# Central Nebraska Groundwater Flow Model

Prepared for

Nebraska Department of Natural Resources

Lincoln, Nebraska

August 5, 2013

# Central Nebraska Groundwater Flow Model

Prepared for

Nebraska Department of Natural Resources, Lincoln, Nebraska

August 5, 2013

Brown AND Caldwell

950 West Bannock Street, Suite 250

Boise, Idaho 83702

# Project Team

## Nebraska Department of Natural Resources

Brandi Flyr

James Gilbert

Mahesh Pun

Amy Wright

Rick Vollertsen

Jesse Bradley

Jim Schneider

## Brown and Caldwell

Robert Wyckoff

Kathleen McHugh

Julie M. Wright

Brent Cain

Wesley Hipke

Kurt Zeiler

Jeff Weaver

## The Flatwater Group

Marc Groff

Isaac Mortensen

# Table of Contents

# List of Figures



# List of Graphs

# List of Tables

# List of Abbreviations

| | |
|---|---|
| AFY | acre-feet per year |
| AID | Ainsworth Irrigation District |
| amsl | above mean sea level |
| ASTM | American Society for Testing and Materials |
| AWDN | Automated Weather Data Network |
| BC | Brown and Caldwell |
| BWS | Basin Water Supply |
| CALMIT | Center for Advanced Land Management Information Technologies |
| CENEB | Central Nebraska |
| cfs | cubic feet per second |
| Coop | Cooperative Observer |
| DEM | digital elevation model |
| ELM | Elkhorn-Loup Model |
| ET | evapotranspiration |
| ft | feet |
| GIS | geographic information system |
| GHB | general head boundary |
| HPAS | High Plains Aquifer Study |
| M | mean |
| MAE | mean absolute error |
| mm | millimeters |
| NASS | National Agricultural Statistics Service |
| NCDC | National Climatic Data Center |
| NDNR | Nebraska Department of Natural Resources |
| NHD | National Hydrography Dataset |
| NRD | Natural Resources District |
| NWI | National Wetlands Inventory |
| PEST | Parameter Estimation |
| RMSE | root mean squared error |
| RSWB | Regional Soil Water Balance |
| $S_s$ | specific storage |
| $S_y$ | specific yield |
| SD | standard deviation |
| SFR2 | Streamflow-Routing Package |
| UNL | University of Nebraska – Lincoln |
| USFWS | United States Fish and Wildlife Service |
| USGS | United States Geological Survey |

# Section 1

# Introduction

The Nebraska Department of Natural Resources (NDNR) is tasked with conducting an annual evaluation of all Nebraska river basins not currently designated as fully appropriated, over-appropriated, or for which a status reversal has not occurred within the past 4 years. Recently, a new methodology for determining basin status in support of the annual evaluation was developed based on a re-creation of the Basin Water Supply (BWS).

The BWS represents the water supply that is available for total use within a river basin, sub-basin, or reach. The BWS is calculated as the total of gaged streamflow, surface water consumptive use, and groundwater depletions. In the context of the new methodology, groundwater depletions are defined as groundwater use, which directly removes water from the BWS and ultimately reduces aquifer discharge (baseflow) to the streams. The general approach of the new methodology is to re-create a time series of the BWS from historical conditions through present day and assess groundwater depletions by comparing simulations of the BWS through time, with and without pumping and recharge associated with irrigation.

NDNR is working to develop new tools or to customize existing tools to support the new methodology for determining basin status using the best scientific data, information, and methodologies available. Where feasible, numerical groundwater flow models are being used to provide quantitative estimates of historical groundwater depletions, via simulations of the historical BWS through the present day. NDNR has determined that an appropriate numerical groundwater flow model would be the best available tool for the annual evaluation in the Lower Niobrara, Loup, and Upper Elkhorn River Basins.

## 1.1 Goals

NDNR contracted Brown and Caldwell (BC) to develop a numerical groundwater flow model to simulate the BWS in central Nebraska (Central Nebraska [CENEB] model) (Figure 1-1). As defined in the goals of the new methodology for determination of basin status, desirable characteristics of the tools utilized for the annual evaluation include:

- Reflect long-term variability (climatic/drought cycles)
- Reflect year-to-year variability in water supply
- Reflect seasonal variability in water supply
- Differentiate between surface water and groundwater demands and impacts (i.e., groundwater pumping and irrigation-related recharge from groundwater and surface water sources)
- Utilize existing datasets/observed data

The overarching goal of the project was to develop a modeling tool capable of simulating groundwater-surface water interactions in support of NDNR's annual evaluation of basin status, reproducing long-term trends under varying hydrologic and hydrogeologic conditions. The approach to CENEB model development was designed to meet this goal and demonstrate the appropriateness of the model for its intended use.

## 1.2 Approach

The CENEB project was designed as a collaborative effort between BC and NDNR. The initial phase of work consisted of a review and assessment of the available data and tools to support CENEB model development for simulation of the Lower Niobrara, Loup, and Upper Elkhorn River Basins in Nebraska and extending into South Dakota. A matrix analysis that summarizes the general results of the review and assessment is provided as Appendix A.

Based on the assessment of available data and tools, a detailed approach to address the goals of the project and support the quantitative assessment of groundwater depletions was developed by BC and NDNR. Pertinent aspects of the new methodology, the desirable characteristics of the modeling tool (listed in Section 1.1), and the ancillary analyses that would be required in support of model development were incorporated into the scope for the CENEB project.

### 1.2.1 Climate Variability and Seasonality

The variability in the water supply from year to year and season to season was a key factor in the re-creation of the BWS time series. NDNR has worked with researchers at University of Nebraska-Lincoln (UNL) and additional experts in agricultural engineering to expand the field-scale, soil water balance model, CropSim, into a state-wide simulation tool. CropSim was developed specifically for Nebraska and is an integral component of groundwater modeling efforts throughout the state. CropSim incorporates weather station data, land use, soil parameters, and crop water demands to estimate recharge, runoff, evapotranspiration (ET), and pumping demands through time.

CropSim was used as the basis for estimating pumping and recharge inputs for the CENEB model, effectively addressing the need to capture climate and water supply variability, as well as differentiating between surface water and groundwater sources. Because the groundwater pumping and irrigation-related recharge are inextricably linked, the use of a single method and consistent set of assumptions to estimate pumping and recharge maintains the balance between these model inputs.

CropSim simulations are based on daily data, and were therefore aggregated into time periods to support the stress periods defined for the CENEB model timeline. To address the need for long-term, year-to-year, and seasonal variability in support of the annual basin evaluations, the CENEB model was designed to simulate the historical period from pre-1940 through 2011. Annual stress periods were used from pre-1940 through 1985; seasonal variations, using monthly stress periods, were simulated for the latter portion of the model timeline, beginning in 1986.

### 1.2.2 Land Use and Baseflow Separation Analyses

The project approach included the development of two large-scale datasets to support the CENEB project: a GIS-based land use analysis and a baseflow separation analysis.

The GIS-based land use analysis was performed by NDNR to provide cropland and rangeland acreages through time, differentiating between surface water and groundwater irrigated lands. The results of this analysis were used in CropSim.

The CENEB model simulates baseflow, or the discharge from the aquifer to the streams. Stream gage data includes all surface water flow and must be analyzed to separate baseflow from the total gaged flow. An in-depth baseflow separation analysis was completed by NDNR to provide baseflow targets for the CENEB model calibration. This dataset was a key component of the project, providing a means to assess the CENEB model simulation of groundwater depletions.

Details on the methods and results of the land use and baseflow separation analyses are provided in later sections.

### 1.2.3 Utilization of Existing Data

A large portion of the area of interest for the annual determinations is included in the active model domain of the Phase II Elkhorn-Loup Model (ELM) (Peterson et al., 2008; Stanton et al., 2010); thus, the ELM structure (cell size, aquifer thickness, and major inflow/outflow boundaries) was used as a basis for development of the CENEB model. The ELM domain does not include the Lower Niobrara River Basin in its entirety; the CENEB model boundary was therefore expanded north of the Nebraska state line into South Dakota to incorporate the Lower Niobrara River and Ponca Creek drainages in the active model domain (Figure 1-1).

A summary of the major differences between the CENEB model and the ELM are listed below; details on CENEB model development and construction are summarized in Sections 4 and 5.

- Expanded active model domain, including a portion of South Dakota, to simulate the majority of the Niobrara River Basin
- Revised location and type of boundary conditions, primarily to the north
- Estimated recharge (except canal recharge) and pumping demands based on CropSim, a regional soil water balance (RSWB) model developed for Nebraska
- Increased number of stream-flow routing cells to simulate smaller order tributaries
- Monthly stress periods beginning in 1986 to capture seasonality
- Calibration to pre-1940 through 2011 water level measurements and long-term hydrographs of estimated baseflow

Key sources of data used in the development of the CENEB model are described in detail in Section 2; other sources of information are referenced as appropriate in later sections describing model conceptualization and construction.

## 1.3 Report Organization

This report generally follows American Society for Testing and Materials (ASTM) guidelines for groundwater flow model documentation (ASTM D 5718-95 [Reapproved 2000]).

Sources of data and a description of analyses performed in support of this project are discussed in Section 2. An overview of the hydrologic setting is provided as Section 3. The conceptual model summary in Section 4 and the discussion and approach to model construction in Section 5 provide details on the groundwater flow system and CENEB model development. The steady-state and transient calibrations to head and baseflow are described in Section 6. Results of the sensitivity analysis to assess the response of the CENEB model to changes in selected model input parameters, and identification of those parameters that most directly influence model results are provided in Section 7. Limitations and proposed refinements for future model updates are presented in Section 8, and an overall project summary with conclusions is provided as Section 9.

Section 2

# Sources of Data

## 2.1 CropSim

The foundations of the CropSim model were developed by Dr. Derrel Martin at UNL and are described in more detail by Martin et al. (1984). The model and process as applied to the CENEB project are described below.

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:

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

| | |
|---|---|
| *P* | Precipitation [inches] |
| *I* | Irrigation [inches] |
| *ET* | Evapotranspiration [inches] |
| *RO* | Runoff [inches] |
| *DP* | Deep percolation [inches] |
| $\Delta SW$ | Change in soil water content [inches] |

### 2.1.1 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 characteristics.

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.
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; many of these attributes vary 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.

### 2.1.2 Output

ET 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. 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.

### 2.1.3 Regional Soil Water Balance (RSWB) Model

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., can all 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 groundwater model.

Numerous soil types are present in the CENEB model domain. For simplicity and compatibility with the CropSim model, they were re-characterized into the CropSim soil classes. Each cell within the CENEB model domain was assigned to 1 of 21 different CropSim soil classes that are present in the CENEB 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 CENEB model cells. This was accomplished using the inverse weighted distance technique from the three nearest stations to the centroid of each cell. The inverse weighted distance technique 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 (Net Irrigation Requirement, the depth of irrigation water efficiently added to the soil profile to meet a crop's full ET requirement) and compute consumptive use, while splitting the excess water between streamflow, recharge, and indirect ET. Finally, the RSWB is used to compile the pumping and recharge results into formatted files for inclusion into the groundwater model.

The CropSim and RSWB components of the CENEB modeling project are described in further detail in a forthcoming report by The Flatwater Group (*in progress*).

## 2.2 Elkhorn-Loup Model (ELM)

The ELM structure was used as a basis for the development of the CENEB model. The ELM is described in detail by Peterson et al. (2008) and Stanton et al. (2010); the main elements of the ELM are summarized below.

The ELM is a one-layer groundwater flow model that simulates approximately 30,000 square miles of the High Plains Aquifer in central Nebraska. The model was built using MODFLOW-2005, a modular, 3-dimensional, finite-difference groundwater modeling package developed by the United States Geological Survey (USGS) (Harbaugh, 2005). The single-layer High Plains Aquifer system simulated by the ELM is assumed to function as a continuous, hydraulically connected water table aquifer.

The active ELM domain includes the Elkhorn River Basin upstream of Norfolk and the Loup River Basin upstream of Columbus. The ELM simulates estimated steady-state and transient groundwater conditions from 1895 to 2005. The model was developed in two phases (Peterson et al., 2008; Stanton et al., 2010); references to the ELM in this report refer to the Phase II ELM published in 2010 unless otherwise specified.

The USGS employed a quasi-steady-state approach to simulate the time period from pre-1895 through 1939 using three stress periods. The period from 1940 to 2005 was simulated in a transient, calibrated simulation, called the Development model, using annual average hydraulic conditions (represented using annual stress periods) for the 66-year simulation. The steady-state simulation periods were defined to coincide with construction and use of canal systems in the model area. Model stresses (prescribed inputs and boundary conditions) in the quasi-steady-state models were therefore constant within each stress period and representative of the estimated prevalent conditions during each time period. The transient model simulation begins in 1940 and represents the onset of significant groundwater pumping and storage of water in Lake McConaughy.

The ELM simulates major rivers and select tributaries using the MODFLOW Streamflow-Routing Package (Prudic et al., 2004) except for the Platte River on the southern model boundary and the Lower Niobrara River just outside of the northern model boundary.

The ELM was calibrated to estimated stream baseflow and water levels during the steady-state simulation and to baseflow and decadal water level changes during the transient simulation. Calibration was achieved through trial-and-error revisions to input parameters and an inverse approach using automated Parameter Estimation (PEST) (Doherty, 2008a—b) to refine estimates of horizontal hydraulic conductivity and recharge from precipitation.

The basic ELM structure (layer thickness, cell size) and the locations of the model boundaries on the south, west, and east were used as the basis for CENEB model development. Additionally, calibrated aquifer parameters from the ELM provided the initial values for hydraulic conductivity, specific yield, and stream conductance for the CENEB model. A summary of the datasets and tools that were the starting point for CENEB model development is provided as Appendix A, including a detailed inventory of ELM datasets that were relied upon for this project. Revisions to the approach were made during model construction, as necessary; a complete description of model construction is presented in Section 5.

## 2.3 Land Use Analysis

A geographic information system (GIS) was used to create a spatially distributed land use dataset for the years 1940–2011 to provide a basis for assumptions regarding water use in CropSim. Land use categories in the model domain included irrigated/dryland corn, soybean, small grains, alfalfa, and rangeland. Cropped lands were categorized with the source of irrigation such as groundwater, surface water or both (comingled), or dryland farmed. The datasets were originally compiled in a field-scale vector format, but the data were eventually aggregated to 640-acre (1 mile by 1 mile) cells to correspond to the groundwater model discretization. The data sources that were used to create the land use dataset are listed in Table 2-1. Snapshots of irrigation land use through time are shown on Figure 2-1.

**Table 2-1. Data Sources Used to Develop CENEB Land Use Datasets**

| Agency/ Organization | Dataset | Period | Type | Use |
|---|---|---|---|---|
| Middle Niobrara NRD | Digitized Certified Acres | 2011 | Spatial-Vector | Groundwater Irrigated Lands Distribution |
| Lower Loup NRD | Digitized Certified Acres | 2011 | Spatial-Vector | Groundwater Irrigated Lands Distribution |
| NDNR | Digitized Surface Water Rights Lands | 2012 | Spatial-Vector | Surface Water Irrigated Lands Distribution |
| NDNR | Registered Wells | 2012 | Spatial-Vector | Groundwater Irrigation first year; post-2005 irrigation areas |
| NDNR | Points of Diversion | 2012 | Spatial-Vector | Surface Water diversion priority year |
| CALMIT | Land Use Dataset | 2005 | Spatial-Vector | Groundwater Irrigated Lands, Dryland Distribution |
| USDA NASS | County Crop Statistics | 1940-2011 | Tabular | County Irrigated Lands, Dryland totals; County Crop types |
| COHYST | Land Use Dataset | 2005 | Tabular | Land Use Distribution in COHYST portion of model area |
| COHYST | Land Use Dataset | 2010 | Spatial | Land Use Distribution in COHYST portion of model area |

*NRD = Natural Resources District*

*COHYST = Platte River Cooperative Hydrology Study*

*NASS = National Agricultural Statistics Service*

The distribution of irrigated lands was developed using a combination of data sources, including the Natural Resources Districts (NRDs), the Center for Advanced Land Management Information Technologies (CALMIT), and NDNR data. NRD-digitized certified acres were considered the authoritative dataset to show the extent of groundwater irrigated lands and were used whenever available. In the absence of digitized certified acres, an updated version of the 2005 CALMIT irrigated parcels dataset was used. Updates were created by digitizing lands associated with post-2005 wells, identified by 2010 aerial imagery interpretation (2011 aerial imagery was not flown for Nebraska). NDNR surface water rights digitized fields were used to show the extent of surface water irrigated lands across the entire study area. Spatial or tabular relationships to wells or surface water points of diversion were used to develop the historical time component (well installation year or surface water priority year) of irrigated lands. Irrigation type was assigned as comingled in areas where surface water and groundwater irrigated lands overlapped.

There was limited data available to create a historical dryland spatial dataset. The 2005 CALMIT land use dataset was the only spatial dataset that showed the extent of dryland over the entire CENEB area. There were no historical time component data (e.g., well installation year, surface water permit year) that could be attributed to dryland. Hence, the creation of historical dryland spatial dataset relied on two overarching assumptions:

- Lands that were dryland farmed in 2005 had potential to be dryland farmed historically
- Lands that are currently groundwater irrigated had potential to be dryland farmed prior to a well installation.

These assumptions are consistent with the general history of arable land cultivation in agricultural areas in the Midwest and Plains. By applying these assumptions, a "potential dryland" spatial dataset was created by combining the irrigation dataset with dryland areas extracted from the 2005 land use dataset. The resulting dataset represented all areas of land that could potentially be dryland farmed in any given year, provided the land was not being used for groundwater irrigation. Land use for the South Dakota expansion area was simplified to be rangeland throughout the model period because relatively little irrigation has been developed there, and because this area was added to buffer boundary effects on the Niobrara River in the groundwater model.

A GIS program was implemented to partition the field-scale land use data into 640-acre cells to show the extent of potentially irrigated and dryland farmed lands at the model cell level.

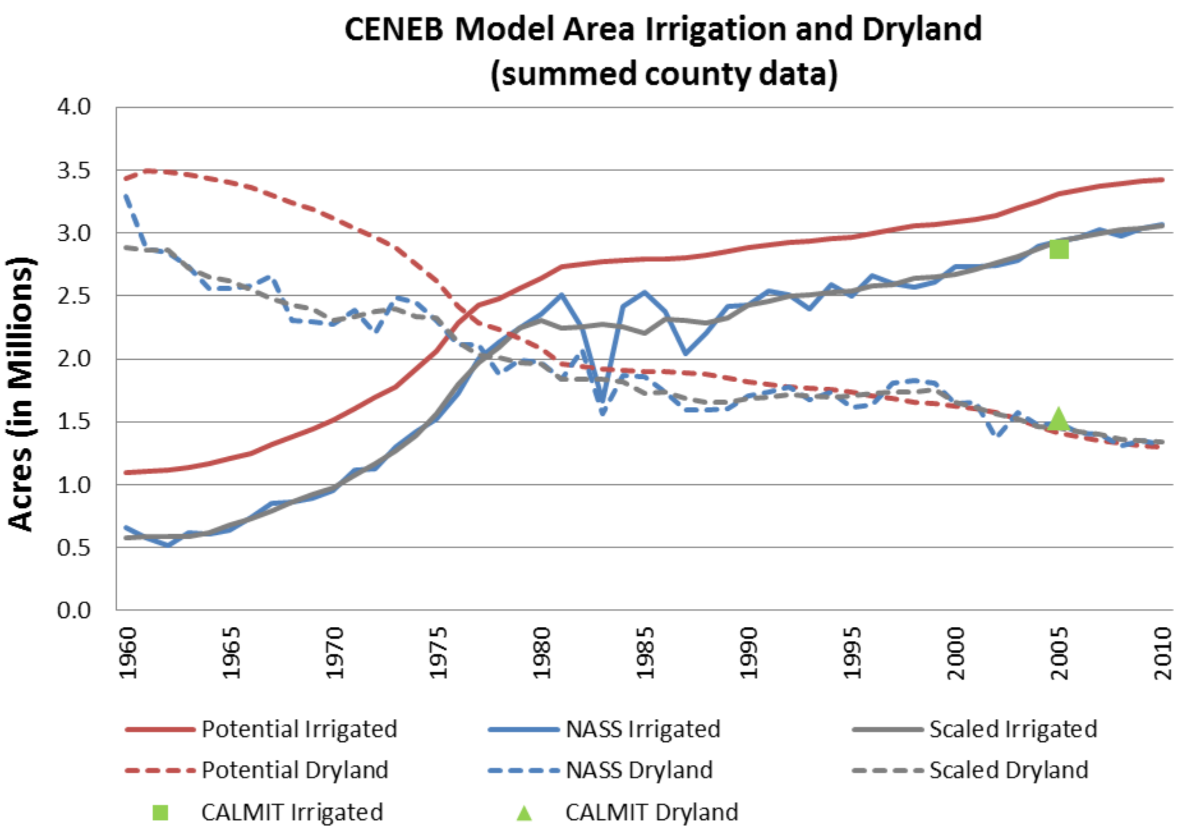
However, it was recognized that the full extent of cropped lands defined as described may or may not actually be farmed in a given year. Therefore, the dryland and irrigated acreages were scaled according to county-level aggregate data from the National Agricultural Statistics Service (NASS), which provided measures of lands under irrigated and dryland cultivation for the CENEB model period. The land use data derived from GIS were aggregated to the county level, then scaled to NASS data using a 5-year moving average so that the estimates and trends in NASS data were captured. It should be noted that an exact match was not desired due to potential reporting discrepancies within the NASS data, and also because the NASS data that was used was based on harvested acres and did not account for acres lost to acts of nature. Because of inconsistencies in the pre-1960 NASS data, the scaling for the years 1940—1960 was based on 1960 NASS data values.

The 2005 CALMIT land use dataset estimates of irrigated and dryland acres were also plotted as a spot check for the CENEB areas. The 2005 CALMIT land use dataset was considered the best data source to show actual irrigated and dryland acres for this year only, because it was based on actual observations of the land via remote sensing.

Graph 2a shows the study area aggregate acreages of all CENEB land use data, the NASS data, the adjusted CENEB data that were scaled to NASS, and the CALMIT data estimates that were used as a spot check. As shown, the land use irrigated acres were higher than NASS reported acres throughout the time period, which indicates that all lands that *could be* irrigated were *not actually* irrigated. The potential dryland acres were also higher than NASS reported acres up until about 1990. This indicates that part of the land that is currently irrigated was actually rangeland in earlier years and not used for dryland as originally assumed. It should also be noted that the 2005 scaled data closely compares to the CALMIT land use dataset estimates. This is a good indicator that reasonable estimates are achieved when using the method described here to create land use datasets for CropSim modeling.

CropSim requires information about crop type, as the reference crop method takes into account that different ET levels occur for different crop types. The NASS dataset was the only available resource to show crop distribution through time. Again, these data were only available at the county scale. The NASS crop type data were assembled for all counties for the years 1960—2011. Corn, soybeans, alfalfa, and small grains were found to be the most prevalent crops in both model areas and were designated as the crops to use for both modeling projects. Normalization by county was implemented so that all cropland would be partitioned into only the designated crop types.

The irrigated and dryland county-based scaling factors were applied to all cells containing irrigated and/or dryland acres in that county. Rangeland was assigned to all space in a cell that was not used for dryland or irrigated crops after the NASS scaling factors had been applied. All areas in South Dakota were assigned as rangeland due to the lack of widespread irrigation development in that area and the relatively minor importance of that buffer zone to the area of interest. Crop types were applied as a homogeneous “crop mix” to all cells containing cropland in that county. The resulting dataset was a tabular dataset that contained information by cell about the number of irrigated and dryland cropland acres, type of irrigation used, and number of rangeland acres.




**Graph 2a. CENEB Model Area Irrigation and Dryland Acreages 1960 - 2011**

## 2.4 Digital Elevation Models

The CENEB project required elevations for defining layer surfaces, monitoring well values, and boundary condition properties. Digital elevation models (DEMs), provide spatially distributed elevations at various resolutions. The 10-meter DEM distributed jointly by the USGS and NDNR (http://www.dnr.ne.gov/databank/dem.html) provides complete coverage for the Nebraska portion of the CENEB model area. The 30-meter DEM distributed by the South Dakota Department of Environment and Natural Resources (http://www.sdgs.usd.edu/digitaldata/dem.html) provides coverage for the South Dakota portion of the CENEB model.

Both datasets were developed through the digitization and tagging of variable-interval topographic contour lines on 7.5-minute USGS quadrangle maps. These digitized contours were interpolated using GIS processes to create the tiled rasters that are distributed via the web sources listed above. The unit of elevation used in these datasets is feet (ft) relative to the National Geodetic Vertical Datum 1929.

## 2.5 Nebraska National Hydrography Dataset (NHD)

The National Hydrography Dataset (NHD) provides a spatial representation of stream and surface water features as a reference for boundary condition assignment in the CENEB model. The NHD is a "comprehensive set of digital spatial data that contains information about surface water features such as lakes, ponds, streams, rivers, springs and wells" (http://dnr.ne.gov/databank/nhd.html) that is developed and maintained in Nebraska through a partnership between the NDNR and the USGS. The NHD consists of vector data types that represent flowlines, water body outlines, points, connectors, and other hydrologic features that, collectively, give scientists and hydrographers a means for mapping and quantifying spatial relationships of a drainage network.

The NDNR maintains and distributes an interpreted NHD for Nebraska basins (including the South Dakota portion of CENEB) that specifically contains polyline features that represent perennial stream and river reaches ( ftp://dnrftp.dnr.ne.gov/Pub/data/NHD_statewide/NHD_Derivatives.zip). In the NHD, a perennial reach is defined as a body of flowing water that contains water throughout the year except for infrequent periods of drought (http://nhd.usgs.gov). This dataset, in conjunction with the more comprehensive NHD flowline datasets (i.e., those containing intermittent, ephemeral, and artificial reaches) and low-flow field survey data, was used as the basis for defining the extent of the surface water system to be simulated in the CENEB model.

The NHD derivatives dataset also includes a spatial representation of irrigation canal paths as polyline features. The three main irrigation district areas – Ainsworth Irrigation District, irrigation districts on the Loup system, and the canal on the north side of the Platte River – are represented in this dataset. The detail varies by canal system but generally contains the main delivery canal with significant distribution laterals. The distribution of the drainage network and canal systems in the CENEB area is shown on Figure 2-2.

## 2.6 Gaging Data

Stream gaging stations throughout the CENEB model area provide a measure of streamflows over time. Streamflows generally consist of a mix of overland runoff, direct precipitation, and groundwater discharge, or baseflow. Estimates of baseflow serve as useful calibration targets for the CENEB model and were derived from daily streamflow data recorded at gaging stations. The gaging stations utilized for streamflow are shown on Figure 2-3; additional details are provided in Section 6. The historical daily stream discharge data at each of these stations was queried from the USGS National Water Information System web service (http://waterdata.usgs.gov/ne/nwis/nwis) and NDNR's internal stream gaging database. The reviewed (non-provisional) NDNR stream gaging data is provided to the public via the web pages at http://dnr.ne.gov/docs/hydrologic2013.html. At the time of the development of the CENEB model, this website was taken offline for revisions and updates, so data was taken directly from the reviewed sets in the internal NDNR database.

Individual farmers and larger irrigation districts throughout the CENEB area divert water from stream channels through canals or pumps for delivery to fields or reservoirs some distance from the channel. This influences the character of the measured hydrographs at stream gages and thus baseflow estimation, so corrections are sought to restore the natural hydrograph. These corrections can be made by adjusting for the diversion of water from the channel. These diversion data are collected and maintained by the NDNR and are part of the gaging data available via the public web page and internal databases. A listing of canal diversion gages utilized for baseflow estimation is provided in Table 2-2.

| Table 2-2. NDNR Canal Gages Used in CENEB Model (Platte canals excluded) | | |
|---|---|---|
| Gage ID | Name | Period of Record<br>Start |
| 1000 | Ainsworth Canal from Snake River And Merritt Reservoir (15-Foot Parshall Flume) | 6/1/1965 – 12/31/2011 |
| 100500 | Mirdan Canal from Calamus Reservoir | 4/1/1987– 12/31/2011 |
| 107000 | Taylor-Ord Canal from North Loup River (Rating Flume) | 5/1/1947 – 12/31/2011 |
| 108000 | Burwell-Sumter Canal from North Loup River (Rating Flume) | 5/1/1947 – 12/31/2011 |
| 76500 | Kent Canal from North Loup River | 4/1/1995 – 12/31/2011 |
| 130000 | Sargent Canal from Middle Loup River (10-Foot Parshall Flume) | 4/1/1957 – 12/31/2011 |
| 90000 | Middle Loup Canal No. 1 from Middle Loup River (Rating Flume) | 1/1/1950 – 12/31/2011 |
| 91000 | Middle Loup Canal No. 2 from Middle Loup River (Rating Flume) | 5/1/1947 – 12/31/2011 |
| 90200 | Middle Loup Canal No. 1 Pump from Middle Loup River | 5/1/1987 – 12/31/2011 |
| 109000 | Ord-North Loup Canal from North Loup River (Rating Flume) | 5/1/1947 – 12/31/2011 |
| 47000 | Farwell (Sherman Feeder) Canal from Middle Loup River (25-Foot Parshall Flume) | 11/1/1962 – 12/31/2011 |
| 93000 | Middle Loup Canal No. 4 from Middle Loup River (Rating Flume) | 5/1/1947 – 12/31/2011 |
| 92000 | Middle Loup Canal No. 3 from Middle Loup River (Rating Flume) | 5/1/1947 – 12/31/2011 |

## 2.7 Climate Data

Climatic conditions greatly influence vegetative growth and thus are a significant input into the CropSim model. A total of 44 weather stations were chosen in and around the model domain to represent the historical climatic conditions. The weather stations listed in Appendix D of the *2013 Annual Evaluation of Availability of Hydrologically Connected Water Supplies; Determination of Fully Appropriated* (NDNR, 2012) served as the initial list. However, by limiting the weather stations to this list, there were several large areas within the model domain that failed to have a nearby weather station. Therefore, additional weather stations were chosen because of their proximity to these gaps. Each of these weather stations needed to have the following characteristics:

- Minimum and Maximum Temperature
- Precipitation
- Records from 1/1/ 1948 or earlier through the end of 2011

Additional weather stations from the National Weather Service (NWS), Cooperative Observer (Coop) network and the Automated Weather Data Network (AWDN) were evaluated. The NWS/Coop network records span a longer period of time but contain limited data as opposed to the AWDN. The AWDN collects more types of data (relative humidity, net radiation, etc.) more frequently, but the historical records are limited (the earliest data starting in the 1980s) and there are fewer stations. Because the simulation period begins in approximately 1940, the NWS/Coop weather stations were considered to be most appropriate to support the CENEB project. The weather station data were reviewed for quality and consistency before being utilized in the CropSim process. Additional details on the processing and aggregation of the climate data will be provided in the forthcoming report that describes the CropSim modeling performed for this project (The Flatwater Group, *in progress*).

## 2.8 Expansion Area – Northern Nebraska and South Dakota

Background information on the geology and hydrogeology in the expansion area in the northern portion of the CENEB model domain relied on the following sources:

- South Dakota Geologic Map (GIS)

- Simulated Ground-Water Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota (Long et al., 2003)
- Simulated Groundwater Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota – Revisions with Data Through Water Year 2008 and Simulations of Potential Future Scenarios (Long and Putnam, 2010)
- Hydrogeology of a Portion of the Sand Hills and Ogallala Aquifer, South Dakota and Nebraska (Rahn and Paul, 1975)
- Hydrogeological Assessment of the High Plains Aquifer in Tripp and Gregory Counties, SD (Filipovic, 2004)
- Development of Niobrara Basin Hydrogeologic and Hydrostratigraphic Framework – Completion Report by J. Ayers (Conservation and Survey Division, 2010).

# Section 3
# Hydrologic Setting

## 3.1 Climate

The long-term average annual precipitation in the model domain was estimated using the National Climatic Data Center (NCDC) database, which contains long-term monthly precipitation data by climate divisions. Precipitation data can vary greatly from year to year, e.g., the annual precipitation for Nebraska in 1940 was 16.4 inches; however, the long-term (1895 to 2011) annual precipitation average is 22.9 inches (NCDC, 2012). Precipitation was calculated by overlaying the NCDC climate divisions on the CENEB model area in GIS. Across the model area, the long-term average precipitation ranges from a high slightly over 28 inches in the eastern portion of the model (NE-Zone 6) to a low of 17 inches on the western edge of the model (NE-Zone 1) (NCDC, 2012). Table 3-1 provides a breakdown of the climate divisions within the model area, the long-term average precipitation for that division, and the percent of the climate division within the model area (climate divisions comprising less than 1 percent of the CENEB model area were not included).

**Table 3-1. CENEB Precipitation by NCDC Climate Division**

| NCDC Climate Division | Long-Term Average Annual Precipitation (inches) | Percent of CENEB Model Domain |
|---|---|---|
| Nebraska | | |
| 1 | 17.3 | 1% |
| 2 | 21.5 | 55% |
| 3 | 26.1 | 10% |
| 5 | 23.9 | 20% |
| 6 | 28.5 | 4% |
| 7 | 20.1 | 5% |
| South Dakota | | |
| 8 | 20.1 | 5% |
| Total Weighted Average | 22.5 | 100% |

[1]*Weighted average based on the amount of climate division in the model area.*

Due to the wide range in precipitation, two major climatic zones are represented in Nebraska: the eastern half of the state has a humid continental climate characterized by large seasonal temperature differences, with warm to hot summers and cold winters, and the western half has a semi-arid climate where the precipitation is less than the potential ET. Average monthly temperatures range from a high of 89.5 degrees Fahrenheit to a low of 8.9 degrees Fahrenheit.

South Dakota has an interior continental climate, with cold, dry winters to hot and semi-humid summers. The average high summer temperature is 90 degrees Fahrenheit; the average low temperatures are below 10 degrees.

## 3.2 Topographic Regions

The state of Nebraska is characterized by distinct topographic regions (Conservation and Survey Division, 1973); the following are found within the CENEB model domain (in order of prominence):

- Sand Hills (dune sands)
- Dissected plains (hilly land eroded by water and wind)
- Plains (sandstone and stream-deposited silt, clay, sand, and gravel overlain by wind-deposited silt)
- Valleys (flat-lying land along the major streams composed of unconsolidated silt, clay, sand, gravel)
- Bluffs and escarpments

The state of South Dakota is characterized by three major topographic regions: the Central Lowlands in the east, the Great Plains to the west, and the Black Hills, a small area near the western edge of the state. The southern half of the Black Hills can be seen on the shaded relief basemap on Figure 1-1. The small, south-central portion of South Dakota included in the CENEB model domain is in the Central Lowlands and includes an extension of the Sand Hills region of Nebraska (Malo, 1997).

Topographic relief in the model region is approximately 3,143 ft, ranging from a high of 4,286 ft above mean sea level (amsl) on the western boundary to a low of 1,143 ft amsl near the eastern model boundary.

## 3.3 Surface Water and Canals

Rivers, streams, and canals within the model domain are shown on Figure 2-2. The model domain includes the Loup River Basin upstream of Columbus, Nebraska, the Elkhorn River Basin upstream of Norfolk, Nebraska, and the majority of the Niobrara River Basin and the Ponca Creek drainage. The major tributaries in these basins, and the acreage included in the active model domain, are summarized in Table 3-2. The Missouri River flows north-northwest along a small section of the northeastern boundary of the model, and the Platte River bounds the model domain on the south. The Keya Paha River, one of the main tributaries of the Niobrara River, extends into the South Dakota portion of the model domain. Ponca Creek drains the remaining portion of South Dakota in the model domain, and discharges to the Missouri River near the northeast model boundary; the confluence of Ponca Creek and the Missouri River is outside of the active model domain. Surface water flow is generally west-east or northwest-southeast.

Canal networks were constructed in Nebraska to facilitate crop irrigation beginning in the late 1800s. The locations of the canal systems within the CENEB domain are shown on Figure 2-2. The Cozad Canal, Dawson Canal, Gothenburg Canal, and Kearney Canal systems began diverting water in 1895 to expand agricultural crop production. In the early to mid-1900s the Elm Creek Canal (1929) and Birdwood Irrigation District (1946) systems were added to the already existing canal networks. The first irrigation districts in the Loup River Basin were not constructed until the mid-1900s (Table 3-3). Irrigation in the Niobrara River Basin is limited to the Ainsworth Irrigation District, which began operating in 1965. During the CENEB model simulation period, the only canal system to begin and then end operations was the Elm Creek Canal system, which ceased water diversions in 1962 (Stanton et al., 2010). Table 3-3 presents the inception years for the individual canal systems located within the CENEB model domain.

| Table 3-2. River Basins in the CENEB Model Domain | | | |
|---|---|---|---|
| River Basin | Major Tributaries in the Model Domain | Area within Model Domain | Percent of Total |
| Niobrara | Keya Paha River<br>Snake River | 8,500 mi$^2$ | 25% |
| Elkhorn | North Fork Elkhorn<br>South Fork Elkhorn | 2,700 mi$^2$ | 11% |
| Loup | Beaver Creek<br>Cedar River<br>North Loup River<br>Calamus River<br>Middle Loup River<br>Mud Creek<br>South Loup River | 14,500 mi$^2$ | 43% |
| Platte | Wood River<br>North Platte River<br>Birdwood Creek | 4,800 mi$^2$ | 17% |
| Missouri | Ponca Creek<br>White River | 1,500 mi$^2$ | 4% |

| Table 3-3. Canal Systems and Irrigation Districts | |
|---|---|
| Name | Startup |
| Cozad Canal System<br>Dawson Canal System<br>Elm Creek Canal System*<br>Gothenburg Canal System<br>Kearney Canal System | Pre-1940 |
| Birdwood Irrigation District | 1946 |
| Middle Loup Public Power and Irrigation District | 1947 |
| North Loup Irrigation District | 1947 |
| Sargent Irrigation District | 1957 |
| Farwell Irrigation District | 1963 |
| Ainsworth irrigation District | 1965 |
| Twin Loups Irrigation District | 1987 |

**Ceased operation in 1962.*

## 3.4 Land and Water Use

Land use in the CENEB model domain is predominantly rangeland/pasture/grasslands of the Sand Hills region; cropland, irrigated and non-irrigated, ranks second. The major crop types are corn and soybeans, with minor cropland in alfalfa and small grains (wheat, oats, barley, rye, and millet). Other land use types – rural communities, lakes, wetlands, and riparian areas – are a small percentage of the total acreage within the model area (CALMIT, 2007).

Land use databases developed by NDNR for this project utilizing CALMIT (2007) and other sources were used to summarize the number of acres of irrigated and non-irrigated cropland within the model domain. Table 3-4 provides a breakdown of these land use types in 1940 and 2011, to illustrate the extensive increase in irrigation during the period of interest.

| Table 3-4. CENEB Cropland Acreages 1940 versus 2011 | | |
|---|---|---|
| Category | Acres in 1940 | Acres in 2011 |
| Irrigated Cropland | 157,558 | 2,972,496 |
| Non-Irrigated Cropland | 3,251,806 | 1,175,673 |
| TOTAL Cropland | 3,409,364 | 4,148,169 |

*Source: GIS Analysis of Land Use conducted by NDNR for this project.*

Agricultural demands for surface water and groundwater in the model domain are a significant portion of the total water budget. Additional demands include hydropower (low consumptive use) and municipal pumping (minor demand).

Table 3-5 presents the acreage of cropland irrigated by surface water and groundwater in 1940 and 2011. Total irrigated acreage increased by approximately 2.8 million acres during this period. By 2011, there were 2.97 million acres of irrigated cropland within the CENEB model area, of which approximately 88 percent were irrigated solely with groundwater and 4 percent were partially groundwater supported (Table 3-5).

| Table 3-5. CENEB Irrigated Land | | |
|---|---|---|
| Type of Irrigation | Acres in 1940 | Acres in 2011 |
| Groundwater | 67,053 | 2,622,482 |
| Surface Water & Groundwater | 6,541 | 110,501 |
| Surface Water | 83,964 | 239,513 |
| TOTAL Irrigated Acres | 157,558 | 2,972,496 |

*Source: GIS Analysis of Land Use conducted by NDNR for this project.*

# 3.5 Geology

The CENEB model domain lies within the extent of the High Plains Aquifer region as described by McMahon et al. (2007). Within the model domain, the High Plains Aquifer is composed of near-surface, generally unconsolidated sedimentary deposits of mid-Tertiary to Holocene age, underlain by relatively impermeable fine-grained sedimentary rocks of Upper Cretaceous to mid-Tertiary age (Peterson et al., 2008). Individual geologic units are variably incorporated into the High Plains Aquifer system depending on lateral and vertical hydraulic connectivity, degree of saturation, and, in older deposits, the presence of secondary permeability resulting from joints and fractures (McMahon et al., 2007; Peterson et al., 2008). Most of the study area is underlain by a variable thickness of Quaternary eolian and alluvial deposits burying Ogallala Formation, Arikaree Group, and White River Group sediments, with the exception of the north end of the model domain, where Quaternary erosion along the Niobrara River and Ponca Creek has exposed the Upper Cretaceous Pierre Shale.

