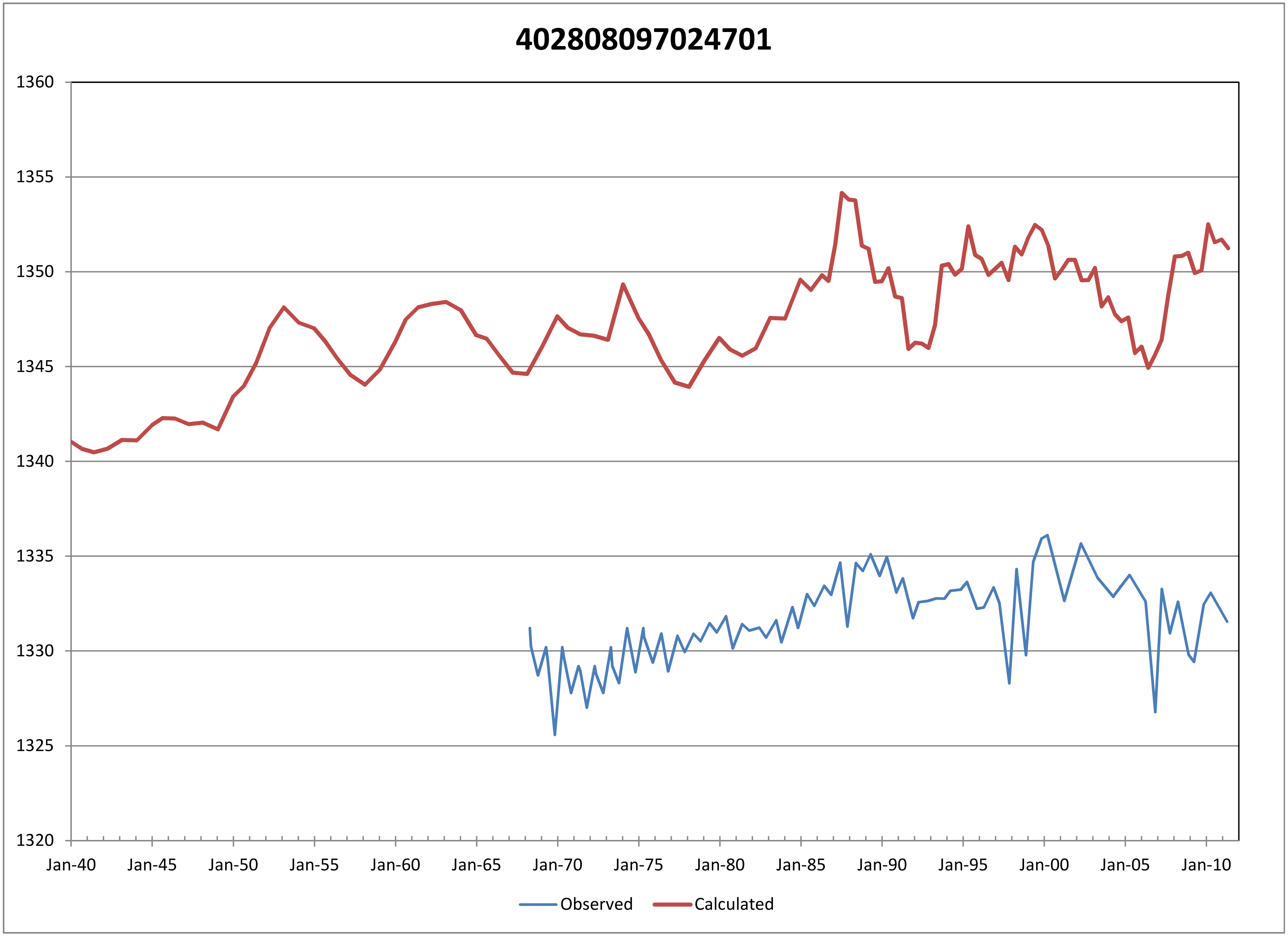
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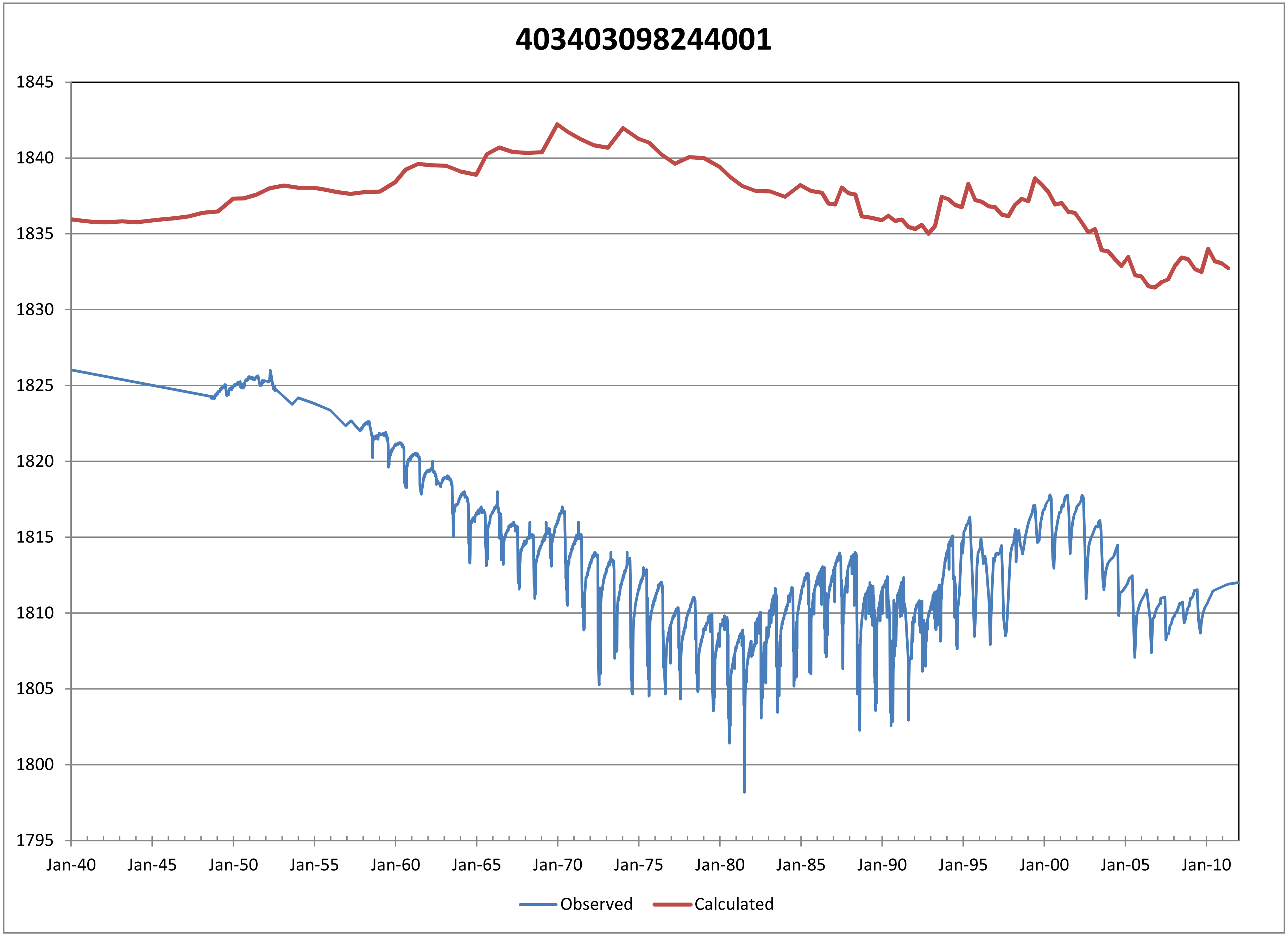