## 3.5.1 Quaternary Deposits

Quaternary deposits consist of alluvial gravel, sand, silt, and clay as well as eolian sands of the Sand Hills area and silty to very fine sandy loess. Quaternary deposits are commonly 0 to 200 ft thick, though locally up to 700 ft thick, and, with sufficient saturated thickness, can be a substantial source of groundwater (Peterson et al., 2008). Deposits are typically unconsolidated, with the exception of local caliche accumulations, and are considered a part of the High Plains Aquifer system where saturated and hydraulically connected to adjacent units (McMahon et al., 2007).

### 3.5.2 Tertiary Ogallala Formation

The Ogallala Formation has the largest areal extent of all the geologic units of the High Plains Aquifer (McMahon et al., 2007) and is nearly ubiquitous across the CENEB model domain. It is a heterogeneous deposit of clay, silt, sand, and gravel associated with aggrading streams derived from Miocene-age highlands to the west that filled and buried paleovalleys carved into pre-Ogallala strata (McMahon et al., 2007). It is typically unconsolidated, with the exception of the upper portion of the formation which is locally cemented by calcium carbonate (caliche) and very locally by silica. Based on exploration drill holes, the maximum thicknesses for Ogallala deposits in the model domain area are approximately 700 ft, with an average thickness of 170 ft (Conservation and Survey Division, 2006). Many of these test holes did not penetrate the entire thickness of the deposit, however, and Peterson et al. (2008) suggest this calculated average thickness underestimates the true average thickness for the area. The Ogallala Formation, as well as overlying Quaternary deposits, are locally absent along the Niobrara River and Ponca Creek at the north end of the model domain (McMahon et al., 2007).

### 3.5.3 Tertiary Arikaree Group

The Arikaree Group is composed of poorly consolidated, tuffaceous sandstone, siltstone, shale, and silty clay (Long et al., 2003). It is generally a low permeability/low conductivity unit but can be a part of the High Plains Aquifer system when exhibiting secondary permeability from fracturing (Long et al., 2003; McMahon et al., 2007). Maximum thickness for this unit is approximately 1,000 ft, and it is absent from the eastern portion of the model domain (McMahon et al., 2007).

### 3.5.4 Tertiary White River Group

White River Group sediments typically consist of poorly consolidated siltstones and claystones, with local fine sandstones (Long et al., 2003). Deposits are typically low permeability/low conductivity, but the Brule Formation, the uppermost unit of the White River Group, locally contributes to the aquifer system where substantial thicknesses of saturated sandstones are present or where joints and fractures have induced secondary permeability (Long et al., 2003; McMahon et al., 2007). Maximum thickness for the Brule Formation is approximately 600 ft, and deposits are absent from the eastern portion of the study area ((McMahon et al., 2007).

### 3.5.5 Cretaceous Pierre Shale

Underlying the High Plains Aquifer in the model domain is the Upper Cretaceous, marine Pierre Shale. The shale is of low permeability and generally not considered a productive unit within the local or regional aquifer system. The unit is up to 1,400 ft thick (Long et al., 2003), and it is locally exposed in the study area along the Niobrara River and Ponca Creek, where Quaternary erosion has removed the overlying strata.

Section 4

# Conceptual Model

The CENEB model structure was based on the ELM, which was expanded to include the portions of the High Plains Aquifer in the Niobrara River Basin and Ponca Creek drainages, extending the model boundary to the north and northeast past the Nebraska state line and into South Dakota. The conceptual model of the aquifer system is described by Peterson et al. (2008) and Stanton et al. (2010) for ELM I and ELM II, respectively, and will not be reproduced in this report. This conceptual model section focuses on a general overview of the previously modeled region, including revisions or updates specific to the CENEB model, and provides details for the model expansion area.

## 4.1 Model Domain

The CENEB active model domain encompasses approximately 34,449 square miles in central Nebraska with a small extension into South Dakota (Figure 1-1). The western boundary is in the Nebraska Sand Hills, the eastern boundary is in the Loess Hills, coinciding with the westernmost extent of glacial till (Peterson et al., 2008). The Platte River flows along the southern boundary, and to the north; the model extends into South Dakota with the boundary defined at the northernmost extent of the Ogallala Formation within the Ponca Creek and Keya Paha drainage basins. Approximately 95 percent of the model domain is in Nebraska; the remaining 5 percent is in central South Dakota.

## 4.2 Aquifer System

### 4.2.1 Hydrostratigraphic Units

The High Plains Aquifer in Nebraska and South Dakota is an unconfined system composed of sedimentary deposits of Quaternary, Tertiary, and Cretaceous age (Figure 4-1). Table 4-1 presents a summary and description of the hydrostratigraphic units comprising the High Plains Aquifer system compiled from various sources.

The aquifer system thins from south to north and from west to east; the base of the aquifer slopes eastward at approximately 8 ft per mile (Peterson et al., 2008). Saturated thickness of the aquifer in the model domain ranges from less than 100 to greater than 600 ft (McMahon et al., 2007).

Table 4-1. Hydrostratigraphic Units of the High Plains Aquifer

| Age | Hydrostratigraphic Unit | Description | Estimated Thickness | Notes |
|---|---|---|---|---|
| Quaternary | Unconsolidated Alluvium | Fluvial floodplain and terrace deposits of gravel, sand, silt, and clay | 0 – 60 | Forms part of High Plains Aquifer where hydraulically connected to underlying Quaternary and Tertiary deposits |
| | Dune Sand | Unconsolidated, very fine to medium-grained eolian sand | 0 – 300 | Comprises large portion of the vadose zone in the Sand Hills region and has high recharge potential; forms part of the High Plains Aquifer where saturated |
| | Loess | Eolian deposit composed of silt with lesser amounts of very fine sand and clay | 0 – 250 | Poorly sorted clay, silt, sand, and gravel, generally unconsolidated; some caliche near the top of the formation |

**Table 4-1. Hydrostratigraphic Units of the High Plains Aquifer**

| Age | Hydrostratigraphic Unit | Description | Estimated Thickness | Notes |
|---|---|---|---|---|
| Tertiary | Ogallala Fm | Heterogeneous sequence of clay, silt, sand, and gravel; locally cemented caliche and silica zones near top of the Fm, forming escarpments. Poorly consolidated sandstone and siltstone. | 0 – 700 | Main stratigraphic unit in the High Plains Aquifer where saturated |
| Tertiary | Arikaree Group | Fine- to very fine-grained sandstone and siltstone | 0 – 1,000 | Forms part of the High Plains Aquifer in parts of the northern High Plains (Nebraska and South Dakota) |
| Tertiary | White River Group (Upper Brule Formation) | Claystone and siltstone with beds of sandstone | 0 – 600 | Upper Brule Formation siltstone forms part of the High Plains Aquifer where jointed and fractured—maximum thickness is 600 ft; base of aquifer where not jointed/fractured |
| Cretaceous | Pierre Shale | Dark-gray to black marine shale | -- | Base of aquifer – low permeability |

*Source: A compilation of data from McMahon et al., 2007; Peterson et al., 2008; Stanton et al., 2010; Chen and Chen, 2004; Kolm and Case, 1983; Rahn and Paul, 1975.*

### 4.2.2 Groundwater Flow

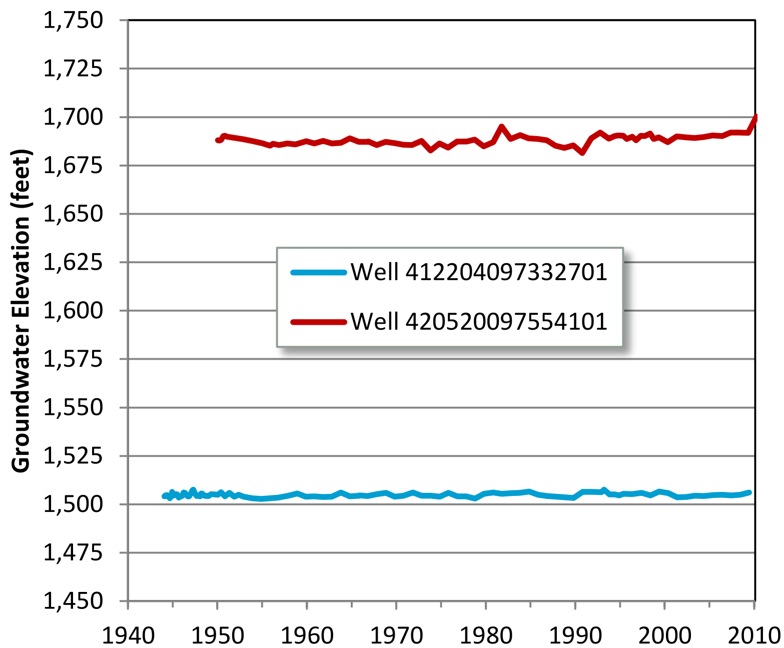
Groundwater in the unconfined High Plains Aquifer within the model domain generally flows from west-northwest to east-southeast as depicted on Figure 4-2 (Conservation and Survey Division, 1996; 2003). The average hydraulic gradient is approximately 0.0019 ft/ft. The maximum water level elevations of approximately 3,850 ft amsl are located along the western model boundary; the lowest water level elevations are less than 1,500 ft amsl and located along the eastern model boundary.

Most of the rivers and tributaries within the CENEB model domain are gaining from groundwater discharge (Nebraska Natural Resources Commission, 1982). The streams gain water from the groundwater system when groundwater levels are higher than the stream bottom and recharge the aquifer when water levels are below the stream bottom, maintaining an equilibrium that is characterized by long-term stability in aquifer water levels.

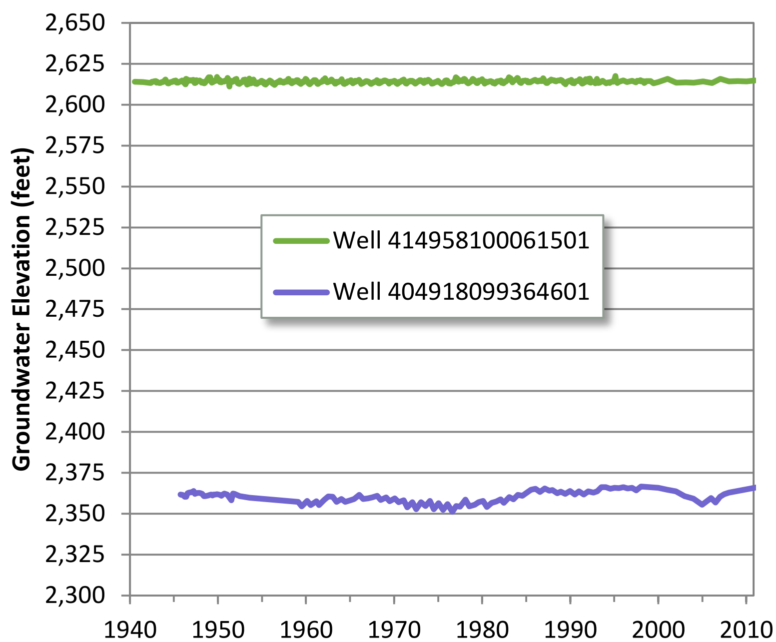
A study by the USGS on the High Plains Aquifer states that water level changes from predevelopment (“before about 1950”) to 2007 across most of the CENEB model area ranged between -10 and +10 ft (McGuire, 2009). Thus, the groundwater flow system has been relatively stable since predevelopment. The USGS analysis shows isolated areas of greater rises and declines scattered throughout the model area; however, most of these areas exhibit less than a 25 ft rise or decline (McGuire, 2009). A comparison of water table contours from 1979 and 1995 (Figure 4-2) demonstrates that there is little to no change in groundwater elevations from 1979 to 1995 in the western portion of the model area and only slight changes exhibited in the east. Four long-term groundwater hydrographs for wells in the southeastern, northeastern, central, and southern portions of the model domain are presented on Graphs 4a and 4b (below) to illustrate the long-term stability of the groundwater system.

### 4.2.3 Vertical and Lateral Hydrologic Boundaries

Groundwater enters the model domain on the west, and exits the domain as underflow to the northeast (toward the Missouri River), to the south (toward the Platte River), and to the east. Groundwater also exits the aquifer system via discharge as baseflow to rivers and streams. The northern boundary of the model is at the northern extent of the productive High Plains Aquifer units (Arikaree Group and Ogallala Formation) in the Keya Paha River and Ponca Creek drainage basins; groundwater does not exit the northern boundary, except to the northeast, near the Missouri River.




**Graph 4a. Long-Term Hydrographs – Southeast (701) and Northeast (101) Model Domain.**




**Graph 4b. Long-Term Hydrographs – Central (501) and Southern (601) Model Domain.**

The vertical limit of the groundwater system is generally defined by bedrock present beneath the High Plains Aquifer materials, either the Tertiary White River Group or Cretaceous Pierre Shale (Table 4-1) that is not jointed or fracture. The low-permeability Pierre Shale is simulated in small portions of the model domain.

## 4.3 Pumping and Recharge

As with much of the plains region, the lands in the CENEB model area were developed by European settlers for agriculture starting in the late 1800s. Much of the arable land was converted to farmland over the next 50 years, but with irrigation limited to riparian corridors where direct diversion of stream water into small ditches and canals was feasible. Organized irrigation districts with more extensive canal networks and reservoirs were developed starting in the late 1930s, with new projects continuing periodically until the completion of Calamus Reservoir on the Calamus River in 1987. The distribution and on-field application of streamflow away from the channel through these irrigation projects leads to deep soil percolation and recharge to the aquifer, at times, in excess of precipitation recharge. Over time, this increased recharge increased the baseflow component of streamflow, particularly in smaller streams where increases are more apparent.

Beyond the development of surface water irrigation districts, the most widespread change to agriculture in the CENEB area was the development of groundwater irrigation in the decades following the end of World War II. Based on the land use analysis performed for the project (Section 2.3), by 1960 irrigation infrastructure (a canal or well) was developed on roughly one million acres in the CENEB area from a mix of surface water and groundwater sources. Within 20 years, this had more than doubled to 2.5 million irrigable acres, with the increase coming almost entirely from new groundwater irrigation. The trend leveled out but continued to rise above 3 million acres (estimated for 2010) as center pivot technology facilitated irrigation on more variable terrain than was feasible with gravity and furrow type irrigation methods.

The conversion of native grassland or rangeland to row crops, the diversion of streamflow across the landscape, and extraction and application of groundwater at such a broad scale shifts the water budget of the aquifer and connected streams. Variable, dynamic, and sometimes competing factors contribute to the net recharge to the High Plains Aquifer under such an altered system. In arid areas or in times of drought, the consumptive use of applied (pumped or diverted) water and precipitation may lead to a net loss of water from the local or regional aquifer- stream system. This loss, evident as a decline in groundwater levels and streamflows, are mitigated by increased recharge and reduced irrigation requirements in wet years or by the targeted conjunctive use of surface and groundwater.

For the CENEB project, the combined complexity of variable climate and agricultural water use is simulated through the CropSim process. The CENEB CropSim analyses indicate an increase in variability of annual recharge that tracks the rise of groundwater use, creating the potential for more frequent imbalances between inflows to and discharges from the aquifer. CropSim estimated pumping and recharge are discussed further in Section 5.9.

## 4.4 Aquifer Parameters

Estimates of streambed conductivity, hydraulic conductivity, and specific yield in the Nebraska and South Dakota portions of the model domain are summarized in Table 4-2. The estimated values for Nebraska are the calibrated ELM values (Stanton et al., 2010), calibrated Sand Hills model values (Chen and Chen, 2004), and the digital database of parameters developed by J. Ayers for the Niobrara River Basin (Conservation and Survey Division, 2010); estimates for South Dakota are from the Rosebud Model (Long et al., 2003; Long and Putnam, 2010) and aquifer test results reported by Rahn and Paul (1975). The estimates of aquifer parameters presented in Table 4-2 were used to constrain the ranges used for model construction and calibration.

| Table 4-2. High Plains Aquifer Parameters | | |
|---|---|---|
| Parameter | Estimated Value<br>Nebraska Portion of Model Domain | Estimated Value<br>South Dakota Portion of Model Domain |
| Hydraulic Conductivity | 5.48 to 107.15 ft/day[1]<br>26.2 to 59.7ft/day[2] (Ogallala)<br>98.4 ft/d to 436.4 ft/day[2] (Alluvium)<br>1.75 to 198 ft/day[3] (Ogallala)<br>0.02 to 48 ft/day[3] (Arikaree) | 0.1 to 84.4 ft/day[4] (Ogallala)<br>0.1 to 5.4 ft/day[4] (Arikaree)<br>42 to 75 ft/day[5] |
| Specific Yield (dimensionless) | 0.002 to 0.260[1]<br>0.036 to 0.27 (Ogallala)[3]<br>0.0015 to 0.226 (Arikaree)[3] | 0.02 to 0.06[4]<br>0.02 to 0.06[5] |
| Streambed Conductivity | 0.075 to 6.0 ft/day[1] | -- |
| SOURCES | [1]ELM, Stanton et al., 2010<br>[2]Sand Hills Model, Chen and Chen, 2004<br>[3]Conservation and Survey Division, 2010 | [4]Rosebud Model, (Long et al., 2003; Long and Putnam, 2010)<br>[5]Rahn and Paul, 1975 |

## 4.5 Sources and Sinks

Groundwater sources and sinks in the CENEB model domain are summarized in Table 4-3. Major sources and sinks include recharge, discharge of groundwater to streams, and groundwater pumping.

| Table 4-3. Groundwater Sources and Sinks | |
|---|---|
| Sources | Sinks |
| Underflow from the west | Underflow to the northeast toward the Missouri River |
| Recharge | Underflow/Discharge to the south (Platte River) |
| Canal leakage | Underflow to the east |
| Stream leakage | Groundwater pumping |
| | Discharge as baseflow to rivers and streams |
| | Evapotranspiration |

## 4.6 Conceptual Water Budget

A conceptual, steady-state water budget for the CENEB model domain was developed prior to model construction to quantify inflows and outflows for the pre-1940 system. A conceptual water budget provides a point of comparison with model-calculated water budgets, and is used to impose constraints during model construction and calibration. Sources of groundwater into the CENEB model include recharge from precipitation and agricultural irrigation, underflow of water into the model domain from the west, stream leakage, and canal leakage. Groundwater leaves the model domain via underflow to the east, groundwater pumping, ET, and discharge to rivers and streams.

The starting point for the CENEB conceptual water budget calculation was preliminary CropSim runs that provided estimates of recharge (minus canal leakage) and pumping for the pre-1940 steady-state period. Additionally, Darcy strip analyses were performed to calculate underflow into and out of the model domain. These budget estimates were then compared to the calibrated, 1939 pseudo-steady-state budget from the ELM to develop a conceptual water budget for the CENEB model. Table 4-4 compares the conceptual, steady-state CENEB model water budget with the pseudo-steady-state ELM budget. A discussion of the individual components in the CENEB conceptual water budget follows.

### 4.6.1 Underflow

Darcy strip analyses were performed to estimate steady-state underflow into the model across the western boundary, and underflow out of the model across the eastern boundary. Water levels from 1979 were used to calculate groundwater flow gradients: 11 ft/mile at the western boundary and 10 ft/mile at the eastern boundary. The flux across the boundary was calculated from the calibrated hydraulic parameters from the steady-state ELM model (Stanton et al., 2010). Underflow into the model area from the west was calculated to be approximately 35,000 acre-ft per year (AFY); underflow out of the model boundary to the east was calculated to be approximately 165,000 AFY (Table 4-4).

### 4.6.2 Recharge and Canal Leakage

Recharge in the model domain includes recharge from precipitation, agricultural recharge, canal leakage, and stream leakage. Precipitation recharge dominates the groundwater flow system water budget; a large portion of this recharge is in the Sand Hills, which cover approximately 55 percent of the CENEB model domain. Precipitation readily enters the coarse-grained, permeable soils in the Sand Hills; the thick unsaturated zone provides storage and prevents losses through evaporation (Chen et al., 2003). A comparison of the mean annual net recharge rate for the Sand Hills (greater than 4 inches [100 millimeters (mm)]) versus the mean annual net recharge rate of 1.14 inches [29 mm] for all of Nebraska (Szilagyi and Josza, 2012) provides an indication of the importance of this region to the aquifer system.

Agricultural recharge is the result of deep percolation of irrigation water applied to cropland. The volume of water entering the aquifer via agricultural recharge increases significantly through time, as it keeps pace with the rise in irrigated acreage.

A preliminary CropSim-derived recharge estimate of 3.75 million AFY for the Nebraska portion of the model was utilized as the starting point for the conceptual CENEB water budget. This preliminary CropSim value compares favorably to the ELM recharge at 4.01 million AFY. The CropSim recharge estimate was based on the water balance approach, as described in Section 4.4.

An independent estimation of recharge based on a water balance by Szilagyi and Jozsa (2012) for the Nebraska portion of the model provides a second point of comparison. Szilagyi and Jozsa (2012) updated previously published mean annual groundwater recharge rates in Nebraska, improving the methodology discussed in their previous paper (Szilagyi et al., 2003) by incorporating 1-kilometer resolution Moderate Resolution Imaging Spectroradiometer (MODIS) data into a water balance approach. In addition to MODIS, the approach uses GIS layers of land cover, land surface, groundwater surface, base recharge, recharge potential, and monthly climatic data. Datasets provided by Dr. Szilagyi (personal communication, 2012) were utilized to estimate recharge in the Nebraska portion of the CENEB model; the resulting value of 3.53 million AFY compares well to the ELM and conceptual CENEB recharge.

Estimates of recharge from CropSim and Szilagyi and Jozsa (2012) do not include canal leakage. Recharge in 1940 from canal leakage in the ELM was 77,000 AFY (Stanton et al., 2010). This water budget output from ELM was included in the conceptual recharge estimate for the CENEB water budget.

### 4.6.3 Pumping

Estimated groundwater pumping of 54,000 AFY was included in the conceptual CENEB budget for the pre-1940 period, derived from land use patterns in regions that utilized groundwater for irrigation (Section 2) and the net corn crop irrigation requirements for the state of Nebraska (NDNR, 2006). Pumping was not simulated in the ELM for the steady-state 1939 period; however, the volume of estimated pumping was an insignificant component of the water budget.

### 4.6.4 Evapotranspiration (ET)

ET in the CENEB model refers to the loss of shallow groundwater from streams and riparian areas. ET associated with agricultural practices is taken into account in the net recharge and pumping estimates from CropSim.

ET in the conceptual CENEB water budget was increased significantly over ELM levels due to:

- The large number of stream cells with adjacent riparian areas added to the model in the northern portion of the domain
- A review of the distribution of riparian areas (United States Fish and Wildlife Service [USFWS], 2012)
- The large potential evaporation rates calculated by Szilagyi and Jozsa (2012)

In many cases, potential evaporation rate exceeds the recharge rate. The total potential evaporation volume of approximately 12 million AFY in Nebraska (Table 4-4) far exceeds all model budget estimates, but serves to illustrate that shallow groundwater can be seriously impacted by ET. The increase of 41 percent in the CENEB conceptual ET for pre-1940 conditions versus ELM was considered plausible, given the larger model domain and the number of model cells that include riparian acreage. Note that this budget component was used to balance the water budget, in conjunction with stream inflows and outflows.

### 4.6.5 Discharge of Groundwater to Rivers and Streams

Surface water systems can either gain baseflow through discharge from the aquifer system or lose baseflow via infiltration. Within the model domain, there are both gaining and losing stream reaches; however, there is a net loss from the aquifer to the streams.

The Niobrara River and the Upper, Middle, and Lower Loup Rivers and their tributaries serve as a groundwater drain for the Sand Hills region. Soils in the Sand Hills are coarser grained than the surrounding areas, and, therefore, have a much greater rate of recharge. Minor amounts of precipitation reach the streams as overland runoff; thus, streamflow is maintained almost wholly by groundwater discharge (Nebraska Natural Resources Commission, 1982).

Along the upper reaches of the Loup River system, groundwater discharge has been estimated to account for 87 to 98 percent of the river's total flow (Nebraska Natural Resources Commission, 1982; Szilagyi et al., 2003; Chen and Chen, 2004; Peterson et al., 2008). Similarly, along the Niobrara River and its tributaries, streamflows are largely derived from groundwater discharge (Bentall and Schaffer, 1979, Soenksen et al., 2010). In the Elkhorn River Basin, Peterson et al. (2008) reported that 66 percent of the baseflow was derived from groundwater discharge.

Stream leakage into the aquifer is a minor CENEB budget component totaling 137,000 AFY. Consistent with the conceptual model, the conceptual water budget reflects a net loss of groundwater to rivers and streams (presented as net Streams OUT in Table 4-4). The net loss to streams totals 2.663 million AFY and compares very well to the ELM budget of 2.467 million AFY (difference of 8 percent).

### 4.6.6 Summary

The conceptual steady-state CENEB water budget of 4.703 million AFY reflects the conceptual model of the High Plains Aquifer system within the model domain. Total volume in the CENEB water budget is 12 percent higher than the ELM water budget due to the increased size of the CENEB model domain and the extent of the additional streams simulated. There are large differences between individual components, i.e., recharge, ET, and boundaries, which are attributed to the use of CropSim for the pumping and recharge inputs and the calculation of boundary inflows and outflows using a Darcy strip analysis.

**Table 4-4. CENEB Steady-State Conceptual Budget (AFY)**

| | CENEB Conceptual Budget Pre-1940 | ELM 1939 Pseudo-Steady-State Budget[1] | Preliminary CropSim Run[2] (Nebraska Only) | Szilagyi and Jozsa (2012)[2] (Nebraska Only) |
|---|---|---|---|---|
| IN | | | | |
| Storage | -- | 14 | -- | -- |
| Boundaries | 165,000 | 90,434 | -- | -- |
| Recharge | 4,401,000 | 4,009,476 | 3,753,000 | 3,528,149 |
| Streams | 137,000 | 94,430 | -- | -- |
| TOTAL Inflows | 4,703,000 | 4,194,354 | | |
| OUT | | | | |
| Storage | -- | 12,606 | -- | -- |
| Boundaries | 35,000 | 331,451 | -- | -- |
| Pumping | 54,000 | -- | 54,000 | -- |
| Evapotranspiration (ET) | 1,814,000 | 1,287,880 | -- | 11,792,000[3] |
| Streams | 2,800,000 | 2,562,053 | -- | -- |
| TOTAL Outflows | 4,703,000 | 4,193,990 | | |
| Net Streams OUT | 2,663,000 | 2,467,623 | -- | -- |

[1]*Pseudo-steady-state simulation: includes storage.*

[2]*Method does not include canal leakage in the recharge estimate.*

[3]*Total potential ET using rates from Szilagyi (digital data provided in personal communication, 2012).*

*Units are AFY (acre-feet per year)*

Section 5

# Numerical Model Development

The CENEB numerical groundwater flow model was constructed based upon the conceptualization of the aquifer system presented in Section 4, utilizing the ELM structure. The starting point for hydraulic parameters was the calibrated ELM values; CropSim-derived estimates were utilized for groundwater pumping and recharge rates. Initial estimates for hydraulic parameters were modified during model development and subsequent calibration (Section 6). This section summarizes model specifications, model development, and the methods and assumptions used for expanding the model domain to the north. The numerical model specifications are presented in Table 5-1.

**Table 5-1. CENEB Model – Specifications**

| | |
|---|---|
| Model Area | Active Domain: 34,449 square miles<br>22,047,270 acres |
| Software | MODFLOW-NWT-SWR1<br>Groundwater Vistas Version 6.40, Build 3.0 |
| Solution Method | NWT — Newton Method using χMD Solver |
| Units | Time: Days<br>Length: Feet |
| Coordinate System | Model: State Plane, North American Datum of 1983 (NAD83), Nebraska, Feet<br>Model Origin (lower left corner): X = 1,054,680 Y = 282,480 (no rotation) |
| Model Grid | 195 rows x 255 columns<br>Active Domain: 34,449 cells<br>Model Grid is coincident with state of Nebraska 1-mile grid system |
| Cell Size | Uniform spacing: 1 mile x 1 mile |
| Simulation Time | 72 Years<br>Pre-1940: Steady State<br>1940-2011: Transient |
| Stress Periods | 359 stress periods, first stress period simulated as steady state |
| Layer Definition | Layer 1: High Plains Aquifer, unconfined<br>Thickness: 27 to 1,176 feet |
| Hydraulic Conductivity | 2.5 to 75.7 ft/day |
| Streambed Conductivity | 0.008 to 0.75 ft/day |
| Specific Yield | 0.002 to 0.260 (dimensionless) |
| Evapotranspiration | 0.000033 to 0.010399 ft/day |
| Boundary Conditions | Constant Head Boundary: Platte River (south) and Missouri River (northeast)<br>General Head Boundary: Portions of the western and eastern edge of model<br>No-Flow Boundary: North model domain boundary; portions of the eastern and western edge of the model |
| Surface Water Interactions | Streamflow-Routing (SFR2) Package<br>Streamflow-Routing: 5,227 cells |

## 5.1 Computer Code Description

The computer code used to simulate groundwater flow for the CENEB model was MODFLOW-NWT, a modular, finite-difference, 3-dimensional groundwater modeling program. MODFLOW-NWT is a standalone program that uses the Newton method for solving non-linear problems (Niswonger et al., 2011). Groundwater Vistas™ Version 6.40 Build 3 (Environmental Simulations, Inc., 2011) was used as the pre- and post-processor and was coupled with ArcGIS™ (Esri, 2011) to facilitate the development of input files and analyses of model output. The generation of 2-dimensional gridded and contour data by geostatistical interpolation techniques (i.e., kriging) was performed using Global Mapper (Blue Marble Geographics, 2013) or Surfer® (Golden Software, Inc., 2008), both of which produce output that can be imported into the numerical model or GIS.

### 5.1.1 Computer Code Assumptions

MODFLOW-NWT uses a finite-difference numerical method for solving a form of the 3-dimensional groundwater flow equation. This technique essentially solves for head by discretizing the flow domain into a computational grid composed of blocks, with nodes at the center of the blocks. For the system of nodes, it is possible to write a series of finite-difference equations derived from the original groundwater flow equation. In general, the finite-difference approximation assumes that all hydraulic parameters, stresses, and inputs are constant (representing average conditions) over the area of a single cell and over the time elapsed during a stress period. Likewise, calculated head and groundwater fluxes are also averaged over the areal extent of a single cell. Implementing the model for a specific problem requires the definition of boundary and initial conditions, as well as estimates of key hydraulic parameters and hydraulic sources and sinks as a function of time.

### 5.1.2 Computer Code Limitations

Numerical solutions using MODFLOW-NWT are dependent upon the scale of the model grid, the time frame of interest, and the behavior of various model inputs and boundary conditions. For regional-scale applications such as the CENEB project, model results may have limited usefulness in investigating groundwater-surface water issues with 1) spatial scales smaller than a single cell or small grouping of cells, and 2) substantially varying groundwater stresses or inputs at a time scale less than a single stress period. In addition, the code is designed to represent changes in baseflow at time scales from months to hundreds of years. At smaller time scales, the code may not accurately simulate short-term transient surface water-groundwater interactions due to quickly changing streamflow conditions (Prudic et al., 2004). Furthermore, careful attention must be paid to head-specified inflow and outflow boundaries, as they are capable of providing unrealistic volumes of water to the domain, while still maintaining appropriate water level conditions. Additionally, extrapolation or interpolation of the model results over large time frames are subject to uncertainties inherent in long-term, transient, predictive model stresses.

## 5.2 Units and Coordinate System

The CENEB model utilizes linear units of ft and temporal units of days. All model features are geo-referenced in the State Plane North American Datum of 1983 (NAD83), Nebraska projection system (Table 5-1).

## 5.3 Model Discretization and Layering

The CENEB model is a one-layer model based on the ELM aquifer geometry, which was extended northward (versus the ELM) to bring the northern tributaries of the Niobrara River as well as the Keya Paha River and Ponca Creek Basins into the active domain. The model has a uniform cell size of 1 mile by 1 mile. The expansion area allows for a more complete evaluation of streamflow depletion scenarios in northern Nebraska. The CENEB model grid is consistent with the state of Nebraska 1-mile grid system.

### 5.3.1 Layer Top and Bottom

A layer top elevation representing land surface was incorporated into the CENEB model to replace the constant elevation from the ELM, using a 10-meter digital elevation model (DEM). The average land surface elevation calculated from the DEM was assigned to each model grid cell. While the ELM aquifer bottom was retained in its entirety, new aquifer bottom elevations were developed for the expansion area. The aquifer bottom elevations in the expansion area were estimated by interpolating bedrock elevation data from the USGS High Plains Aquifer Study (HPAS) (Gutentag et al., 1984) using the kriging method. Aquifer thickness was then calculated based on average land elevation and the newly kriged aquifer bottom.

Additionally, a check was run on constant head stages and stream bottoms. In locations where the aquifer bottom elevation was either below the constant head stage or below the stream bottom elevation, or that resulted in a thickness of less than 20 ft, the aquifer bottom was set by default to 20 ft below the constant head stage or stream bottom. These areas were then buffered and re-kriged to allow a smooth integration with the remainder of the aquifer bottom dataset.

### 5.3.2 Revisions to Layer Thickness

Based on initial model test runs, groundwater elevations were over-simulated in areas where the aquifer was exceptionally thin. Based upon a review of available USGS well databases, the aquifer is likely thicker than what was estimated from average ground surface elevation and the interpolated aquifer bottom surface derived from HPAS data. Consequently, in the northern portion of the model domain where the aquifer thickness was between 20 and 50 ft, the bottom elevation was decreased by 40 ft to provide a thicker flow zone. Where the aquifer thickness was between 50 and 90 ft, bottom elevation was decreased by 20 ft.

The aquifer bottom was also lowered slightly in the northeast corner of the domain near the Missouri River. In this area, elevations change rapidly across cells; thus, utilizing an average surface elevation in a 1-mile cell from the 10-meter DEMs resulted in bottom elevations that were higher than ground surface elevations in neighboring cells. Aquifer bottom elevations were decreased slightly in this area to rectify the problem.

The discretization of layer thickness in the northern and northeastern portions of the model domain was designed to establish a generalized flow regime in the expansion areas. Providing a thicker zone for local groundwater flow likely does not significantly change the flow volume simulated by the model but improves the model's ability to simulate realistic gradients. After adjustments, the total thickness of layer 1 ranged from 27 to 1,176 ft, with an average thickness of approximately 500 ft (Table 5-1).

## 5.4 Stress Periods and Initial Conditions

Stress periods in the CENEB model were defined such that the steady-state and transient model solutions were calculated sequentially in a single model run. This allowed the refinement of model stresses, inflows, and hydraulic parameters simultaneously for both the steady-state (pre-1940) and transient (1940 through 2011) timelines. The simulation period was discretized into a total of 359 stress periods. The first stress period is defined as a steady-state simulation, with the remaining 358 stress periods assigned to the transient simulation. Annual stress periods are simulated from 1940 through 1985. Beginning in 1986 and continuing through 2011, stress periods decrease to monthly intervals. Table 5-2 summarizes the stress period setup in the CENEB model; the correlation between model time and calendar time for all stress periods is provided as Appendix B.

| Table 5-2 Stress Period Timelines and Parameters | | | | | |
|---|---|---|---|---|---|
| Stress Period | Simulation | Time Simulated | Stress Period Length | Number of Time Steps | Time Step Multiplier |
| 1 | Steady State | Pre-1940 | -- | 1 | 1 |
| 2–47 | Transient | 1940–1986 | Annual | 10 | 1.2 |
| 48–395 | Transient | 1987–2011 | Month | 3 | 1.2 |

Starting heads for the initial steady-state stress period were assigned as the top of layer 1 and allowed to drain until simulated head and fluxes met the prescribed convergence criteria. Model-calculated heads from the steady-state simulation were then used as the initial conditions for the transient simulation.

## 5.5 Model Boundaries

CENEB model boundaries are shown on Figure 5-1; model boundaries include no-flow boundaries, general head boundaries (GHBs), and constant head boundaries. No-flow boundaries were assigned to cells in areas where flow directions parallel model boundaries and groundwater neither enters nor leaves the model domain, or where the aquifer is not present. Groundwater levels in the simulation are kept constant at constant head boundaries through the addition or subtraction of the required flow within the cell. GHBs are allowed to vary in reference to a constant head estimate assumed to exist outside the model domain at a fixed distance. Thus the model estimates an amount of inflow to or outflow from the model domain based on the gradient between the GHB and the outside reference head.

Selected cells along the western and eastern edge of the CENEB model were assigned GHB conditions with the reference head estimated for a location 2 miles away from the active model boundary. These GHBs initially used head elevations based on the 1995 water table contour map developed by the Conservation and Survey Division at UNL (2003). This approach differs from the ELM, where constant head boundaries were used to simulate groundwater discharge either entering or leaving the model at these locations. The GHB cells on the western edge of the CENEB model generally coincide with the ELM constant head boundaries; however, on the eastern edge of the CENEB model, the GHBs cover a slightly greater area than ELM due to flow direction interpretations derived from the 1995 groundwater contour map. All CENEB constant head and GHBs were time invariant. Conductance values for the general head boundaries were adjusted during model calibration (Section 6).

Constant head boundaries were assigned to the southern and far northeastern areas of the model representing the Platte River and the Missouri River, respectively. Water level elevations for these constant head boundaries were defined using the minimum elevation within the model grid cell from a 10-meter DEM to represent groundwater discharge to the rivers. The constant head boundary along the southern edge of the model generally has the same footprint in both the CENEB model and the ELM, except for Lake McConaughy. In the ELM, Lake McConaughy was represented using a GHB whereas in the CENEB model, the lake is simulated using a constant head boundary. Constant head values were considered appropriate to capture a reasonable approximation of lake levels in a location along the boundary that is distal to the area of interest.

Model expansion of the CENEB model to the north resulted in the addition of 31 constant head cells to simulate aquifer flow out of the model to the northeast toward the Missouri River, as depicted on the 1979 and 1995 groundwater contour maps (Conservation and Survey Division, 1996; 2003).

## 5.6 Rivers and Streams

Rivers and streams located within the active CENEB model domain (not located on boundaries such as the Platte and Missouri Rivers) were represented using the Streamflow-Routing Package (SFR2)

(Niswonger and Prudic, 2010). The SFR2 package is capable of simulating unsaturated flow where the water table is disconnected from the stream network. However, for the CENEB model this feature was not implemented and it was assumed that any unsaturated zone flow between the streambed and the aquifer occurred over a length of less than a few meters such that the time required for seepage to reach the water table is negligible (Niswonger and Prudic, 2010).

The CENEB model purpose dictated the addition of new stream cells to the ELM structure, using a comprehensive approach to include stream segments with any observed or measured flow, in accordance with the requirements of the evaluation for which the model was built. The CENEB approach to the definition of stream cells was designed to capture the character of the drainage network as precisely as possible given the limitation of 1-mile grid cells. The guidelines below, and professional judgment, were used to simplify the model representation of the surface water system, particularly in areas with numerous and closely spaced tributaries. The analysis was performed in GIS, by overlaying the perennial reaches from the NHD (USGS, 2012) on the model grid.

Stream cells were added to the original ELM dataset based on the following guidelines:

- Include rivers, streams, and tributaries categorized as perennial in the NHD (USGS, 2012)
- Include tributaries longer than 2 to 3 miles
- Include stream reaches beyond the NHD perennial extent that were categorized as having measureable flow in Peterson and Strauch (2007); stream reaches that were reported as “no flow” in this study (i.e., 5 cubic ft per second [cfs] or less) should not automatically be excluded
- In the Niobrara River Basin where short, first-order tributaries (headwater streams, i.e., the smallest streams in the system, with no permanently flowing tributaries) are numerous, include every other tributary or every third tributary to provide a means for aquifer discharge in the region
- Extend the major stream segments (Niobrara, Snake, North Loup, Calamus, Middle Loup, Dismal, and South Loup Rivers) in the upstream direction to the headwaters, if located within the active model domain

New stream cells were added in the model expansion area to simulate the Keya Paha River, and Ponca Creek, and to include tributaries along the north mainstem of the Niobrara River. New stream cells were added to the Elkhorn and Loup River systems to encompass the headwaters and the larger tributaries. CENEB model stream cells are shown on Figure 5-1. A total of 5,227 stream cells are defined in the model domain, representing 7,415 miles of streams.

Stream cells were combined into stream segments in the CENEB model to facilitate parameterization. Depending on the settings specified in the SFR2 package, a segment is a group of cells that may have uniform or linearly changing properties such as stream width (Niswonger and Prudic, 2010). In the CENEB model, parameters values used to characterize the streambed are specified for each reach and do not linearly vary within a stream segment. Stream cell parameters were defined based on DEMs, ELM inputs, and analyses performed for this project, as discussed in the following sections.

### 5.6.1 Stream Width, Bottom Elevation, and Length

Stream widths were carried over from the ELM where available. For newly defined CENEB stream cells, NDNR performed an aerial photo review to estimate stream width in support of this project. Stream bottom was estimated as the minimum elevation within a model grid cell from a 10-meter DEM. Bottom elevations in the western and central portions of the model were adjusted for some stream reaches during model calibration (Section 6).

Stream lengths used the entire length of the digitized stream within a model cell based on the NHD and a GIS analysis. In areas where a small section of the stream strayed outside of a stream cell, this small section was added to the stream cell length, thereby ensuring that the model represents the entire length of the streams and rivers.