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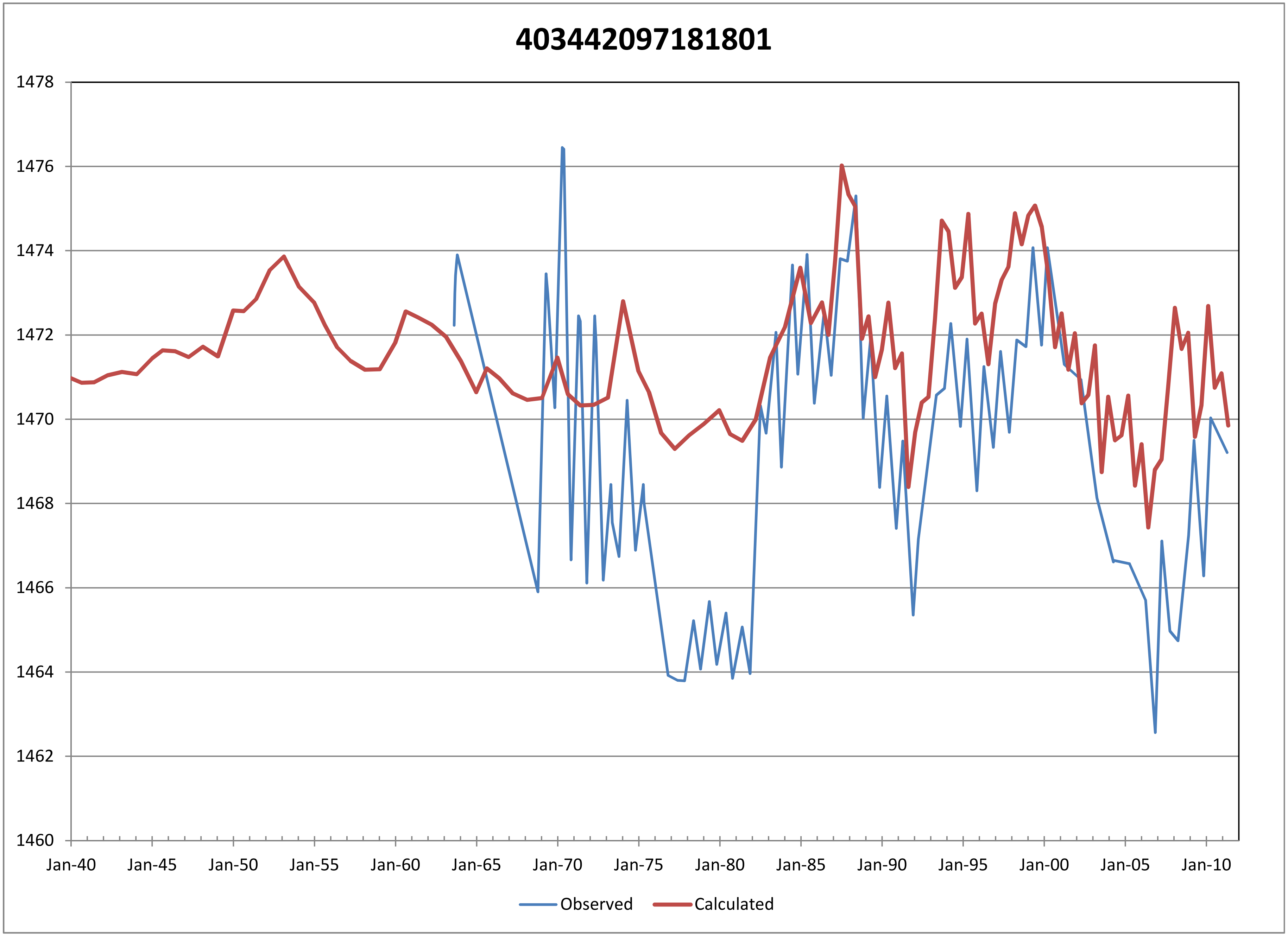
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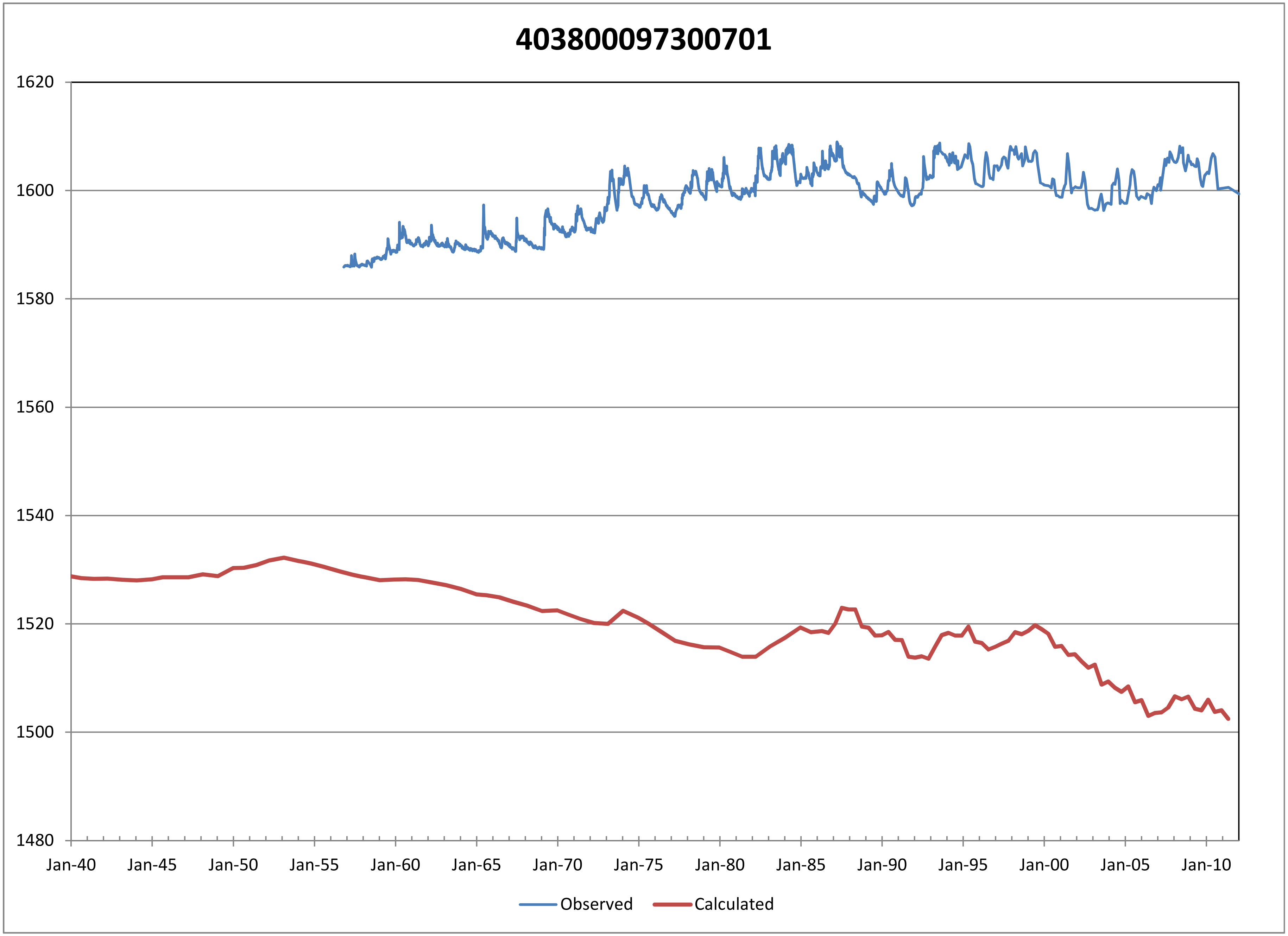

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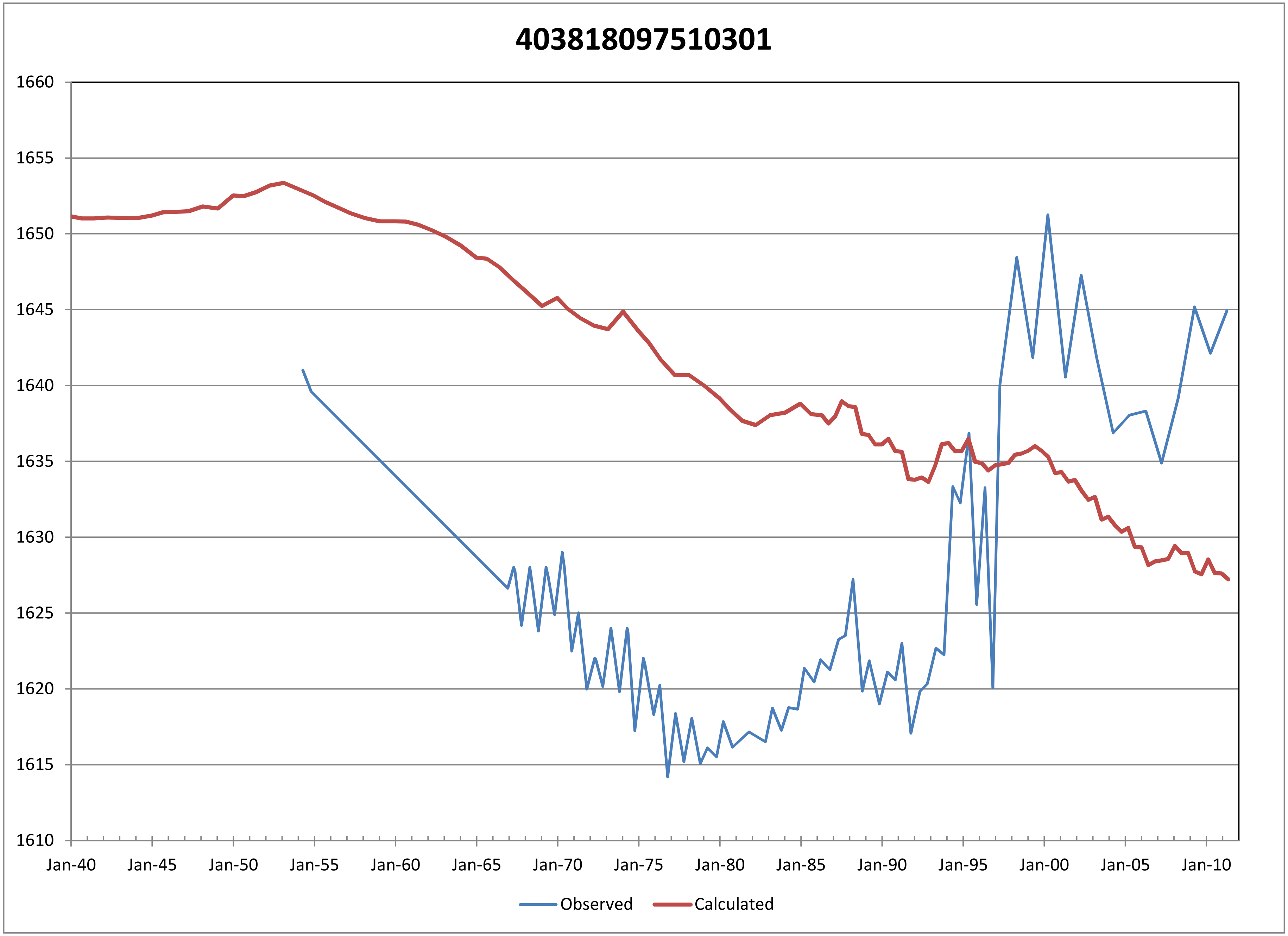
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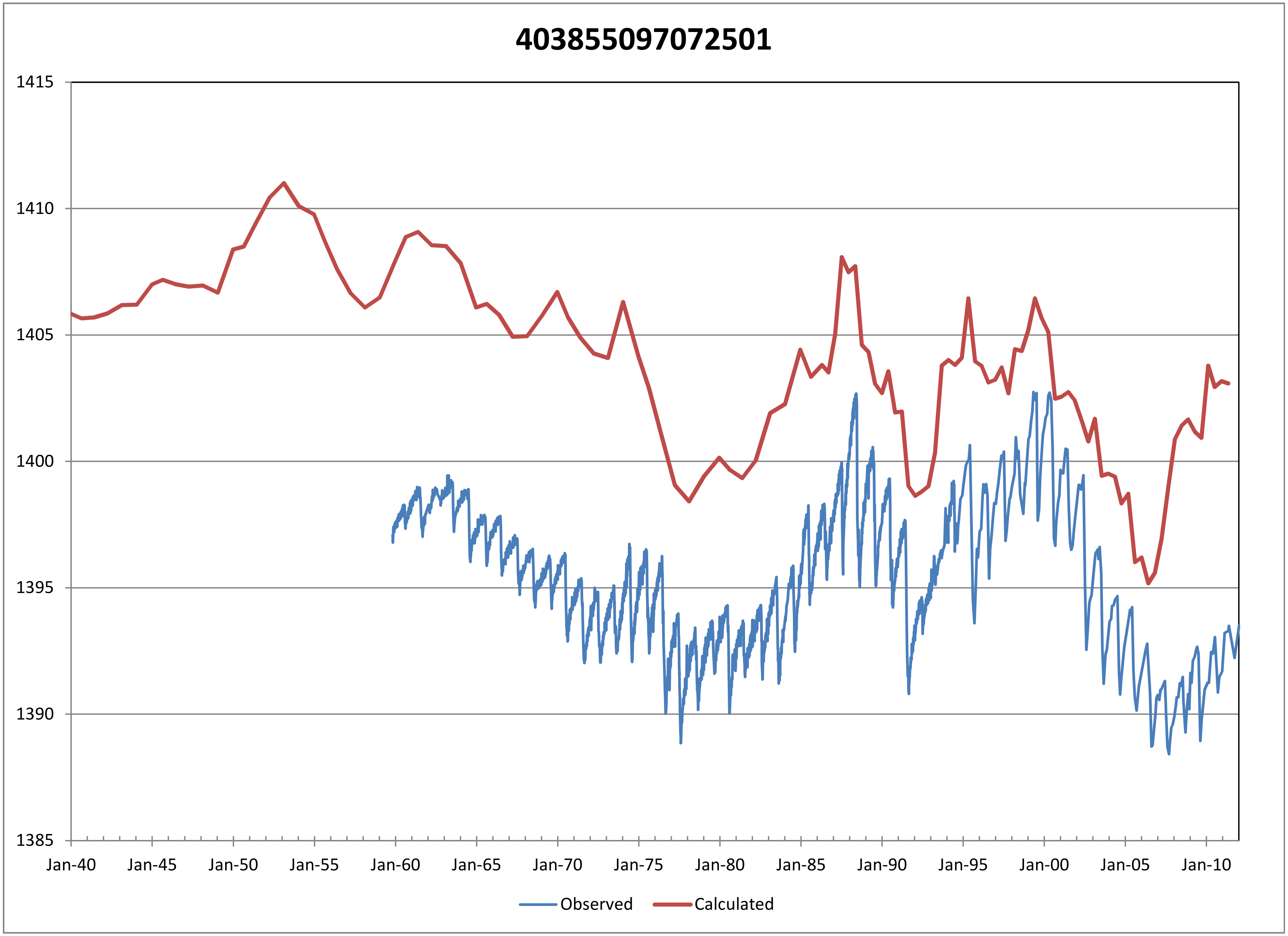
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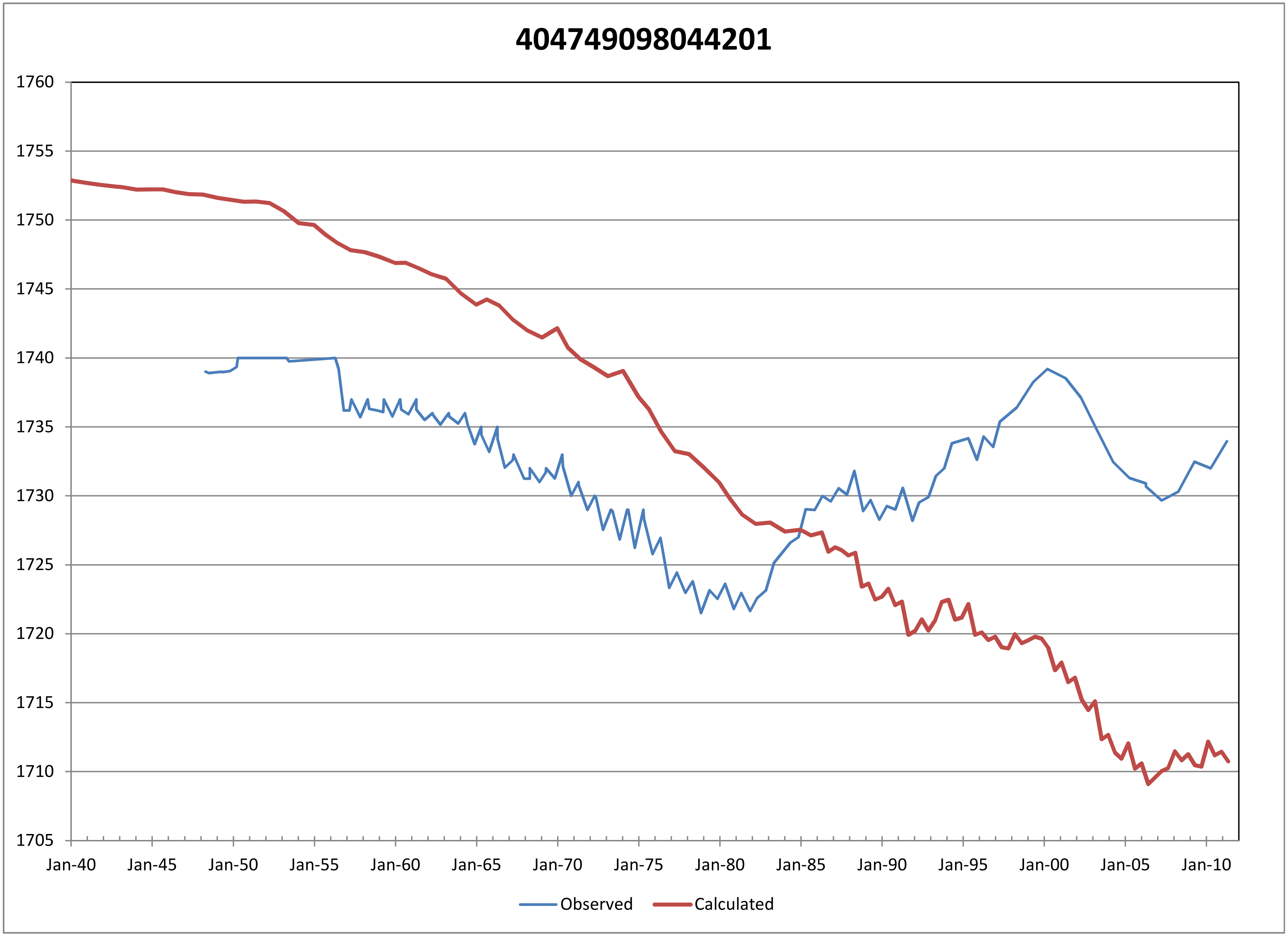