### 5.6.2 Stream Slope, Thickness, and Depth

Stream slope was calculated as the difference between the minimum and maximum stream bottom elevation within a stream segment divided by the length of the segment. Where stream segments were greater than six reaches (6 miles) long, slope was calculated over two or more sections of that segment. For one-cell segments, an adjoining cell or segment was utilized for the slope calculation.

Streambed thickness was set to 1 ft; this parameter was not varied during model construction and calibration. However, the stream conductance term, which is based on streambed thickness and the material properties of the streambed, was adjusted during model calibration.

The SFR2 package was parameterized to simulate streams as wide rectangular channels (i.e., MODFLOW *icalc* variable = 1). This condition uses the Manning's equation to solve for stream depth during model simulations.

### 5.6.3 Stream Conductivity

Initial stream hydraulic conductivities were assigned the same hydraulic conductivity values as the ELM where the respective stream cells overlapped. For new stream cells, hydraulic conductivity values were initially assigned a value of 0.2 ft/day, a value representative of calibrated ELM stream cells; in areas where the streams or rivers overlie the Pierre Shale, hydraulic conductivity was assigned as 0.01 ft/day. Stream hydraulic conductivity was then adjusted during calibration.

### 5.6.4 Prescribed Baseflow

The headwaters of the Niobrara River are not contained within the active model domain. For all stress periods, an average representative baseflow discharge equal to 80 cfs was assigned to the stream cell where the Niobrara River enters the domain. This prescribed baseflow was estimated based on the long-term hydrograph for the *Niobrara River near Gordon NE* stream gage (06457500), located upstream, outside of the active model domain.

## 5.7 Hydraulic Parameters

Initial estimates of hydraulic parameters (i.e., hydraulic conductivity and specific yield) were imported into the CENEB model from the ELM, where available. Estimates of hydraulic conductivity and specific yield from the Conservation and Survey Division (2010) were utilized in the Nebraska portion of the expansion area, and HPAS data (Gutentag et al., 1984) were utilized in the South Dakota portion of the expansion area.

Additional sources for hydraulic parameters were evaluated for localized regions within the model domain, including the Rosebud model, which was developed for a small region in the northwest corner of the expansion area (Long et al., 2003; Long and Putnam, 2010); the Nebraska Sand Hills model (Chen and Chen, 2004); and a summary of hydraulic parameters for the Sand Hills region in Nebraska and South Dakota by Rahn and Paul (1975).

Estimates of hydraulic conductivity in the Sand Hills portion of the expansion area were compared to ELM values, and smoothed based on kriging and GIS to ensure consistency. Hydraulic conductivity estimates in other regions of the expansion area were assigned based on the range of values presented in the conceptual model (Section 4) which were then compared to the calibrated ELM values. Abrupt changes in these estimates were smoothed, as appropriate, or retained if warranted based on the stratigraphy (i.e., Pierre Shale). These initial hydraulic conductivity values were adjusted during CENEB model calibration; the final calibrated range of hydraulic conductivity values are presented in Table 5-1 and on Figure 5-2.

Estimates of specific yield in the CENEB model were based on ELM values, and on published data sources for the expansion area. The results were evaluated to ensure consistency, and smooth the transition into the expansion area. The distribution of specific yield estimates in the CENEB model domain is shown on Figure 5-3. These values were not varied during calibration.

## 5.8 Evapotranspiration (ET)

ET processes are simulated both with CropSim and with MODFLOW for the CENEB model. CropSim simulates ET from the land surface and soils as a result of precipitation and applied irrigation water – it does not explicitly consider shallow groundwater sources to ET; the land surface ET processes are incorporated into the pumping and recharge estimates derived from CropSim.

MODFLOW simulates ET as discharge of near-surface groundwater that can be considered to result from phreatophyte and riparian vegetation water use (not included in CropSim) and discharge from shallow wetlands and Sandhill lakes. Initial ET rates in the CENEB model relied on calibrated ET rates from the ELM; however, the spatial distribution of ET differs between the two numerical groundwater models as described below.

To produce a spatial distribution of ET in the CENEB model, the National Wetlands Inventory (NWI) database from the United States Fish and Wildlife Service (USFWS, 2012) was reviewed to identify wetlands within the model domain. The NWI database is a repository for the extent, status, and approximate location of current and historical wetland mapping projects, and is available in GIS format, by state. The Nebraska and South Dakota NWI files were downloaded in 2012 and utilized to identify model grid cells where a minimum of 640 acres (7 percent of the cell) was characterized as wetlands. These cells were retained for assigning ET rates in CENEB.

Additionally, infrared imagery for CENEB stream reaches was reviewed to determine the health and extent of vegetation in riparian areas (Esri, 2013). ET rates were not prescribed along the streams where vegetation was not robust (i.e., certain reaches in the Sand Hills). On smaller order tributaries (i.e., smaller streams) where vegetation appeared healthy, ET rates were assigned only to the cell containing the channel node. Along higher order stream networks, a 0.5-mile buffer was applied to streams, and cells that intersected the buffer zone were also assigned ET rates.

Once model cells requiring simulation of ET were identified, rates were assigned by locating the closest ELM cell where ET was prescribed and assigning that rate to the respective CENEB model cell. Cells along the Niobrara River segments that were not simulated in the ELM were assigned a uniform ET rate consistent with the calibrated ELM values for the Niobrara River. Similarly, the Keya Paha River and Ponca Creek stream cells were assigned ET rates in the same range as the Niobrara River. This approach maintained the general increasing trend in ET rates from north to south in the model domain (Figure 5-4).

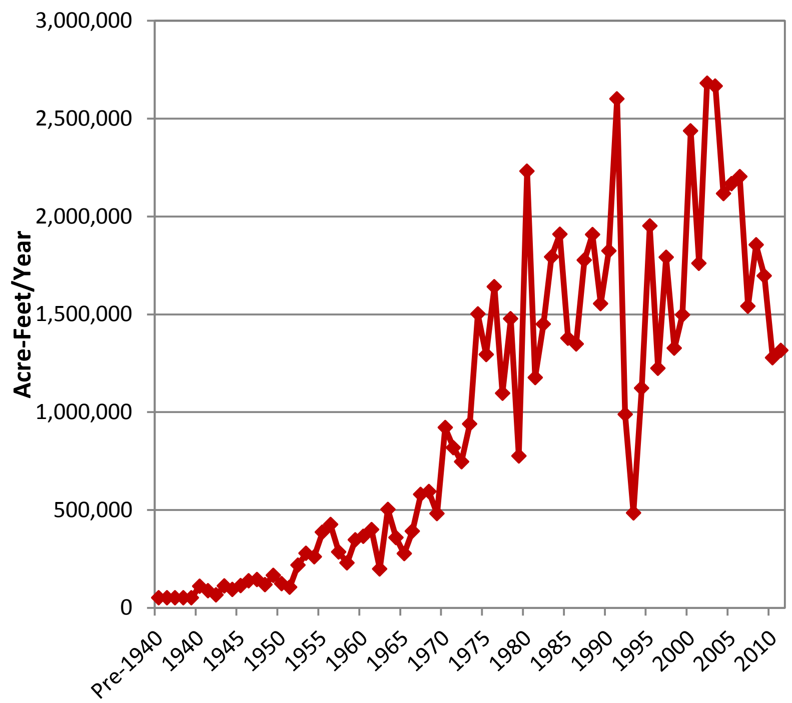
During model calibration, the spatial extent of prescribed ET cells along the lower sections of the Elkhorn River was slightly expanded. Otherwise, the spatial distribution of ET in the CENEB model was not revised during model calibration. Final ET rates for the CENEB model are shown on Figure 5-4.

## 5.9 CropSim-Derived Pumping and Recharge

The CENEB CropSim process produces an estimate of annual groundwater pumping and recharge for the 1940—1985 period and monthly estimates for the remaining simulation period from 1986 through 2011. Graph 5a shows the increase in annual groundwater pumping through time, reflecting the upsurge in irrigation infrastructure installation throughout the model area starting in the 1970s.

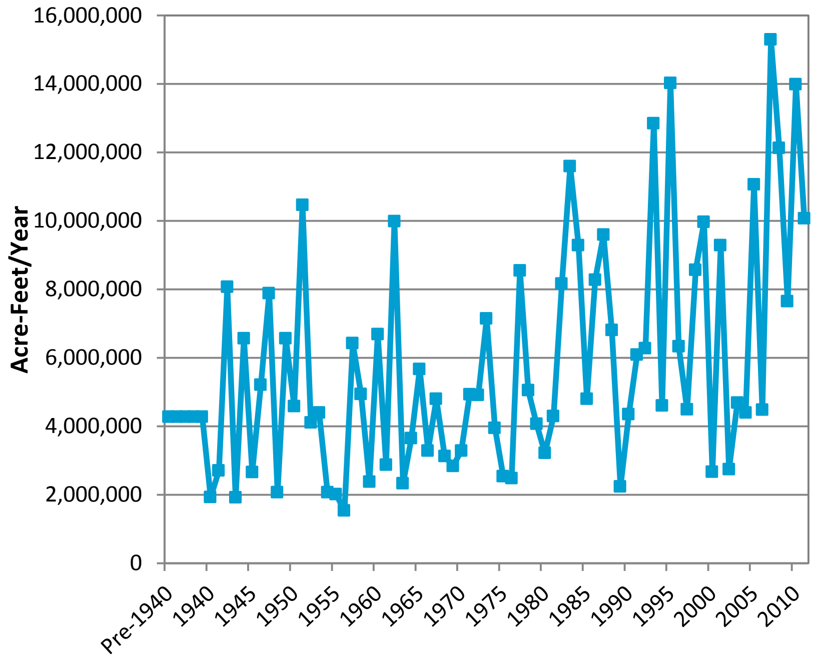
Superimposed on this increasing groundwater extraction trend are the effects of annual climatic variation, notably the decreased pumping in the wet years of the early 1990s and the peak pumping in the drought years of the early 2000s. Figure 5-5 shows that this pumping tends to be concentrated in the dissected plains to the south and east of the Sand Hills, within the Platte River valley, and on the flatter lands along and between the Elkhorn River and the lower Niobrara River. The figure also shows that the land use and CropSim datasets captured the pumping that occurs in more dispersed locations throughout the Sand Hills and on the flat uplands along the Niobrara River.

All pumping simulated by the CropSim process was assumed to occur within and fully penetrate the same portion of the High Plains Aquifer simulated in the groundwater model. This assumption is considered valid at the regional scale of the CENEB model but may not necessarily hold at local scales, particularly where the High Plains Aquifer thins and an underlying unit may provide adequate supply for a single well. Wells likely do not fully penetrate the entire aquifer in areas of exceptional thickness, as in the Sand Hills area. However, as pumping is relatively minimal in this area, the effect of partial penetration on simulated regional heads and baseflow discharge was expected to be insignificant.




**Graph 5a. Groundwater Pumping in the CENEB Model – Pre-1940 through 2011.**

The time series in Graph 5b depicts annual recharge within the CENEB model domain. The year-to-year variation captures wet and dry cycles superimposed on the aggregate effects of farming and land use. The use of CropSim to simulate deep percolation as recharge influx to the groundwater model assumes instantaneous vertical transport through the vadose zone. This assumption may be less valid for short stress periods (days to weeks) and thick vadose zones dominated by fine sediments. For the CENEB model, with annual and monthly stress periods and relatively shallow groundwater, this assumption is expected to be valid for evaluation of model responses over regional areas and multi-year time periods.




**Graph 5b. Total Recharge in the CENEB Model – Pre-1940 through 2011.**

# 5.10 Canal Recharge

Because CropSim simulations do not include seepage losses to groundwater from irrigation canals, CropSim recharge rates were adjusted to incorporate canal leakage. The adjustment was made by directly adding ELM canal leakage rates (Stanton et al., 2010) to CropSim recharge rates in the appropriate model cells for simulation years 1940 through 1985. For simulation periods from 1986 through 2011, annual ELM canal leakage rates were modified to account for monthly stress periods in the CENEB model. This revision was performed by calculating the annual canal leakage volume per cell in the ELM model and then calculating the rate required to apply the same volume over an irrigation season spanning from May through September. Monthly canal seepage rates were then added to monthly CropSim recharge rates in the appropriate model cells. Finally, the ELM model canal leakage rates only covered a time period through 2005. In the CENEB model, 2005 annual ELM canal recharge estimates were used to calculate monthly canal seepage rates in the CENEB model for years 2006 through 2011. This method of incorporating canal recharge into the CENEB model was utilized to represent losses to groundwater from all canals within the model domain except the laterals in the Ainsworth Irrigation District (AID) in the northern portion of the CENEB model. NDNR estimated canal recharge for the AID laterals (described below); losses to the aquifer from the main AID canal were carried over from the ELM.

The AID in Brown County and a small portion of Rock County is served by water from Merritt Reservoir. The reservoir was completed in May 1964 with first deliveries to lands in the AID occurring in the summer of 1965. The water released from the reservoir during irrigation season is diverted downstream from the release point (NDNR gage 00001000) and travels eastward through approximately 53 miles of concrete-lined main canal. At the end of the lined canal there are roughly 170 miles of unlined laterals that deliver water to fields. The process of delivering water though the AID system results in seepage losses that are not accounted for in the CropSim estimates of recharge. To account for this, losses from the main canal were carried over from the ELM, and an additional dataset of estimated seepage losses from laterals was created for the portion of the model period over which the district has been operational, 1965 through 2011.

The total volume of seepage water was calculated as a percentage of the volume diverted over each month (for 1986 through 2011) or year (for 1965 through 1985). This percentage, or “loss factor,” was set at 0.35, meaning that 35 percent of the water diverted was lost to seepage over the given time period. This value is within the range of similar loss factors observed on other canal systems in the state.

The total seepage volume was then distributed to model cells containing laterals using the ratio of lateral length within a cell to the total length of all laterals in the system. This assumes that all sections of the lateral system leak water equally and in proportion to the amount of water diverted. This assumption may not hold at very small time increments but is reasonable over the longer term.

The resulting distributed recharge datasets included additional recharge rates for each cell for every stress period in the model. The AID canal recharge estimates were then added to the base recharge inputs from CropSim, and canal recharge carried over from the ELM. Recharge rates representing AID lateral losses were further evaluated during calibration.

# Section 6
# Calibration

The calibration exercise provides confidence that the model is capable of simulating known groundwater system responses based on historical observations, and is performed prior to using the model for predictive simulations. To facilitate calibration, the stress period design incorporates an initial steady-state simulation (stress period 1) representing long-term average conditions prior to 1940, that is followed directly by the transient stress periods (2 through 359) representing changes in the groundwater system from 1940 through 2011. This functionality ensures that parameter changes made during the transient calibration exercise are automatically included in the steady-state trials, eliminating any disconnect between the steady-state and transient models.

## 6.1 Calibration Approach

Calibration is the process of modifying model parameters within a fixed ranged of reasonable estimates to improve the match between the predicted and observed hydraulic heads, baseflow, and other relevant hydrogeologic data. These observed data are referred to as calibration “targets.” Initial estimates for hydrogeologic parameters are varied within an observed or estimated range of values to improve the model’s ability to simulate these targets.

The range of plausible estimates for hydrogeologic parameters provides constraints on the calibration exercise (1) to ensure that inputs remain defensible based on known conditions within the aquifer and (2) to limit the non-unique nature of the model results to a set of realistic input conditions. The model variables adjusted during calibration may include hydrogeologic parameters such as hydraulic conductivity and streambed conductance, as well as prescribed inputs such as recharge and ET rates.

The strategy in a transient calibration where hydraulic stresses or boundary conditions are changing is to match calibration targets which represent snapshots of the hydrogeologic system through time. Both qualitative and quantitative methods of comparison were used to assess the ability of the CENEB model to simulate observed historical conditions.

The standard of practice in calibration is to identify constraints and select calibration targets early in the modeling process. Constraints were presented in the conceptual model (Section 4) and include ranges for hydraulic parameters and specific components of the conceptual steady-state water budget. The calibration targets were selected in the early stages of model development and consist of observed (field-measured) water levels and calculated stream baseflow (NDNR, 2012) through time.

Model parameters and stresses that were varied and tested during model construction and calibration of the CENEB model included: horizontal hydraulic conductivity, natural and agricultural recharge, streambed conductance, canal recharge, ET, general head boundary conductance, and constant head magnitudes. Although all model parameters and stresses were evaluated during the model construction and calibration, the CENEB model was primarily calibrated to hydraulic conductivity, ET, and recharge from both natural and agricultural sources.

### 6.1.1 Goals of Calibration

The calibration process was accomplished by moving from qualitative to quantitative assessments of the model-simulated heads and baseflows. Initially, hydraulic parameters were adjusted to produce the general flow directions and gradients for steady-state and transient periods. This step relied on the conceptualization of the system, understanding of the geology and hydrogeology, professional judgment, and assumptions. The primary goal of the qualitative calibration was to match the observed flow regime, as defined by the 1995 water level contour map (Conservation and Survey Division, 2003) and simulate general trends in groundwater-surface water interactions, such as a total net discharge to the surface water system from the aquifer. Localized variations in the model-simulated versus observed water level contours were deemed acceptable; however, the generalized flow regime and the influences of the river systems on the flow regime needed to match field observations. The second goal of the qualitative calibration was to match the general trends observed in both head and baseflow hydrographs. Once the flow directions and general hydrograph trends approximated the generalized flow regime through time, the calibration process expanded to include quantitative evaluations based on calibration targets.

During calibration, a residual is calculated to assess the “fit” of the model-calculated (or simulated) targets to those actually observed. The residual is the observed (or field-measured) value minus the simulated value. Positive residuals indicated that model values are too low, and negative residuals indicate that model values are too high, as compared to observed conditions. A residual value of 0 represents a perfect fit between the simulated and observed values. The goal of the calibration is to minimize statistical properties of the residuals while remaining within the acceptable range for water budget components, hydraulic parameters, and flow regime requirements.

Plotting the residuals on a map showing the simulated water level contours provides an indication of the spatial distribution of error and helps guide the calibration process. Trends in the distribution of error, such as clusters of values that are all too high or too low, indicate spatial bias.

Calibration statistics based on the residual are used as a quantitative measure of the ability of the model to match calibration targets. Calibration statistics that were used to evaluate the calibration included:

- Mean Error (ME) – the arithmetic average of all residuals, which provides an indication of bias
- Mean Absolute Error (MAE) – the arithmetic average of the absolute value of the residuals, which provides a better indication of the average magnitude of residual error than the ME
- Root Mean Squared Error (RMSE) – the square root of the average of the squares of the residuals (also conceptualized as generalized standard deviation), which provides a useful measure of the variability of the error by adding statistical weight to larger errors
- Standard Deviation (SD) – the arithmetic standard deviation of all residuals, providing a measure of the spread, or magnitude, of residual errors
- Minimum Residual – the lowest residual (negative), indicating the largest difference between the simulated and observed values, where the model value is too high
- Maximum Residual – the highest residual (positive), indicating the largest difference between the simulated and observed values, where the model value is too low
- Total Number of Observations – a count of the number of observations available for model calibration
- Range in Observations – the difference between the highest and lowest observed head in the aquifer, which provides a measure of the total hydraulic gradient across the model domain
- Scaled MAE – MAE as a percent of the total range in head or baseflow, which provides a measure of how well the model simulates the total hydraulic gradient and the variation in stream baseflow across the model domain
- Scaled RMSE – RMSE as a percent of the total range in head or baseflow, which provides additional weighting to larger residuals when estimating how well the model simulates the total hydraulic gradient and the variation in stream baseflow across the model domain

When the ratio of the MAE to the range of observed head values in the system is small, discrepancies between simulated and observed values comprise only a small part of the overall simulated model response (Anderson and Woessner, 1992). One of the goals of the quantitative calibration was that the MAE and RMSE of the head residuals should be less than 2 percent of the total head change across the model for any given calibration period (Scaled MAE or RMSE). As total head change across the model is 2,696 ft, the MAE and RMSE should be less than 54 ft.

Similarly, the MAE of the baseflow residuals should be a small percentage of the total range in baseflow; a goal of 5 percent was set for the scaled baseflow MAE as well as the scaled baseflow RMSE. The goals for the baseflow residuals are slightly higher than the goals for the head residuals because of the large variability in observed baseflow values for individual gages and the range in observations overall, from a low of 0 cfs to a high of 3,438 cfs. Statistics for each of the main river systems were calculated, and a close review of key baseflow hydrographs was performed for the Niobrara, Elkhorn and Loup Rivers at the gages representing baseflow out of the model near the eastern boundary.

Throughout the calibration process, the numerical minimization of residuals was balanced with the overarching qualitative goal of achieving a reasonable representation of the flow regime and the interactions between surface water and groundwater.

## 6.2 Adjustments to Model Parameters/Inputs during Calibration

### 6.2.1 CropSim – Iterative Calibration Process

Agricultural pumping and recharge (excluding canal recharge) were prescribed model inputs based on CropSim (Section 4.4). Because CropSim simulates all processes related to precipitation, runoff, infiltration, crop water use, and aquifer recharge for agricultural as well as rangeland and undeveloped land use types, revisions or adjustments to any input resulted in a complete revision of pumping and recharge inputs for the CENEB model. This holistic approach to the development of pumping and recharge inputs also ensured that the two most important prescribed model inputs were always in balance.

The initial CropSim-generated pumping and recharge were imported into the CENEB model and evaluated to identify areas needing improvement, and then a new CropSim run was performed. This iterative process was repeated four times during the CENEB model calibration; changes made to CropSim included variations in input parameters and general model improvements, as described in Table 6-1.

**Table 6-1. CropSim Versions used in the CENEB Calibration Process**

| CropSim Version | Revisions (versus Original Version) | Author | Notes |
|---|---|---|---|
| Run001 | Original version | NDNR | Initial run utilizing the original version of the RSWB Suite and general irrigation practice and coefficient zone assumptions |
| Run002a | Code Improvement | The Flatwater Group | Employed an updated version of the RSWB that included improvements to the calculation of ET gain. The new version also decreased run time and discretized intermediate output data. No intentional changes were made to the recharge–only those changes incidental to code revision. |
| Run003 | Parameters<br>Reorganization | The Flatwater Group | Global but minor adjustments targeted at groundwater model calibration; reorganized the output files as follows: 1940-1985 annual, 1985-1999 monthly, and 2000-2010 monthly |
| Run004 | Parameters<br>Model Improvement | The Flatwater Group | Reprocessing of the distributed CropSim data. Additional weather stations were added to fill in spatial gaps. Malfunctioning weather station were removed when apparent. Actual weather data was used to produce the CropSim data for the years 1940-1949 as opposed to copying the information available in 1950. The model was also extended through 2011. The predevelopment CropSim results were created using a conglomerate of the weather from each station in its median precipitation year (1951-2011). |

### 6.2.2 Stream-Flow Routing Parameters

Streams were represented in the model using the SFR2 package, which allows simulation of both stream baseflows and groundwater-surface water interactions. Flow across the streambed is simulated using a form of Darcy's law that is defined by the following equation:

$$Q = \frac{K * L * W}{D}(h_s - h_a)$$

where *Q* is volumetric flow between the stream and the aquifer ($ft^3/d$), *K* is the hydraulic conductivity of the streambed sediments (ft/day), *L* is stream length (ft/day), *W* is stream width (ft), *D is* streambed thickness (ft), $h_s$ is head in the stream (ft), and $h_a$ is head in the aquifer (ft) (Prudic et al., 2004).

Early versions of the CENEB model underestimated baseflows along certain stream lengths. To increase simulated baseflows, variables comprising the conductance term (*K L W / D*) were adjusted; however, baseflow exhibited very little sensitivity to conductance parameters.

Initial stream bottom elevations were assigned using the minimum 10-meter DEM elevation value that occurred within a model grid cell (1 mile x 1 mile). A decrease of 15 ft or less was considered an acceptable adjustment to account for error in stream bottom elevation, given that DEM minima may not accurately capture actual streambed elevation within a 1-square-mile model cell. To improve simulated stream baseflow conditions, stream bottom elevations were decreased by between 5 ft and 12 ft in the following basins: the Snake River (7 ft), Gordon Creek (7 ft), Schlagel Creek (7 ft), Fairfield Creek (5 ft), Plum Creek (5 ft), Dutch Creek (5 ft), Long Pine Creek (7 ft), Short Pine Creek (7 ft), Bone Creek (7 ft), the Middle Loup River above the confluence with the Dismal River (8 ft), the Dismal River (12 ft), Wild Horse Creek (12 ft), and the Calamus River (10 ft).

### 6.2.3 Specific Yield and Specific Storage

Specific yield ($S_y$) values from the ELM Phase II model were imported into the CENEB model. In the expansion area, $S_y$ was initially defined based on nearby values from the ELM Phase II with the lowest values assigned to the outcrops of the Pierre Shale. $S_y$ was adjusted in the expansion area during initial model construction; this parameter was not adjusted during model calibration.

Specific Storage ($S_s$) values from the ELM were not transferred to the CENEB model because of the approach MODFLOW-NWT uses when simulated heads are above ground surface. Specifically, when using the Layer Property Flow Package in MODFLOW-NWT, the code implements a storage formulation using $S_s$ whenever the top layer is defined as convertible and simulated heads are higher than ground surface. Under this condition, $S_s$ is multiplied by cell thickness as part of the solution used to simulate internal groundwater flow (Harbaugh, 2005).

Groundwater levels simulated near or slightly above the ground surface in the CENEB model represent areas where the groundwater table is near the surface and where discharge to local surface water is occurring. Flooded areas simulated with the model are assumed to be within the general error of the model. Since a simulated water table above ground surface in the CENEB model does not represent confined flow conditions, the $S_s$ parameter was assigned a value that returned $S_y$ whenever the water table was simulated above land surface. This was achieved by assigning $S_s$ values equal to the $S_y$ divided by aquifer thickness at each respective cell. Adjustments to $S_s$ result in the same groundwater flow solution under both flooded cell and water table condition scenarios.

### 6.2.4 Canal Recharge

Canal recharge rates from the ELM Phase II model were used as a starting point for simulating canal losses to groundwater, except for leakage from the AID laterals; initial estimates of AID lateral recharge were based on the assumption that 35 percent of total diversions would be lost to seepage over the simulation time period. Adjustments to AID canal recharge were made during calibration, resulting in an overall increase in lateral canal recharge equivalent to approximately 43 percent of total diversions. The adjusted rates produced results in the groundwater model consistent with historical observed head and baseflow responses.

## 6.3 Water Level Targets

The complete database of water levels for the CENEB model domain consists of 232,695 water levels for 7,922 wells, spanning the time period from 1905 to 2011. Well locations in the model domain are shown on Figure 6-1. This large dataset was heavily concentrated in the eastern portion of the model, where clusters of observation points could greatly bias the calibration statistics. It was recognized that changes in the residual statistics would be relatively minor if this entire dataset were used for calibration, even for significant changes in model inputs. A smaller subset of this database was deemed more desirable for the purpose of providing meaningful calibration targets and residuals.

The selection of water level targets for the CENEB model calibration included three steps:

- Identification and selection of steady-state targets
- Identification and selection of specific years with adequate spatial coverage to minimize bias
- Selection of wells with long-term hydrograph datasets

### 6.3.1 Steady-State Water Level Targets

Relatively few water levels were available for the pre-1940 period in the CENEB model domain, particularly in South Dakota; however, given the relatively undeveloped nature of the land within the model domain and the stability of the groundwater flow system over time, it was deemed appropriate to utilize water level measurements from later years as representative targets to calibrate the pre-1940 steady-state simulation.

The steady-state water level targets for the CENEB model include water level data from 1905 through 1940 in the Nebraska portion of the model. The earliest water level measurement in the database for the South Dakota portion of the model was in 1953; select data through 1960 were used to represent steady-state conditions to supplement coverage in this region.

Initially, the number of targets for the steady-state time period totaled 472 records. The number of targets was reduced to eliminate data clusters via a GIS-based analysis: wells with similar water levels that were in close proximity to each other were thinned, and multiple measurements for a single location were reduced to a single target that was representative of the pre-1940 time period. Professional judgment was used to select wells and measurements to be used in the final steady-state water level target dataset, shown on Figure 6-2; a total of 121 targets were used in the steady-state CENEB model calibration (Table 6-2).

| Table 6-2. Summary of Water Level Targets – CENEB Model | | | | |
|---|---|---|---|---|
| Year | Simulation | Stress Periods | Time Step | Number of Targets |
| Pre-1940 | Steady State | 1 | 1 | 121 |
| 1946 | Transient | 8 | 10 | 195 |
| 1964 | Transient | 26 | 10 | 440 |
| 1976 | Transient | 38 | 10 | 1,042 |
| 1985 | Transient | 47 | 10 | 1,091 |
| 2000 | Transient | 216-227 | 3 | 978 |
| 2011 | Transient | 348-359 | 3 | 868 |
| Sub-Total | | | | 4,735 |
| Long-Term Water Level Hydrographs | Steady-State and Transient | Multiple | | 21,508 |
| TOTAL TARGETS[1] | | | | 24,140 |

*[1]Total number of targets in the long-term hydrographs is 21,508; of these, 2,103 are included in the steady-state or specific year counts.*

### 6.3.2 Transient Water Level Targets for Specific Years

A summary of the total number of water level observations for each year in the model simulation was reviewed as the first step in the selection of transient water level targets. To assess the spatial distribution of these potential targets the model domain was divided into 12 zones based on latitude, longitude, and the Nebraska-South Dakota state line (Figure 6-3), and the number of potential targets per zone was summed for each year of the model timeline. Based on this analysis, the first year with adequate spatial coverage in all zones was 1946. The spatial distribution of targets improved and the number of potential targets increased substantially in the late 1970s, and 5 additional years were added to the transient calibration target dataset, as shown in Table 6-2. The optimal time between these calibration periods was defined as approximately 10 years; however, a longer time span was acceptable for earlier time periods as the datasets were more limited prior to the 1970s. Including the pre-1940 period, seven specific calibration periods were identified (Table 6-2).

For each year, the water level target dataset was reviewed according to specific guidelines (listed below) and professional judgment, and the dataset was thinned to remove bias. The approach to data reduction took into account that the CENEB model simulates annual stress periods through 1985, then monthly stress periods from 1986 through 2011. Guidelines included the following:

- In all cases, the goal for the spatial distribution of water level targets was one well per township, selecting wells close to the center of the township.
- For annual stress periods and wells with multiple measurements during a single year, water levels from October, November, or May, in that order, were preferred, as those time periods were considered to be more representative of an annualized water level and less influenced by seasonal pumping stresses. Only one record was used for each year.
- For monthly stress periods, wells with monthly or quarterly water levels were preferred in order to capture seasonality. Multiple measurements in a single month were reduced to a single target by using the measurement closest to the month end.

This approach resulted in a spatial and temporal distribution of water level targets that provided meaningful statistical measures of calibration.

### 6.3.3 Long-Term Hydrographs

To fully assess the model's ability to capture trends and assess seasonal changes in groundwater conditions, a total of 43 wells with long-term water level measurements were added to the target dataset. Two to three wells within each of the 12 zones were selected for long-term hydrograph targets based on well location, period of record, and trends in the individual hydrographs. The locations of the 43 wells used for long-term hydrograph calibration are presented on Figure 6-3. The total number of calibration targets from these hydrographs is 21,508 (Table 6-2).

## 6.4 Baseflow Targets

Estimates of the groundwater contribution to streamflow (baseflow) over time were assembled for the 74 gage points listed in Table 6-3 with the spatial distribution shown on Figure 6-4.

Numerous methods exist for estimating baseflow in a river or stream, all relying on various assumptions, quantity of data, and quality of data. The approach used for developing the baseflow values for the CENEB project involved a multi-step process that included: 1) obtaining data from USGS and NDNR sources for stream gages with significant periods of record throughout the Niobrara, Loup, and Elkhorn River Basins (see Section 2.6); 2) adjusting gage records to account for the impact of canal diversions where applicable in the Loup River Basin; 3) applying an automated, one-parameter digital filter to the daily gage records; and 4) aggregating these values as appropriate for the steady-state, annual, and monthly model stress periods.

Daily stream gage data for the available period of record within the range from 1890 to 2011 were downloaded from the USGS National Water Information System web server and the NDNR internal gage databases. The data download was limited to those gages within the CENEB model boundary but outside of the Platte River watershed boundary. Gage data for canal systems that divert water from CENEB area rivers outside the Platte River were also downloaded. A list of canal gage stations used is provided in Table 6-4.

Baseflow separation methods presume a full, natural hydrograph for proper application. In portions of the Loup River Basin, water is diverted from channels during the irrigation season to supply canals and reservoirs, modifying the natural flow that normally would have reached downstream gages. To account for this, the daily canal diversion records were added to the daily gage records at stations downstream of canal diversions to restore the in-channel flow budget according to the following:

$$Natural\ Hydrograph\ (Q_{nat}) = Gage\ Flow\ \left(q_{gage}\right) + Canal\ Diversions - Canal\ Returns$$

In the Loup River Basin, canal systems generally have minimal returns (i.e., spills of flowing water from the end of a canal back into a river or stream) and thus gage data for use in the mass balance equation above were sparse or non-existent.

**Table 6-3. USGS Stream Gages Used as Baseflow Target Locations – CENEB Model**

| Gage ID | Name | Period of Record | | Number of Observations |
|---|---|---|---|---|
| | | Start | End | |
| 6453500 | Ponca Creek At Anoka | Dec-1950 | Sep-1994 | 141 |
| 6453550 | Ponca Creek At Lynch | Dec-1961 | Dec-1964 | 4 |
| 6453600 | Ponca Creek At Verdel | Dec-1958 | Oct-2011 | 339 |
| 6458500 | Bear Creek Near Eli | Dec-1948 | Dec-1953 | 6 |
| 6459000 | Niobrara River Near Cody | Dec-1948 | Dec-1957 | 10 |
| 6459175 | Snake River At Doughboy | Dec-1982 | Nov-2011 | 316 |
| 6459200 | Snake River Above Merritt Reservoir | Dec-1963 | Dec-1981 | 19 |
| 6459500 | Snake River Near Burge | Dec-1947 | Nov-2011 | 329 |

| Table 6-3. USGS Stream Gages Used as Baseflow Target Locations – CENEB Model | | | | |
|---|---|---|---|---|
| Gage ID | Name | Period of Record | | Number of Observations |
| 6460900 | Minnechaduza Creek Near Kilgore | Dec-1958 | Dec-1974 | 17 |
| 6461000 | Minnechaduza Creek At Valentine | Dec-1948 | Sep-1994 | 143 |
| 6461500 | Niobrara River Near Sparks | Dec-1946 | Nov-2011 | 352 |
| 6462000 | Niobrara River Near Norden | Dec-1953 | Sep-1986 | 40 |
| 6462500 | Plum Creek At Meadville | Dec-1948 | Sep-1994 | 142 |
| 6463080 | Long Pine Creek Near Long Pine | Dec-1980 | Mar-1991 | 69 |
| 6463500 | Long Pine Creek Near Riverview | Dec-1948 | Nov-2011 | 349 |
| 6463720 | Niobrara River At Mariaville | Jan-1986 | Sep-1991 | 69 |
| 6464100 | Keya Paha R Near Keyapaha | Jan-1986 | Oct-2011 | 311 |
| 6464500 | Keya Paha R At Wewela | Jan-1986 | Oct-2011 | 311 |
| 6464900 | Keya Paha River Near Naper | Dec-1958 | Nov-2011 | 340 |
| 6465000 | Niobrara River Near Spencer | Dec-1941 | Aug-2001 | 234 |
| 6465310 | Eagle Creek Near Redbird | Dec-1979 | Oct-1991 | 77 |
| 6465440 | Redbird Creek At Redbird | Dec-1981 | Sep-1994 | 110 |
| 6465500 | Niobrara River Near Verdel | Dec-1959 | Oct-2011 | 338 |
| 6465680 | North Branch Verdigre Creek Near Verdigre | Dec-1980 | Sep-1992 | 86 |
| 6465700 | Verdigre Creek Near Verdigre | Apr-2002 | Oct-2011 | 115 |
| 6466400 | Bazile Creek At Center | Sep-2002 | Oct-2011 | 98 |
| 6466500 | Bazile Creek Near Niobrara | Jan-1986 | Oct-2011 | 227 |
| 6775000 | Middle Loup River At Seneca | Dec-1948 | Dec-1953 | 6 |
| 6775500 | Middle Loup River At Dunning | Dec-1946 | Nov-2011 | 352 |
| 6775900 | Dismal River Near Thedford | Dec-1967 | Nov-2011 | 331 |
| 6776000 | Dismal River Near Gem Nebr | Dec-1947 | Dec-1953 | 7 |
| 6776500 | Dismal River At Dunning | Dec-1946 | Sep-1995 | 157 |
| 6777000 | Middle Loup River Near Milburn | Dec-1952 | Dec-1964 | 10 |
| 6777500 | Middle Loup River At Walworth | Dec-1941 | Dec-1960 | 20 |
| 6778000 | Middle Loup River At Sargent | Dec-1957 | Dec-1969 | 13 |
| 6779000 | Middle Loup River At Arcadia | Dec-1962 | Sep-1994 | 129 |
| 6780000 | Middle Loup River At Rockville | Dec-1962 | Dec-1975 | 10 |
| 6782000 | South Loup River Near Cumro | Dec-1946 | Dec-1953 | 8 |
| 6782500 | South Loup River At Ravenna | Dec-1941 | Dec-1975 | 26 |
| 6783000 | Mud Creek Near Broken Bow | Dec-1950 | Dec-1953 | 4 |
| 6783500 | Mud Creek Near Sweetwater | Dec-1947 | Nov-2011 | 351 |
| 6784000 | South Loup River At Saint Michael | Dec-1944 | Oct-2011 | 353 |
| 6784300 | Oak Creek Near Loup City | Dec-1953 | Dec-1964 | 11 |
| 6784500 | Oak Creek Near Dannebrog | Dec-1950 | Dec-1957 | 8 |
| 6784800 | Turkey Creek Near Dannebrog | Dec-1966 | Nov-2011 | 324 |
| 6785000 | Middle Loup River At Saint Paul | Dec-1962 | Oct-2011 | 335 |
| 6785500 | North Loup River At Brewster | Dec-1946 | Dec-1951 | 6 |
| 6786000 | North Loup River At Taylor | Dec-1947 | Nov-2011 | 351 |
| 6787000 | Calamus River Near Harrop | Dec-1978 | Aug-1997 | 149 |
| 6787500 | Calamus River Near Burwell | Dec-1941 | Dec-1985 | 45 |
| 6788500 | North Loup River At Ord | Dec-1952 | Nov-2011 | 346 |
| 6788988 | Mira Creek Near North Loup | Dec-1980 | Nov-2011 | 318 |
| 6789000 | North Loup River At Scotia | Dec-1947 | Dec-1969 | 23 |

| Table 6-3. USGS Stream Gages Used as Baseflow Target Locations – CENEB Model | | | | |
|---|---|---|---|---|
| Gage ID | Name | Period of Record | | Number of Observations |
| 6789500 | Davis Creek Near Cotesfield | Dec-1949 | Dec-1958 | 10 |
| 6790500 | North Loup River Near Saint Paul | Dec-1947 | Nov-2011 | 351 |
| 6791000 | Spring Creek At Cushing | Dec-1949 | Dec-1953 | 5 |
| 6791500 | Cedar River Near Spalding | Dec-1945 | Nov-2011 | 349 |
| 6791750 | Cedar River At Primrose | Dec-1960 | Dec-1964 | 5 |
| 6791800 | Cedar River At Belgrade | Dec-1960 | Dec-1965 | 6 |
| 6792000 | Cedar River Near Fullerton | Dec-1941 | Nov-2011 | 357 |
| 6792500 | Loup River Power Canal Near Genoa[1] | Dec-1943 | Oct-2011 | 354 |
| 6793500 | Beaver Creek At Loretto | Dec-1945 | Nov-2011 | 327 |
| 6794000 | Beaver Creek At Genoa | Dec-1941 | Oct-2011 | 356 |
| 6796973 | Elkhorn River Near Atkinson | Dec-1983 | Nov-2011 | 315 |
| 6796978 | Holt Creek Near Emmet | Dec-1979 | Sep-1989 | 52 |
| 6796985 | Elkhorn River At Emmet | Dec-1980 | Dec-1982 | 3 |
| 6797500 | Elkhorn River At Ewing | Dec-1948 | Oct-2011 | 349 |
| 6798000 | South Fork Elkhorn River Near Ewing | Dec-1948 | Nov-2011 | 326 |
| 6798300 | Clearwater Creek Near Clearwater | Dec-1962 | Sep-1991 | 80 |
| 6798500 | Elkhorn River At Neligh | Dec-1940 | Nov-2011 | 356 |
| 6798800 | Elkhorn River At Meadow Grove | Dec-1961 | Dec-1965 | 5 |
| 6799000 | Elkhorn River At Norfolk | Dec-1946 | Oct-2011 | 351 |
| 6799080 | Willow Creek Near Foster | Dec-1976 | Nov-2011 | 322 |
| 6799100 | North Fork Elkhorn River Near Pierce | Dec-1961 | Nov-2011 | 337 |
| | TOTAL | Dec-1950 | Nov-2011 | 12,901 |

*[1]Stream gage records for 6792500 and 6793000 were combined to develop a record for this location.*

| Table 6-4. NDNR Canal Gages Used to Adjust Baseflow Target Time Series – CENEB Model | | | |
|---|---|---|---|
| Gage ID | Name | Period of Record | |
| | | Start | End |
| 1000 | Ainsworth Canal from Snake River And Merritt Reservoir (15-Foot Parshall Flume) | 6/1/1965 | Present |
| 100500 | Mirdan Canal from Calamus Reservoir | 4/1/1987 | Present |
| 107000 | Taylor-Ord Canal from North Loup River (Rating Flume) | 5/1/1947 | Present |
| 108000 | Burwell-Sumter Canal from North Loup River (Rating Flume) | 5/1/1947 | Present |
| 76500 | Kent Canal from North Loup River | 4/1/1995 | Present |
| 130000 | Sargent Canal from Middle Loup River (10-Foot Parshall Flume) | 4/1/1957 | Present |
| 90000 | Middle Loup Canal No. 1 from Middle Loup River (Rating Flume) | 1/1/1950 | Present |
| 91000 | Middle Loup Canal No. 2 from Middle Loup River (Rating Flume) | 5/1/1947 | Present |
| 90200 | Middle Loup Canal No.1 Pump from Middle Loup River | 5/1/1987 | Present |
| 109000 | Ord-North Loup Canal from North Loup River (Rating Flume) | 5/1/1947 | Present |

| Table 6-4. NDNR Canal Gages Used to Adjust Baseflow Target Time Series – CENEB Model | | | |
|---|---|---|---|
| Gage ID | Name | Period of Record | |
| | | Start | End |
| 47000 | Farwell (Sherman Feeder) Canal from Middle Loup River (25-Foot Parshall Flume) | 11/1/1962 | Present |
| 93000 | Middle Loup Canal No. 4 from Middle Loup River (Rating Flume) | 5/1/1947 | Present |
| 92000 | Middle Loup Canal No. 3 from Middle Loup River (Rating Flume) | 5/1/1947 | Present |

An automated filter was chosen to separate runoff and baseflow components of daily streamflow because of the number of gages to be analyzed and the long periods of record. A one-parameter digital filter was used, in a process consistent with the Web-Based Hydrograph Analysis Tool hosted by Purdue University (https://engineering.purdue.edu/~what/) (Lyne and Hollick, 1979; Nathan and McMahon, 1990; Arnold and Allen, 1999).