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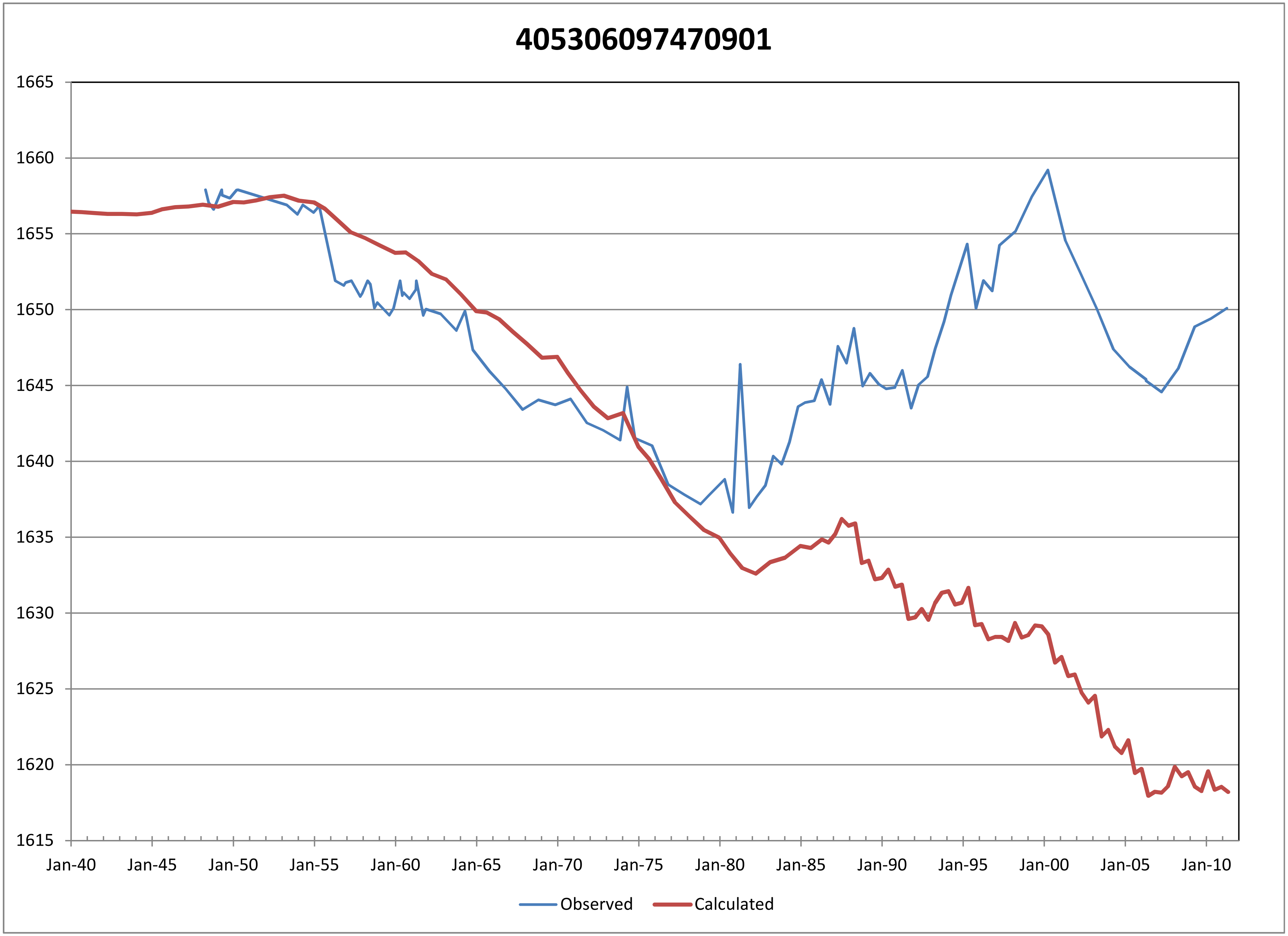
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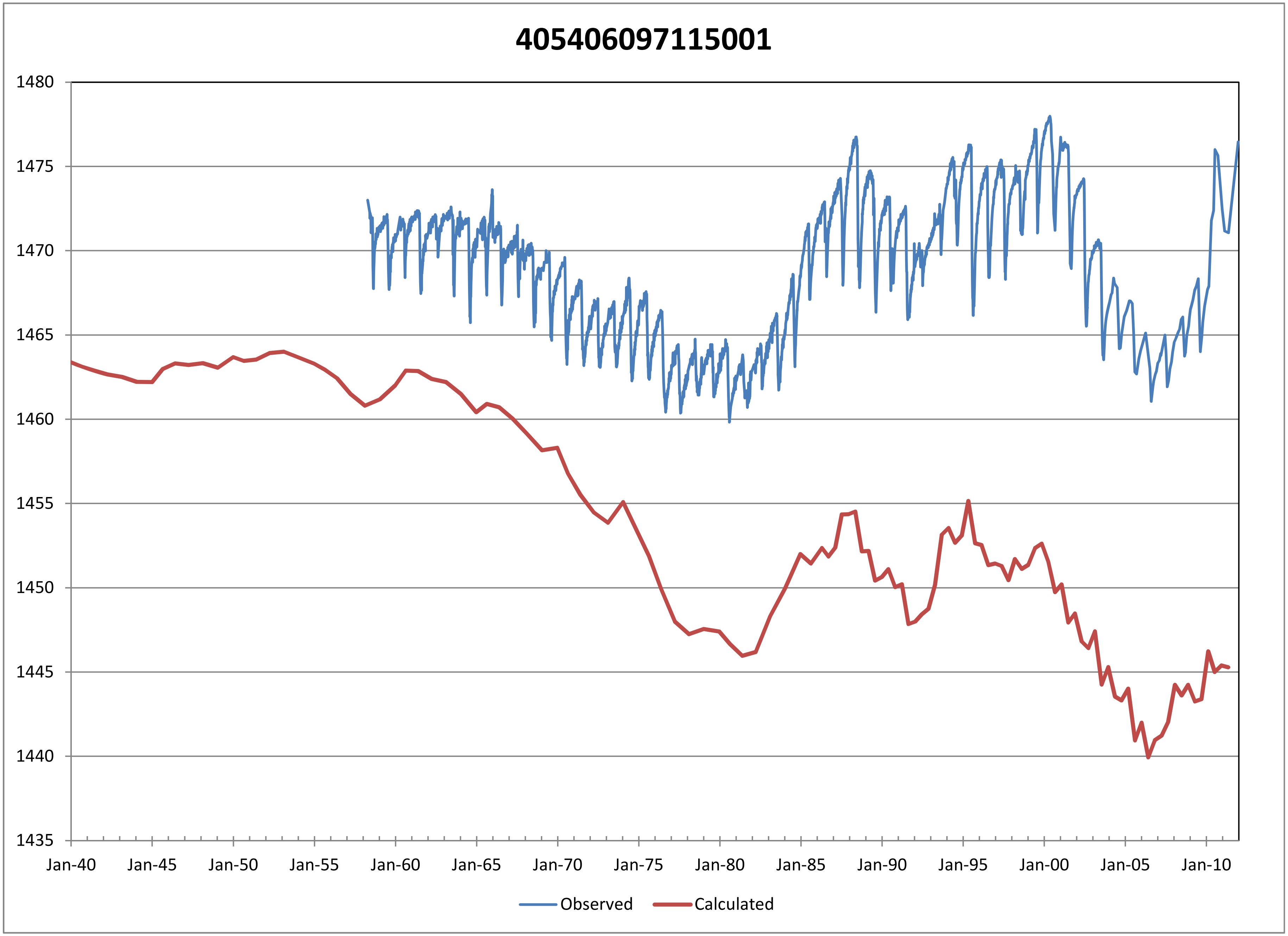