The equation for the filtering algorithm is:

$$q_k = a * q_{k-1} + \frac{(1+a)}{2} * (y_k - y_{k-1})$$

*where*:

$\boldsymbol{q}_{\boldsymbol{k}}$ *is the direct runoff at time step* $k$;

$\boldsymbol{q}_{\boldsymbol{k-1}}$ *is the direct runoff at time step* $k-1$;

$\boldsymbol{y}_{\boldsymbol{k}}$ *is the total streamflow at time step* $k$;

$\boldsymbol{y}_{\boldsymbol{k-1}}$ *is the total streamflow at time step* $k-1$;

$\boldsymbol{a}$ *is the filter parameter*

This equation was incorporated into an automated process written using Python (version 3.2) to create a dataset with daily values of runoff and baseflow.

The daily baseflow values were aggregated to long-term, yearly, and monthly values to create a time series appropriate for the steady-state, annual, and monthly stress periods that are simulated with the model. Steady-state baseflow targets were calculated as the long-term median of the daily separated baseflow values for representative periods. These representative periods were chosen manually based on known changes to gages or system hydrology (e.g., reservoir construction) and visual inspection of long-term hydrographs. Annual and monthly baseflow values were calculated as the median of daily separated baseflow values for that time period. A description and factors considered relative to the estimated baseflow record at each gage are provided in Table 6-5.

| Table 6-5. USGS Stream Gage Descriptions | | |
|---|---|---|
| Gage ID | Name | Notes |
| 6453500 | Ponca Creek At Anoka | Upstream gage on tributary to Missouri River; zeros in target indicate dry conditions, not missing data |
| 6453550 | Ponca Creek At Lynch | Middle gage on tributary to Missouri River; very short record |
| 6453600 | Ponca Creek At Verdel | Downstream gage on tributary to Missouri River, near confluence |

| Table 6-5. USGS Stream Gage Descriptions | | |
|---|---|---|
| Gage ID | Name | Notes |
| 6458500 | Bear Creek Near Eli | Gage on tributary to Niobrara River; short record but continuous |
| 6459000 | Niobrara River Near Cody | Gage on Snake River between upstream confluence with Bear Creek and downstream confluence with Medicine Creek; short record but continuous |
| 6459175 | Snake River At Doughboy | Most upstream gage on the Snake River, above and unaffected by Merritt Reservoir |
| 6459200 | Snake River Above Merritt Reservoir | Gage at inlet to Merritt Reservoir, which started operations in 1964 |
| 6459500 | Snake River Near Burge | Gage below Merritt Reserovoir with split record (null data for 1964-1985); pre-1964 data is unaffected by Reservoir operations; post-1964 record reflects releases and diversions and is not a valid indicator of natural stream or baseflow |
| 6460900 | Minnechaduza Creek Near Kilgore | Upstream gage on tributary to Niobrara River; between South Dakota border and confluence with Spring Creek; short record but continuous |
| 6461000 | Minnechaduza Creek At Valentine | Downstream gage on tributary near confluence with Niobrara River |
| 6461500 | Niobrara River Near Sparks | Gage on Niobrara River downstream of Crooked Creek in northeast Cherry County |
| 6462000 | Niobrara River Near Norden | Gage on Niobrara River just downstream from Fairfield Creek on southwest border of Keya Paha County; short record but continuous |
| 6462500 | Plum Creek At Meadville | Gage on tributary to Niobrara River, near confluence |
| 6463080 | Long Pine Creek Near Long Pine | Upstream gage on south-side tributary to Niobrara River; at eastern edge of Ainsworth Irrigation district and affected by excess recahrge from applied irrigation water |
| 6463500 | Long Pine Creek Near Riverview | Downstream gage on south-side tributary to Niobrara River, near confluence; at eastern edge of Ainsworth Irrigation district and affected by excess recahrge from applied irrigation water (started in 1964) |
| 6463720 | Niobrara River At Mariaville | Middle gage on Niobrara River, at lower end of National Scenic River area; short record |
| 6464100 | Keya Paha R Near Keyapaha | Downstream gage on tributary to Niobrara, north of border with South Dakota |
| 6464500 | Keya Paha R At Wewela | Upstream gage on tributary to Niobrara, north of border with South Dakota |
| 6464900 | Keya Paha River Near Naper | Downstream gage on tributary to Niobrara River, near confluence |
| 6465000 | Niobrara River Near Spencer | Gage on Niobrara River just above the Spencer Hydropower dam |
| 6465310 | Eagle Creek Near Redbird | Gage on tributary to Niobrara River, near confluence; short record but continuous |
| 6465440 | Redbird Creek At Redbird | Gage on tributary to Niobrara River, near confluence; short record but continuous |
| 6465500 | Niobrara River Near Verdel | Gage on Niobrara River downstream from confluence with Steel Creek and upstream of confluence with Pishel Creek |
| 6465680 | North Branch Verdigre Creek Near Verdigre | Gage on tributary to Verdigree Creek, just prior to confluence with Schindler Creek; short record but continuous |
| 6465700 | Verdigre Creek Near Verdigre | Gage on tributary to Niobrara Creek, near confluence; short record but continuous |
| 6466400 | Bazile Creek At Center | Upstream gage on Bazile Creek; null data for 10/1/2004 through 9/30/2005; Nov-Dec 2011 gage data was estimated and provisional at time of baseflow target processing |
| 6466500 | Bazile Creek Near Niobrara | Downstream gage on Bazile Creek; Null data from 10/1/1995 through 9/30/2002 when gage was not operated by USGS; Nov-Dec 2011 gage data was estimated and provisional at time of baseflow target processing - excluded from dataset |
| 6775000 | Middle Loup River At Seneca | Most upstream gage on Middle Loup River; short, early record |

**Table 6-5. USGS Stream Gage Descriptions**

| Gage ID | Name | Notes |
|---|---|---|
| 6775500 | Middle Loup River At Dunning | Last gage on Middle Loup River prior to confluence of Dismal River; long-term, continuous record |
| 6775900 | Dismal River Near Thedford | Most upstream long-term gage on Dismal River |
| 6776000 | Dismal River Near Gem Nebr | Middle gage on Dismal River; short record |
| 6776500 | Dismal River At Dunning | Final gage on Dismal River before joining Middle Loup River; continuous record |
| 6777000 | Middle Loup River Near Milburn | First gage downstream of confluence of Dismal River and Middle Loup River; short record but unaffected by canal diversions |
| 6777500 | Middle Loup River At Walworth | Affected by Sargent Canal Diversion starting in 1957; only 3 months of gage data were recorded for 1940 and so was excluded from the targets |
| 6778000 | Middle Loup River At Sargent | Calibration dataset limited to 1957-1969 time period as this is the extent of gaged diversions for the Sargent Canal that affect the flow at the Sargent gage on the Middle Loup River; only 1 month of gage record exist for 1970, so that year was not included in the calculation of an annual target |
| 6779000 | Middle Loup River At Arcadia | First main gage downstream of Middle Loup diversions; affected by diversions at Middle Loup Canals 1-4 and Farwell (Sherman Feeder) Canal |
| 6780000 | Middle Loup River At Rockville | Most downstream gage on Middle Loup River, affected by all Middle Loup diversions (same as Arcadia gage); missing/null data for 10/1/1964 through 9/30/1967 - annual targets for years 1964-1967 should be removed from calibration set |
| 6782000 | South Loup River Near Cumro | Most upstream gage on South Loup River; short, early record |
| 6782500 | South Loup River At Ravenna | Middle gage on South Loup River, final gage upstream of confluence with Mud Creek; missing/null data for 10/1/1958 through 9/30/1967 - annual targets for years 1964-1967 removed from calibration set |
| 6783000 | Mud Creek Near Broken Bow | Most upstream gage on Mud Creek, tributary to the South Loup River; short, early record |
| 6783500 | Mud Creek Near Sweetwater | Most downstream gage on Mud Creek, above confluence with South Loup River; long-term record with gage maintenance split between USGS (1946-1994) and NDNR (1994-present); zeros in baseflow data indicate dry river not null value; direct diversions of surface water may cause local and/or short term perturbations to natural flow - these are not accounted for in the baseflow targets |
| 6784000 | South Loup River At Saint Michael | Most downstream gage on the South Loup River, above confluence with Middle Loup; continuous record |
| 6784300 | Oak Creek Near Loup City | Downstream of Sherman Reservoir (operation started 1962-63); small tributary expected to have little/no baseflow until effects of reservoir recharge in mid-1960s; model should simulate as dry |
| 6784500 | Oak Creek Near Dannebrog | Most downstream gage on Oak Creek, a tributary to Middle Loup River; bisects Loup Basin Reclamation District (Farwell Main, Central, and South Canals); record too early and short to show effects of irrigation districts recharge |
| 6784800 | Turkey Creek Near Dannebrog | Most downstream gage on Turkey Creek, a tributary to Middle Loup River; bisects Loup Basin Reclamation District (Farwell Main, Central, and South Canals); long-term gage maintenance split between USGS (1966-1994) and NDNR (1994-present) with no record for 10/1/1970-9/30/1978; shows effects of excess recharge from irrigation districts that started operations in the mid-1960s |
| 6785000 | Middle Loup River At Saint Paul | Most downstream gage on the Middle Loup River, above confluence with the North Loup; long-term, continuous record; affected by all irrigation district canal diversions along the Middle Loup (as at Arcadia) |
| 6785500 | North Loup River At Brewster | Most upstream gage on North Loup system; split record with early years and more recent 2010-present; only North Loup gage unaffected by canal |

| Table 6-5. USGS Stream Gage Descriptions | | |
|---|---|---|
| Gage ID | Name | Notes |
| | | diversions |
| 6786000 | North Loup River At Taylor | Long-term, continuous record; affected by the Taylor-Ord diversion starting in 1947 and continuing through present |
| 6787000 | Calamus River Near Harrop | Most upstream gage on the Calamus River, above Calamus Reservoir; gage record split between USGS (1978-1997) and NDNR (1998-2004); NDNR data not used as it was under review at the time of target development; unaffected by canal diversions |
| 6787500 | Calamus River Near Burwell | Downstream gage on Calamus River, downstream of Reservoir and the Mirdan Diversion; gage record split between USGS (1940-1995) and NDNR (1995-2004); NDNR data not used due to internal review at the time of target development; affected by Mirdan Canal diversion and the Calamus Reservoir, both starting operations in 1987 |
| 6788500 | North Loup River At Ord | First gage downstream of confluence of Calamus River with North Loup; gage record split between USGS (1952-1994) and NDNR (1994-present); affected by Taylor-Ord, Kent, and Mirdan canal diversions |
| 6788988 | Mira Creek Near North Loup | Only gage on tributary to North Loup River; no irrigation district canals diverted off this channel but affected by excess recharge from applied irrigation water on Twin Loups Reclamation District and North Loup PP&I District that surround it; record split between USGS (1979-1994) and NDNR (1994-2004); NDNR field office staff have observed increase in flow at this gage starting in the 1980s |
| 6789000 | North Loup River At Scotia | Downstream of Mira Creek confluence; affected by Ord-North Loup Diversion and all others upstream (as at Ord); record for 1970 is inomplete and thus excluded from annual target |
| 6789500 | Davis Creek Near Cotesfield | Small tributary to North Loup River with short, early record; expected effects from irrigation district activity should be minimal |
| 6790500 | North Loup River Near Saint Paul | Most downstream gage on North Loup River; long-term, continuous record; affected by all irrigation district canal diversion on the North Loup system |
| 6791000 | Spring Creek At Cushing | Tributary to the Loup River downstream of conflucence of North Loup and Middle Loup; direct diversions of surface water may cause local and/or short term perturbations to natural flow |
| 6791500 | Cedar River Near Spalding | Most upstream gage on Cedar River; a signifcant tributary to Loup River – long-term, continuous record |
| 6791750 | Cedar River At Primrose | Middle gage on Cedar River – short, early record |
| 6791800 | Cedar River At Belgrade | Middle gage on Cedar River – short, early record |
| 6792000 | Cedar River Near Fullerton | Most downstream gage on the Cedar River; a signifcant tributary to Loup River – long-term, continuous record |
| 6792500<br>6793000 | Loup River Power Canal Near Genoa<br>Loup River Near Genoa | These gages were used to build the natural flow hydrograph on the Loup River near Genoa; the record used in the target is the sum of the power canal diversions and the remaining channel flow |
| 6793500 | Beaver Creek At Loretto | Beaver Creek is the most downstream major tributary to the Loup River above Columbus; Upstream gage with no gage record for 1954-1981 |
| 6794000 | Beaver Creek At Genoa | Beaver Creek is the most downstream major tributary to the Loup River above Columbus; downstream gage with long-term, continuous record |
| 6796973 | Elkhorn River Near Atkinson | Upstream gage on Elkhorn River |
| 6796978 | Holt Creek Near Emmet | Gage on tributary to Elkhorn River – short record |
| 6796985 | Elkhorn River At Emmet | Middle gage on Elkhorn River – very short record |
| 6797500 | Elkhorn River At Ewing | Middle gage on Elkhorn River – long-term, continuous record |
| 6798000 | South Fork Elkhorn River Near Ewing | Gage on Tributary to Elkhorn River, near confluence |
| 6798300 | Clearwater Creek Near | Gage on Tributary to Elkhorn River, near and downsteam of confluence |

| Table 6-5. USGS Stream Gage Descriptions | | |
|---|---|---|
| Gage ID | Name | Notes |
| | Clearwater | with Snake Creek |
| 6798500 | Elkhorn River At Neligh | Gage on Elkhorn River, near and downstream of confluence with Antelope Creek |
| 6798800 | Elkhorn River At Meadow Grove | Gage on Elkhorn River, just upstream of confluence with Buffalo Creek; very short record |
| 6799000 | Elkhorn River At Norfolk | Gage on Elkhorn River near downstream confluence with North Fork Elkhorn River |
| 6799080 | Willow Creek Near Foster | Gage on tributary to North Fork Elkhorn River |
| 6799100 | North Fork Elkhorn River Near Pierce | Gage on tributary to Elkhorn River between confluences with Willow Creek and Hadar Creek |

## 6.5 Calibration Results – Qualitative

Prior to the calculation of calibration statistics, a qualitative review of the simulated flow regime was performed to assess the general flow system and to provide a subjective indication of the difference between simulated and field-measured (observed) heads.

### 6.5.1 Steady-State Flow Regime

The goal of the steady-state simulation was to approximate the general flow regime in order to provide reasonable initial conditions for transient runs. The simulated steady-state water level contours shown on Figure 6-5 capture the west-to-east groundwater flow pattern and the influence of the river systems on the pre-1940 groundwater flow regime. Simulated steady-state water levels range from a high of 3,982 ft amsl to a low of 1,201 ft amsl. An observed water level contour map for this pre-development time period is not available; however, a comparison of the simulated steady-state water level contours with observed 1979 and 1995 water level contours shown on Figure 4-2 indicates that the flow regime is fairly stable through time and that the model reasonably simulates observed groundwater flow conditions.

### 6.5.2 Transient Flow Regime

The simulated flow regime for 1995 is compared to observed 1995 water level contours developed by the Conservation and Survey Division (2003) on Figure 6-6. There is good agreement between the observed and calculated flow regime, with the exception of the region north of the Platte River, between the 2,800- and 3,200-ft water level contours. Model-simulated water levels are too low in this region, as shown by the gap between the simulated and observed water level contours. This slight bias is further discussed in the quantitative assessment of the model calibration (Section 6.6).

Observed versus simulated water level and baseflow hydrographs were reviewed to ensure that general trends through time are well reproduced by the model. The simulated trends are in close agreement with observed data (Appendices D and E), and the hydrographs indicate that the monthly stress periods (beginning in 1986) capture seasonal fluctuations.

### 6.5.3 Groundwater/Surface Water Interaction

The dominant process in the CENEB model is the interaction between groundwater and surface water. As indicated in Section 4, discharge from the aquifer to surface water when water levels in the aquifer are elevated is a key process to be simulated. A good calibration to observed water levels and the flow regime in the aquifer system was considered to be a key step in the calibration process, as this would be a significant factor in the model's ability to simulate groundwater/surface water interactions.

The aquifer is recharged by the surface water system in some locations; however, this component of the water budget is relatively minor. Figure 6-7 depicts gaining and losing reaches simulated with the CENEB model in December 2011.

# 6.6 Water Budgets

## 6.6.1 Steady-State Water Budget

The water budget for steady-state conditions (pre-1940) was compiled from the output of the calibrated CENEB model from Stress Period 1 and annualized in units of AFY. The total annualized water budget for pre-1940 is 4,736,821 AFY (Table 6-4). The predominant water budget component in the pre-1940 groundwater flow system is recharge to the aquifer, which is balanced by discharge to streams and ET. Groundwater pumping and boundary conditions are relatively insignificant budget components in the pre-development steady-state system.

**Table 6-4. CENEB Steady-State Water Budget**

| Water Budget Component | Steady-State (pre-1940) Annualized Budget (Acre-Feet Per Year) |
|---|---|
| IN | |
| Constant Head | 31,486 |
| Head Dependent Boundaries | 214,428 |
| Recharge | 4,274,627 |
| Stream Leakage | 216,280 |
| TOTAL IN | 4,736,821 |
| OUT | |
| Constant Head | 100,297 |
| Wells | 51,000 |
| Evapotranspiration | 1,937,493 |
| Head Dependent Boundaries | 27,364 |
| Stream Leakage | 2,620,666 |
| TOTAL OUT | 4,736,820 |
| IN minus OUT | 1 |
| % Difference | 0% |

Due to the uncertainty in many of the conceptual water budget estimates for the steady-state flow system, variations between individual budget components were deemed acceptable when comparing the CENEB steady-state water budgets (conceptual and simulated) and the ELM steady-state water budget (Table 6-5). However, because CENEB model parameters were in part based on the calibrated ELM model, significant variability was not anticipated.

| Table 6-5. Comparison of Conceptual versus Simulated Steady-State Water Budgets | | | |
|---|---|---|---|
| | CENEB Simulated Steady-State Water Budget (Acre-Feet/Year) | CENEB Conceptual Steady-State Water Budget (Acre-Feet/Year) | ELM II Steady-State Water Budget (Acre-Feet/Year) |
| IN | | | |
| Storage | -- | -- | 14 |
| Boundaries | 245,914 | 165,000 | 90,434 |
| Recharge | 4,274,627 | 4,401,000 | 4,009,476 |
| Stream Leakage | 216,280 | 137,000 | 94,430 |
| TOTAL | 4,736,821 | 4,703,000 | 4,194,354 |
| OUT | | | |
| Storage | -- | -- | 12,606 |
| Boundaries | 127,661 | 35,000 | 331,451 |
| Wells | 51,000 | 54,000 | -- |
| Evapotranspiration | 1,937,493 | 1,814,000 | 1,287,880 |
| Stream Leakage | 2,620,666 | 2,800,000 | 2,562,053 |
| TOTAL | 4,736,820 | 4,703,000 | 4,193,990 |
| COMPARISON OF NET BUDGET COMPONENTS | | | |
| Total IN minus OUT | 1 | 0 | 364 |
| Net Stream Leakage OUT | 2,404,386 | 2,663,000 | 2,467,623 |
| Net Boundaries IN (positive) OUT (negative) | 118,253 | 130,000 | -241,017 |

The increased size of the CENEB model domain and the incorporation of CropSim-generated pumping, recharge from precipitation, and agricultural recharge resulted in a redistribution of water between CENEB and ELM budget components, and a 13 percent increase in the total budget (Table 6-5).

The CENEB simulated steady-state water budget compares favorably to the conceptual steady-state water budget; the total difference between these budgets is 33,821 AFY, or 1 percent. The largest differences between the conceptual versus simulated budgets are for recharge, stream leakage, and ET. Recharge estimates for the conceptual steady-state budget were developed based on preliminary simulations using CropSim (Section 4.6.3). Due to refinements in the CropSim inputs during calibration, the difference between the conceptual and the final simulated recharge is approximately 126,000 AFY. Changes in the prescribed recharge inputs were largely balanced by discharge to streams and ET.

The net stream leakage (i.e., the difference between the inflow and outflow) and net inflow from boundary conditions are also compared in Table 6-5 and reflect very close agreement between the conceptual and simulated CENEB water budgets.

### 6.6.2 Transient Water Budget

The 2011 transient water budget was compiled from CENEB model output and is approximately 14,000,000 AFY (Table 6-6). This water budget represents the 2011 calendar year period and was calculated as the difference between the cumulative water budget at the end of 2011 versus the end of 2010.

The seasonal variability in recharge and agricultural pumping is evident when comparing the irrigation season versus non-irrigation season water budgets (Table 6-7). Recharge is highest during the wet season in June, drops to one-third the June levels by August, and is insignificant in December.

Groundwater pumping must offset months with lower rainfall thus is highest in August, and drops to zero in the off season (December).

**Table 6-6. CENEB 2011 Transient Water Budget**

| Water Budget Component | 2011 Transient Budget (Acre-Feet Per Year) |
|---|---|
| IN | |
| Storage | 3,659,320 |
| Constant Head | 32,657 |
| Head Dependent Boundaries | 204,711 |
| Recharge | 10,078,053 |
| Stream Leakage | 173,586 |
| TOTAL | 14,148,327 |
| OUT | |
| Storage | 6,391,185 |
| Constant Head | 125,789 |
| Wells | 1,315,427 |
| Evapotranspiration | 2,121,212 |
| Head Dependent Boundaries | 46,265 |
| Stream Leakage | 4,143,710 |
| TOTAL | 14,143,588 |
| IN minus OUT | 4,739 |
| % Difference | 0.03% |

**Table 6-7. Comparison of June, August, and December 2011 Water Budgets**

| Water Budget Component | June 2011 (Acre-Feet /Month) | August 2011 (Acre-Feet/Month) | December 2011 (Acre-Feet /Month) |
|---|---|---|---|
| IN | | | |
| Storage | 108,322 | 765,102 | 347,737 |
| Constant Head | 2,538 | 3,036 | 2,778 |
| Head Dependent Boundaries | 17,040 | 17,002 | 16,983 |
| Recharge | 2,448,823 | 727,989 | 82,357 |
| Stream Leakage | 14,836 | 17,429 | 13,488 |
| TOTAL | 2,591,559 | 1,530,558 | 463,343 |
| OUT | | | |
| Storage | 1,765,433 | 155,828 | 83,151 |
| Constant Head | 11,157 | 10,189 | 10,218 |
| Wells | 20,752 | 695,766 | -- |
| Evapotranspiration | 420,169 | 329,324 | 22,501 |
| Head Dependent Boundaries | 3,965 | 3,894 | 3,800 |
| Stream Leakage | 370,098 | 334,981 | 343,751 |
| TOTAL | 2,591,574 | 1,529,982 | 463,421 |
| IN minus OUT | -15 | 576 | -78 |
| % Difference | 0.00% | 0.04% | -0.02% |

## 6.7 Calibration Results – Quantitative

The quantitative analysis of the model calibration utilized statistical measures of model residuals, as described in Section 6.1.2 and comparisons of observed versus simulated water levels and stream baseflows. Long-term hydrographs of observed versus simulated water levels for 43 wells representing all major zones within the model domain are provided as Appendix C. Stream baseflow hydrographs comparing observed versus simulated baseflows are provided as Appendix D.

### 6.7.1 Quantitative Results – Hydraulic Heads

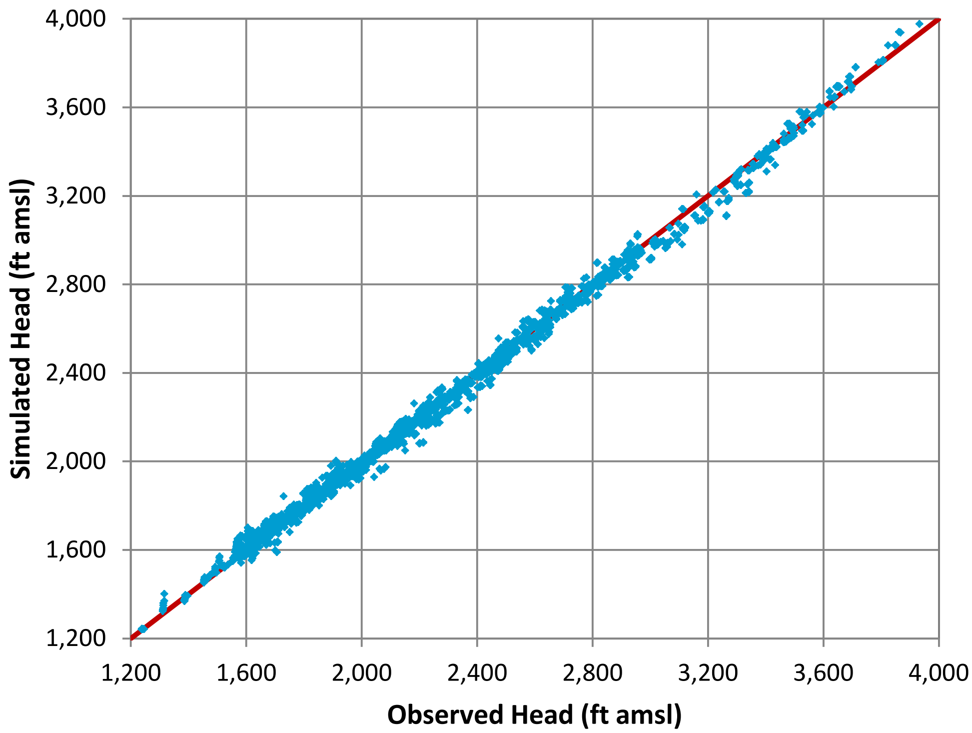
Calibration statistics for all head residuals for both steady-state and transient stress periods are presented in Table 6-8. The statistics are well within the goals established for the CENEB model calibration: MAE as a percent of total range in observations is 0.74 percent (goal: less than 2 percent), and the RMSE as a percent of total range in observations is 1.03 percent (goal: less than 2 percent). The MAE for the model calibration is 20 ft, less than half the calibration goal of 54 ft. The ME of 3 ft indicates that the observed heads are slightly higher than the calculated heads (averaged over the model domain); the very low magnitude of the mean indicates that there is not a significant bias overall.

A plot of the observed versus model-simulated head targets is presented below to graphically illustrate the calibration; points that plot on or near the perfect fit line (in red on Graph 6a) indicate a close match between observed and simulated water levels. Overall, Graph 6a illustrates that the residuals are clustered along the perfect fit line, with model values slightly low in the range from 3,000 to 3,300 ft amsl.

**Table 6-8. Head Residual Calibration Statistics[1] – CENEB Model**

| Statistical Measure | Result |
|---|---|
| Mean Error (ft) | 3 |
| Mean Absolute Error (ft) | 20 |
| Residual Std. Deviation (ft) | 28 |
| RMS Error (ft) | 28 |
| Minimum Residual (ft) | -113 |
| Maximum Residual (ft) | 157 |
| Number of Observations | 24,140 |
| Range in Observations (ft) | 2,696 |
| MAE as a % of Total Range in Observations | 0.74% |
| RMSE as a % of Total Range in Observations | 1.03% |

[1]*Residual = OBSERVED minus CALCULATED head.*




**Graph 6a. Simulated versus Observed Head Targets**

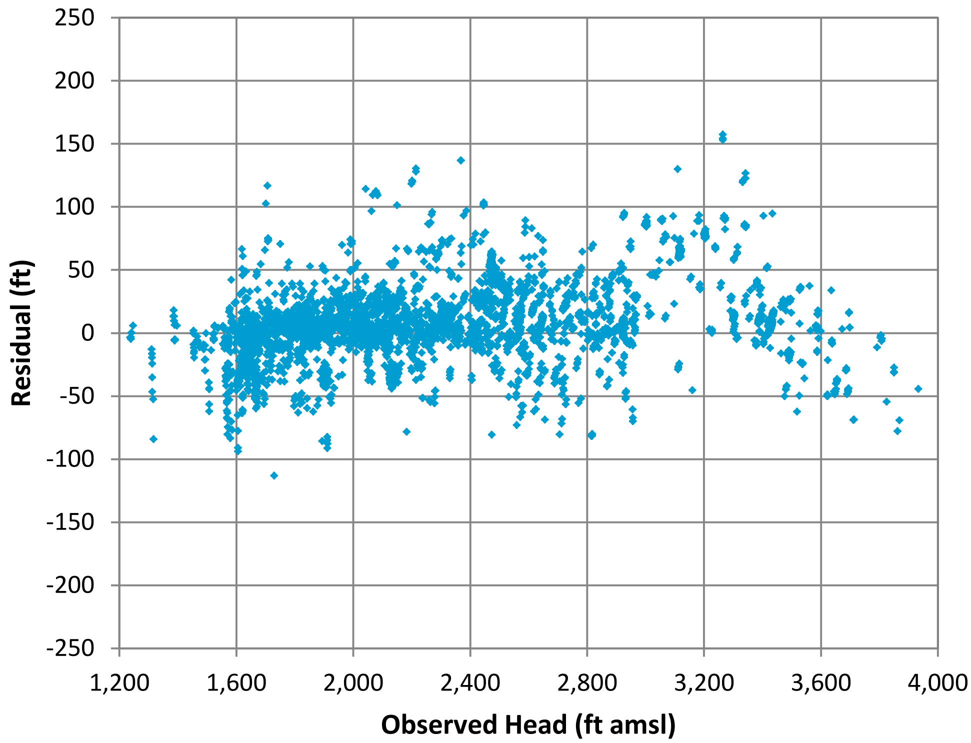
#### 6.7.1.1 Potential Bias in Model Results

The relationship between the observed head and the residual is a useful tool to assess potential bias in the calibration results by zone (Graph 6b). Head values increase from east to west across the model domain; thus, Graph 6b shows that there are more targets in the east (lower heads) than in the west, consistent with the highest concentration of wells. Approximately 91 percent of all residuals are in the range from -50 to 50 ft.

There is a slight local-scale bias (model too low, positive residual) in simulated groundwater elevations from approximately 3,000 to 3,300 ft amsl, corresponding to the region of slightly low simulated water levels in the Sand Hills, north of the Platte River in the west-central portion of the model domain. Trends evident on Graph 6b also reflect that there are many more positive than negative residuals in the range from 2,400 to 2,800 ft amsl. However, these graphs reflect multiple observations in long-term water level hydrograph data, which can impact interpretations based solely on plots of all data through time. Simulated water level contours and residuals for 2011 are presented on Figure 6-8 to examine the spatial distribution of resdiuals across the model domain. Residuals that indicate a very close match between observed and simulated heads (±10 ft) are shown in gray in order to highlight any patterns formed by large residuals, both positive and negative.

The patterns shown on Figure 6-8 indicate two localized areas of bias in water levels: the model tends to underestimate heads in a portion of the Sand Hills region (as noted above), and overestimate heads along the lower reaches of the Elkhorn River and within the North Elkhorn River watershed, along the eastern boundary of the model.

The central portion of the Loup River watershed appears to have a bias where simulated water levels are too low, however, there are a large number of residuals in the range of ±10 ft interspersed with positive residuals (Figure 6-8), and this is not considered to be an area of concern.




**Graph 6b. Observed Head Targets versus Residuals**

Generally, the model tends to underestimate stream baseflow in the Sand Hills region where there is a positive bias in water levels (model values too low). During calibration, hydraulic parameters were adjusted in an attempt to reduce bias in heads while increasing simulated baseflow to achieve a better match with observed conditions; parameters that were adjusted include: ET rates and distribution, stream bottom elevations, and stream conductance. Higher values of aquifer hydraulic conductivity were effective in increasing simulated baseflow. The consequence of higher aquifer hydraulic conductivity, however, lowered groundwater elevations. Ultimately, the bias in heads was minimized as much as possible while optimizing the calibration with respect to baseflow.

Similarly, baseflows tended to be higher than observed values along lower portions of the Elkhorn River and in the North Elkhorn River watershed, where there is a negative bias in simulated water levels (model values too high). In these areas, increasing aquifer hydraulic conductivity to reduce groundwater elevations resulted in an overestimation of baseflow. As a result, aquifer hydraulic conductivity was maintained at lower values to ensure an adequate baseflow calibration; this approach resulted in heads that are generally overestimated in the northeastern portion of the domain. The overestimation of heads was minimized as much as possible while maintaining agreement between observed and simulated baseflow.

The areas of local bias were evaluated and improved to the extent feasible, while maintaining a balance between the calibration to heads and baseflows. With respect to the model purpose, these two areas of bias are not significant in terms of potential effects on simulating groundwater-surface water interactions.

#### 6.7.1.2 Flooded Cells

The groundwater model is not constrained to simulate water levels below ground surface. Simulated heads that are above ground surface simply represent a slight excess in groundwater head related to the simulated flux in a model cell. These cells are characterized as “flooded,” but do not actually represent surface water in the model simulation. As part of the model performance evaluation, flooded cells were analyzed to evaluate areas where the model simulates heads above ground surface. (In the CENEB model, the average DEM value was used to define ground surface elevation.) Five different stress periods were reviewed to assess the occurrence of flooded cells (stress periods 41, 62, 158, 223, and 358). These stress periods were chosen in order to capture variability in stresses over the entire simulation, ranging from relatively dry to relatively wet conditions.

Approximately 1,202 of the total 49,275 model cells simulate groundwater levels above the ground surface for the selected stress periods, based on an average DEM value as the ground surface elevation. Given that each model cell represents average conditions over a square-mile area, the average topographic elevation may not be the best indicator that simulated groundwater heads would actually be above ground surface over large portions of the model cell. When the maximum DEM values are used to define land surface for the model cells, the number of flooded cells decreases by approximately 82 percent, and the flooded cells are limited to a few small regions. Regions of the model that remain flooded even after implementing the maximum DEM elevation primarily include small areas within South Dakota along Ponca Creek and the downstream portions of the Elkhorn River.

#### 6.7.1.3 Statistics for Specific Stress Periods

Statistics summarizing the results of calibration for steady state, for specific years in the transient simulation, and for the long-term hydrographs are presented in Table 6-9. In all cases, calibration statistics exceed the calibration goals. It should be noted that model stress periods changed from annual to monthly beginning in 1986. No discernible difference in the quality of the calibration is evident in the 2000 and 2011 calibration statistics (versus previous years), indicating a successful transition to monthly stresses.

Table 6-9. Steady-State and Transient Head Residual Calibration Statistics[1] – CENEB Model

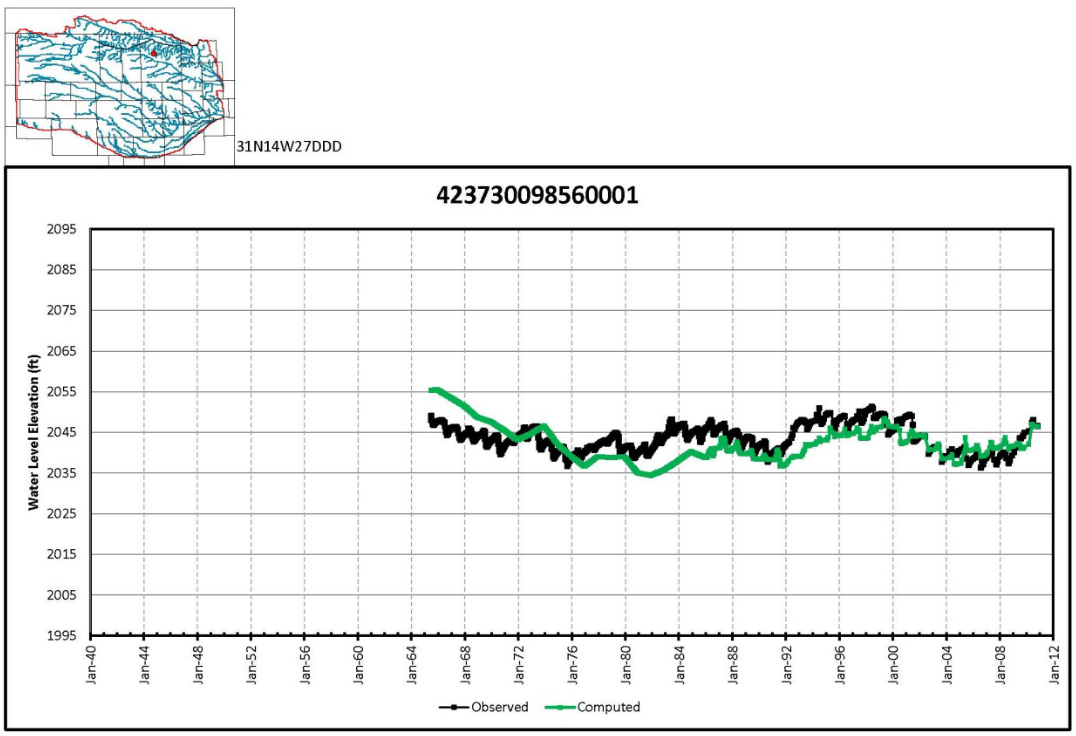
| Year | Number of Targets | Range in Observations (feet) | Mean Error (feet) | Mean Absolute Error (MAE) (feet) | MAE as % of Total Head Change | Root Mean Squared Error (RMSE) (feet) | RMSE as % of Total Head Change | Standard Deviation (feet) | Minimum Residual | Maximum Residual |
|---|---|---|---|---|---|---|---|---|---|---|
| Pre-1940 | 121 | 2,382 | 6 | 18 | 0.7% | 29 | 1.2% | 28 | -113 | 114 |
| 1946 | 195 | 2,691 | 1 | 11 | 0.4% | 18 | 0.7% | 18 | -78 | 117 |
| 1964 | 440 | 2,460 | 10 | 18 | 0.7% | 27 | 1.1% | 25 | -78 | 102 |
| 1976 | 1,042 | 2,613 | 2 | 22 | 0.8% | 29 | 1.1% | 29 | -86 | 130 |
| 1985 | 1,091 | 2,567 | 4 | 22 | 0.8% | 29 | 1.1% | 29 | -82 | 130 |
| 2000 | 978 | 2,537 | 7 | 22 | 0.9% | 31 | 1.2% | 30 | -84 | 157 |
| 2011 | 868 | 2,537 | 3 | 22 | 0.9% | 32 | 1.2% | 31 | -94 | 154 |
| Hydrographs | 21,508 | 1,996 | 3 | 20 | 1.0% | 27 | 1.4% | 27 | -58 | 92 |
| TOTAL[2] | 24,140 | 2,696 | 3 | 20 | 0.7% | 28 | 1.0% | 28 | -113 | 157 |

[1]*Residual = OBSERVED minus CALCULATED head.*

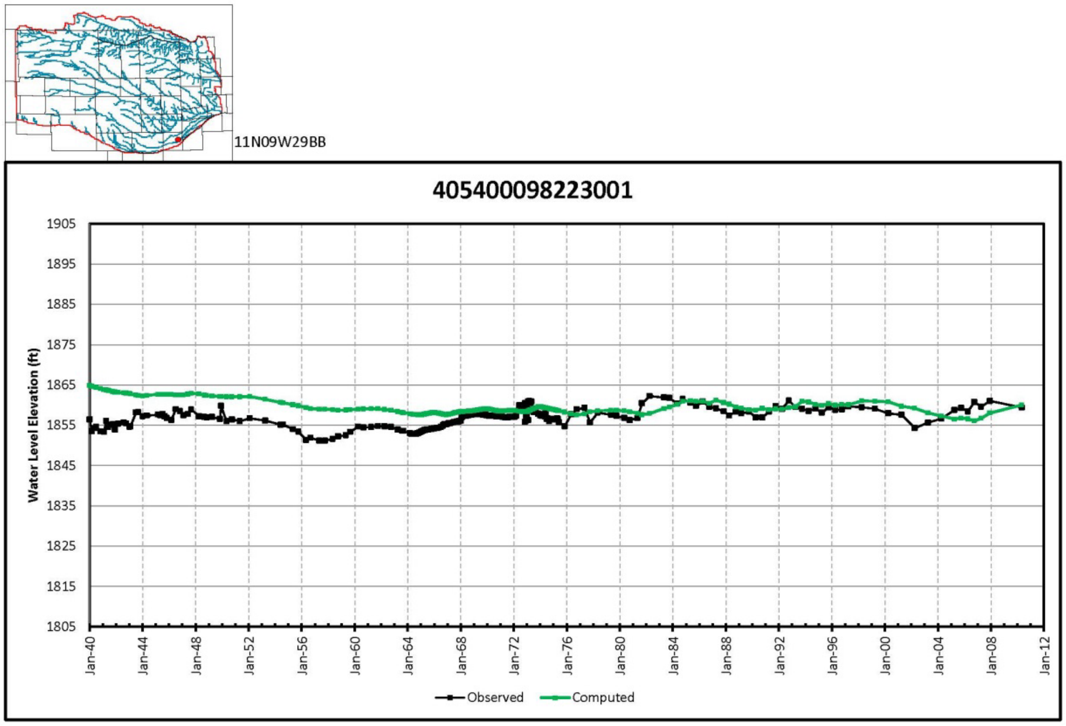
[2]*Total number of targets in the long-term hydrographs is 21,508; of these, 2,103 are included in the steady-state or specific year counts and statistics.*

### 6.7.1.4 Long-Term Hydrographs

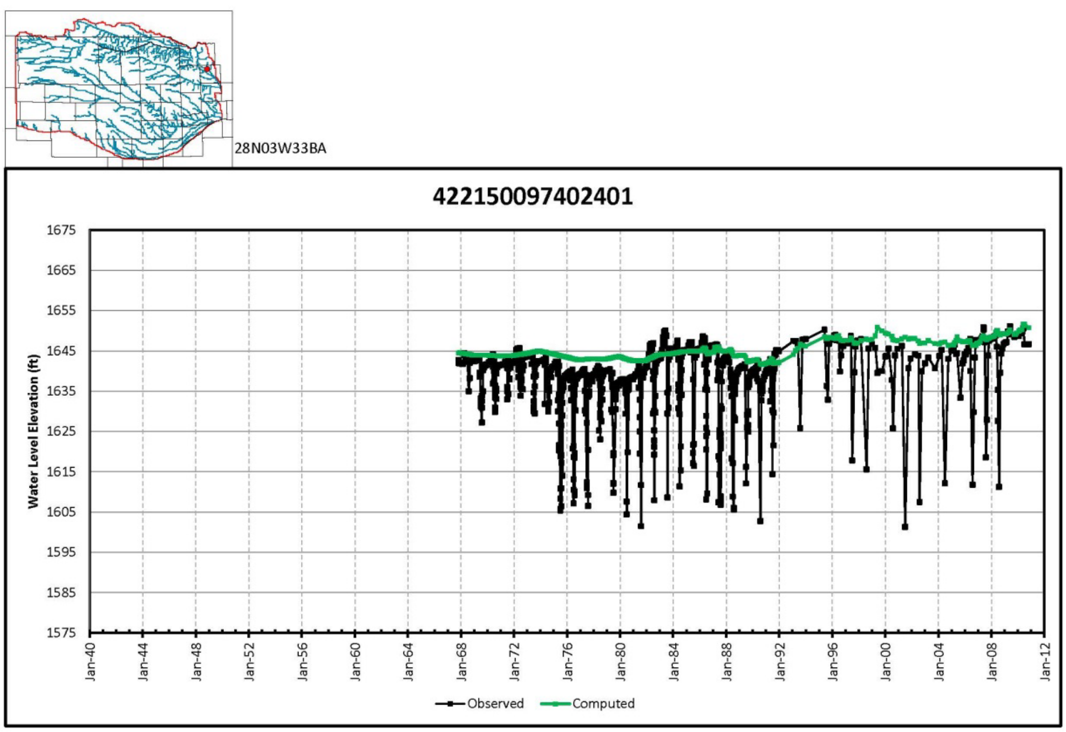
A total of 43 water level hydrographs are provided as Appendix C, comparing observed versus simulated water levels through time. These wells were selected as targets based on (1) their location within the model area, and (2) the availability of relatively long-term, continuous water level measurements. The agreement between simulated and observed hydrographs is good to excellent for all the sub-regions simulated and general trends were well reproduced, as shown on Graphs 6c through 6f. The model is not able to simulate all of the small-scale perturbations in observed water levels, due to the model cell size and length of the stress periods. However, beginning in 1986 with the start of monthly stress periods, it is apparent that the resolution in the simulated hydrographs changes from a generalized trend to a seasonal trend that more closely captures short-term fluctuations.