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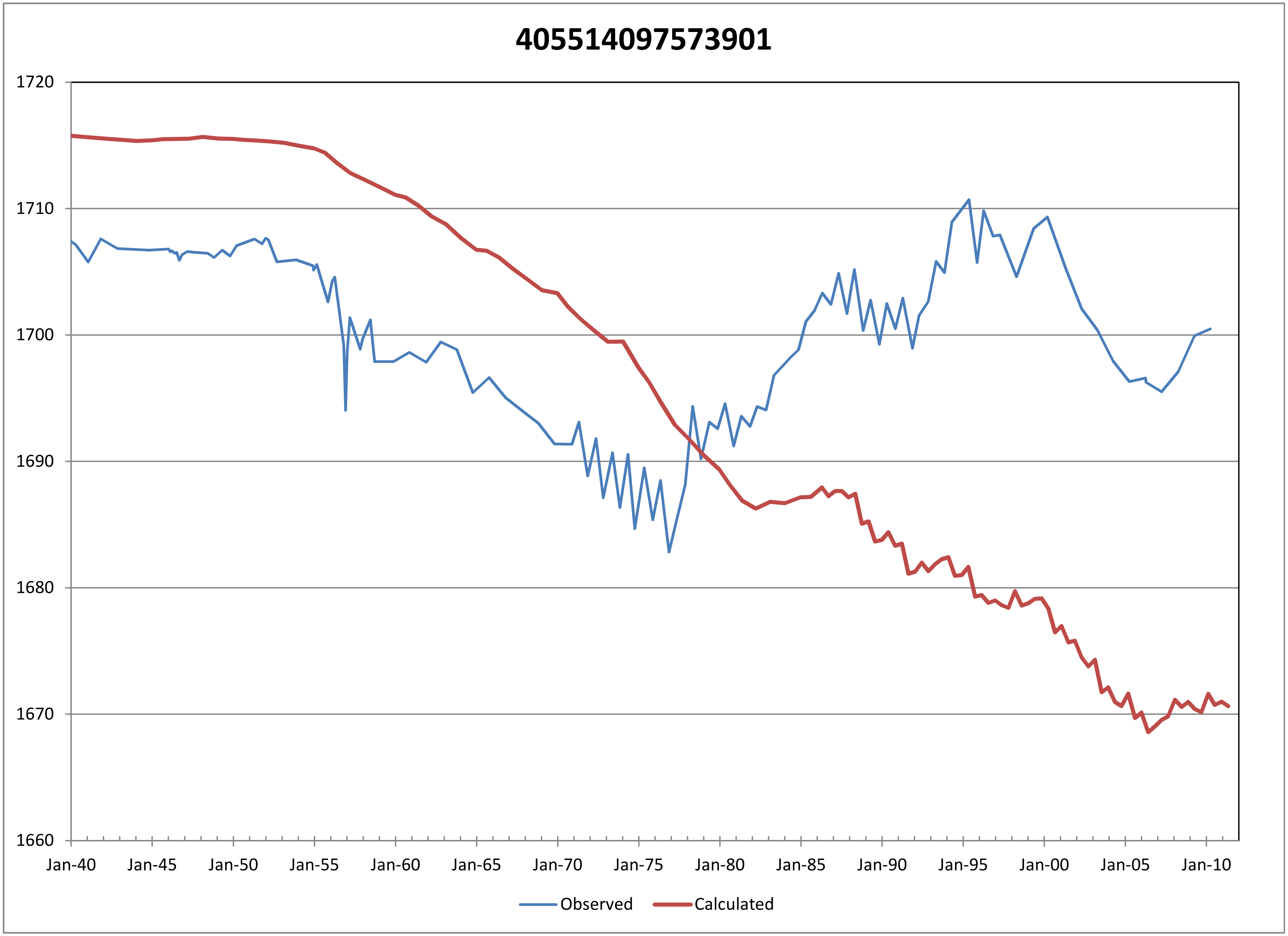
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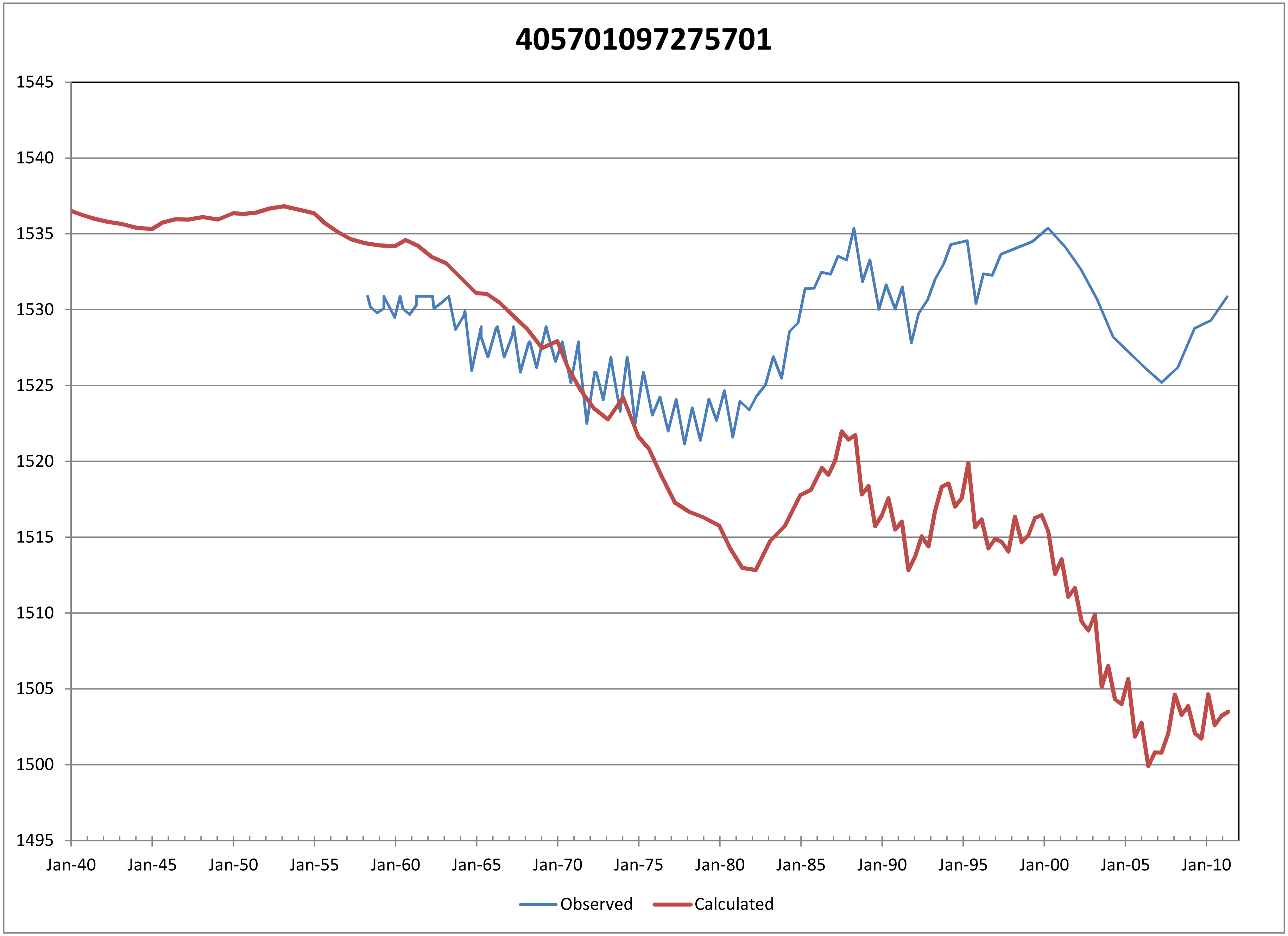