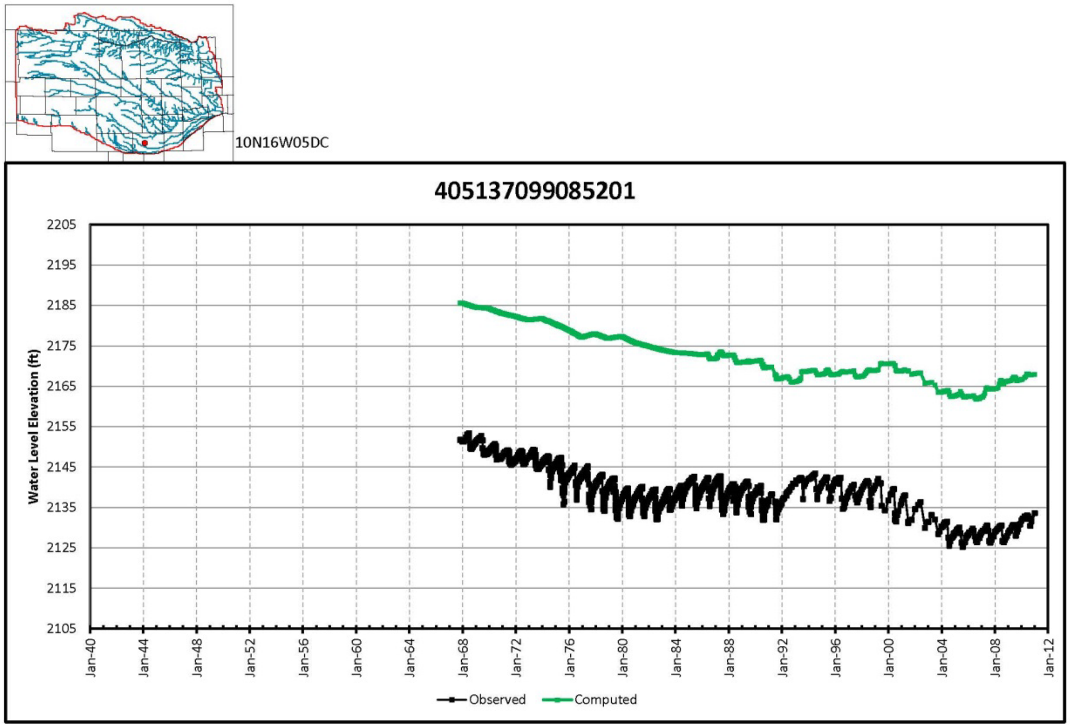

**Graph 6c. Observed vs. Simulated Hydrograph for Well 4237300985600001**




Graph 6d. Observed vs. Simulated Hydrograph for Well 405400098223001




Graph 6e. Observed vs. Simulated Hydrograph for Well 422150097402401




**Graph 6f. Observed vs. Simulated Hydrograph for Well 405137099085201**

Targets shown on Graphs 6c through 6e indicate a very close match between observed and simulated water levels. On Graph 6f, there is an approximately 30-ft difference between the simulated and observed water levels, which may be attributed to uncertainties in observed elevations, to local effects that are not captured in the regional-scale model, or to a needed adjustment in local model parameters. However, the simulated hydrograph shown on Graph 6f matches the observed trends very closely, including the long-term decline from 1968 to 1988 and the more recent water level rise from 2008 through 2011. Given that there are uncertainties in the targets and limitations to the model's ability to simulate conditions on a small, local scale, effectively simulating the long-term trends was considered to be an important goal of the calibration.

### 6.7.2 Quantitative Results – Baseflow

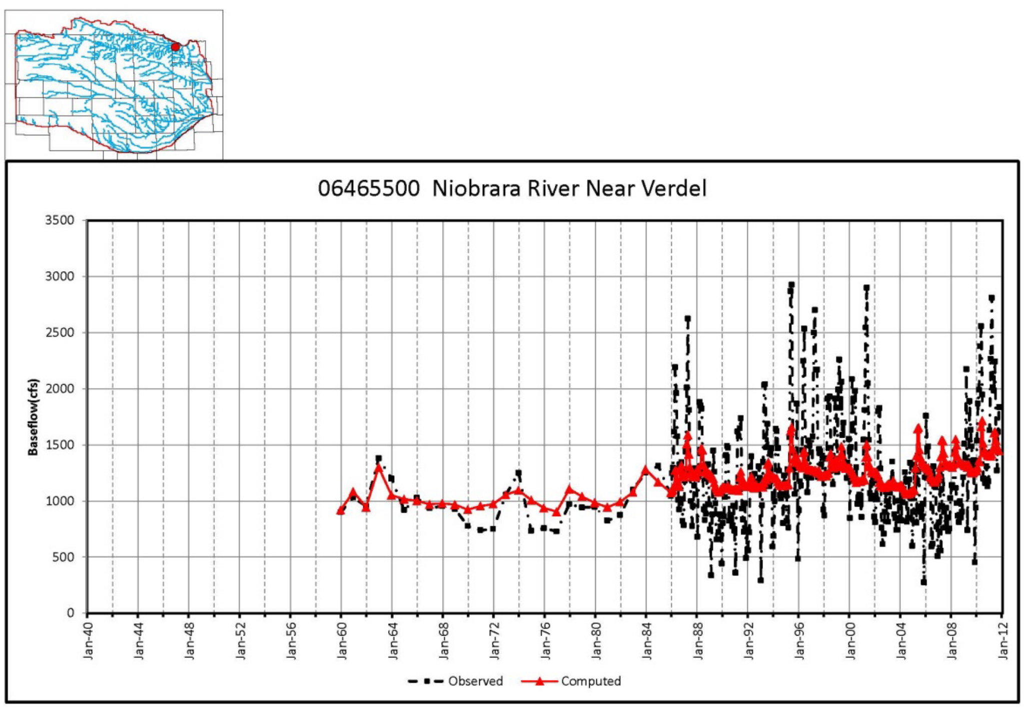
Calibration statistics for all baseflow residuals for both steady-state and transient stress periods are presented in Table 6-10. The statistics are well within the goals established for the CENEB model calibration: MAE as a percent of total range in observations is 2.36 percent (goal: less than 5 percent), and the RMSE as a percent of total range in observations is 4.72 percent (goal: less than 5 percent). The MAE for the model calibration is 81 cfs, less than half the calibration goal of 172 cfs. The statistics indicate a good overall calibration to the baseflow targets.

The observed versus simulated baseflow hydrographs provided as Appendix D demonstrate that the CENEB model is capable of simulating general trends as well as short term (monthly) oscillations, effectively capturing the interaction between stream baseflow and groundwater. Graphs 6g through 6l are hydrographs comparing observed versus simulated baseflow for the key stream gages on the largest rivers in the model domain.

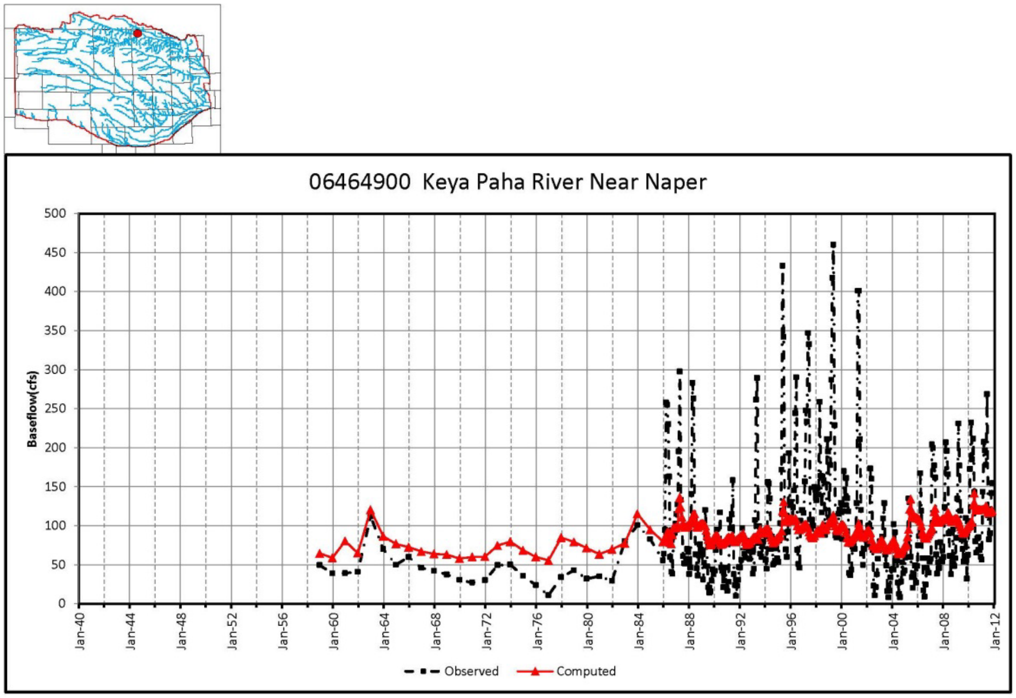
| Table 6-10. Baseflow Residual Calibration Statistics[1] – CENEB Model | |
|---|---|
| **Statistical Measure** | **Result** |
| Mean Error (cfs) | -5 |
| Mean Absolute Error (cfs) | 81 |
| Residual Std. Deviation (cfs) | 162 |
| RMS Error (cfs) | 162 |
| Minimum Residual (cfs) | -1,809 |
| Maximum Residual (cfs) | 1,558 |
| Number of Observations | 12,901 |
| Range in Observations (cfs) | 3,438 |
| MAE as a % of Total Range in Observations | 2.36% |
| RMSE as a % of Total Range in Observations | 4.72% |

*[1]Residual = OBSERVED minus CALCULATED baseflow.*

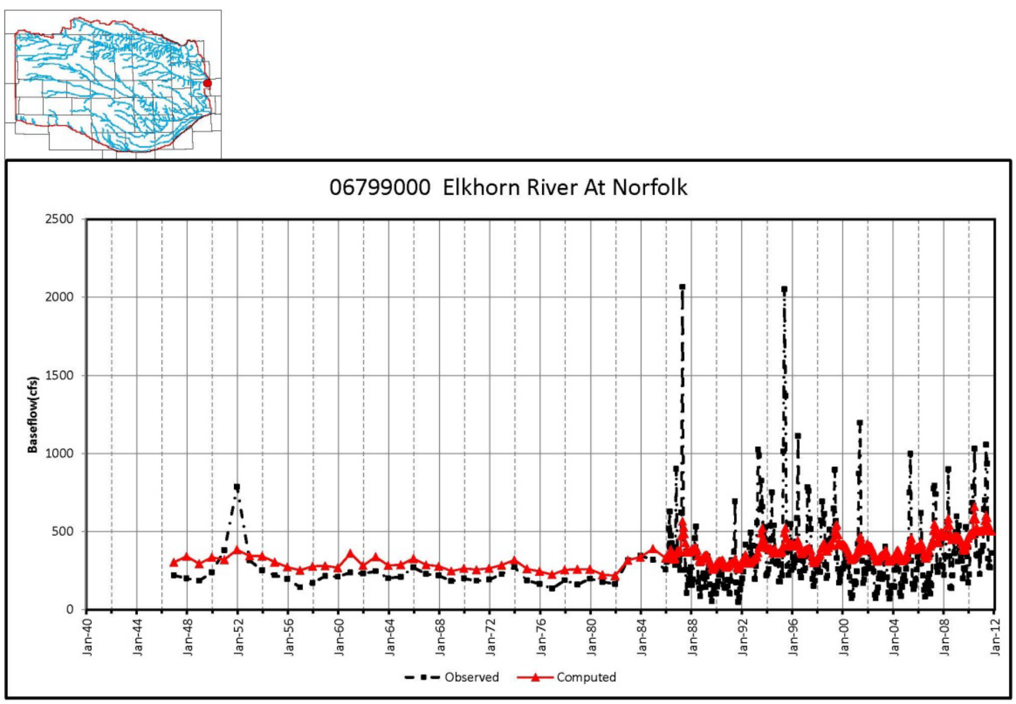
Trends are captured very well for both the early period (through 1985) with annualized stress periods, and during the later period (post-1985) with monthly stress periods. The model is not able to reproduce the abrupt highs and lows in the observed baseflow hydrographs during the period from 1986 through 2011 which are likely the result of variations occurring at time scales less than a month, but the simulated peaks closely match the trends in observed data. For some of the more variable baseflow hydrographs (Keya Paha near Naper, Niobrara near Verdel), the simulated baseflow follows a general trendline that represents the average or median of the observed baseflow.



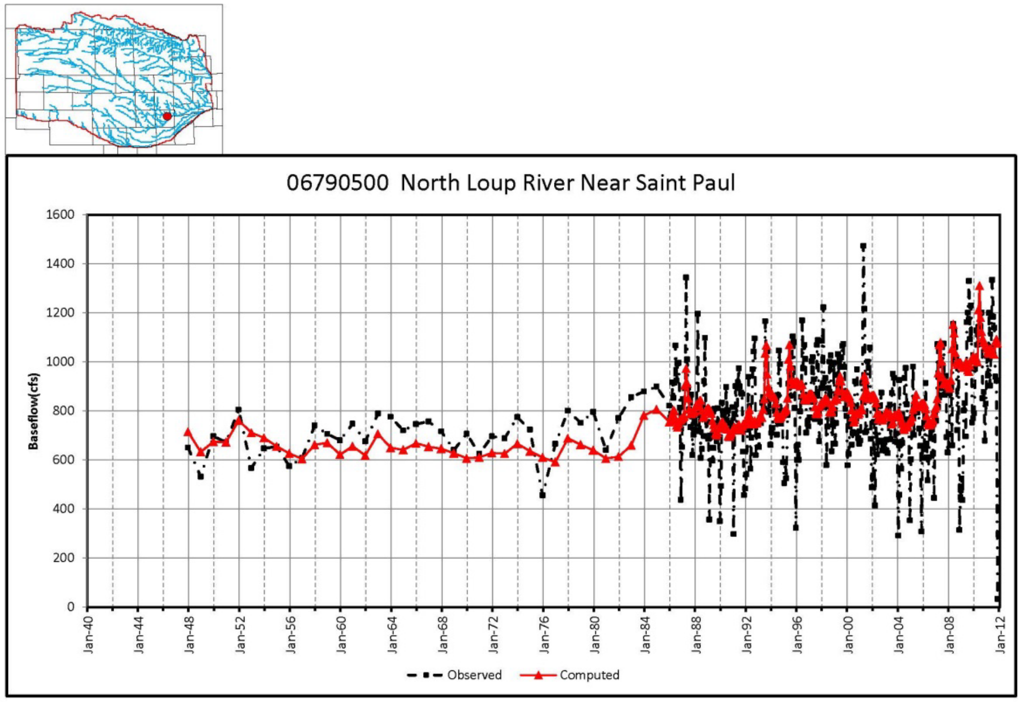

**Graph 6g. Observed vs. Simulated Baseflow – Niobrara River near Verdel.**



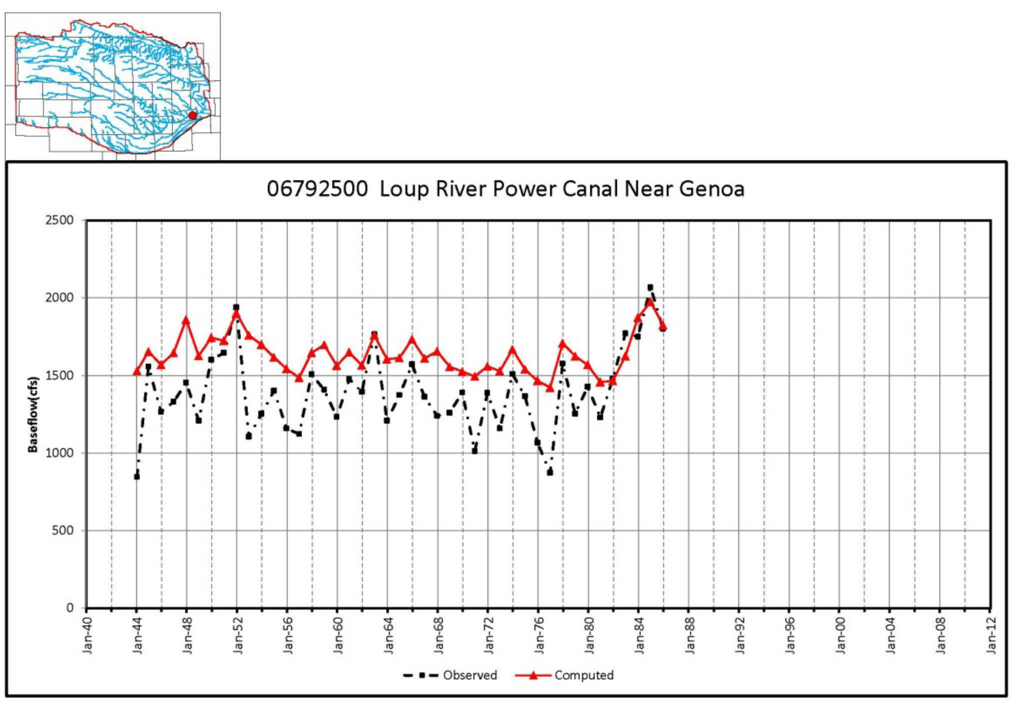

**Graph 6h. Observed vs. Simulated Baseflow – Keya Paha River near Naper.**




**Graph 6i. Observed vs. Simulated Baseflow – Elkhorn River at Norfolk.**

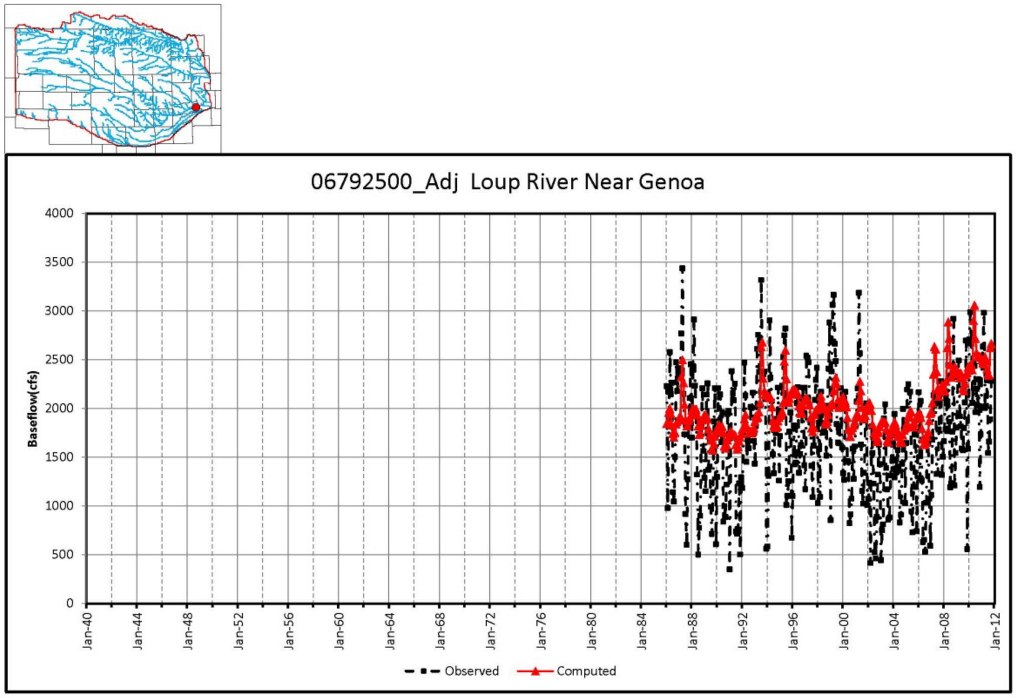



**Graph 6j. Observed vs. Simulated Baseflow – North Loup River near St. Paul.**




Graph 6k. Observed vs. Simulated Baseflow -- Loup River near Genoa.

*Data are from Loup River Near Genoa gage (06793000) adjusted by the Loup Power Canal diversions (gage 06792500).*




**Graph 6l. Observed vs. Simulated Baseflow – Loup River near Genoa.**

*Data are from Loup River Near Genoa gage (0679300) adjusted by the Loup Power Canal diversions (gage 06792500).*

Statistics summarized by the main river systems (Niobrara, Loup, and Elkhorn) are provided in Table 6-11; Ponca Creek (a direct tributary of the Missouri River) is not reflected in this table. Significant differences between baseflow residuals statistics for all targets versus the statistics by major river basin are not evident, except for the MAE of 63 cfs in the Elkhorn River Basin (versus an MAE of 81 cfs for all targets from Table 6-10).

**Table 6-11. Baseflow Residual Calibration Statistics for River Basins[1] – CENEB Model**

| River Basin[2] | Number of Targets | Range in Observations (cfs) | Mean Error (ME) (cfs) | Mean Absolute Error (MAE) (cfs) | MAE as % of Total Range | Root Mean Squared Error (RMSE) (cfs) | RMSE as % of Total Range |
|---|---|---|---|---|---|---|---|
| Niobrara River Basin | 3,783 | 2,925 | -4.2 | 88 | 2.99% | 173 | 5.92% |
| Elkhorn River Basin | 2,496 | 2,066 | -13 | 63 | 3.04% | 119 | 5.76% |
| Loup River Basin | 5,813 | 3,438 | -0.5 | 92 | 2.67% | 180 | 5.25% |

[1]*Residual = OBSERVED minus CALCULATED baseflow.*

[2]*Ponca Creek (tributary to the Missouri River) not reflected in these statistics.*

The MAE for all baseflow residuals for the entire period of record at each target location is posted on Figure 6-9. The largest MAE values are associated with relatively high-flow gages on the mainstems of the river systems that exhibit a large variation in highs and lows over a short period (example shown on Graphs 6k and 6l, above).

### 6.7.3 Summary

CENEB model construction and calibration were assessed by the modeling team to evaluate the model conceptualization and mathematical representation of the boundary conditions in the context of the objectives of the project. The appropriateness of the boundaries and the system conceptualization is frequently more important than achieving the smallest differences between simulated and observed water levels and baseflow (Reilly and Harbaugh, 2004). During this review, the boundary conditions (type and location) were verified as appropriate and reasonable for the objectives of the project and had no undue influence on the flow regime in the areas of interest within the major river basins. The generalized simulation of the South Dakota portion of the model was deemed acceptable as this area, relatively distal to the areas of interest, improved the model's ability to simulate that portion of the Niobrara River Basin in Nebraska.

A balance between qualitative and quantitative measures of calibration was employed to produce a reasonable representation of the conceptual model and sources of water, while minimizing the discrepancies between observed and measured water levels and baseflow. As such, differences between the simulated and observed water levels and baseflow were deemed reasonable for the objectives of the project, when satisfying the overarching goal of reproducing long-term trends.

A good calibration to qualitative and quantitative targets was achieved with the CENEB model based on:

- Acceptable approximations of the steady-state and transient flow regimes, as demonstrated by the match between observed and simulated water level contours
- Model's ability to reproduce general trends in the simulated, long-term water level and baseflow hydrographs
- Monthly stress periods that capture seasonal variations
- Residual head and baseflow statistics that meet/exceed the calibrations goals

The simulated head and flow distributions capture the magnitude and direction of the water level contours, and the agreement between simulated and observed hydrographs provides a measure of the ability of the model to reproduce observed long-term trends under differing hydrologic conditions. Because the model is shown to be a reasonable representation of observed surface water and groundwater flow conditions, there is a high level of confidence in the model for its intended use in assessing the BWS.

Section 7

# Sensitivity Analysis

A sensitivity analysis was performed to assess the response of the CENEB model calibration to changes in selected model input parameters, and to identify those parameters that most directly influence model results. A parameter in a groundwater model is considered to be sensitive when small changes in that parameter produce significant changes in model output (i.e., calibration statistics). Assessing model sensitivity provides a general measure of the robustness of model construction, uniqueness of calibration, and an understanding of how parameter uncertainty impacts model results.

## 7.1 Design

The sensitivity analysis was designed to quantify variability in model results due to uncertainty in estimated hydraulic parameter values (e.g., hydraulic conductivity) and uncertainty in prescribed model inputs (e.g., recharge). The sensitivity study was also used to evaluate the impact of hydraulic parameters and prescribed inputs on stream baseflows over time.

To assess the sensitivity of the CENEB model to key model parameters, hydraulic conductivity, streambed conductance, and specific yield were varied within a reasonable range for the type of geologic material to assess the resulting impacts on model calibration. Hydraulic conductivity and streambed conductance were selected based on experience and observations during the calibration phase; specific yield was included because of the potential for the model to be sensitive to storage. These three input parameters were increased and decreased by up to 25 percent, and the resulting impacts on the model calibration and baseflow mass balance were tabulated. The results indicated that variations of up to 25 percent adequately captured the model sensitivities, thus the range was not expanded further.

To address uncertainty in the prescribed model inputs, recharge and pumping were included in the sensitivity analysis. Recharge and pumping were increased and decreased by up to 25 percent in all cells and for all stress periods to assess the resulting impacts on the model calibration and baseflow mass balance. Table 7-1 summarizes the model inputs that were varied, the original range parameter values, and the test range.

**Table 7-1. Sensitivity Analysis Design – CENEB Model**

| Variable | Initial Values | Percent Change | Test Values |
|---|---|---|---|
| **Hydraulic Parameters** | | | |
| Hydraulic Conductivity | 2.5 to 75.6 ft/day | +25 to -25 | 1.9 to 94.6 ft/day |
| Stream Conductance | 0.2 to 1,657,005 $ft^2$/day | +25 to -25 | 0.1 to 2,071,226 $ft^2$/day |
| Specific Yield | 0.002 to 0.26 | +25 to -25 | 0.0014 to 0.325 |
| **Prescribed Inputs** | | | |
| Recharge | 5.90 million AFY | +25 to -25 | 4.43 to 7.38 million AFY |
| Pumping | 1.03 million AFY | +25 to -25 | 0.77 to 1.29 million AFY |

## 7.2 Results

During calibration, it was observed that relatively significant changes in the model-simulated head and baseflows correlated with a 0.8- to 1-ft change in the MAE for head residuals, or a 5- to 10-cfs change in the MAE for baseflow residuals. These threshold values were used as a guideline to categorize the sensitivity level of the model to changes in parameters and inputs.

Stream baseflow was one of the key metrics used to evaluate the sensitivity of the CENEB model. Average annual baseflow was calculated for the calibrated version of the CENEB model and for all sensitivity simulations, using the cumulative net stream gain (Stream Out minus Stream In) from the model-calculated water budget for the entire 72-year simulation divided by 72 years (total simulation time) to produce an annual average baseflow. The change in the average annual baseflow, versus the calibrated model, provided a metric to evaluate sensitivity that is directly linked to the model purpose. The size of the CENEB model and the relatively large average annual baseflow volumes (2.7 million AFY) were taken into consideration when developing a guideline to assess sensitivity with this metric; a 2 percent change in the average annual baseflow or 54,000 AFY was considered to be the threshold for sensitivity.

### 7.2.1 Hydraulic Conductivity

Increases/decreases of up to 25 percent in hydraulic conductivity values are within the range of plausible variability for this hydraulic parameter, which is an order-of-magnitude estimate. Additionally, calibrated values from the ELM were retained as starting estimates in the CENEB model thus the plausible range of estimates for this parameter was narrow and relatively well constrained at the start of the CENEB model calibration. The model was sensitive to a decrease in hydraulic conductivity by 15 percent and very sensitive to a decrease of 25 percent (Table 7-2 and Graph 7a); these changes increased the MAE by 0.8 and 2.1 ft, respectively.

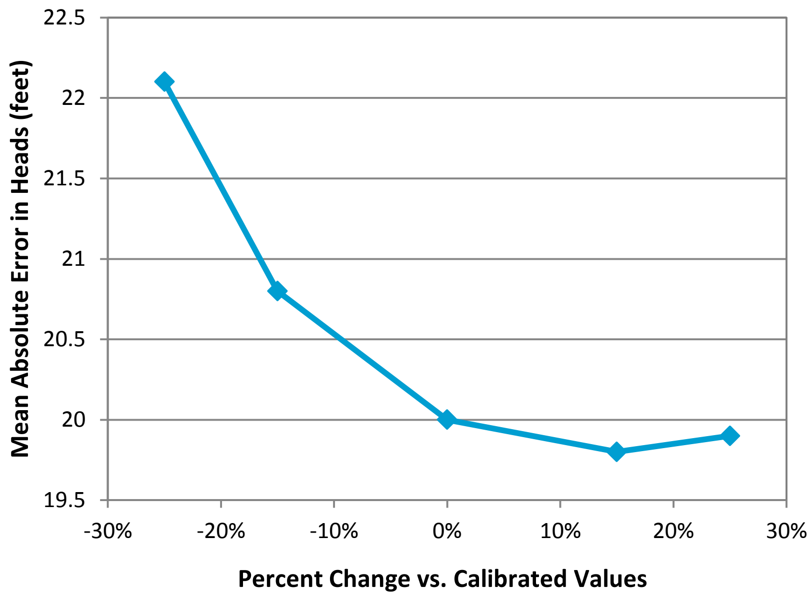
The model was insensitive to increases in hydraulic conductivity when evaluating the MAE for head and baseflow residuals, however, the mean of the head residuals (7 to 9 ft) and average annual baseflow increased significantly (up to 122,835 AFY) as compared to the calibrated values. This translates to lower head in the aquifer, and more water discharged to streams, resulting in a bias that adversely impacts calibration. The sensitivity analysis confirmed that the calibrated hydraulic conductivity values resulted in a good balance between the water levels in the aquifer and stream baseflow.

**Table 7-2. Sensitivity Analysis Results – Hydraulic Conductivity (Kx, Ky)**

| Percent Change Versus Calibrated Value | Head Residuals[1] | | | Baseflow Residuals[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean (ft) | MAE (ft) | Scaled MAE | Mean (cfs) | MAE (cfs) | Scaled MAE | Average Annual Baseflow Mass Balance (AFY)[2] | Change in Average Annual Baseflow Mass Balance (AFY) |
| 25% | 9 | 19.9 | 0.737% | -17.2 | 82.5 | 2.40% | 2,801,699 | 122,835 |
| 15% | 7 | 19.8 | 0.734% | -12.5 | 81.8 | 2.38% | 2,754,626 | 75,761 |
| 0 | 3 | 20.0 | 0.741% | -5.0 | 81.0 | 2.36% | 2,678,864 | -- |
| -15% | -1 | 20.8 | 0.773% | 3.6 | 80.9 | 2.35% | 2,592,879 | -85,985 |
| -25% | -5 | 22.1 | 0.821% | 10.4 | 81.4 | 2.37% | 2,528,176 | -150,688 |

*[1]Residual = OBSERVED minus CALCULATED value.*

*[2]The average annual baseflow is calculated by dividing the cumulative net stream gain (Stream Out minus Stream In) for the entire simulation period by the number of years in the simulation, i.e., 72 years.*




**Graph 7a. Sensitivity Analysis – Hydraulic Conductivity**

### 7.2.2 Stream Conductance

As noted in Section 8.1, streambed conductance in the CENEB model is generally very high (up to 1,657,004.5 ft²/day), consistent with the conceptual model that indicates a strong hydraulic connection between the aquifer and the streams. Increasing streambed conductance values during calibration did not significantly change baseflow, as that process is more dependent upon aquifer hydraulic conductivity; conversely, large reductions in stream conductance would be inconsistent with the conceptual model, hence the sensitivity analysis was limited to a 25 percent increase/decrease in stream conductance.

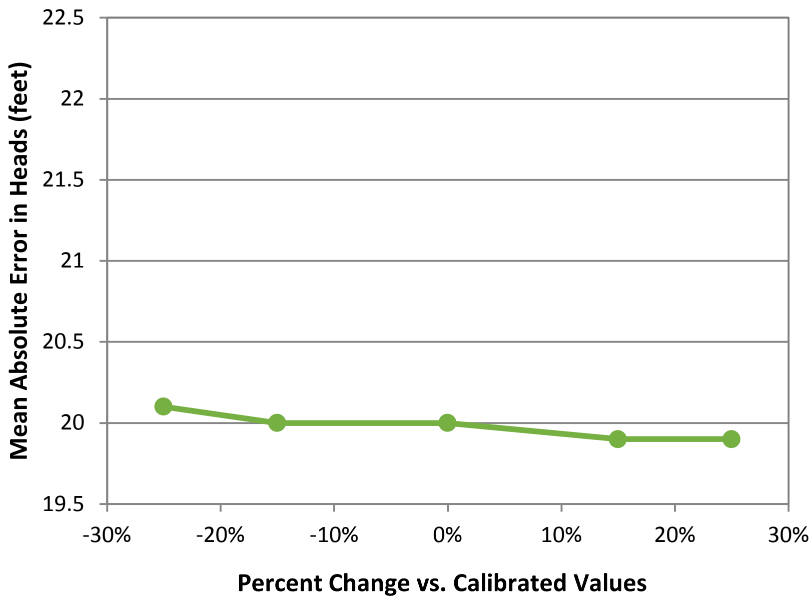
As expected, the model was insensitive to increases/decreases of up to 25 percent in stream conductance (Table 7-3 and Graph 7b). The sensitivity analysis confirmed that the calibrated hydraulic conductivity values are within the range that produces the best calibration statistics for head and baseflow residuals.

**Table 7-3. Sensitivity Analysis Results – Streambed Conductance**

| Percent Change versus Calibrated Values | Head Residuals[1] | | | Baseflow Residuals[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean Error (ft) | MAE (ft) | Scaled MAE | Mean (cfs) | MAE (cfs) | Scaled MAE | Average Annual Baseflow Mass Balance (AFY)[2] | Change in Average Annual Baseflow Mass Balance (AFY) |
| 25% | 4 | 19.9 | 0.738% | -8 | 80.9 | 2.35% | 2,702,738 | 23,874 |
| 15% | 3 | 19.9 | 0.739% | -7 | 80.9 | 2.35% | 2,694,354 | 15,490 |
| 0 | 3 | 20.0 | 0.741% | 5 | 81.0 | 2.36% | 2,678,864 | -- |
| -15% | 3 | 20.0 | 0.743% | -2 | 81.2 | 2.36% | 2,659,300 | -19,565 |
| -25% | 2 | 20.1 | 0.745% | -0.4 | 81.3 | 2.37% | 2,642,682 | -36,182 |

[1]*Residual = OBSERVED minus CALCULATED value.*

[2]*The average annual baseflow is calculated by dividing the cumulative net stream gain (Stream Out minus Stream In) for the entire simulation period by the number of years in the simulation, i.e., 72 years.*




**Graph 7b. Sensitivity Analysis – Stream Conductance**

### 7.2.3 Specific Yield

The model's sensitivity to increases/decreases of up to 25 percent in specific yield was evaluated; results are shown in Table 7-4 and on Graph 7c. The inverse relationship between specific yield and average annual baseflow can be seen in Table 7-4, reflecting that higher storage in the aquifer reduces baseflow.

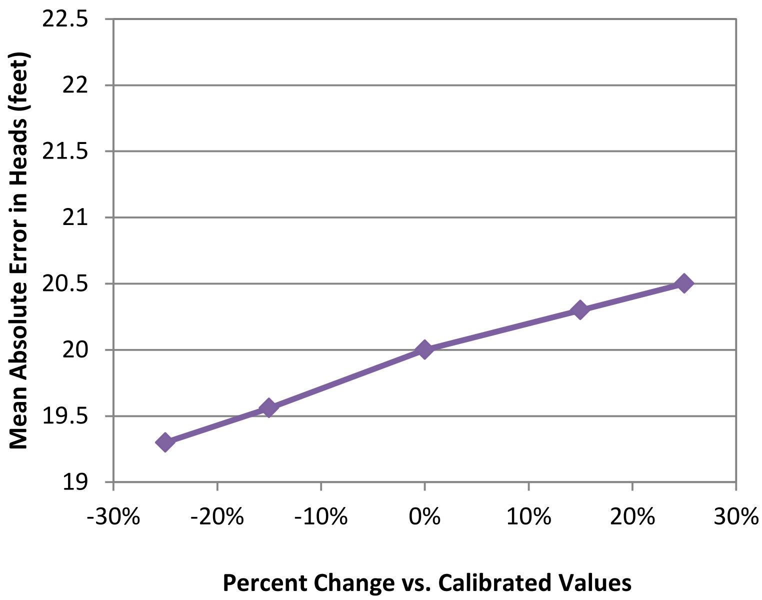
The model was insensitive to increases in specific yield of up to 25 percent and insensitive to a decrease of 15 percent; the model was sensitive to the maximum increase of 25 percent, as shown by the 7 cfs decrease in the mean of the baseflow residuals (from -5 to -12 cfs) and the increase of 229,831 AFY in average annual baseflow. Statistically, a slight decrease in specific yield throughout the model domain would improve calibration, although it was found that locally, this adjustment introduced negative impacts on the baseflow calibration. The calibrated specific yield values were retained as they resulted in the best overall calibration statistics for observed water level and baseflow residuals.

**Table7-4. Sensitivity Analysis Results – Specific Yield**

| Percent Change versus Calibrated Values | Head Residuals[1] | | | Baseflow Residuals[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean Error (ft) | MAE (ft) | Scaled MAE | Mean (cfs) | MAE (cfs) | Scaled MAE | Average Annual Baseflow Mass Balance (AFY)[2] | Change in Average Annual Baseflow Mass Balance (AFY) |
| 25% | 3 | 20.5 | 0.760 | -1 | 81.4 | 2.37 | 2,655,047 | -23,817 |
| 15% | 3 | 20.3 | 0.753 | -2 | 81.2 | 2.36 | 2,663,844 | -15,020 |
| 0 | 3 | 20.0 | 0.741 | -5 | 81.0 | 2.36 | 2,678,864 | -- |
| -15% | 3 | 19.6 | 0.726 | -9 | 81.0 | 2.36 | 2,697,336 | 18,471 |
| -25% | 3 | 19.3 | 0.715 | -12 | 81.2 | 2.36 | 2,908,696 | 229,831 |

[1]*Residual = OBSERVED minus CALCULATED value.*

[2]*The average annual baseflow is calculated by dividing the cumulative net stream gain (Stream Out minus Stream In) for the entire simulation period by the number of years in the simulation, i.e., 72 years.*




**Graph 7c. Sensitivity Analysis – Specific Yield**

### 7.2.4 Recharge

Increases and decreases of 15 percent in recharge equate to an annual average change of ±885,600 AFY or ±119 AFY of recharge per mile of stream (based on total simulated stream length of 7,415 miles). Increases and decreases of 25 percent equate to an annual average change of ±1.476 million AFY, or ±199 AFY of recharge per mile of stream.

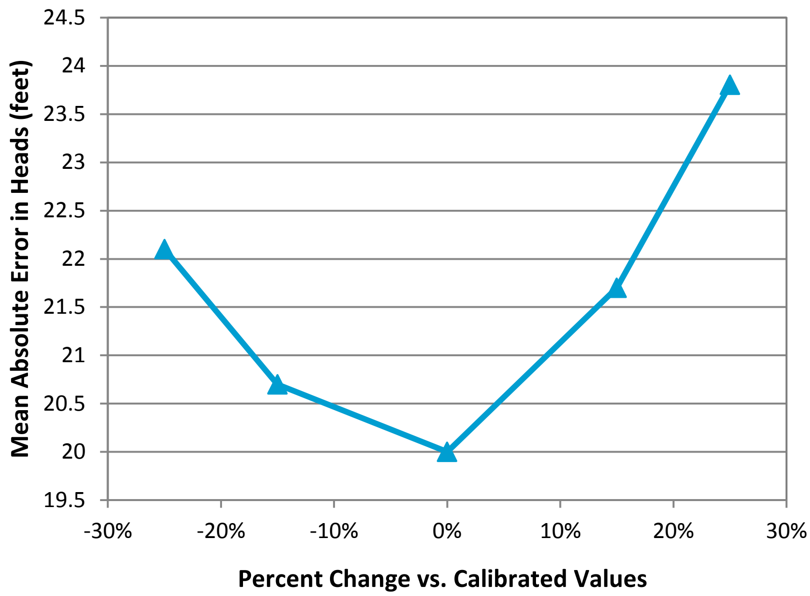
The model was very sensitive to increases/decreases in recharge of 15 to 25 percent; these changes in the prescribed recharge rates adversely affected all calibration metrics, especially baseflow (Table 7-5 and Graph 7d). The change in the baseflow mass balance was consistently in the range of 60 percent of the volumetric increases/decreases in recharge, and underscores the direct relationship between these two budget components. The sensitivity analysis confirmed that the calibrated recharge rates resulted in the best calibration statistics for observed water level and baseflow residuals.

**Table 7-5. Sensitivity Analysis Results – Recharge**

| Percent Change versus Calibrated Values | Head Residuals[1] | | | Baseflow Residuals[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean (ft) | MAE (ft) | Scaled MAE | Mean (cfs) | MAE (cfs) | Scaled MAE | Average Annual Baseflow Mass Balance (AFY)[2] | Change in Average Annual Baseflow Mass Balance (AFY) |
| 25% | -8 | 23.8 | 0.882 | -102 | 122.8 | 3.57 | 3,603,270 | 924,405 |
| 15% | -3 | 21.7 | 0.806 | -62 | 98.6 | 2.87 | 3,225,595 | 546,730 |
| 0 | 3 | 20.0 | 0.741 | -5 | 81.0 | 2.36 | 2,678,864 | -- |
| -15% | 10 | 20.7 | 0.767 | 51 | 88.3 | 2.57 | 2,153,547 | -525,317 |
| -25% | 15 | 22.1 | 0.820 | 86 | 105.7 | 3.07 | 1,821,140 | -857,724 |

*[1]Residual = OBSERVED minus CALCULATED value.*

*[2]The average annual baseflow is calculated by dividing the cumulative net stream gain (Stream Out minus Stream In) for the entire simulation period by the number of years in the simulation, i.e., 72 years.*




**Graph 7d. Sensitivity Analysis – Recharge**

### 7.2.5 Pumping

Increases and decreases of 15 percent in pumping equate to an annual average change of ±154,700 AFY; increases and decreases of 25 percent in pumping equate to an annual average change of ±257,800 AFY. The change in the baseflow mass balance was consistently in the range of 24 to 25 percent of the volumetric increases/decreases in pumping (Table 7-6).

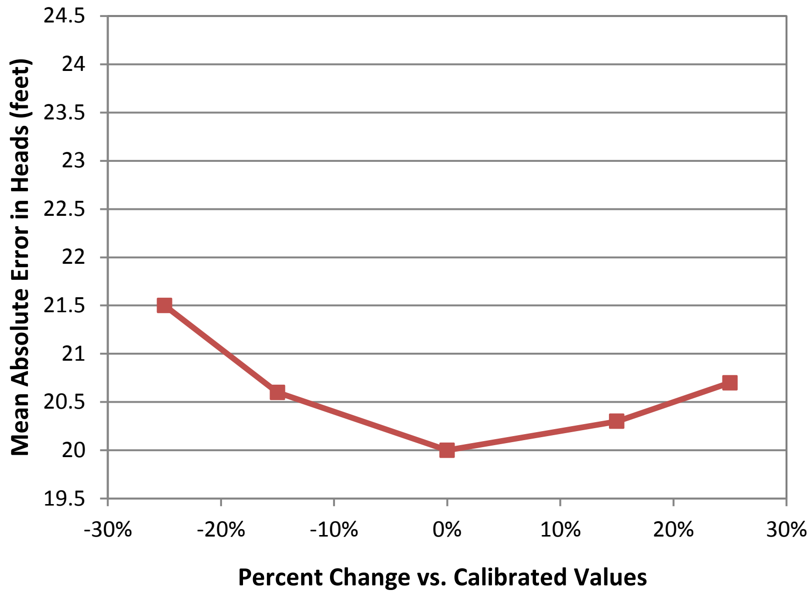
The model was sensitive to increases/decreases in pumping of 25 percent but relatively insensitive to increases/decreases of 15 percent (Table 7-6 and Graph 7e). Decreases in pumping had a larger impact on both head and baseflow residuals than increases; relatively large changes in the mean of the baseflow residuals indicates a response to decreases in pumping on the local scale that indicate a bias with simulated baseflow higher than observed baseflow.

**Table 7-6. Sensitivity Analysis Results – Pumping**

| Percent Change versus Calibrated Values | Head Residuals[1] | | | Baseflow Residuals[1] | | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean (ft) | MAE (ft) | Scaled MAE | Mean (cfs) | MAE (cfs) | Scaled MAE | Average Annual Baseflow Mass Balance (AFY)[2] | Change in Average Annual Baseflow Mass Balance (AFY) |
| 25% | 7 | 20.7 | 0.767 | 3 | 79.4 | 2.31 | 2,617,349 | -61,516 |
| 15% | 5 | 20.3 | 0.752 | -0.3 | 79.9 | 2.33 | 2,641,634 | -37,230 |
| 0 | 3 | 20.0 | 0.741 | -5 | 81.0 | 2.36 | 2,678,864 | -- |
| -15% | 1 | 20.6 | 0.763 | -10 | 82.4 | 2.40 | 2,717,492 | 38,628 |
| -25% | 0.1 | 21.5 | 0.799 | -13 | 83.4 | 2.43 | 2,744,020 | 65,156 |

[1]*Residual = OBSERVED minus CALCULATED value.*

[2]*The average annual baseflow is calculated by dividing the cumulative net stream gain (Stream Out minus Stream In) for the entire simulation period by the number of years in the simulation, i.e., 72 years.*




**Graph 7e. Sensitivity Analysis – Pumping**

## 7.3 Summary

Results from the sensitivity analysis are summarized in Table 7-7. The numerical model was insensitive to stream conductance, to specific yield (except for a 25 percent increase), and to ±15 percent changes in pumping. For all other parameters and inputs, the model was sensitive to very sensitive.

**Table 7-7. Summary of Sensitivity Analysis Results**

| Hydraulic Parameter or Prescribed Model Input | Increase/Decrease versus Calibrated Values | | | |
|---|---|---|---|---|
| | +25 Percent | +15 Percent | -15 Percent | -25 Percent |
| Hydraulic Conductivity | Very Sensitive | Sensitive | Sensitive | Very Sensitive |
| Stream Conductance | Insensitive | Insensitive | Insensitive | Insensitive |
| Specific Yield | Sensitive | Insensitive | Insensitive | Insensitive |
| Recharge | Very Sensitive | Very Sensitive | Very Sensitive | Very Sensitive |
| Pumping | Sensitive | Insensitive | Insensitive | Sensitive |

The sensitivity analysis results (Tables 7-2 through 7-6) included an evaluation of the changes in the baseflow mass balance that resulted from varying parameters and prescribed model inputs (pumping and recharge). In all cases, variations that reduced the volume of water in the aquifer (i.e., decreased pumping, higher storage values, etc.) resulted in a reduction in baseflow. Similarly, changes to the model that would increase the amount of water in the aquifer (i.e., increased recharge, higher streambed conductance, etc.) resulted in an increase in baseflow. The model response to variations in pumping and recharge was proportionate to the volumetric change in these inputs, demonstrating the model's ability to simulate changes in baseflow caused by subtle as well as large-scale changes in stresses.

The estimated hydraulic parameters and prescribed inputs used in the calibrated model were confirmed by the sensitivity analysis as producing the best overall calibration statistics with a good balance between simulated water levels and baseflows. Thorough model testing during calibration and the sensitivity analysis support the use of the CENEB model as a robust tool for assessing the BWS and baseflow depletions within the model domain.

Section 8

# Limitations and Refinements

## 8.1 Limitations of the Model

The CENEB model was developed through a detailed process including calibration and a sensitivity analysis subject to independent review and oversight. As such, the model is a well-developed tool for use in assessing BWS and stream depletions. However, all models have a degree of uncertainty related to model simulations. These uncertainties arise due to the accuracy, nature, timing, and location of field measured conditions, and application of the model is limited based on the range of uncertainty in model inputs and assumptions. The CENEB model represents a balance of flows entering the regional model domain from recharge and underflow, and exiting as pumping, ET, and baseflow to surface water. The balance achieved through calibration represents the best available understanding of groundwater-surface water interactions in the river basins. The results of the sensitivity analysis indicate that the model results can be sensitive to various inputs such as recharge and hydraulic conductivity; however, calibrated values produced the best results based on both qualitative and quantitative assessment on the local and regional scales. When considered in combination, the results of both the calibration and sensitivity analysis result in a high level of confidence in the use of the model for simulations of baseflow depletions through time.

Use of the CENEB model should be limited to the intended goals that were identified for the model (Section 1.1). The CENEB model is a regional-scale model with a 1-mile by 1-mile cell size; this type of model is useful for large-scale simulations, i.e., on the watershed or sub-watershed scale. The CENEB model is well suited for an analysis of the BWS in support of annual determinations of basin status. Use of the model for focused, small-scale predictions such as wellfield design or predicting baseflow to tributary streams smaller than the scale included in the SFR2 package is not recommended.

## 8.2 Potential Model Refinements

While the CENEB model is an appropriate tool for large-scale assessments of groundwater-surface water interactions, certain modifications have been identified that may improve the model's ability to match observed conditions. Based on the results of model calibration and the sensitivity analysis, the predictive ability of the CENEB model could potentially be improved from a focused, localized evaluation of recharge, particularly in the upstream reaches of the Loup River system in the Sand Hills, in South Dakota, and in the furthest downstream reaches of the Elkhorn River. This evaluation could be restricted to improving recharge estimates only, or it could include modifications to groundwater pumping.

The transition to monthly estimates of pumping and recharge beginning in 1986 improved the model's ability to simulate seasonal fluctuations and trends. However, CropSim appears to perform less reliably at the monthly level for calculating recharge during wetter periods, generally resulting in a large influx of water into the aquifer system over a short time period. This aspect of the CropSim-generated recharge inputs could be improved in future model updates.

In addition, future modeling efforts may include refinement of aquifer thicknesses in the northern and northeastern portion of the model domain. Assumptions related to aquifer thickness in these areas have been extrapolated from conditions within the ELM, and generalized in order to produce a viable flow system.

Although model calibration is reasonable and uses a long history of groundwater level and surface baseflow targets, some local areas within the model domain were noted as having minor biases in predicted groundwater levels. These areas of bias are not considered significant given that they represent a balance between groundwater heads, system physical parameters, and surface baseflows. However, additional model testing and calibration in these areas may result in calibration improvements and removal of bias to improve overall model performance.

Section 9

# Summary and Conclusions

BC and NDNR collaborated to develop a numerical groundwater flow model of the Lower Niobrara, Loup, and Upper Elkhorn River Basins in central Nebraska (CENEB). The CENEB model was developed to ultimately be used as a primary tool for NDNR's annual evaluation of basin status.

The primary goal of the CENEB model project was to develop an appropriate tool that characterizes the BWS from historical through present day conditions and to use the model to evaluate surface water depletions from the BWS resulting from changes in pumping and recharge associated with irrigation.

## 9.1 Model Development

The CENEB model utilized parts of an existing flow model (ELM) as a starting point for expansion and refinement to meet NDNR's purposes. Significant refinements and expansions undertaken to create the CENEB model include the following:

- Expanded active model domain, including a portion of South Dakota, to simulate the majority of the Niobrara River Basin
- Revised location and type of boundary conditions, primarily to the north
- Estimated recharge (except canal recharge) and pumping demands based on CropSim, a RSWB model developed for Nebraska
- Increased number of streamflow routing cells to simulate smaller order tributaries
- Monthly stress periods beginning in 1986 to capture seasonality
- Calibration to pre-1940 through 2011 water level measurements and long-term hydrographs of estimated baseflow

An additional refinement to the CENEB model that differentiates it from previous flow models of the region is the use of CropSim, a RSWB model developed for Nebraska. CropSim was used to provide estimates of pumping and recharge as inputs for the CENEB model. Because these prescribed model inputs are inextricably linked, a single method to estimate precipitation recharge, cropland recharge, and irrigation pumping maintained the natural balance between the two main stresses on the aquifer system. The use of CropSim proved to enhance and streamline model development and calibration.

## 9.2 Model Performance

Following development of the CENEB model, model performance was assessed using defined qualitative and quantitative calibration goals that included evaluation of simulated baseflow, groundwater elevations, and water budgets. The appropriateness of the conceptualization of the groundwater system and the mathematical representation of boundary conditions were also evaluated during calibration, and were found to be reasonable for the objectives of the project. The balance between water levels in the aquifer and baseflow in the streams achieved through calibration represents the best available understanding of groundwater-surface water interactions in the river basins.

A balance between qualitative and quantitative measures of calibration was employed to produce a reasonable representation of the conceptual model and sources of water, while minimizing the discrepancies between observed and measured water levels and baseflow. As such, differences between the simulated and observed water levels and baseflow were deemed reasonable for the objectives of the project.

The sensitivity analysis results (Tables 7-2 through 7-6) included an evaluation of the changes in the baseflow mass balance that resulted from varying parameters and prescribed model inputs (pumping and recharge). In all cases, variations in these parameters and inputs resulted in a proportional increase or decrease in baseflow, demonstrating the model's ability to simulate changes in baseflow caused by subtle as well as large-scale changes in stresses. The estimated hydraulic parameters and prescribed inputs used in the calibrated model were confirmed by the sensitivity analysis as producing the best overall calibration statistics with a good balance between simulated water levels and baseflows.

## 9.3 Model Review and Quality Control

The CENEB model was subject to peer review by qualified, senior modeling professionals throughout each step of the model design, conceptualization, construction, calibration, and sensitivity analysis. The model review process included:

- Discussion and confirmation of model conceptualization and assumptions by senior reviewers
- Evaluation of the model design and conceptualization in the context of its intended purpose
- A review of all boundary conditions, including revised boundaries to the north, to ensure that the mathematical representation of the boundaries was reasonable for the project objectives
- Confirmation and verification of model inputs and analyses
- A detailed review of calibrated model input and output in a formalized quality control process
- An evaluation of water budget discrepancies (i.e., percent difference between water in and water out of the aquifer) and solver performance that resulted in the use of MODFLOW-NWT for the project
- A professional review of model concepts and implementation performed by a senior modeler not involved in the model design or development processes, to provide the equivalent of an independent 3rd party review

The review process was designed to ensure reasonable model assumptions and that these assumptions were appropriately implemented within the model code. Descriptions of model setup, calibration, and sensitivity analysis provided in this report were also independently reviewed for completeness and accuracy.

## 9.4 Conclusion Statement

Calibration of the CENEB model to steady state pre-1940 groundwater conditions and to transient conditions from 1940 through 2011 demonstrates the model's ability to simulate known long-term fluctuations in land use, recharge, pumping, groundwater flow, and groundwater-surface water interactions. The quantitative and qualitative calibration goals of the project were met and exceeded in every case. This level of calibration, verified spatially and at multiple time periods, demonstrates the model's ability to reproduce long-term trends under varying hydrologic and hydrogeologic conditions (Section 6), and that the model reasonably represents known surface water and groundwater flow conditions. Furthermore, a sensitivity study was performed to evaluate the response of the CENEB model calibration to changes in selected model input parameters and stresses (Section 7). The sensitivity analysis indicated that the model is sensitive to moderate shifts in pumping and very sensitive to variability in recharge. The strength of the CENEB model calibration, confirmation of the model conceptualization with respect to the model purpose, and the demonstration of model sensitivity to changes in groundwater pumping and recharge support the conclusion that the model is an appropriate tool for assessing the BWS and baseflow depletions within the model domain.

# References


American Society for Testing and Materials (ASTM), 2000. *Standard Guide for Documenting a Ground-Water Flow Model Application*, D 5718-95 (Reapproved 2000).

Anderson, Mary P., and William W. Woessner, 1992. *Applied Groundwater Modeling: Simulation of Flow and Advective Transport,* Academic Press, San Diego, 1992.

Arnold, J. G. and Allen, P. M., 1999. *Validation of Automated Methods for Estimating Baseflow and Groundwater Recharge from Stream Flow Records.* Journal of American Water Resources Association, 35:411-424.

Bentall, R., and F. B. Schaffer, 1979, *Availability and Use of Water in Nebraska*, 1975. University of Nebraska, Conservation Survey Division, Nebraska Water Survey Paper 48.

Blue Marble Geographics, 2013, Global Mapper™ software.

Center for Advanced Land Management Information Technologies (CALMIT), 2007. 2005 Nebraska Land Use Patterns: Lincoln Nebraska CALMIT, remote-sensing image, scale 1:100,000, accessed October 2011 at http://www.calmit.unl.edu/2005landuse/statewide.shtml.

Chen, X., Chen X., Rowe, C., Hu, Q., and Anderson M., 2003. "Geological and Climatic Controls on Streamflows in the Nebraska Sand Hills," *Journal of the American Water Resources Association,* 39(1):217-228.

Chen, X. and X. Chen, 2004. *Simulating the Effects of Reduced Precipitation on Ground Water and Streamflow in the Nebraska Sand Hills*, Journal of the American Water Resources Association (JAWRA), 40(2):419-430.

Conservation and Survey Division, 1973. Topographic Regions Map of Nebraska, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Conservation and Survey Division, 1996. *Configuration of the Water Table, 1979*, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, digital data.

Conservation and Survey Division, 2003. *1995 Water Table Contours*, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, digital data.

Conservation and Survey Division, 2010. *Development of Niobrara Basin Hydrogeologic and Hydrostratigraphic Framework – Completion Report*, School of Natural Resources, University of Nebraska-Lincoln, June.

Doherty, John, 2008a. PEST, Model Independent Parameter Estimation User Manual (5th ed): Brisbane, Australia, Watermark Numerical Computing.

Doherty, John, 2008b. PEST, Model Independent Parameter Estimation – Addendum to user manual (5th ed): Brisbane, Australia, Watermark Numerical Computing.

Environmental Simulations, Inc., 2011, Guide to Using Groundwater Vistas, version 6.

Esri, 2011, ArcGis™ software, version 10.1.

Esri, 2013, ArcGis™ digital data.

Filipovic, D., 2004. *Hydrogeologic Assessment of the High Plains Aquifer in Tripp and Gregory Counties, South Dakota,* South Dakota Geological Survey Open File Report 90-UR.

The Flatwater Group, in progress. *Central Nebraska (CENEB) Model: Regionalized Soil Water Balance Model*.

Golden Software, Inc., 2008, Surfer® software.

Gutentag, E. D., Heimes, F. J., Korthe, N. C., Luckey, R. R., and Weeks, J. B., 1984. *Geohydrology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming*, U.S. Geological Survey Professional Paper 1400-B, 63 p.

Harbaugh, A. W., *MODFLOW-2005, the U.S. Geological Survey Modular Ground-Water Model – The Ground-Water Flow Process*, U.S. Geological Survey Techniques and Methods 6 – A16, 2005, 253 pp.

Kolm, K. E., and Case, H. L. III, 1983. *A Two-Dimensional, Finite-Difference Model of the High Plains Aquifer in Southern South Dakota*, U.S. Geological Survey Water-Resources Investigations Report 83-4175.

Long, A. J., Putnam, L. D., and Carter, J. M., 2003. *Simulated Ground-Water Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota*, U.S. Geological Survey, Scientific Investigations Report 03-4043, Reston, Virginia, 69 p.

Long, A. J. and Putnam, L. D., 2010. *Simulated Groundwater Flow in the Ogallala and Arikaree Aquifers, Rosebud Indian Reservation Area, South Dakota – Revisions with Data Through Water Year 2008 and Simulations of Potential Future Scenarios,* U.S. Geological Survey, Scientific Investigations Report 2010-5105, 54 p.

Lyne, V. D. and Hollick, M. 1979. *Stochastic time-variable rainfall-runoff modeling*. Hydrology And Water Resources Symposium, Institution of Engineers Australia, Perth. pp. 89-92.

Malo, 1997. South Dakota's Physiographic Regions fact sheet, Northern State University CUEST Center for Environmental Education, Aberdeen, SD, http://www3.northern.edu/natsource/EARTH/Physio1.htm, Date of Access: May 18, 2012.

Martin, D. L., Watts, D.G., and Gilley, J.R., 1984. *Model and Production Function for Irrigation Management*, Biological Systems Engineering: Papers and Publications. Paper 58.

McGuire, V. L., 2009. *Water-Level Changes in the High Plains Aquifer, Predevelopment to 2007, 2005-06, and 2006-07*. U. S. Geological Survey Scientific Investigations Report 2009-5019.

McMahon, P. B., Dennehy, K. F., Bruce, B. W., Gurdak, J. J., and Qi, S. L., 2007. *Water-Quality Assessment of the High Plains Aquifer, 1999-2004*: U.S. Geological Survey Professional Paper 1749, 136 pp.

Nathan, R. J. and McMahon, T. A., 1990. Evaluation of automated techniques for baseflow and recession analysis. Water Resources Research, 26, 1465-1473.

NCDC, 2012. Long-Term Monthly Precipitation Data by Climate Division, National Climatic Data Center, National Oceanic and Atmospheric Administration, http://www.ncdc.noaa.gov/climate-information, digital data.

NDNR, 2006. DNR Methods Used for Historical Consumptive Use Calculations, May.

NDNR, 2012. Annual Evaluation of the Determination of Hydrologically Connected Water Supplies; Determination of Fully Appropriated, December 21, 2012.

NDNR, 2013. Land Use Study for the CENEB Model Project, unpublished GIS analysis.

Nebraska Natural Resources Commission, 1982, *Policy Issue Study on Instream Flows*, Conservation and Survey Division, University of Nebraska-Lincoln.

Niswonger, R. G. and Prudic, D. E., 2010. *Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams – A modification to SFR1*, U.S. Geological Survey Techniques and Methods 6 – A13, Version 1.30, April 2010, 50 pp.

Niswonger, R. G., Panday, S., and Ibaraki, M., 2011. *MODFLOW-NWT, A Newton Formulation for MODFLOW-2005*, U.S. Geological Survey Techniques and Methods 6 – A37, 2011, 44 pp.

Peterson, S. M., Stanton, J. S., Saunders, A. T., and Bradley, J. R., 2008. Simulation of Ground-water Flow and Effects of Ground-water Irrigation on Base Flow in the Elkhorn and Loup River Basins, Nebraska: U.S. Geological Survey Scientific Investigations Report 2008-5143, 65 p.

Peterson, S. M., and Strauch, K. R., 2007. Streamflow Measurements in North-Central Nebraska, November 2006: U.S. Geological Survey Data Series 332, 29 p.

Prudic, David E., Konikow, Leonard and Banta, Edward, *A New Streamflow-Routing (SFR1) Routing Package to Simulate Stream-Aquifer Interaction with MODFLOW-2002*, U.S. Geological Survey Open-File Report 2004-1042.

Rahn, P. H., and Paul, H. A., 1975. Hydrogeology of a Portion of the Sand Hills and Ogallala Aquifer, South Dakota and Nebraska, *Ground Water*, Vol. 13, No. 5, September-October 1975.

Reilly, T.E., and Harbaugh, A.W., 2004. Guidelines for Evaluating Ground-Water Flow Models, U.S. Geological Survey Scientific Investigations Report 2004-5038, Version 1.01, 30 p.

Soenksen, P. J., B. B. Flyr, J. S. Alexander, and N. J. Schaepe, 2010, *Streamflow Gains and Losses in the Niobrara River Basin*, Nebraska, 1980 and 2009, Journal of Environmental Hydrology, Volume 18.

Stanton, J. S., Peterson, S. M., and Fienan, M. N. 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.

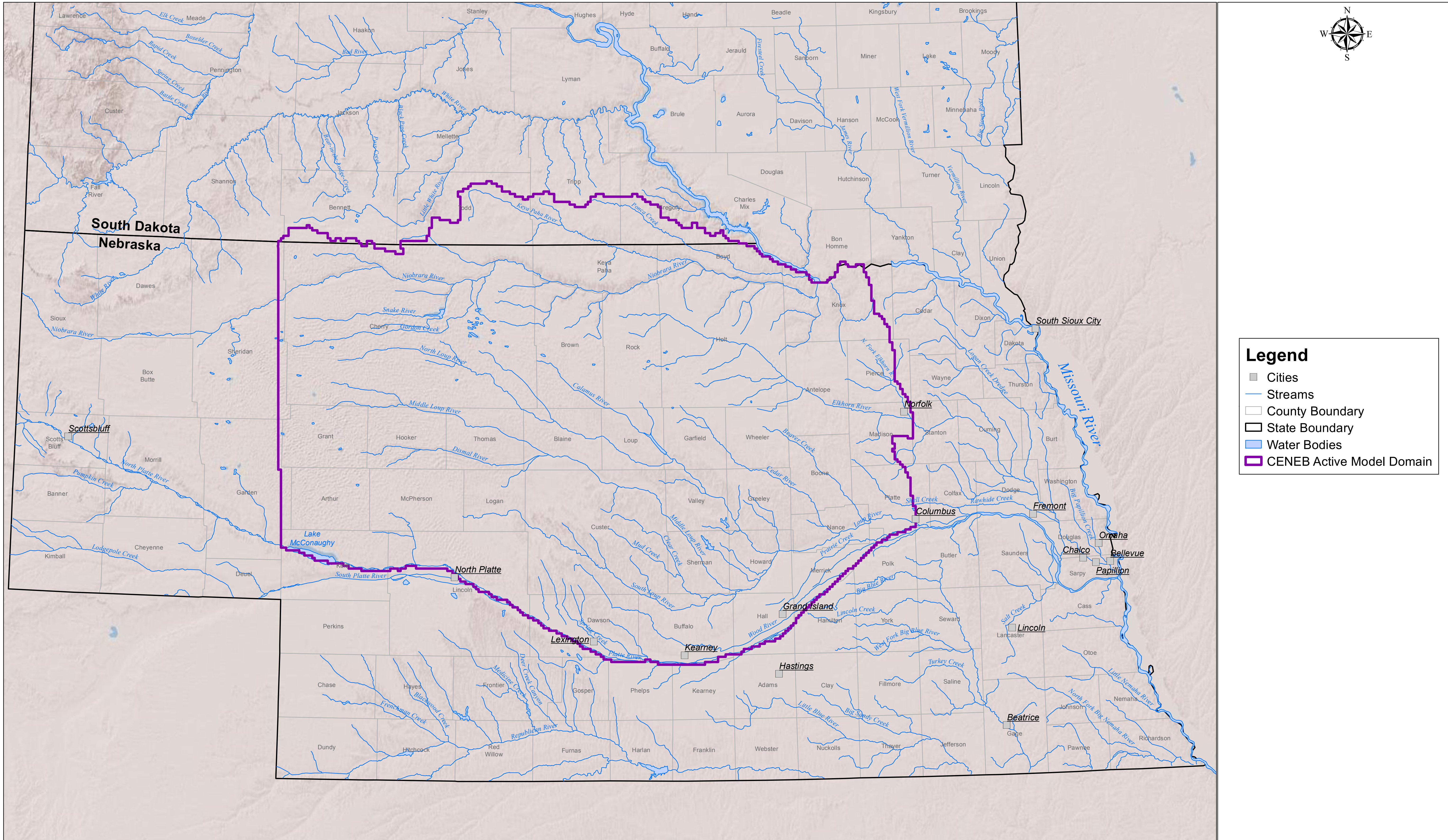
Szilagyi, J., Harvey, F. E., and Ayers, J. F., 2003. "Regional Estimation of Total Recharge to Ground Water in Nebraska*," Ground Water 43, no. 1: 63-69.*

Szilagyi, J. and Jozsa, J., 2012, *MODIS-Aided Statewide Net Groundwater-Recharge Estimation in Nebraska*, unpublished study.

United States Fish and Wildlife Service (USFWS), 2013. National Wetlands Inventory, digital database: http://www.fws.gov/wetlands/.

United States Geological Survey (USGS) 2012. National Hydrography Dataset: http://nhd.usgs.gov/.

# Figures




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief- ESRI

Projection: Nebraska State Plan (FIPS 2600)

NAD 1983 Feet

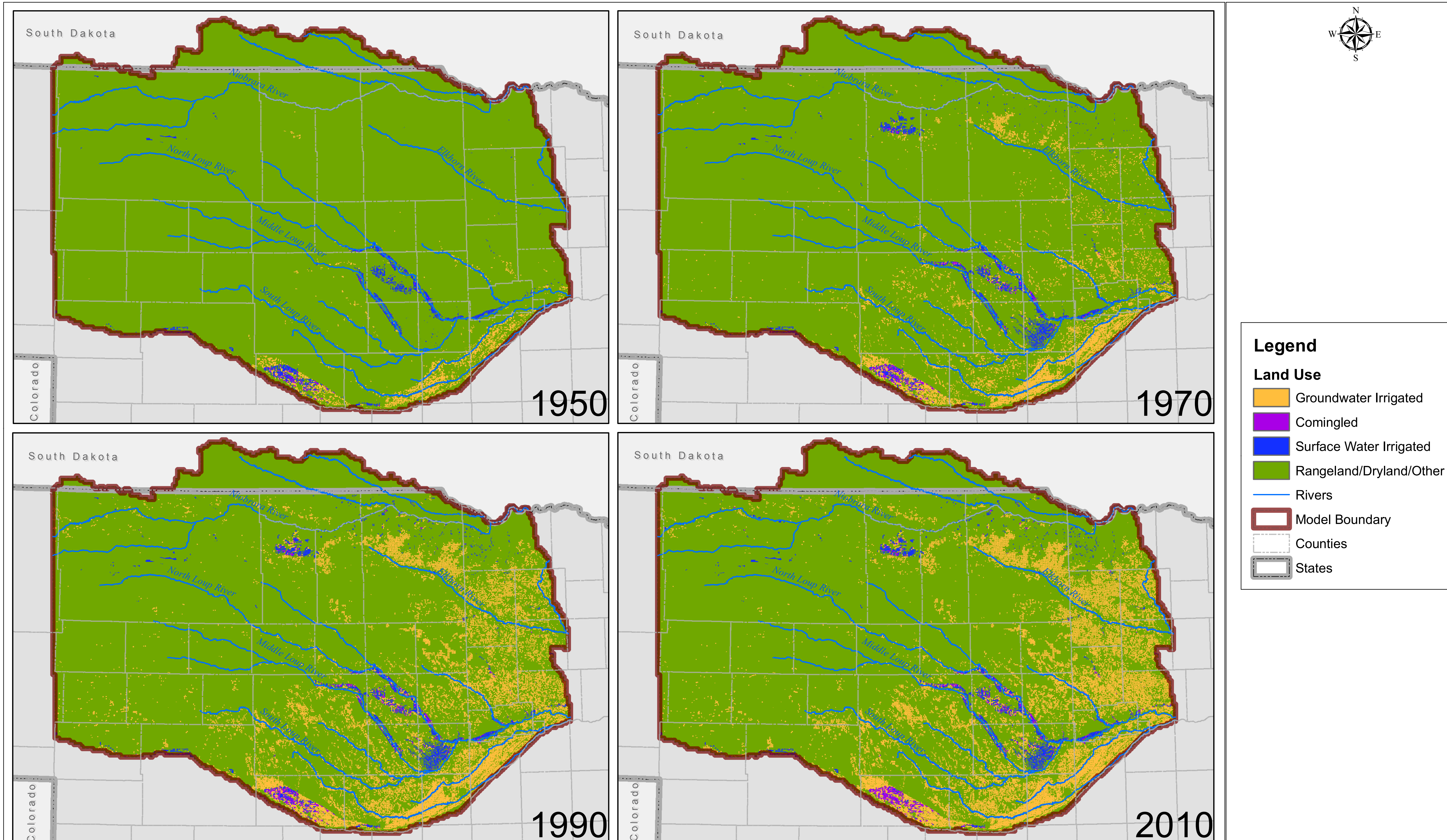
0 10 20 40 Miles

1 in = 35 miles

Nebraska Department of Natural Resources

**Figure 1-1**
**Location Map**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figure_1-1_Template1_11x17L.mxd




Brown AND Caldwell

Date: 07/17/2013

Project No: 142198

Client: NDNR

Sources: LLNRD Digitized Certified Acres datasets
MNNRD Digitized Certified Acres datasets
2005 CALMIT Irrigated Pivots and Other Irrigation datasets
NDNR Surface Water Rights Digitized Fields
NDNR Points of Diversion dataset
NDNR Registered Groundwater Wells dataset
2012 Farm Service Agency aerial imagery
National Hydrography Dataset

Projection/Datum: Nebraska State Plane/ NAD 1983

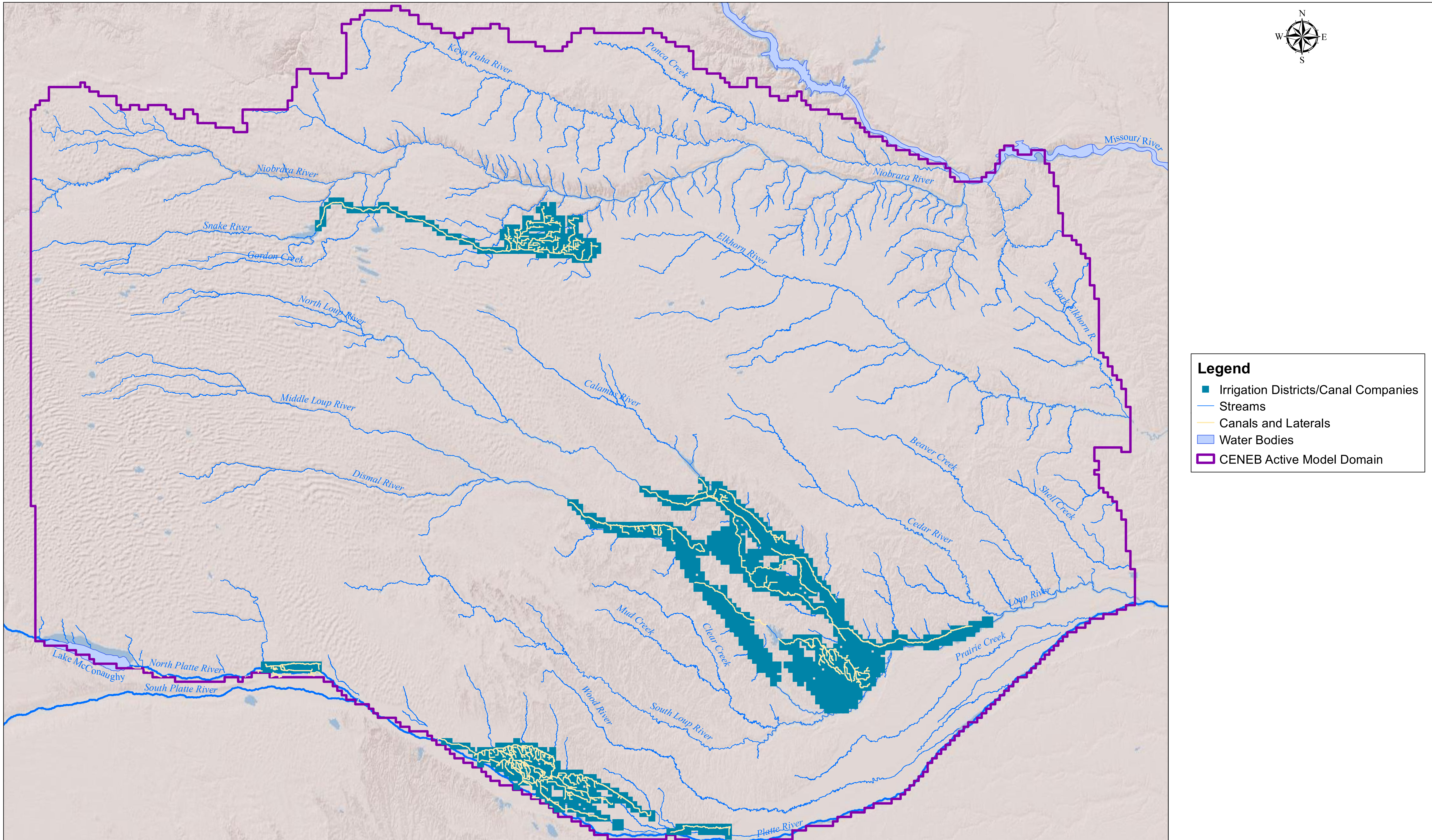
1 in = 43 miles

0 5 10 20 30 40 Miles

Nebraska Department of Natural Resources

**Figure 2-1**
**CENEB Historical Irrigation Snapshots**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\\\SERVER16\awright\CENEB\Documents\figures\CENEBmodelsYearlySnapshots_NoDryland.mxd