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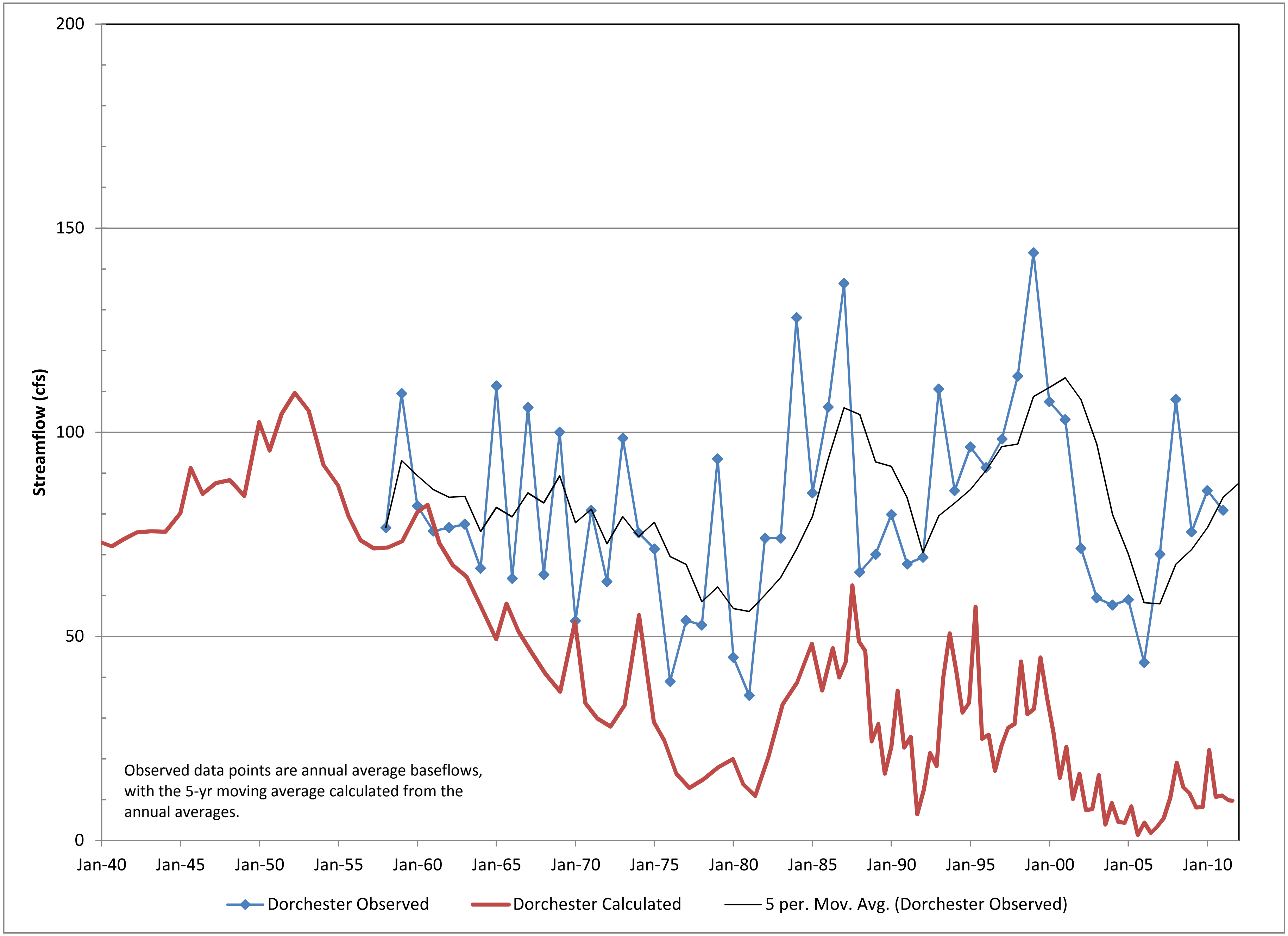
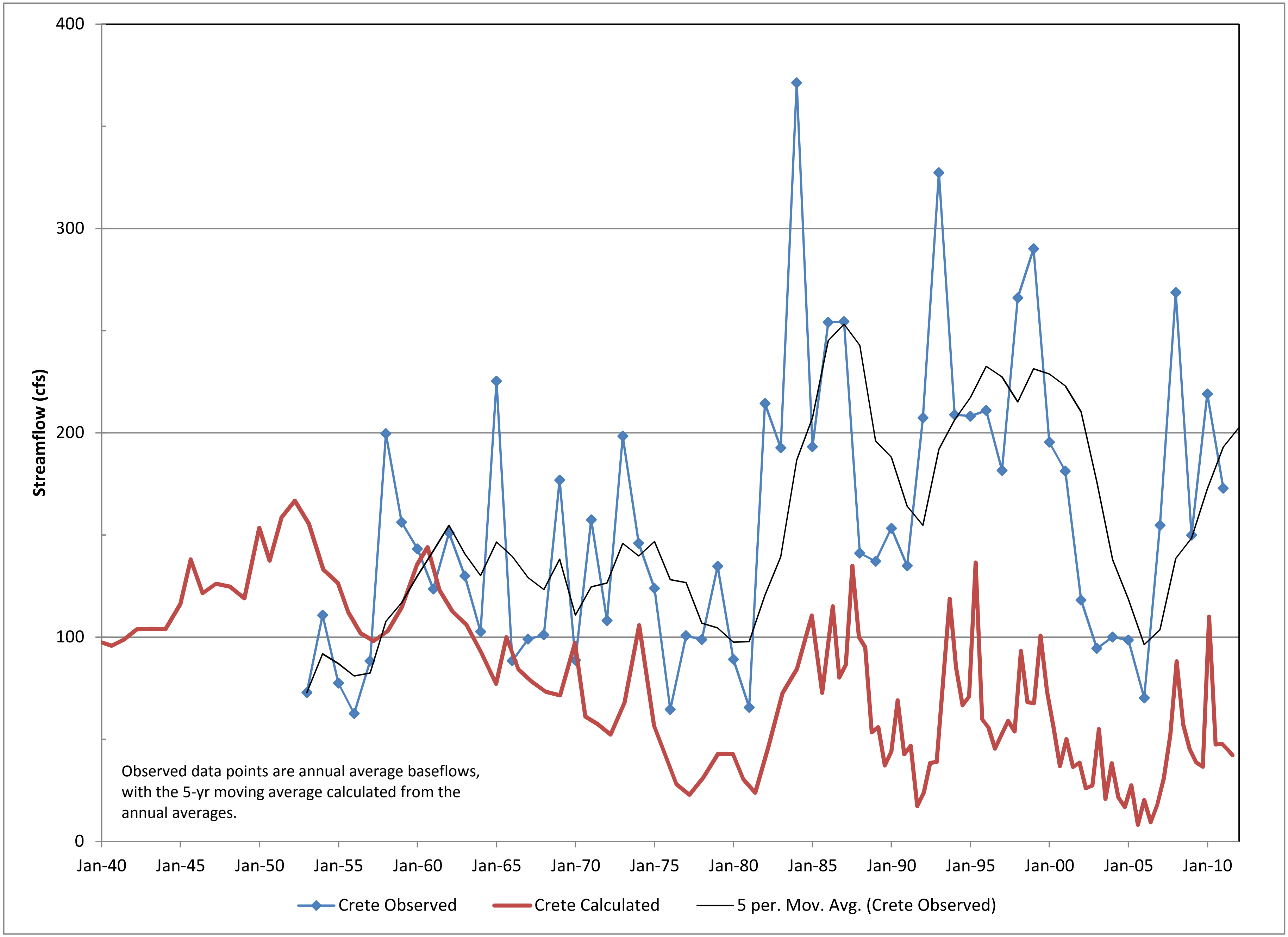
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed
Calculated

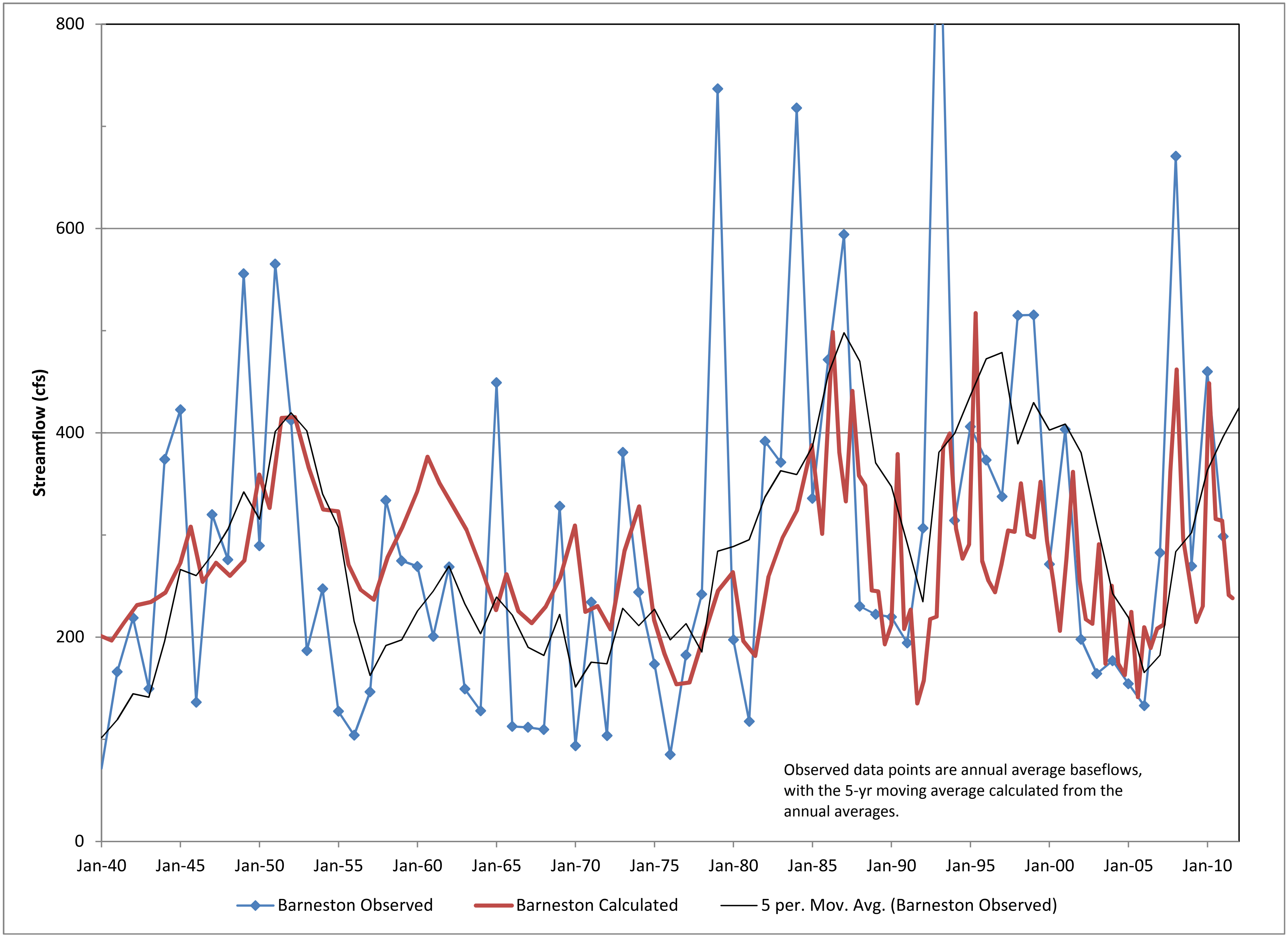
Appendix G – Stream Gauge Hydrographs

Appendix G contains streamflow hydrographs that illustrate the observed changes in base flow at several gauged locations, plus the model predicted base flow at that gauge from the transient simulation. Results are representative of CROPSIM004 run.