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

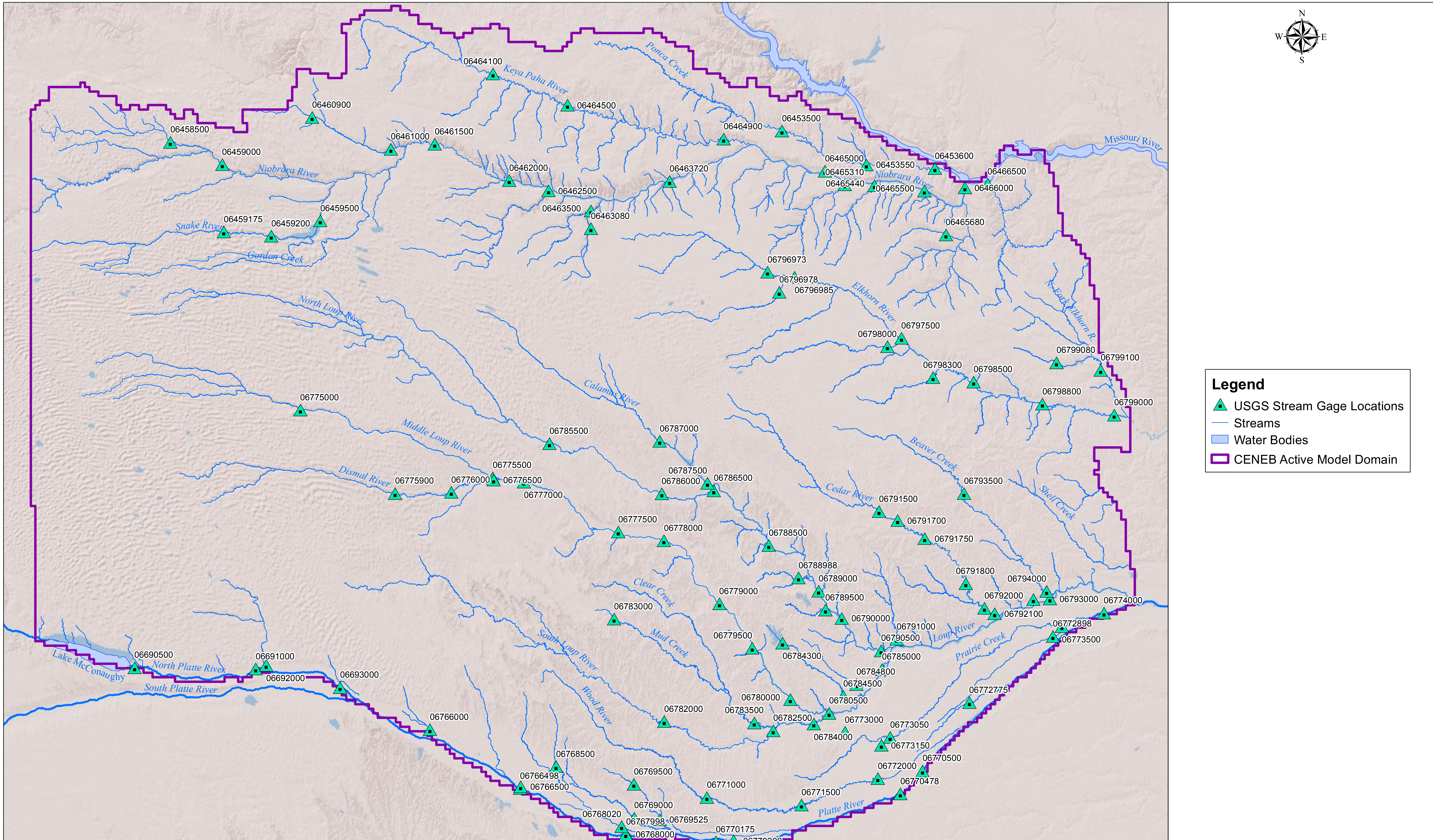
0 5 10 20 Miles
1 in = 20 miles

Nebraska
Department of Natural Resources

**Figure 2-2**
**Streams, Irrigation Districts, and Canals**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_2-2_2-3_4-2 StreamsCanalsGages WLContours.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

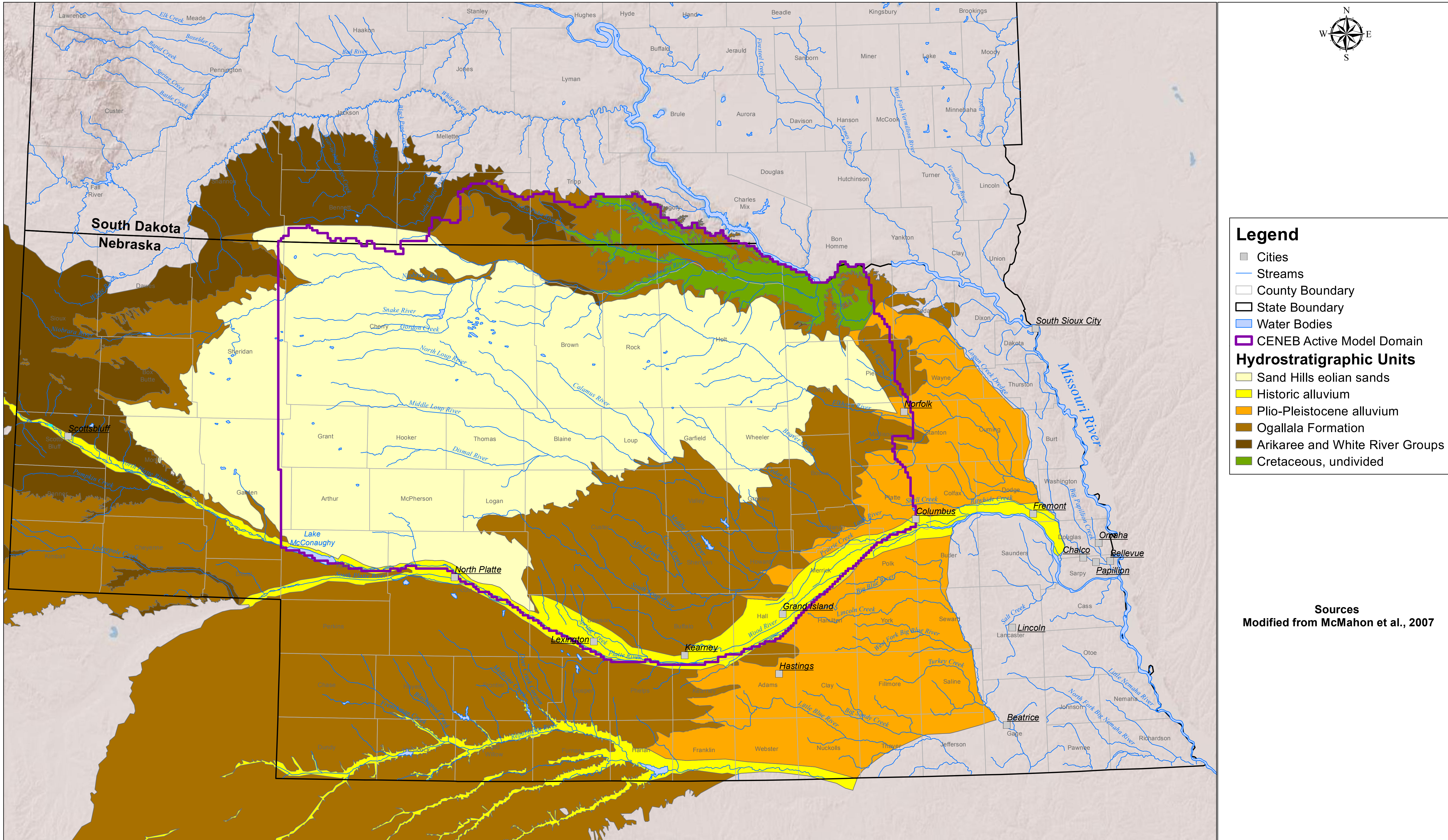
0 5 10 20 Miles
1 in = 20 miles

Nebraska
Department of Natural Resources

**Figure 2-3**
**USGS Gaging Stations in the Model Domain**
**CENEB Model Report**
**State of Nebraska**

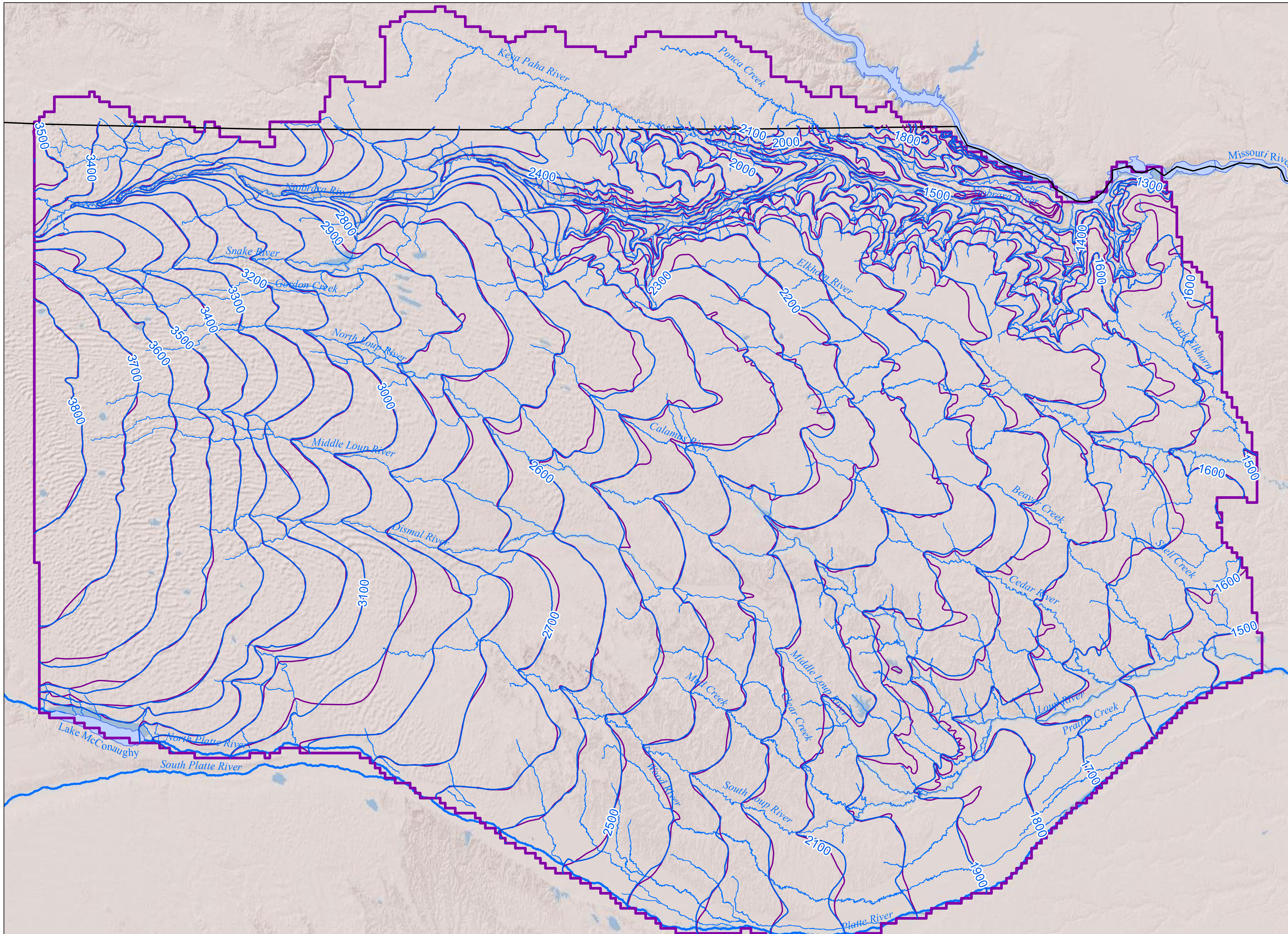
Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_2-2_2-3_4-2 StreamsCanalsGages WLContours.mxd

User: ccikoski




<table>
<tr>
<td>Brown AND Caldwell</td>
<td>Date: 07/22/2013<br>Project No: 142198<br>Client: NDNR</td>
<td>Basemap: Shaded Relief- ESRI<br>Projection: Nebraska State Plan (FIPS 2600)<br>NAD 1983 Feet</td>
<td>0 10 20 40 Miles<br>1 in = 35 miles</td>
<td>Nebraska<br>Department of Natural Resources</td>
<td>Figure 4-1<br>Hydrostratigraphic Units<br>CENEB Model Report<br>State of Nebraska</td>
</tr>
</table>

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figure_3-1_largeScale_Geology_20130712.mxd




## Legend

- 1979 Water Level Contours
- 1995 Water Level Contours
- State Boundary
- Streams
- Water Bodies
- CENEB Active Model Domain

**NOTE:**
**Contour Interval = 100 ft**
**Contours not available for South Dakota**

**Sources**
**1979 Water Level Contours:**
**Conservation and Survey Division, 1996**

**1995 Water Level Contours:**
**Conservation and Survey Division, 2003**

Brown AND Caldwell

Date: 07/22/2013
Project No: 142198
Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

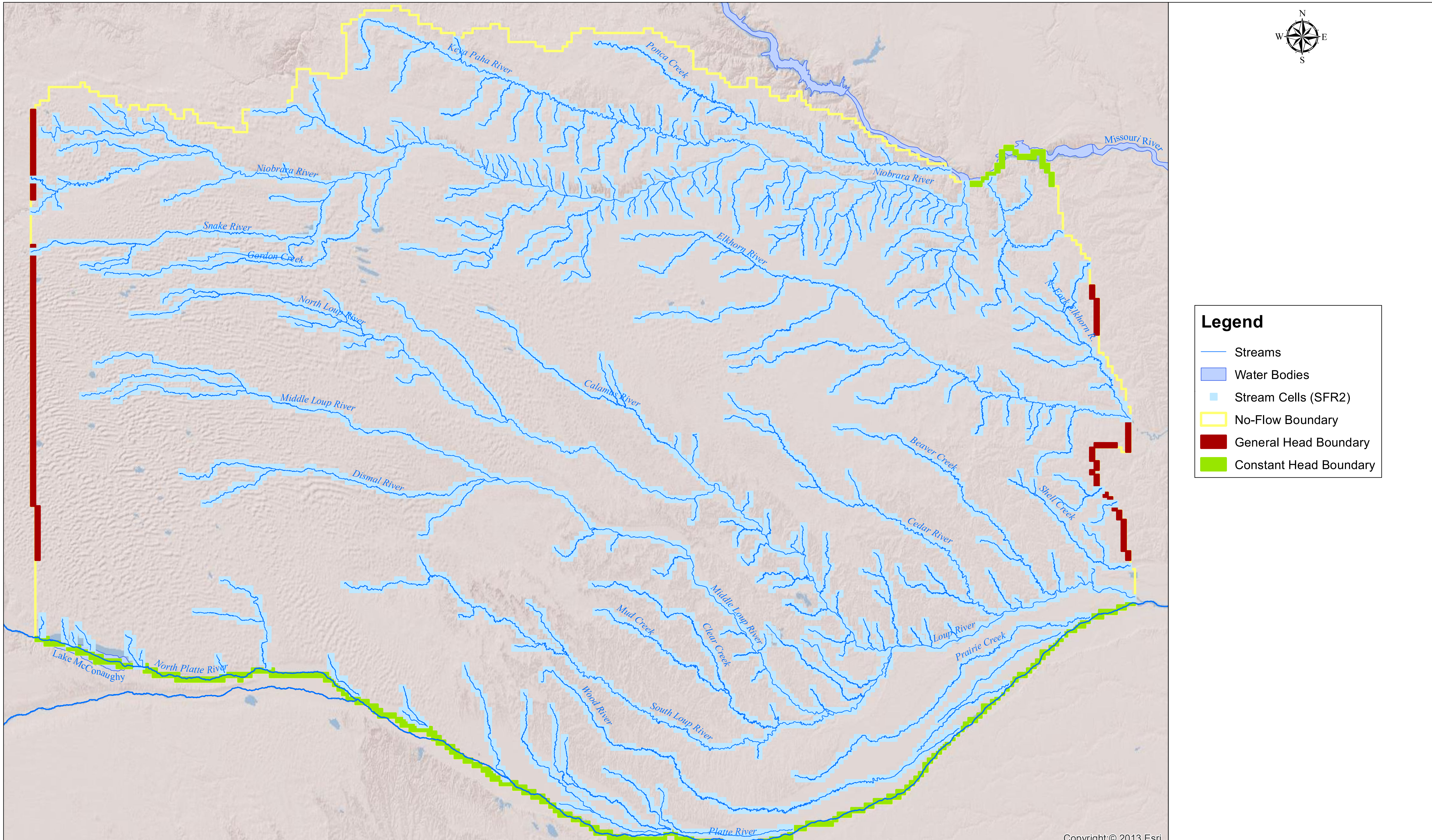
0 5 10 20 Miles
1 in = 20 miles

Nebraska Department of Natural Resources

**Figure 4-2**
**1979 and 1995 Water Level Contours**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_2-2_2-3_4-2 StreamsCanalsGages WLContours.mxd

User: jwright




Brown AND Caldwell

Date: 8/2/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

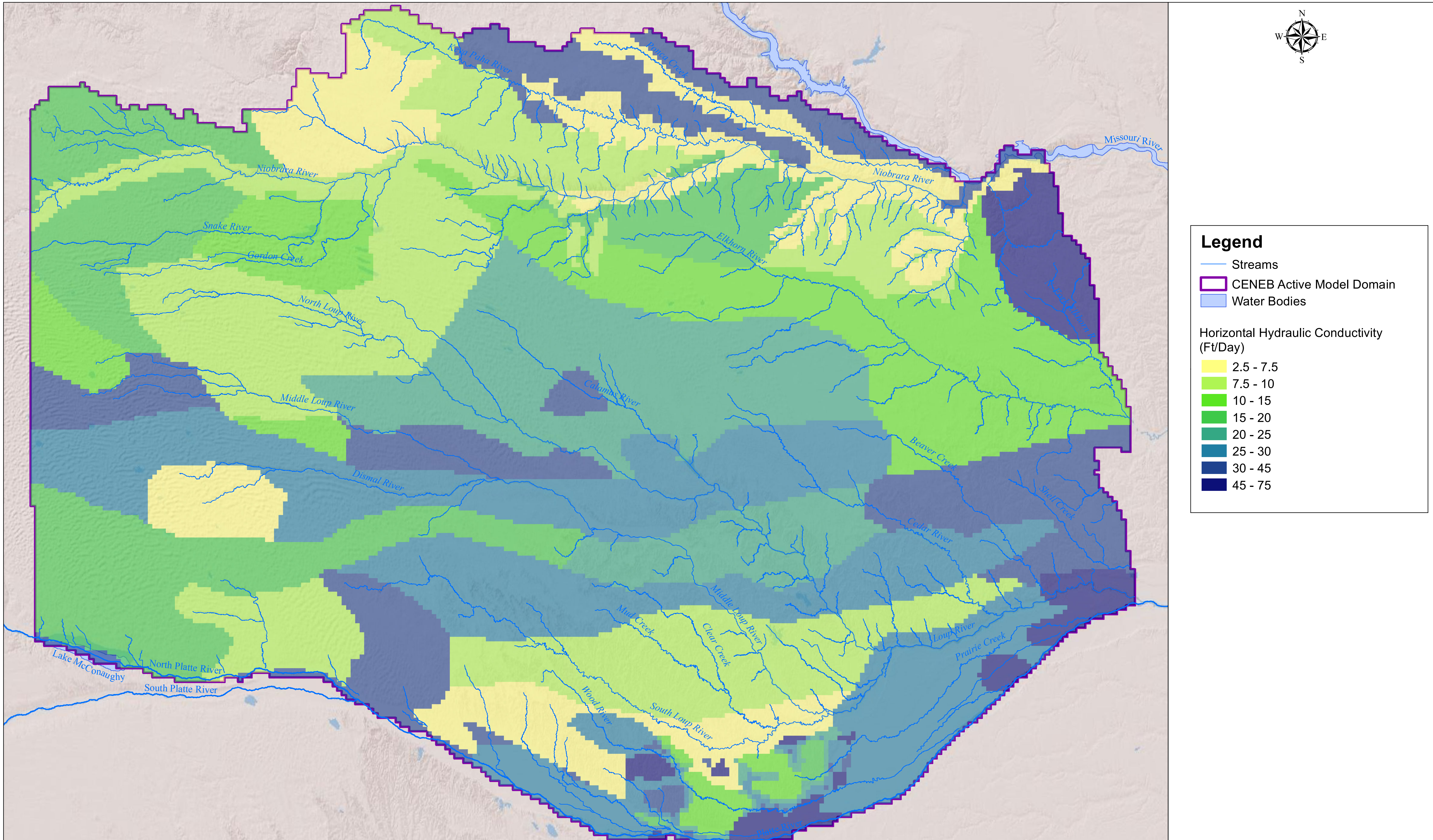
0 5 10 20 Miles
1 in = 20 miles

Nebraska Department of Natural Resources

**Figure 5-1**
**Boundary Conditions and Stream Cells**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-1.mxd

User: jwright




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

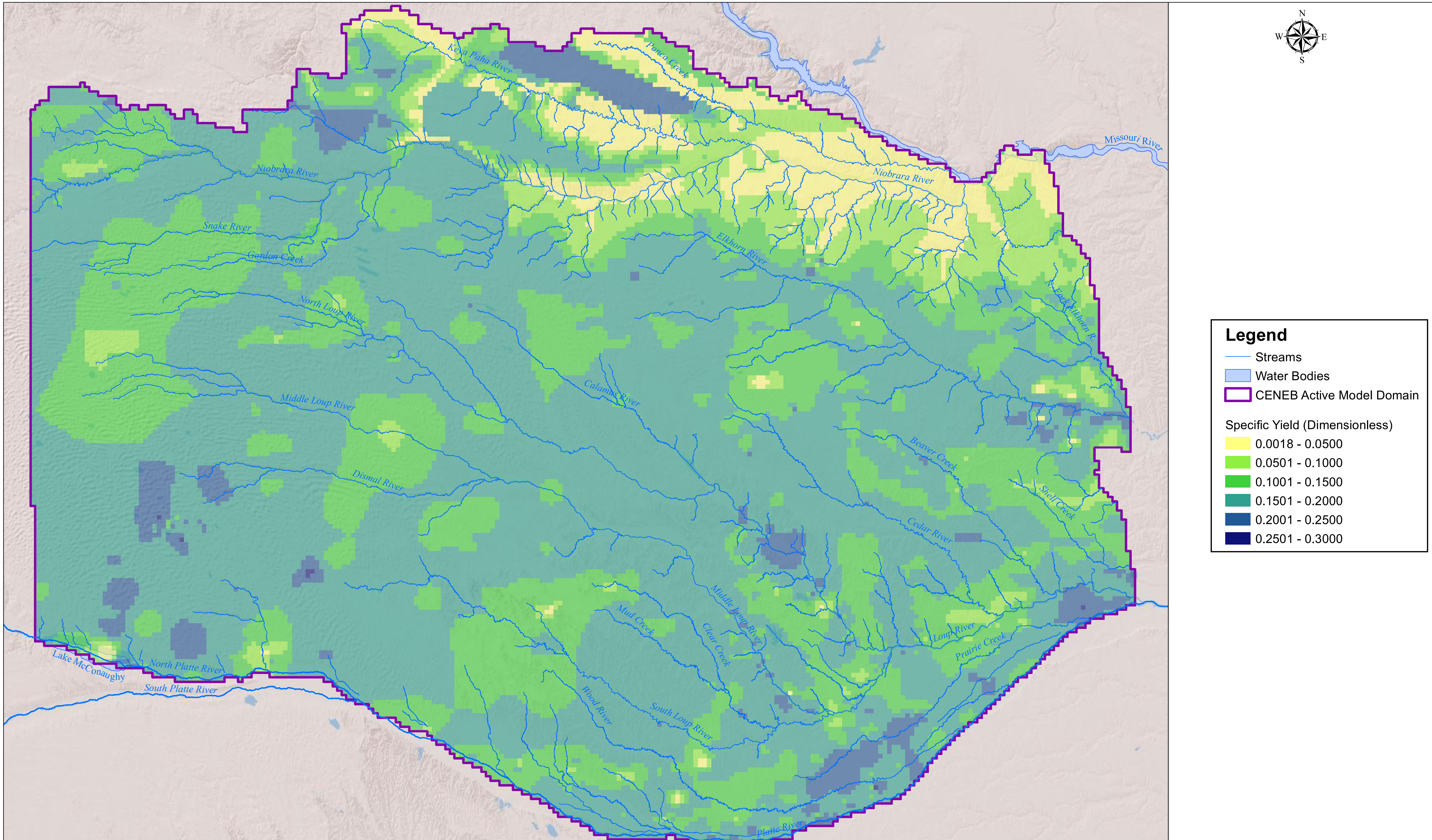
Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

Nebraska
Department of Natural Resources

**Figure 5-2**
**Hydraulic Conductivity Distribution**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-1_5-2_5-3_5-4_Boundaries-K-Sy-ET.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

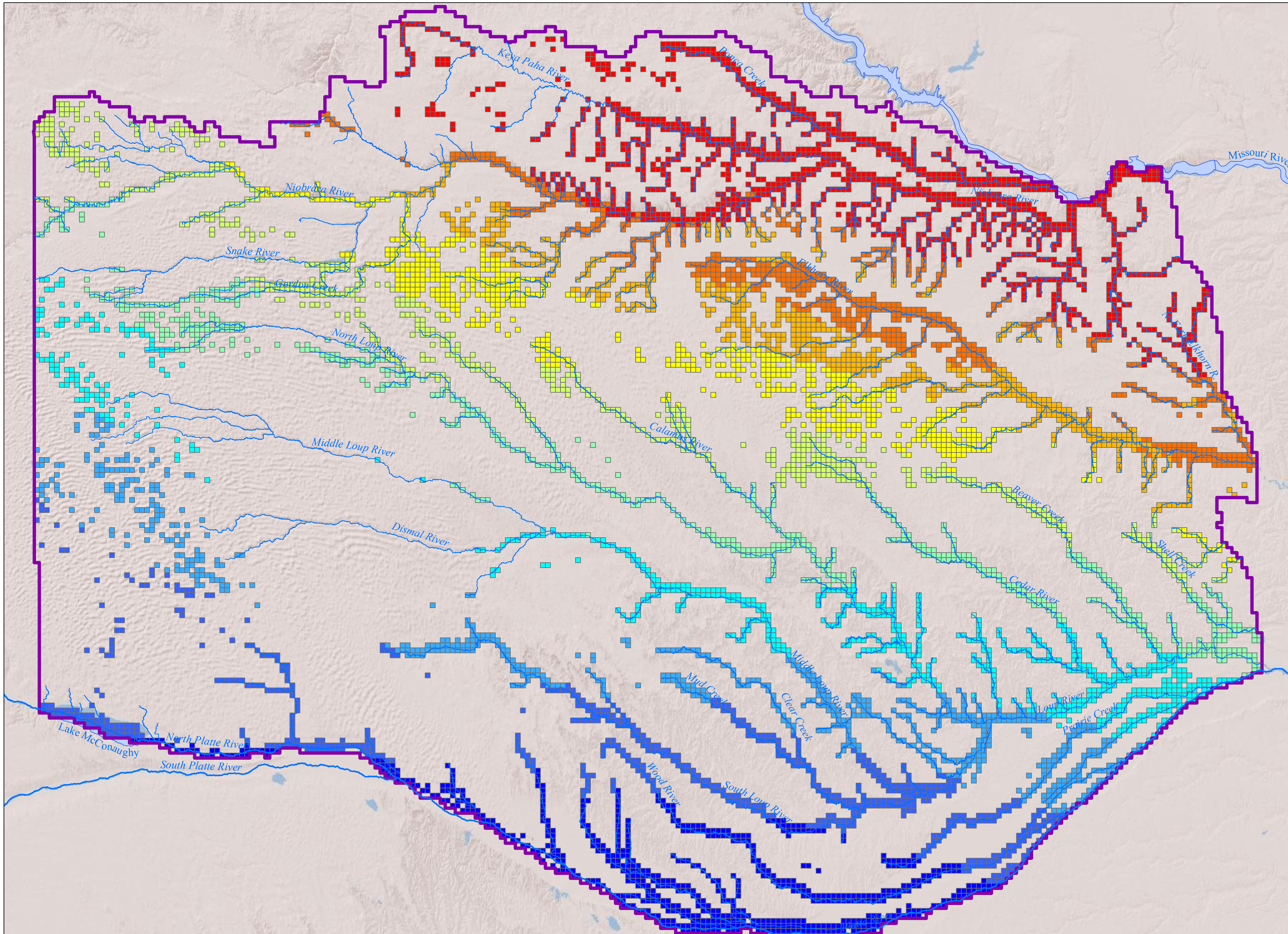
Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

Nebraska
Department of Natural Resources

**Figure 5-3**
**Specific Yield Distribution**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Temp\Fig5-3_Spec_Yield_Dist_JJT_06142013.mxd

User: ccikoski




N
W E
S

**Legend**

- Streams
- Water Bodies
- CENEB Active Model Domain

Evapotranspiration Rates (Feet/Day)

- 0.00103 - 0.00132
- 0.00133 - 0.00135
- 0.00136 - 0.00141
- 0.00142 - 0.00158
- 0.00159 - 0.00174
- 0.00175 - 0.00188
- 0.00189 - 0.00223
- 0.00224 - 0.00249
- 0.00250 - 0.00288
- 0.00289 - 0.00369

Brown AND Caldwell

Date: 07/22/2013
Project No: 142198
Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

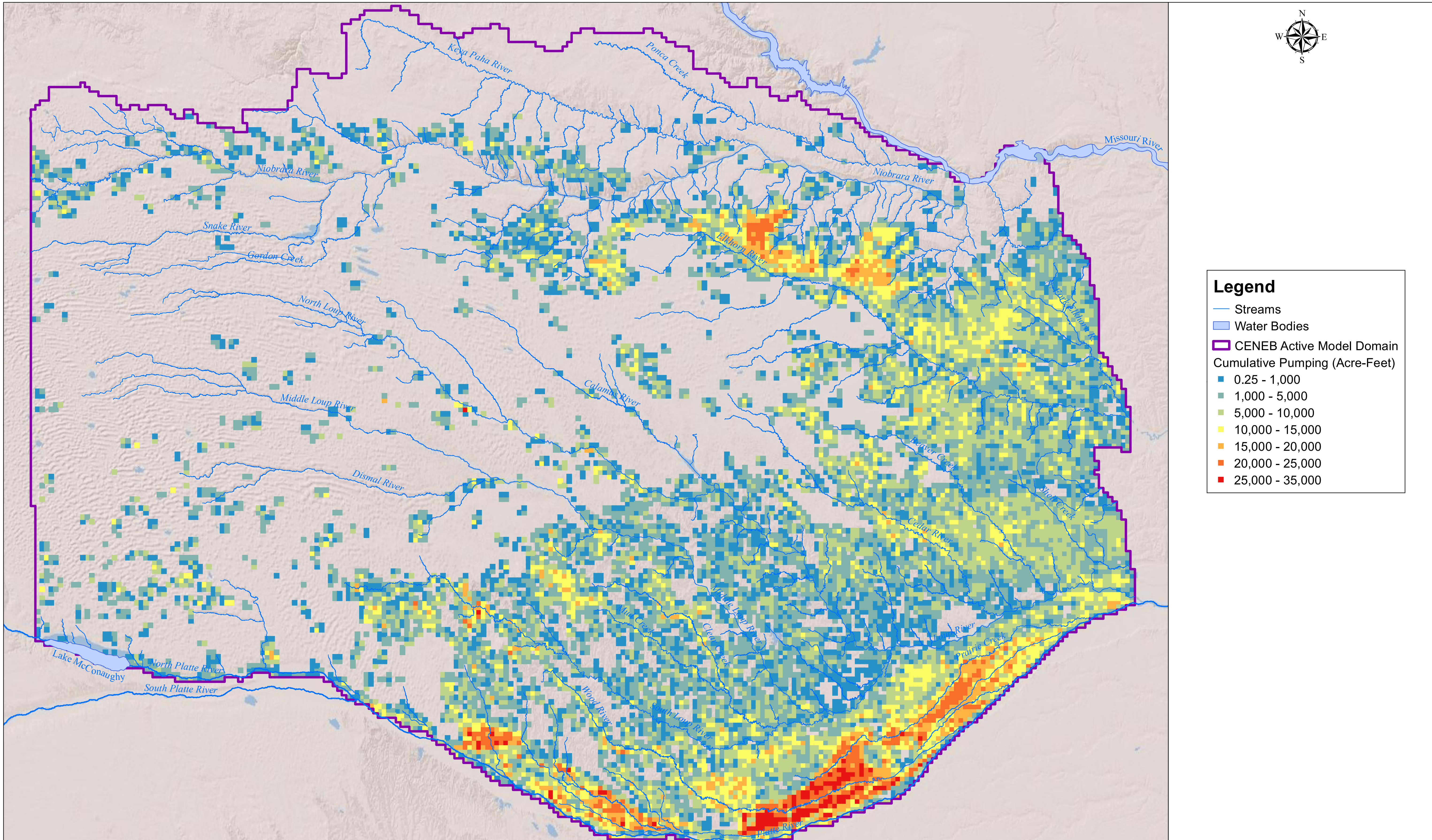
0 5 10 20 Miles
1 in = 20 miles

Nebraska
Department of Natural Resources

**Figure 5-4**
**Evapotranspiration Rates**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Temp\Fig5-4_Evapotrans_JJT_06142013.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

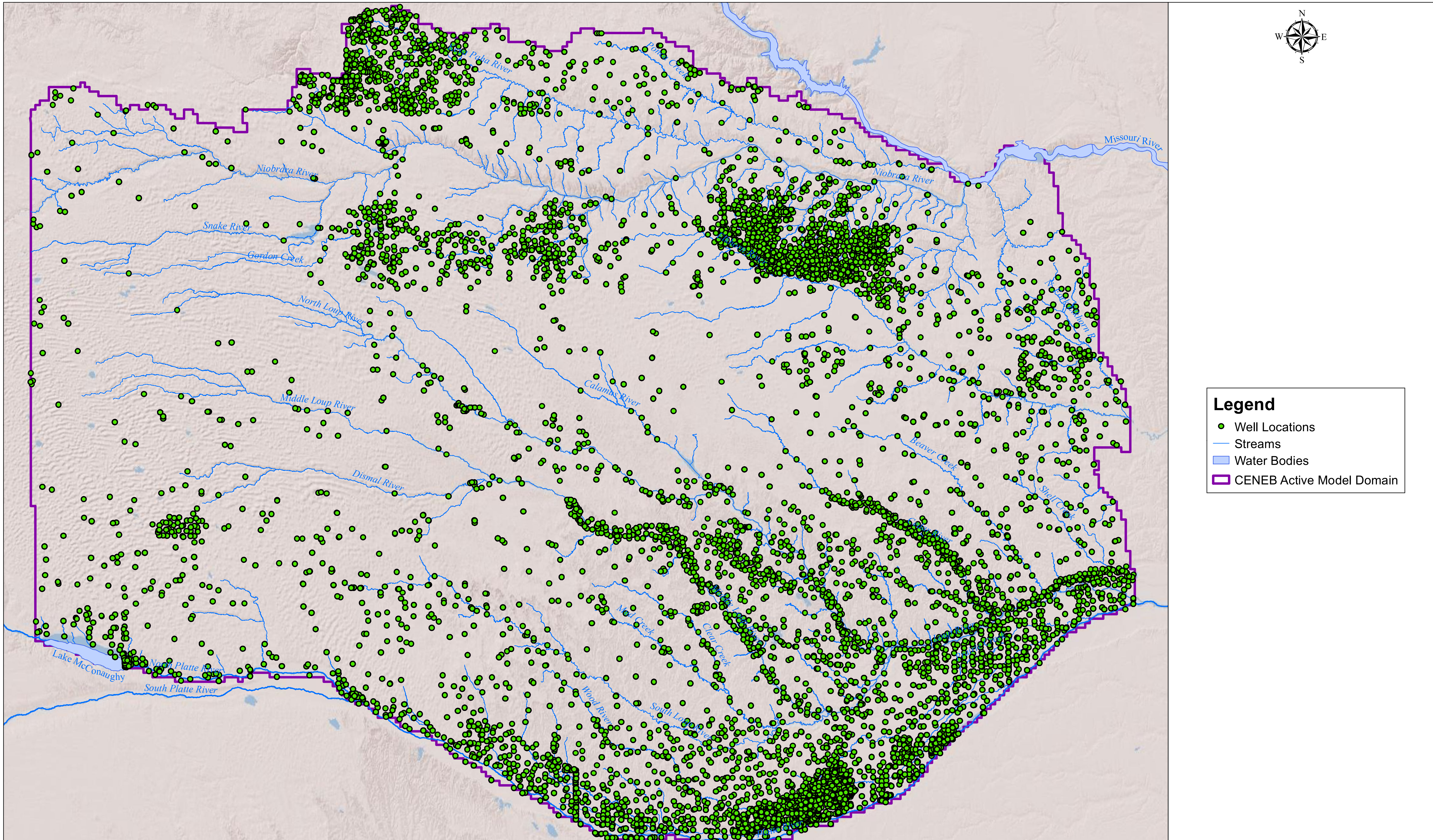
0 5 10 20 Miles
1 in = 20 miles

Nebraska Department of Natural Resources

**Figure 5-5**
**Distribution of Pumping Stresses**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013
Project No: 142198
Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

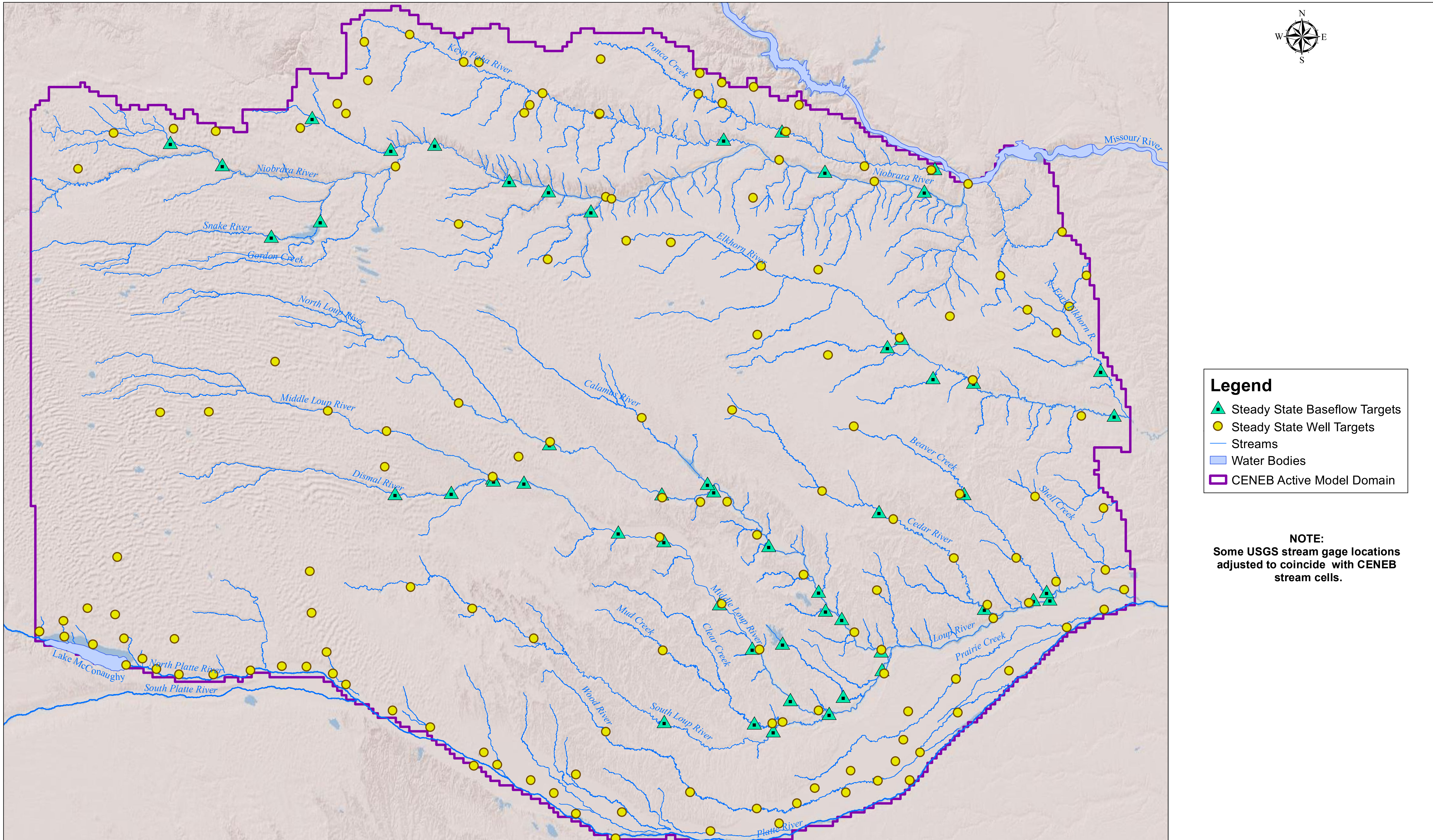
0 5 10 20 Miles
1 in = 20 miles

Nebraska Department of Natural Resources

**Figure 6-1**
**Wells Located in the CENEB Model Domain**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

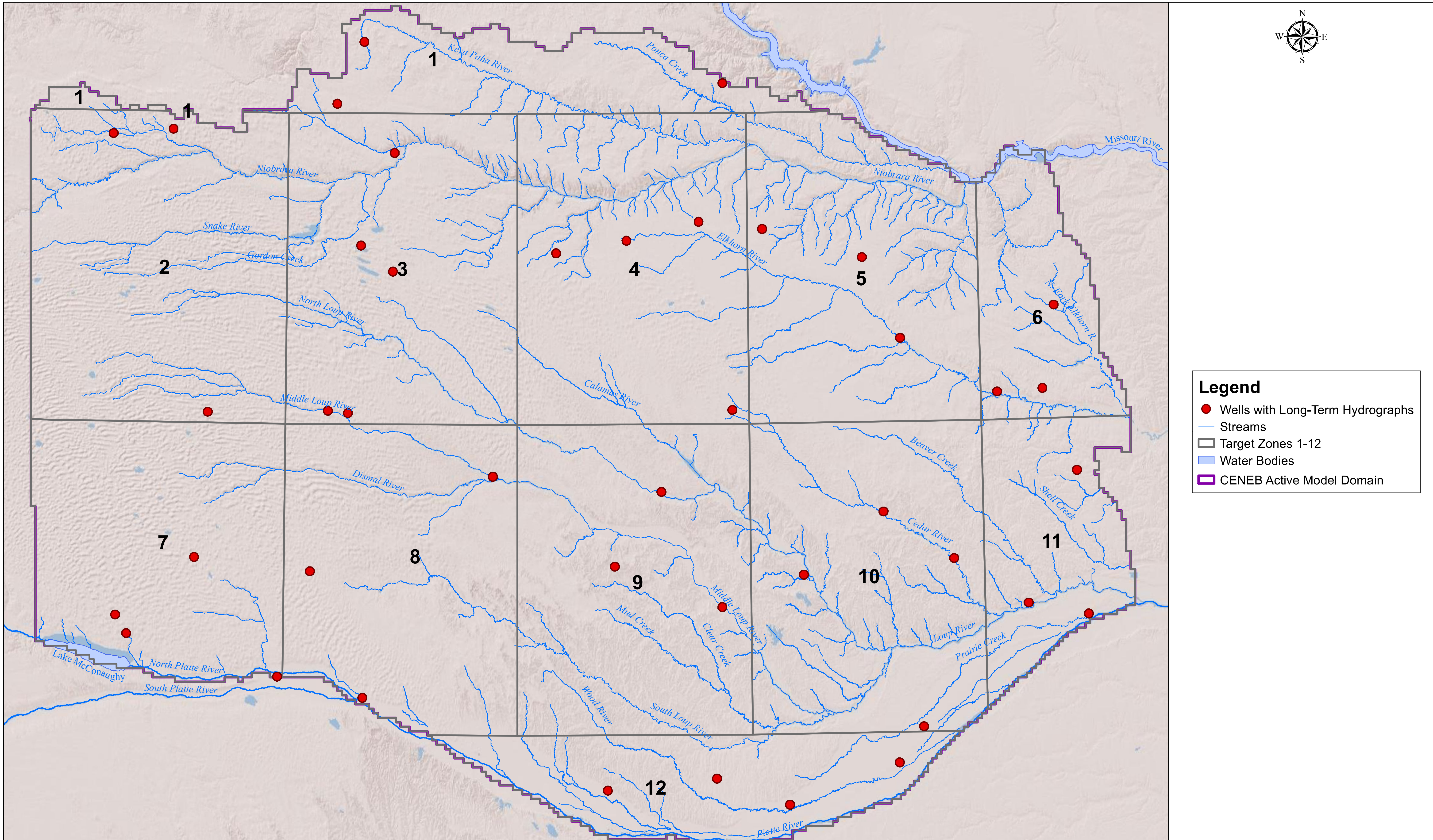
Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