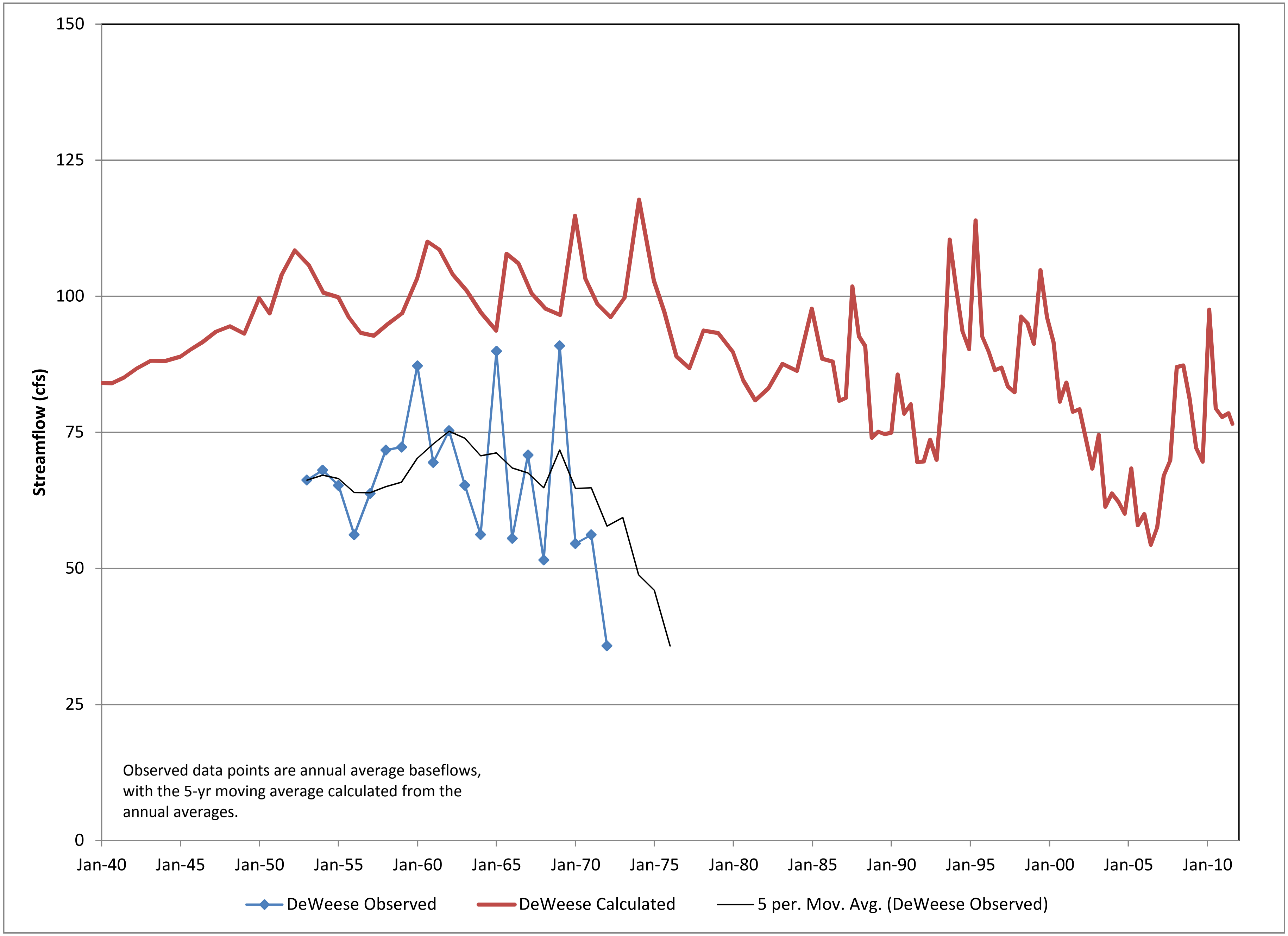


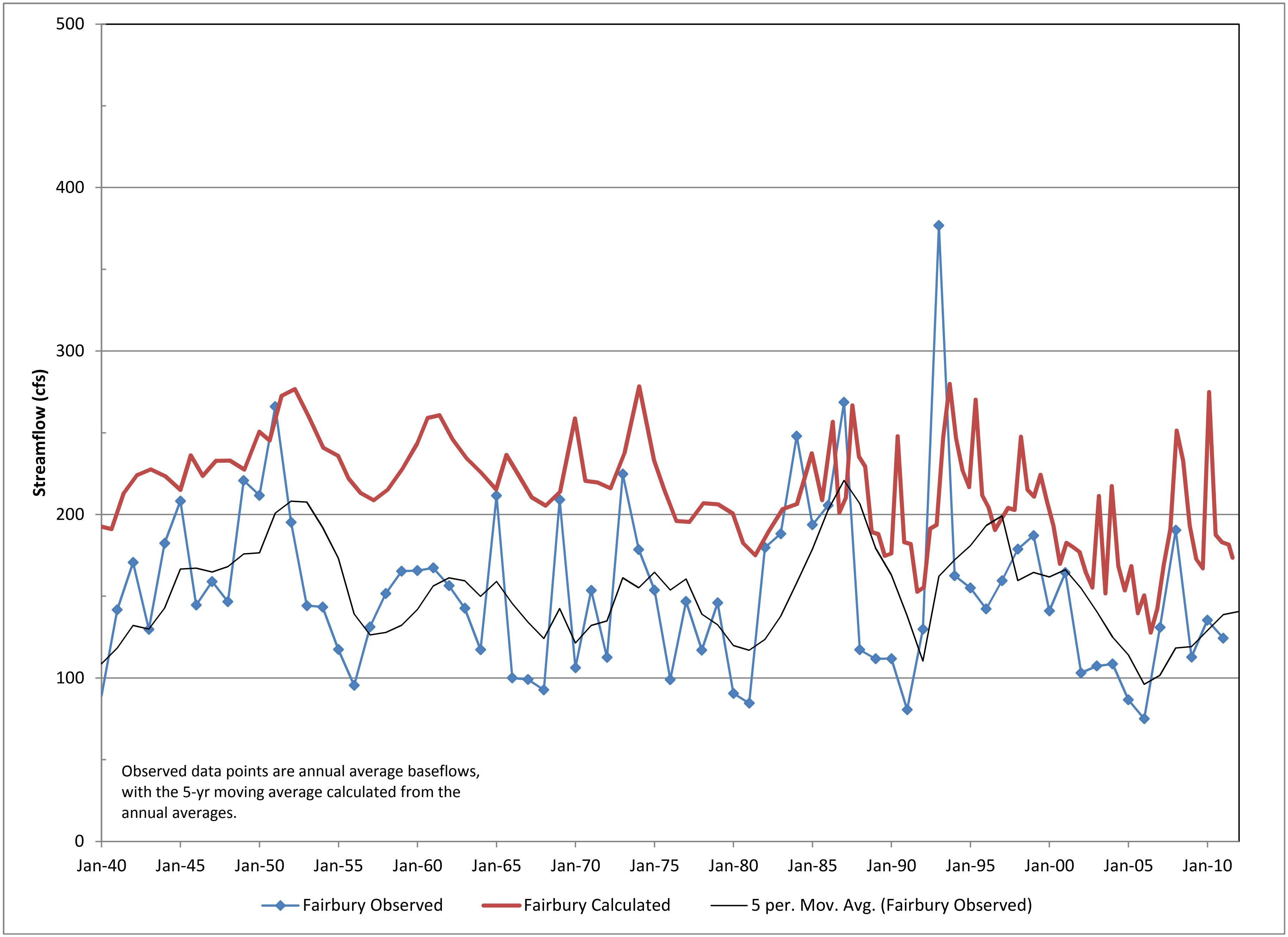
Streamflow (cfs)
200
150
100
50
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Dorchester Observed
Dorchester Calculated
5 per. Mov. Avg. (Dorchester Observed)


400
300
200
100
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Crete Observed
Crete Calculated
5 per. Mov. Avg. (Crete Observed)

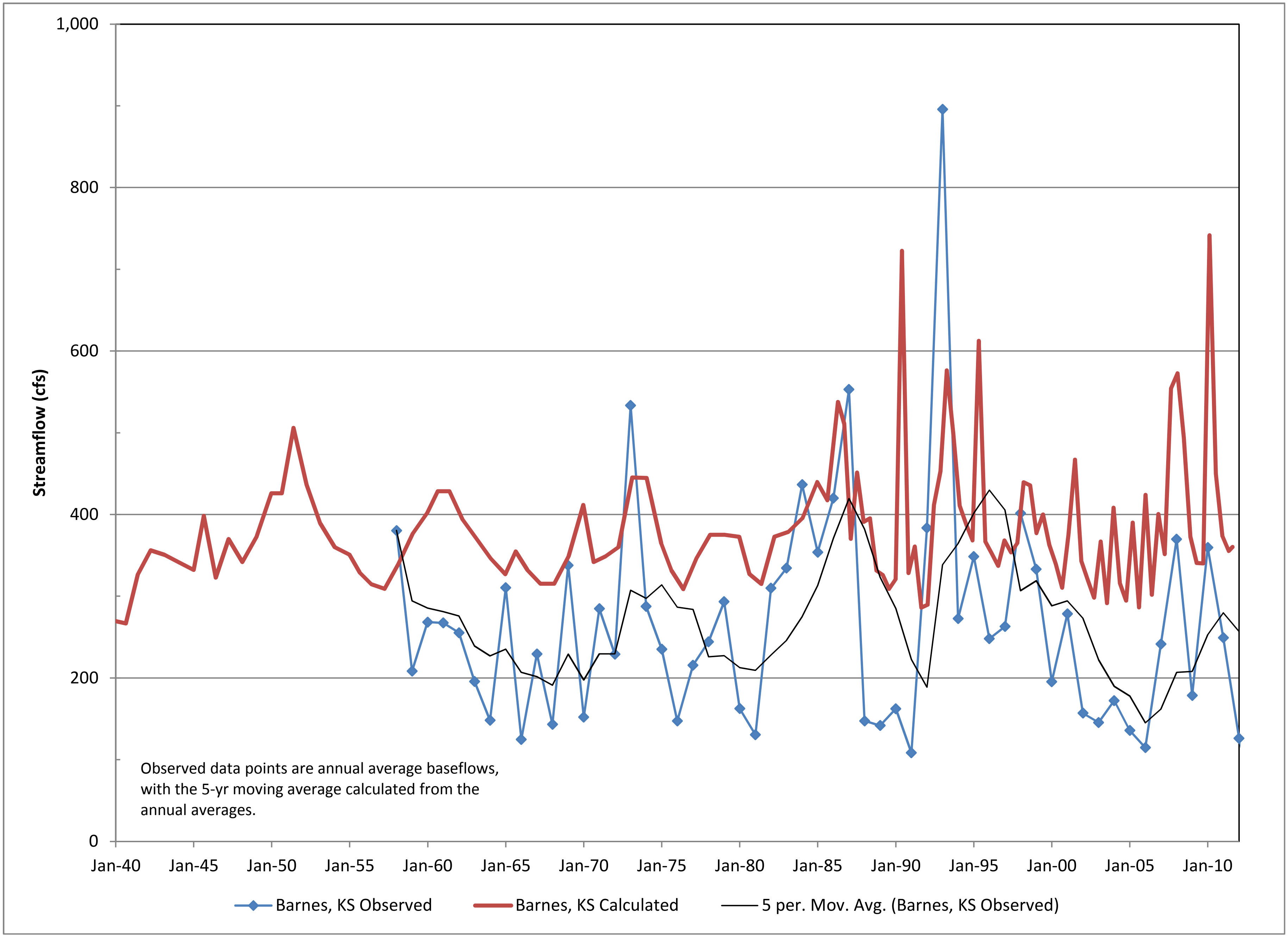


Streamflow (cfs)
800
600
400
200
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Barneston Observed
Barneston Calculated
5 per. Mov. Avg. (Barneston Observed)

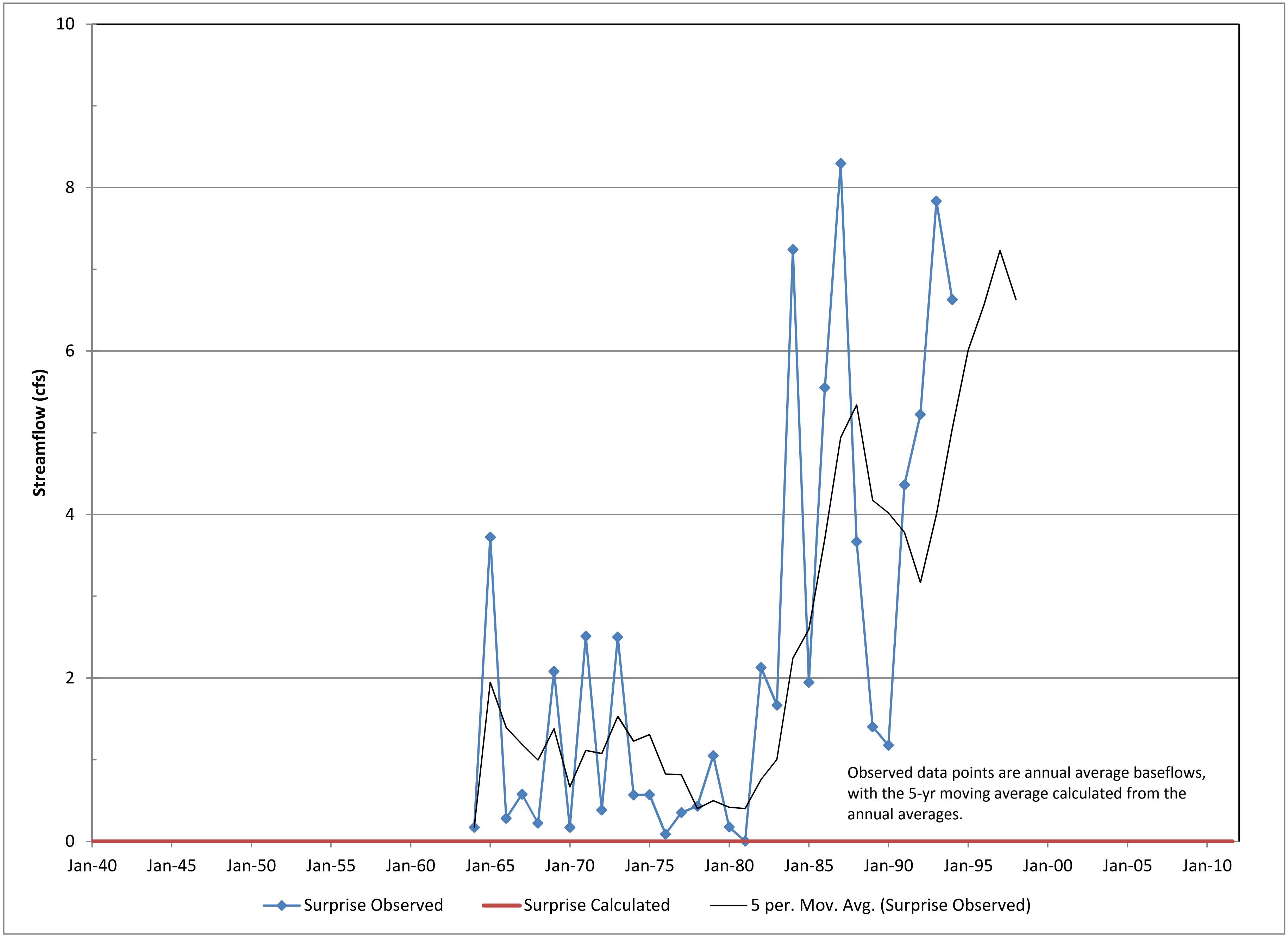

150
125
100
75
50
25
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
DeWeese Observed
DeWeese Calculated
5 per. Mov. Avg. (DeWeese Observed)

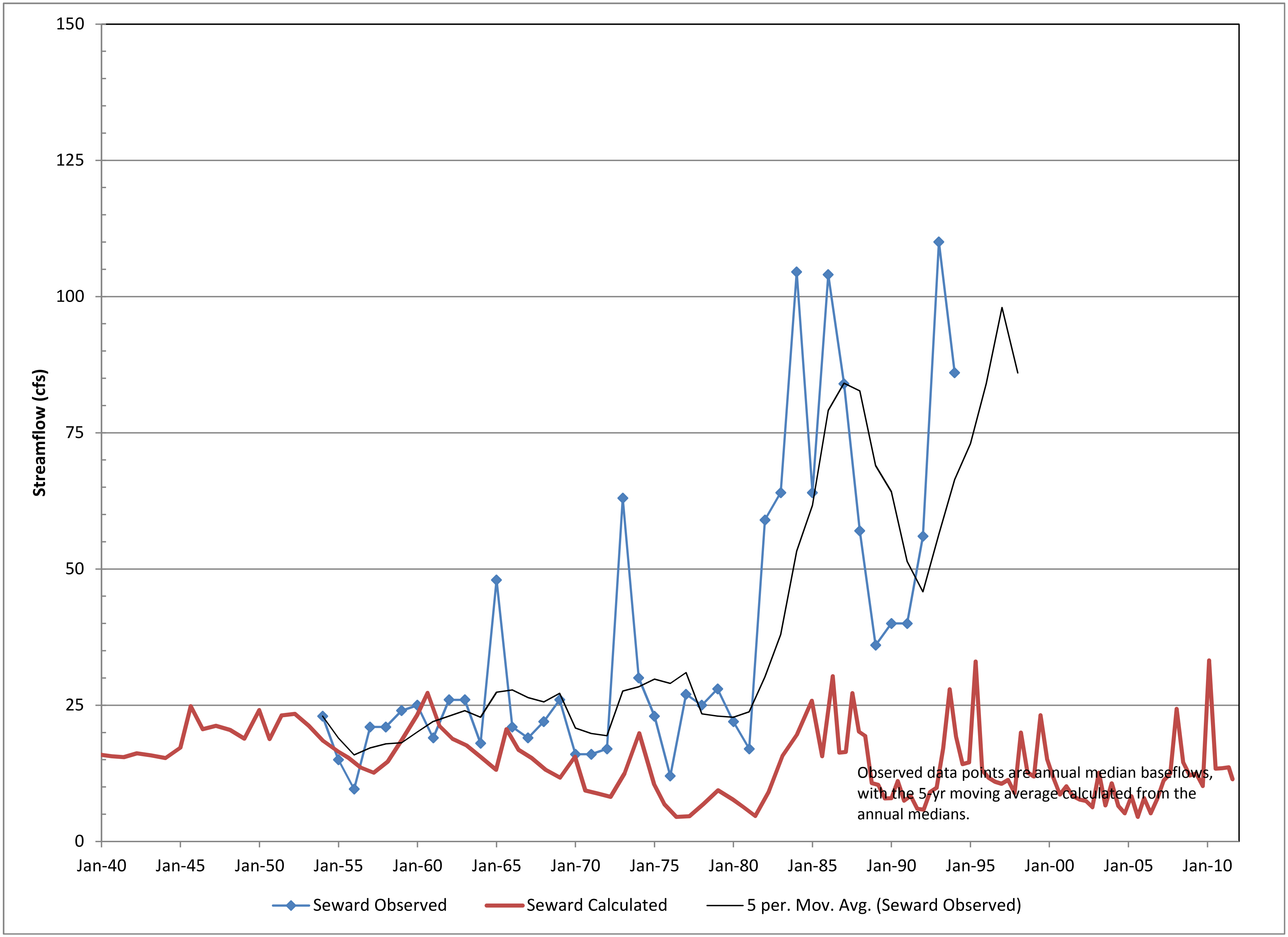


500
400
300
200
100
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Fairbury Observed
Fairbury Calculated
5 per. Mov. Avg. (Fairbury Observed)

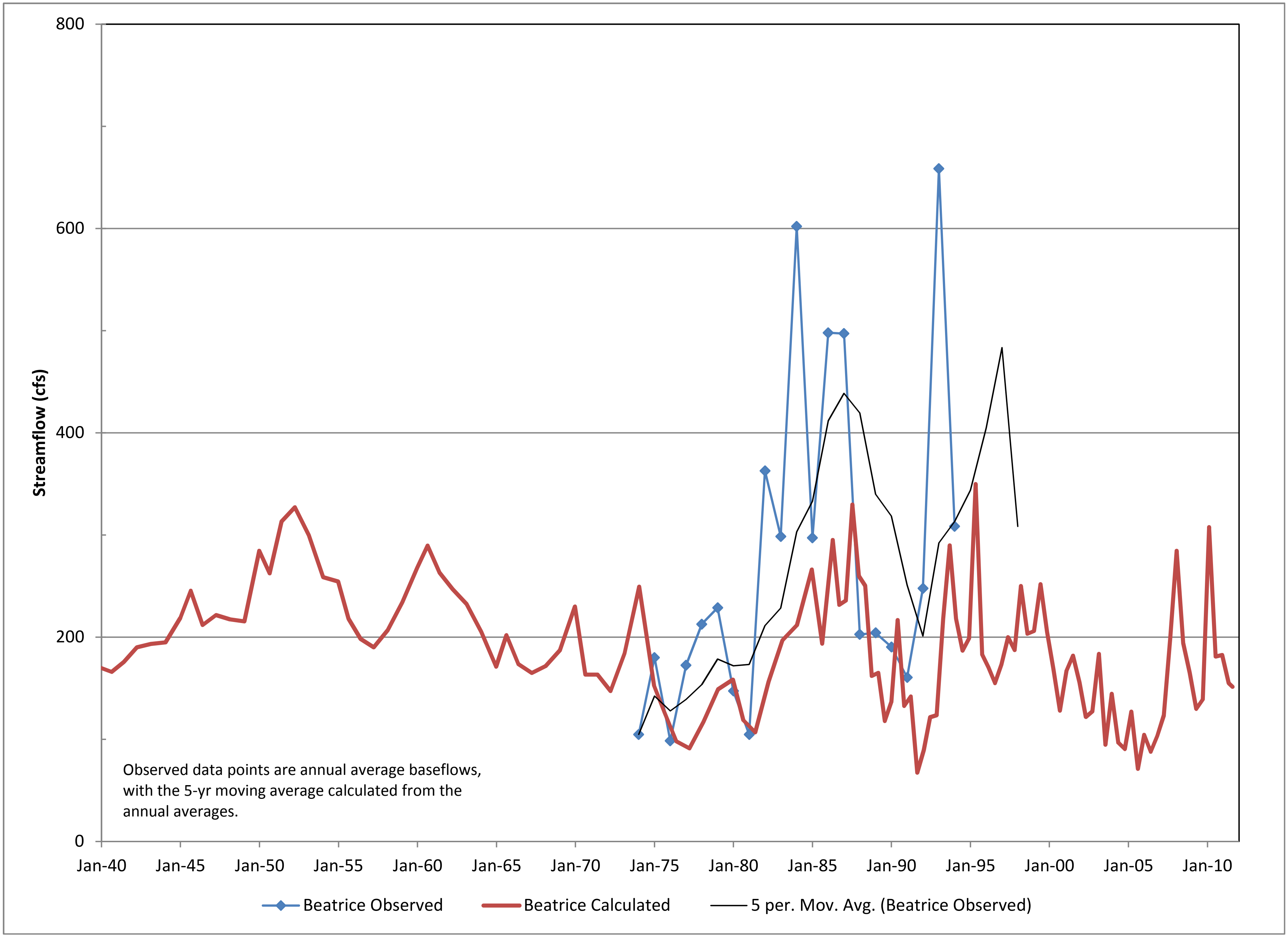


1,000
800
600
400
200
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Barnes, KS Observed
Barnes, KS Calculated
5 per. Mov. Avg. (Barnes, KS Observed)

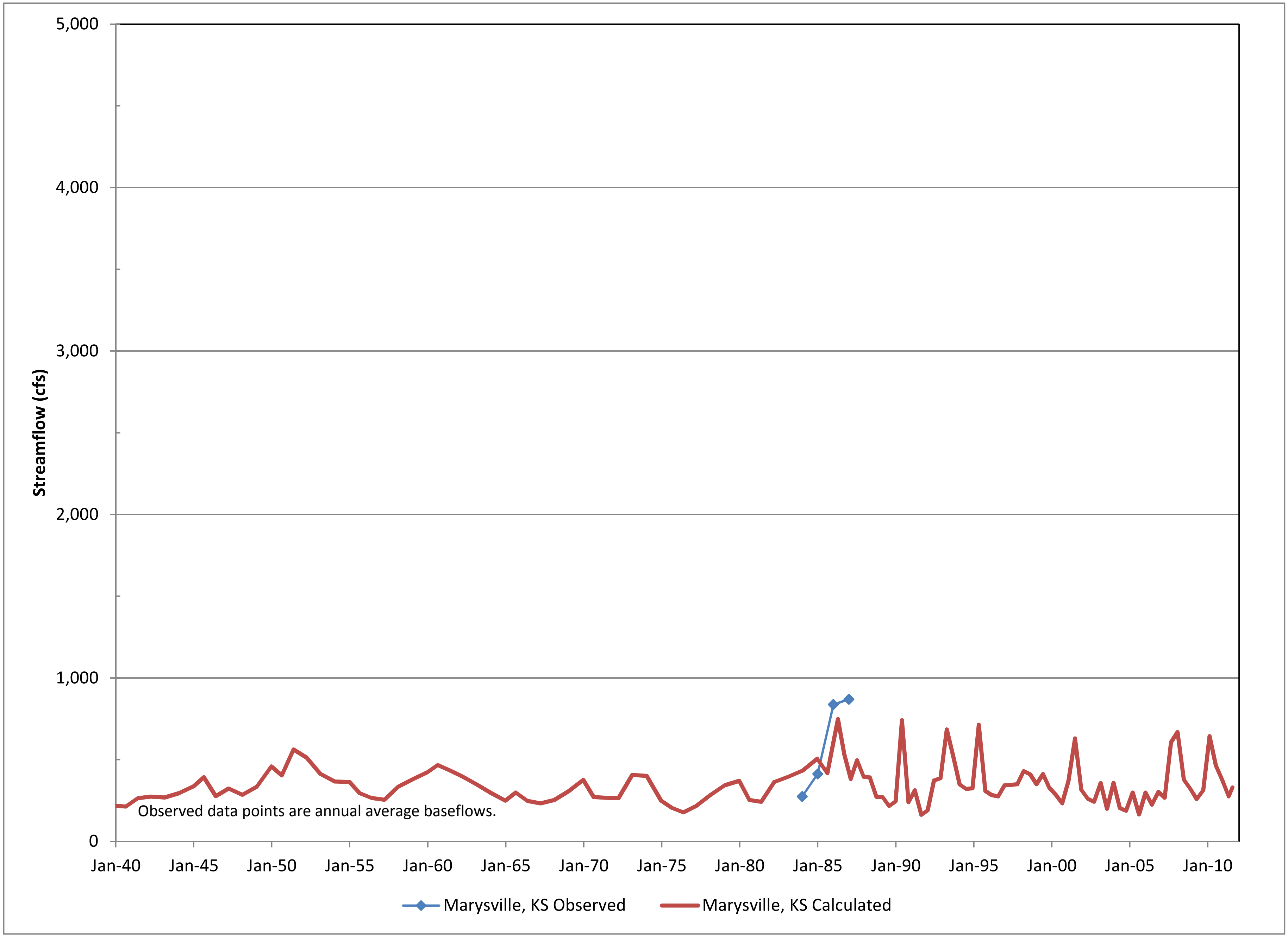

10
8
6
4
2
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Surprise Observed
Surprise Calculated
5 per. Mov. Avg. (Surprise Observed)



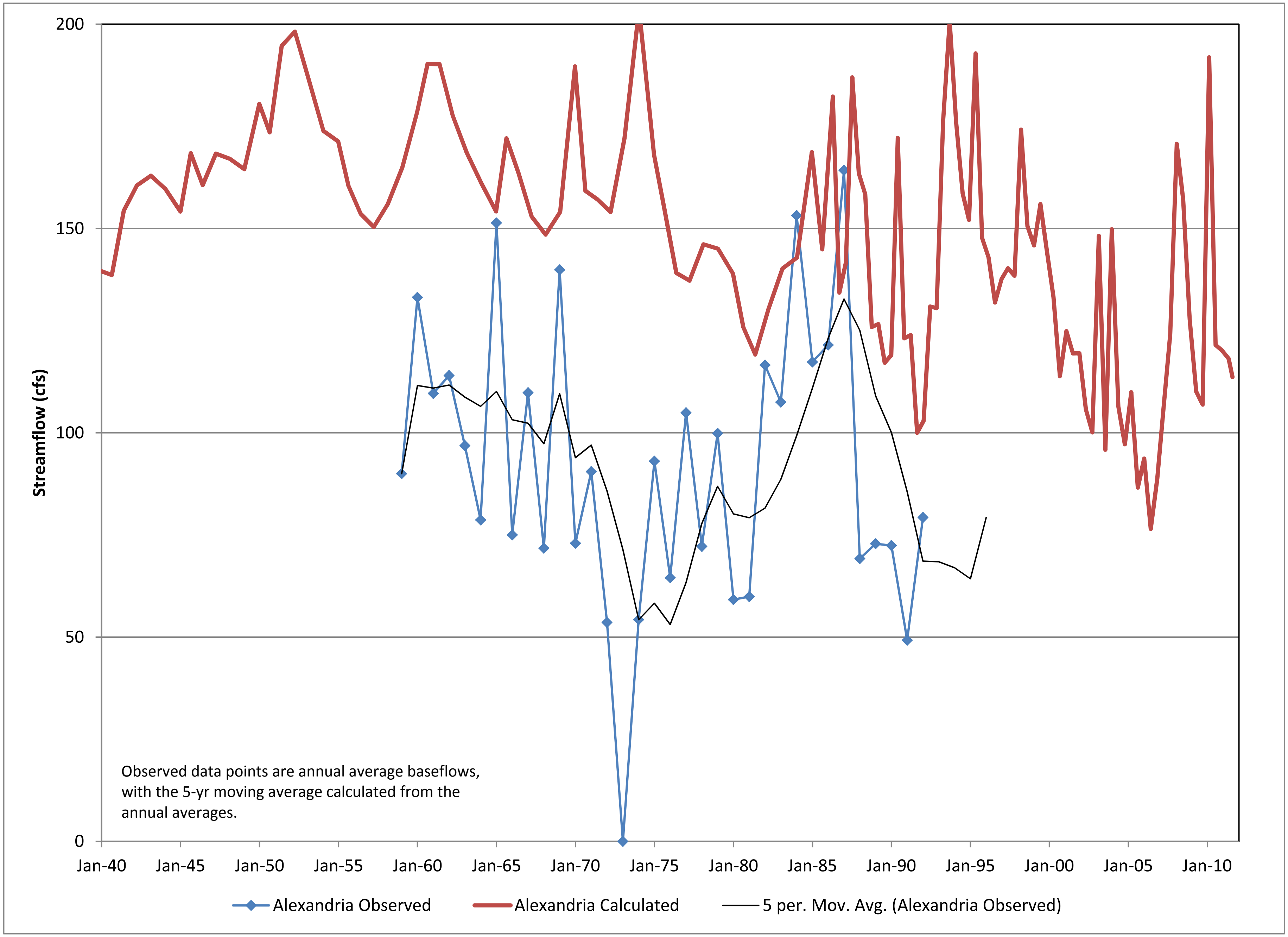
Streamflow (cfs)
150
125
100
75
50
25
0
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual median baseflows, with the 5-yr moving average calculated from the annual medians.
Seward Observed
Seward Calculated
5 per. Mov. Avg. (Seward Observed)



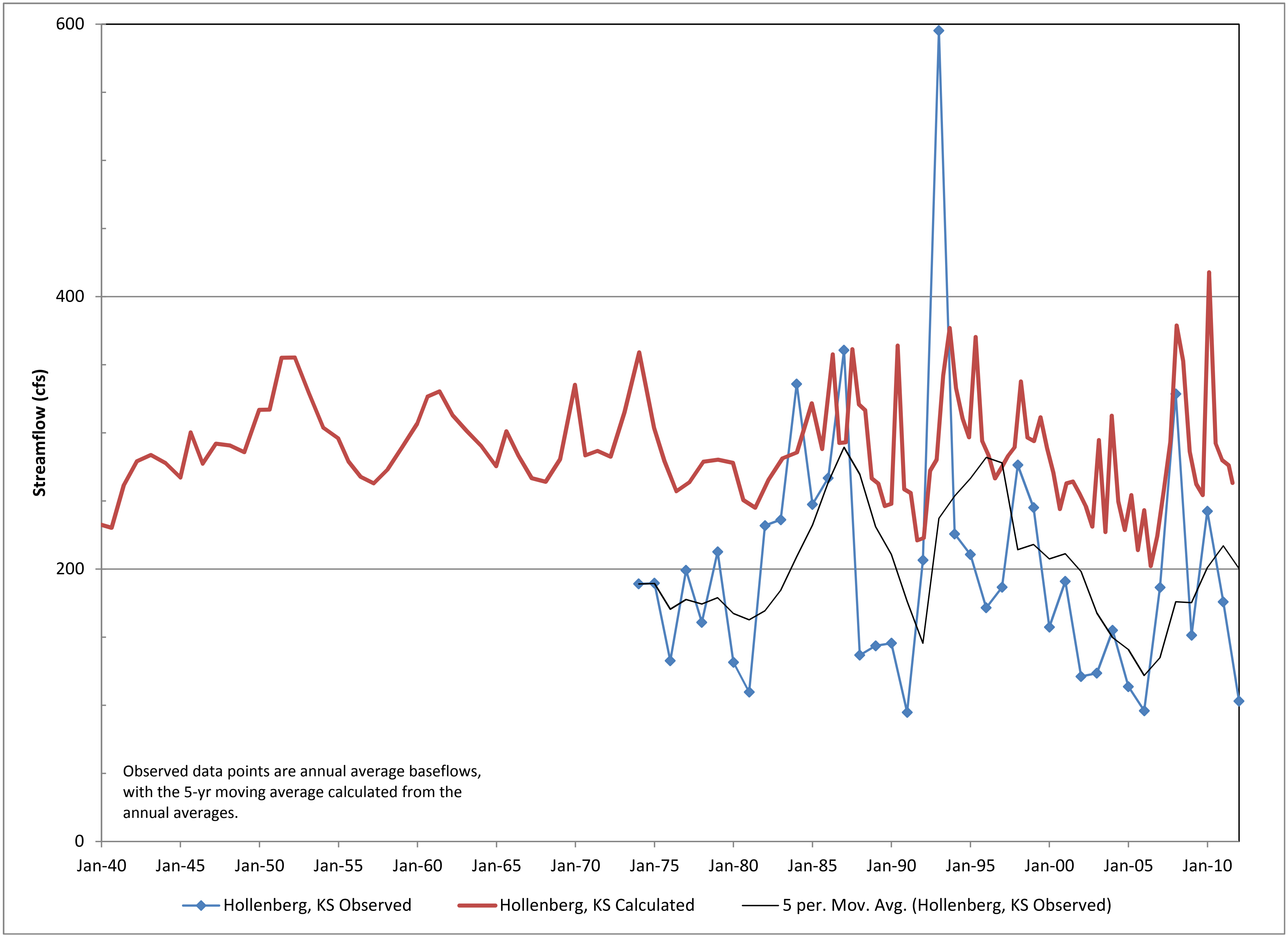
800
600
400
200
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Beatrice Observed
Beatrice Calculated
5 per. Mov. Avg. (Beatrice Observed)



Streamflow (cfs)
5,000
4,000
3,000
2,000
1,000
0
Observed data points are annual average baseflows.
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Marysville, KS Observed
Marysville, KS Calculated



200
150
100
50
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Alexandria Observed
Alexandria Calculated
5 per. Mov. Avg. (Alexandria Observed)


600
400
200
0
Streamflow (cfs)
Jan-40
Jan-45
Jan-50
Jan-55
Jan-60
Jan-65
Jan-70
Jan-75
Jan-80
Jan-85
Jan-90
Jan-95
Jan-00
Jan-05
Jan-10
Observed data points are annual average baseflows, with the 5-yr moving average calculated from the annual averages.
Hollenberg, KS Observed
Hollenberg, KS Calculated
5 per. Mov. Avg. (Hollenberg, KS Observed)