Nebraska Department of Natural Resources

**Figure 6-2**
**Steady State Calibration Targets**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

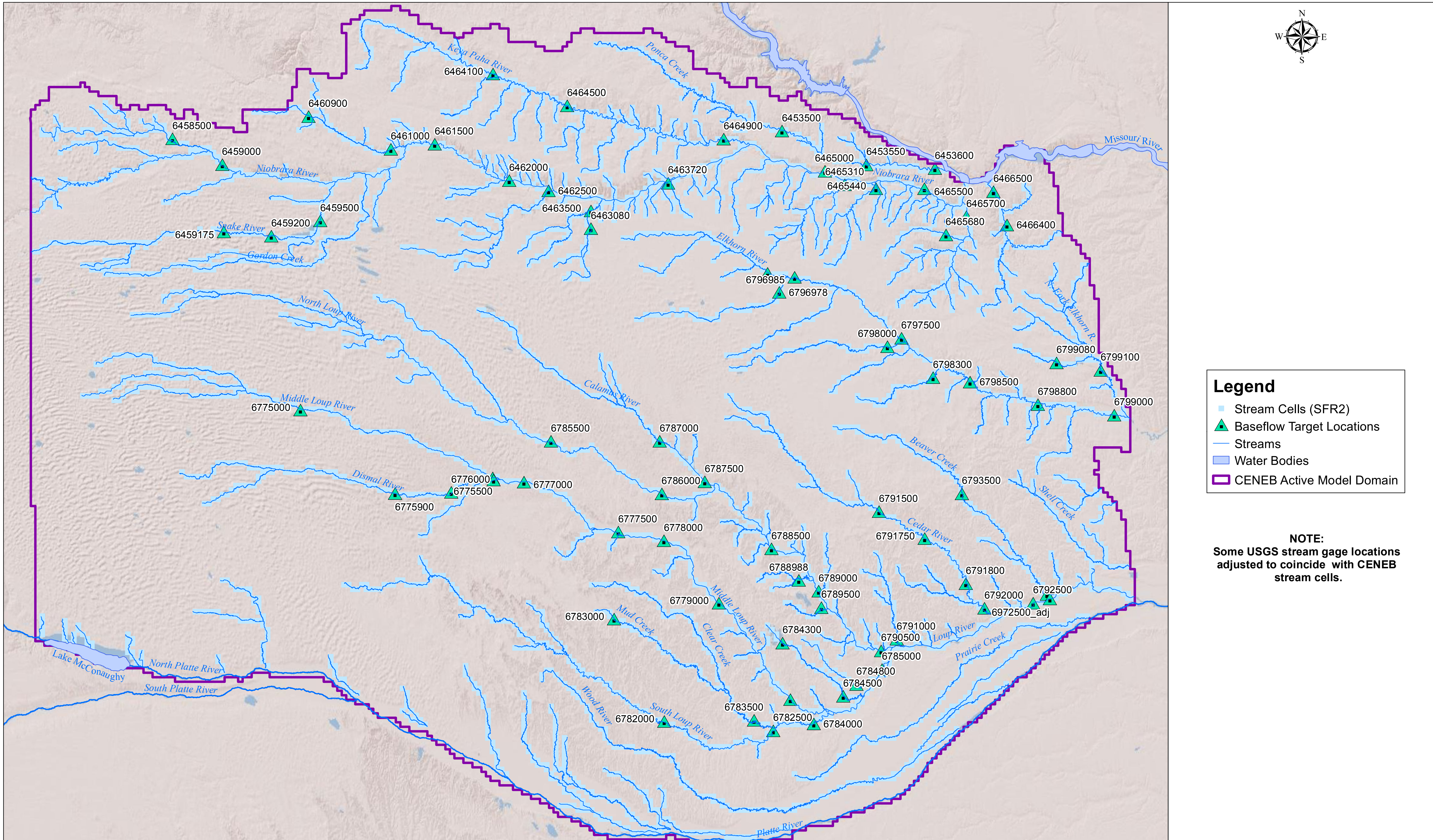
0 5 10 20 Miles
1 in = 20 miles

Nebraska Department of Natural Resources

**Figure 6-3**
**Well Targets with Long-Term Hydrographs**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI

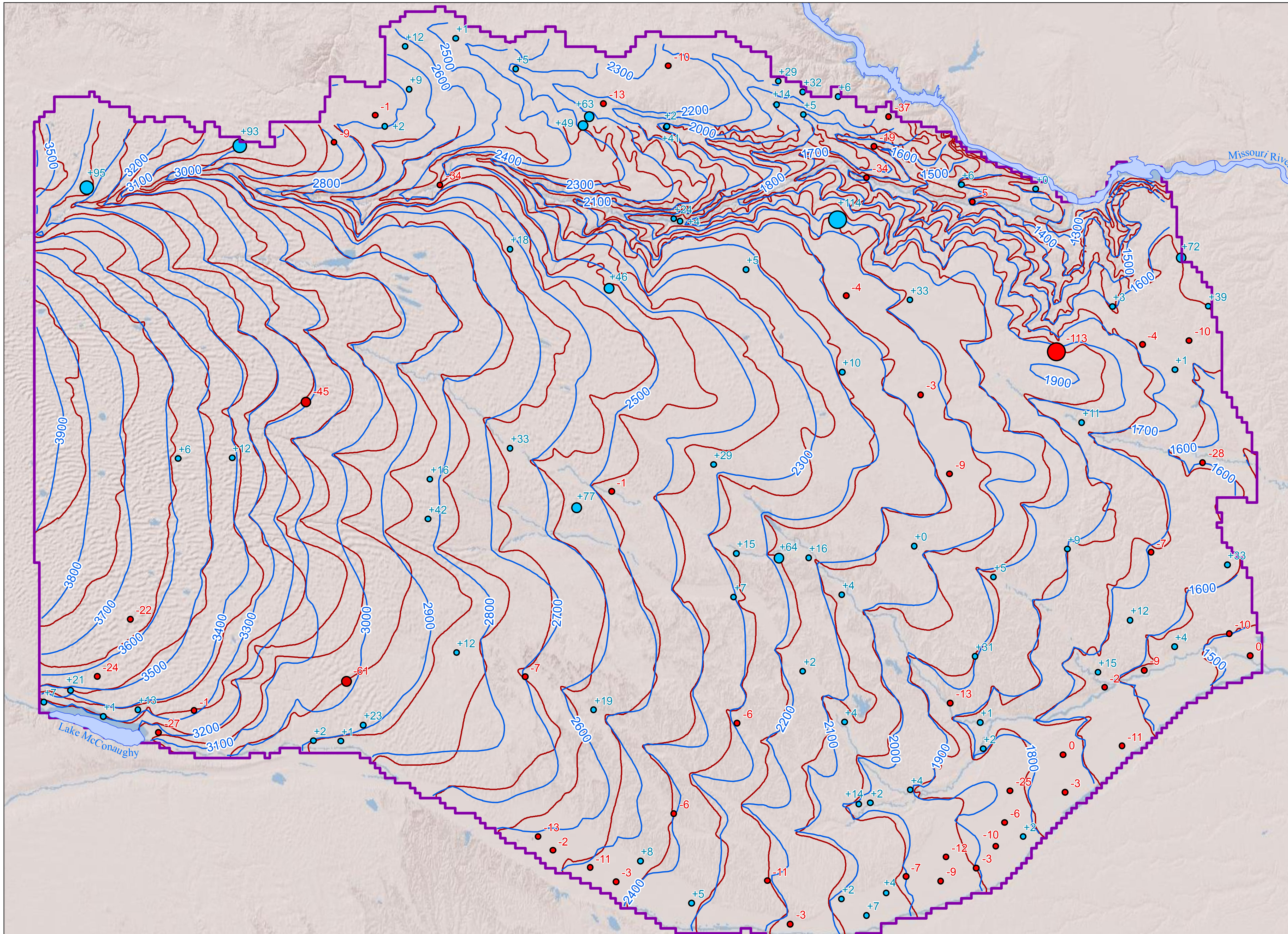
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

Nebraska Department of Natural Resources

**Figure 6-4**
**Stream Gages Used as Baseflow Targets**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




**Legend**

- Steady-State Water Level Contours
- 1979 Water Level Contours
- Water Bodies
- CENEB Active Model Domain

Steady-State Head Residuals (Ft)

- -113 - -110
- -110 - -80
- -80 - -45
- -45 - 0
- +1 - +44
- +44 - +79
- +79 - +110
- +110 - +114

**NOTES:**
**Contour interval of 100 ft**
**Residual = Observed minus Simulated Head**

**Sources**
**Steady-State Water Level Contours:**
**CENEB Model Output**

**1979 Water Level Contours:**
**Conservation and Survey Division, 1996**

Brown AND Caldwell

Date: 07/22/2013
Project No: 142198
Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

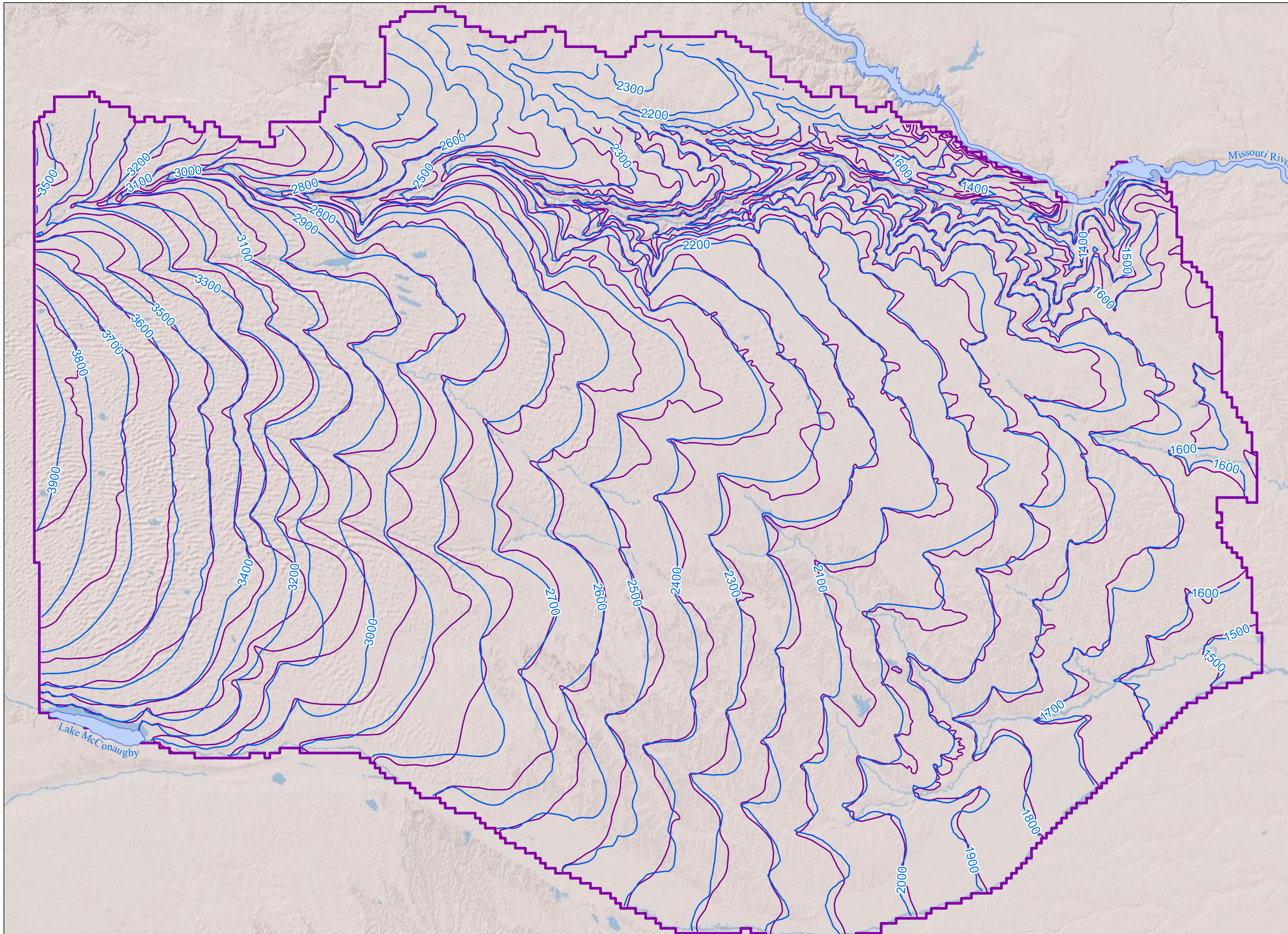
0 5 10 20 Miles
1 in = 20 miles

Nebraska
Department of Natural Resources

**Figure 6-5**
**Steady State Water Level Contours/Residuals**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




N W E S

## Legend

- 1995 Simulated Water Level Contours
- 1995 Observed Water Level Contours
- Water Bodies
- CENEB Active Model Domain

**NOTE:**
**Contour Interval = 100 ft**

**Sources**
**1995 Simulated Water Level Contours:**
**Dec 1995 CENEB Model Output**

**1995 Observed Water Level Contours:**
**Conservation and Survey Division, 2003**

Brown AND Caldwell

Date: 07/22/2013
Project No: 142198
Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

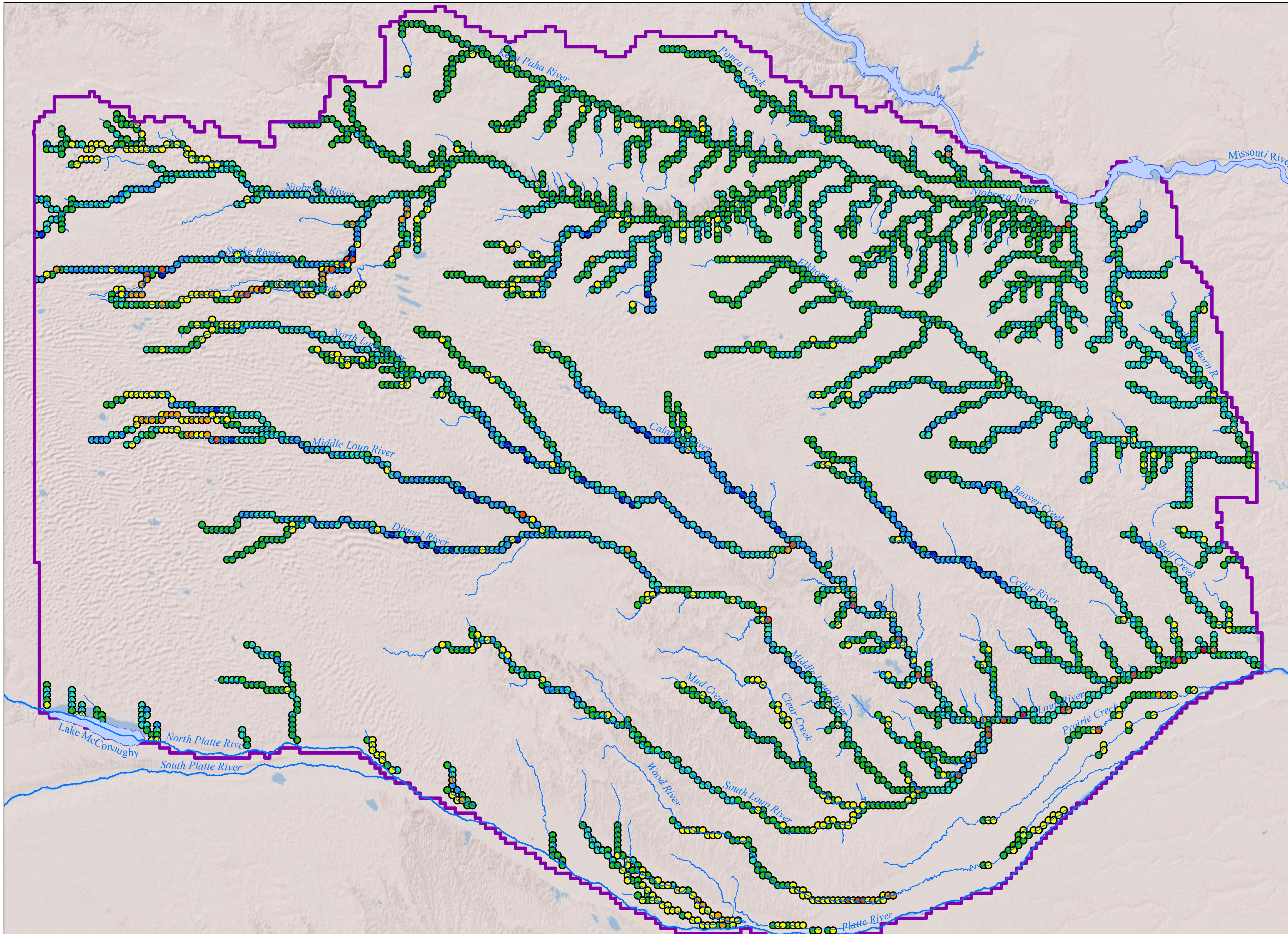
0 5 10 20 Miles
1 in = 20 miles

Nebraska Department of Natural Resources

**Figure 6-6**
**Observed vs. Simulated Water Level Contours**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figures_5-5_6-1_6-2_6-3_6-4 Pumping and Wells_ctc20130610.mxd

User: ccikoski




**NOTES:**
**Gaining = Aquifer discharges to stream**
**Losing = Stream recharges aquifer**
**Values represent the gain or loss for Dec 2011**

**Sources**
**Gaining and Losing Stream Segments:**
**Dec 2011 CENEB Model Output**

Brown AND Caldwell

Date: 07/22/2013
Project No: 142198
Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

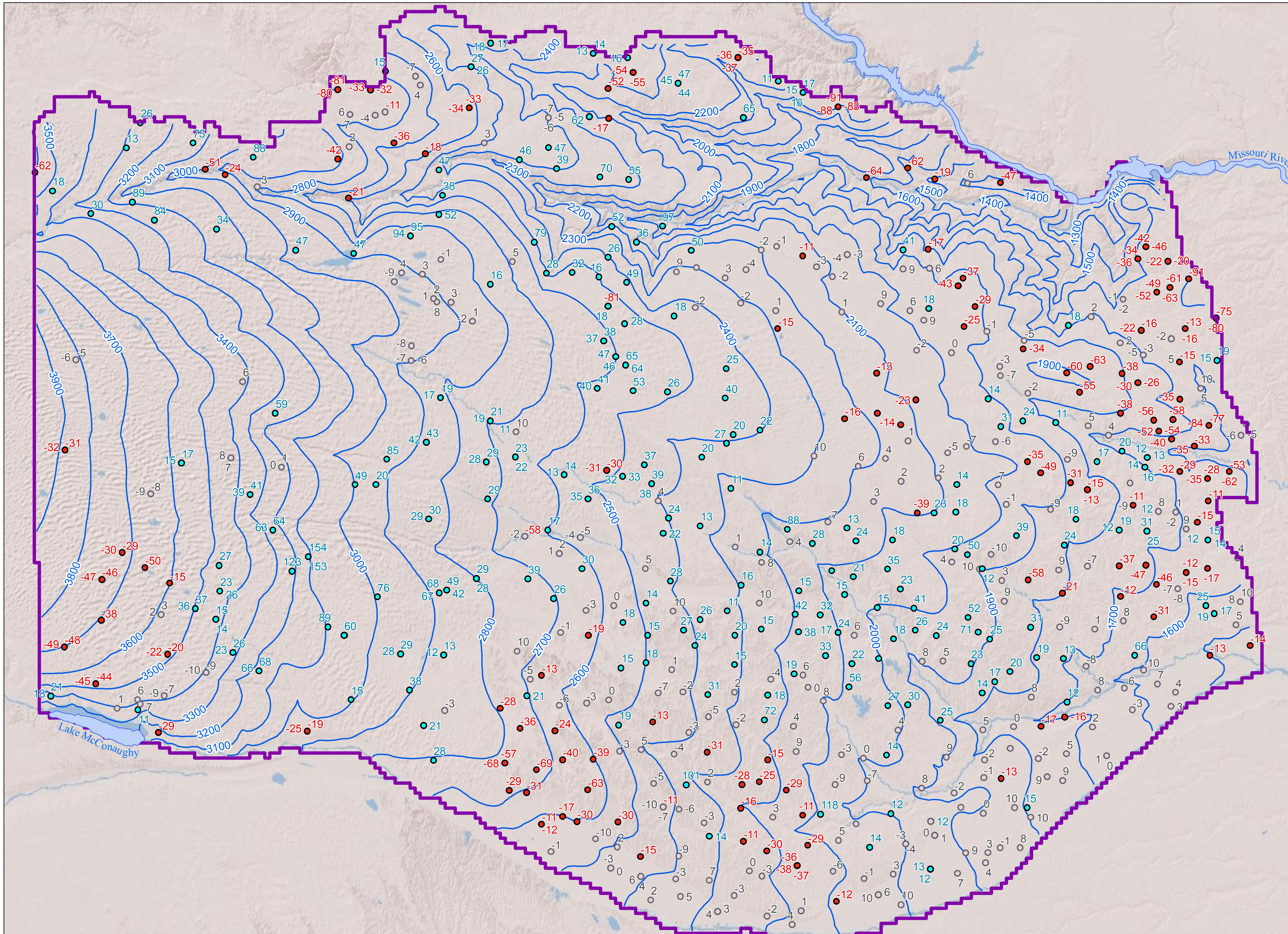
0 5 10 20 Miles
1 in = 20 miles

Nebraska
Department of Natural Resources

**Figure 6-7**
**2011 Simulated Gaining and Losing Reaches**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figure_6-8_6-9 Residuals maps.mxd

User: ccikoski




N
W E
S

## Legend

- 2011 Simulated Water Level Contours
- Water Bodies
- CENEB Active Model Domain

2011 Head Targets with Residuals (Ft)

- -94 - -10
- -10 - +10
- +10 - +154

**NOTES:**
**Contour interval of 100 ft**
**Residual = Observed minus Simulated Head**
**Targets with more than one residual label are wells with multiple measurements in 2011.**

**Sources**
**2011 Simulated Water Level Contours: Dec 2011 CENEB Model Output**

Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

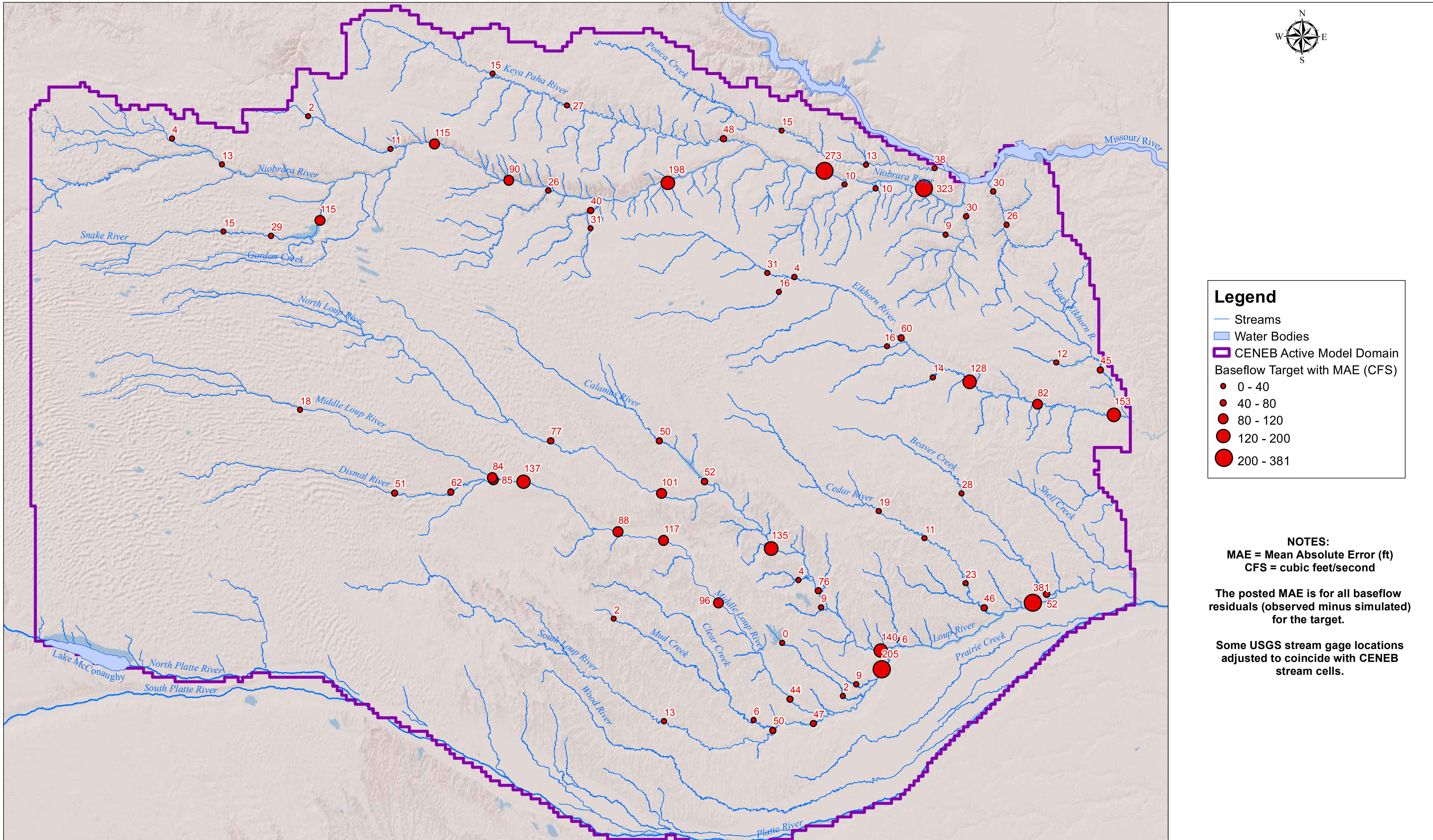
Miles
0 5 10 20
1 in = 20 miles

Nebraska
Department of Natural Resources

**Figure 6-8**
**2011 Simulated Water Levels and Residuals**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figure_6-8_6-9 Residuals maps.mxd

User: ccikoski




Brown AND Caldwell

Date: 07/22/2013

Project No: 142198

Client: NDNR

Basemap: Shaded Relief - ESRI
Projection: Nebraska State Plan (FIPS 2600)
NAD 1983 Feet

Nebraska Department of Natural Resources

**Figure 6-9**
**MAE in Baseflow Residuals by Gage**
**CENEB Model Report**
**State of Nebraska**

Path: Bcboi02\J:\Nebraska Dept of Natural Resources\142198 - NDNR Phase II - CENEB Model\GIS\MXDs\ReportFigures\Figure_6-8_6-9 Residuals maps.mxd

User: jwright

# Appendix A: Matrix of Data Sources for CENEB

**Table C-1. Matrix Analysis – Phase II ELM Review/Assessment**

| Model Input, Stress, Boundary or Dataset | Dataset: Source and Description | USGS Approach in ELM Phase II | Variable used in Calibration? | Steady State | Transient (DEV) | Limitations | Use for NDNR Model? |
|---|---|---|---|---|---|---|---|
| **MODEL STRUCTURE** | | | | | | | |
| Layer Top | Defined by USGS | Constant elevation (10,000 ft amsl), all cells | | | | Obscures potential issues with model, i.e., flooding | No. Set Layer Top to land surface elevation. Use 10-meter DEMs to define surface elevation |
| Layer Bottom | Conservation and Survey Division, 1998<br>Base of Principal Aquifer for the Elkhorn Loup model area, McGuire and Peterson, 2008<br>Test-hole drilling and surface and borehole geophysics. | Aquifer consists of the Ogallala Group, which overlies silts of the Tertiary-age Arikaree Group across the western one-half of the ELM area, and overlies poorly permeable Cretaceous-age shale and limestone; revised from Phase one based on test-hole drilling and surface and borehole geophysics | | | | | Yes |
| Cell Size | | Uniform grid -- 1 mile by 1 mile (Phase I grid was 2 mile by 2 mile) | | | | | No. Refine to 0.5 mile x 0.5 mile<br>Refined grid with the use of 10-meter DEMs will aid in more accurately simulating streams and groundwater pumping as well as clearly showing model flooding |
| Active Model Area | | Refined due to the increased grid resolution (versus Phase I). Areas with no aquifer thickness along the Niobrara River remained inactive | | | | | No. Model is to be extended to the north to include all of the Lower Niobrara basin, to comply with regulatory requirements for annual determinations |
| **BOUNDARY CONDITIONS** | | | | | | | |
| North – Niobrara River | Conservation and Survey Division 1996a, 1996b); Cretaceous-age bedrock | Stream package (SFR) forms boundary where the Niobrara River exists within the active model domain; areas with no aquifer thickness along the Niobrara River were made no-flow boundaries | | √ | √ | | Partially. Model is to be extended to the north to include all of the Lower Niobrara basin, to comply with regulatory requirements for annual determinations |
| West – Sand Hills | 1995 Water Level Contour Map, Conservation and Survey Division, 2003 | Constant heads based on 1995 water level map | | √ | √ | | TBD. Sand Hills region is an important recharge zone for the aquifer system. General Head Boundaries should be evaluated during conceptualization. |
| South – Platte River | Digital Elevation Model with 30-meter resolution (NDNR, 1997) | Lowest point of DEM within model cell to represent groundwater discharge to the Platte River | | √ | √ | | Yes, although the boundaries should be thoroughly evaluated before they are used. STR cells could be an alternative. |
| East – Loess Hills | 1995 Water Level Contour Map, Conservation and Survey Division, 2003 | Constant heads based on 1995 water level map | | √ | √ | | TBD. General Head Boundaries should be evaluated during conceptualization. |
| Lake McConaughy | | General Head Boundary: simulated 1940 SS water level used as starting head for DEV simulation. Annual values were either actual values (if higher than SS value) or set at SS level | | | √ | Lake level boundary never set below the simulated SS 1940 level, creates an artificial limit | If reported lake levels are available for the time period of interest, this could become a prescribed input. This isn't likely to have a large impact on the system, although the calibration indicates some issues in this region. |
| **HYDRAULIC PARAMETERS** | | | | | | | |
| Horizontal hydraulic conductivity | Conservation and Survey Division (2005a) ; Goeke and others, 1992) | Initially based on transmissivity values, refined manually during calibration; further refined using PEST | Manual and PEST | √ | √ | Calibrated specifically to the ELM Phase II water level change model | Use as a starting point. |
| Specific yield | Conservation and Survey Division (2005b) | Interpolated from 1,055 test hole logs | | √ | √ | | Use as a starting point. |
| Specific storage | -- | Spatially uniform value of 0.00001 ft-1 | | √ | √ | | Yes. This is not a significant parameter in a one-layer model with water table conditions. |
| Evapotranspiration | CALMIT – 2005 land use map | Cells with 20 acres of open water, streams, wetland, riparian woodlands have ET defined; 5-foot extinction depth; ET surface elevation sent to the 25th percentile of land surface elevation within each individual cell | Manual | √ | √ | Relies on 2005 data only; limited to 20 acres or more of open water | No. Use CROPSIM model output. Could use these data for comparison. |

**Table C-1. Matrix Analysis – Phase II ELM Review/Assessment**

| Model Input, Stress, Boundary or Dataset | Dataset: Source and Description | USGS Approach in ELM Phase II | Variable used in Calibration? | Steady State | Transient (DEV) | Limitations | Use for NDNR Model? |
|---|---|---|---|---|---|---|---|
| **PRESCRIBED MODEL INPUTS AND STRESSES** | | | | | | | |
| Municipal Pumping | Measured and reported municipal pumping 2001-2005 (NDNR, 2007) | Measured and reported pumping, primarily from 2004, was applied as a constant over the 1940 through 2005 period. | | | √ | Assumes current pumping is representative of pumping over the 60 years previous. Note: municipal pumping accounts for only ~3% of total pumping | Possibly. These inputs may not be significant in a regional model, although better estimates may improve localized results. May be useful to compare the 2004 reported demands to census populations, and calculate a per capita demand, then use census data to roughly estimate municipal demand for prior decades. |
| Irrigation Pumping | CALMIT – 2005 land use map (2007)<br>Census of Agriculture county-level crop statistics<br>Surface-water-irrigated acreage maps and annual totals from NDNR, 4 Irrigation Districts, and Bureau of Reclamation | USGS developed annual land use maps to identify irrigated acreage, then categorized the results as surface- or groundwater- irrigated land<br><br>Net irrigation value derived from: land use maps, an interpolation of the number and location of groundwater- and surface-water-irrigated acres, the amount of water needed by crops, the portion of the crop water requirement that was met by precipitation, measured pumpage values, and the amount of the measured pumpage returning to the aquifer | | | √ | | No. Use CROPSIM model output. |
| Recharge - Precipitation | Runoff-recharge watershed model (Strauch and Linard, 2009) | Long-term average recharge by surface water drainage basins was based on runoff-recharge model for Elkhorn and Loup drainages, no annual variations in SS; 4- to 9-year periods were held constant in DEV model. Applied to every cell in the model. Resulting values adjusted during manual and automated calibration steps | Manual and PEST | √ | √ | No annualized data specific to a single year in the DEV model; stress periods were lumped together thus recharge was constant for 4 to 9 years; watershed model limitations: results failed to meet statistical adequacy criteria for 2 out of 3 performance measures. | No. Use CROPSIM model output. |
| Recharge – Irrigated cropland<br><br>Recharge – Non-irrigated cropland | CALMIT – 2005 land use map (2007)<br>Census of Agriculture county-level crop statistics | USGS developed annual land use maps, using the 2005 land use map as a starting point<br><br>Additional recharge added to cells with irrigated crop land and non-irrigated crop land– rate applied was a constant, acreage changed through time, based on annual crop statistics by county. Eventually defaulted to a constant value of 1.0 inch/year for irrigated cropland and 0.5 inch/year for non-irrigated cropland. | | √ | √ | The spatial distribution of crop land based on a single time period, 2005, adjusted based on C of A statistics, available every 5 years 1950-2002. No data available to refine the 1940-1949 time period. | No. Use CROPSIM model output. |
| Recharge – Canal seepage | Irrigation districts provided calculations of annual canal and lateral losses, based on water mass balance for part of 1940-2005 period. | Pre-1940: estimated to be 43% of the yearly water diverted from the Platte River, minus any water returned via the Cozad, Dawson, Gothenberg, Elm Creek, or Kearney Canal Systems. Recharge applied uniformly to all cells coinciding with a canal, lateral, or irrigated land.<br>1940-2005: Recharge applied uniformly to all cells within the respective irrigation district.<br>Recharge rates for cells were adjusted along the Ainsworth, Mirdan and Geranium canals to reflect areas with greater potential for interaction between surface water and groundwater based on geophysical data. | | √ | √ | | Yes. This parameter not part of CROPSIM modeling. |
| Recharge – Excess Irrigation | | Not simulated for over-application of surface water. Implicitly simulated in the net groundwater pumping estimates; total pumping reduced by 20% to account for this parameter. | | | | | No. Use CROPSIM model output. |

**Table C-1. Matrix Analysis – Phase II ELM Review/Assessment**

| Model Input, Stress, Boundary or Dataset | Dataset: Source and Description | USGS Approach in ELM Phase II | Variable used in Calibration? | Steady State | Transient (DEV) | Limitations | Use for NDNR Model? |
|---|---|---|---|---|---|---|---|
| **STREAM PACKAGE PARAMETERS** | | | | | | | |
| Locations of Streams and Tributaries | Synoptic baseflow measurements along stream reaches (Peterson and Strauch, 2007) | Simulated in the model if >5 cfs of baseflow measured in 2006 synoptic survey.<br>Bazile and Willow Creeks included because they were of particular interest | | √ | √ | | Yes, as a starting point. In some areas, reaches or tributaries will need to be added. |
| Elevation of Streambed | Digital Elevation Model with 30-meter resolution (NDNR, 1997) | Elevations were assigned from the DEM, which was queried at regular intervals along each stream reach; values were interpolated linearly between the assigned elevations | | | | | No. Revise streambed elevation based on 10-meter DEMs |
| Ks of Streambed | | Initially set to Kh of model cell the stream reach was located within; manually adjusted; geophysical data was used to help adjust in areas where the data existed | Manual | | | | Yes. These inputs were based on field work, a GIS-based assessment, and estimates of Ks derived from transmissivity estimates (UNL, 2005a). These data are therefore strongly supported by field data collection and analysis. Note: width, thickness and Ks are variables used to calculate the streambed conductance, which is the parameter used by MODFLOW. |
| Streambed Thickness | | Uniform 1 ft thick; lumped in streambed conductance | | | | | |
| Stream Width | Synoptic baseflow measurements along stream reaches (Peterson and Strauch, 2007) | Measurements of stream width were made at 250 locations | | | | | |
| **CALIBRATION DATASETS** | | | | | | | |
| Baseflow Targets | Synoptic baseflow measurements along stream reaches (Peterson and Strauch, 2007)<br>Annual baseflow estimated from streamflow data NDNR, 2008; USGS, 2008 | 38 annual target stations (1,435 targets) from baseflow separation analyses; 165 targets for 2005 based on the 2006 synoptic survey; 20 locations were estimated based on streamflow records for pre-1940 data. | | √ | √ | | Yes. |
| SS Water Level Targets | USGS National Water Information System | 506 water level targets over the spring months from 1928 to 2002 | | √ | | | Yes. |
| Trasient Water Level Change Targets | USGS National Water Information System | USGS calculated water level change over a decade: 1945-55, 1955-65, 1975-85, 1985-95 and 1995-2005. Decadal changes. | | | √ | | No. Use direct water level measurements. |

*Ks* *Hydraulic conductivity of the streambed materials*
*Kh* *Horizontal hydraulic conductivity*
*PEST* *Parameter Estimation Software (Doherty, 2008a and 2008b)*
*SS* *Steady State Model*
*DEV* *Development Model*

# Appendix B: CENEB Stress Periods

| Stress Period | Time Represented (End of SP) Month | Year | Days in Stress Period | Elapsed Time (days) |
|---|---|---|---|---|
| 1 | | Pre-1940 | 1 | 1 |
| 2 | Dec | 1940 | 365 | 366 |
| 3 | Dec | 1941 | 365 | 731 |
| 4 | Dec | 1942 | 365 | 1096 |
| 5 | Dec | 1943 | 365 | 1461 |
| 6 | Dec | 1944 | 365 | 1826 |
| 7 | Dec | 1945 | 365 | 2191 |
| 8 | Dec | 1946 | 365 | 2556 |
| 9 | Dec | 1947 | 365 | 2921 |
| 10 | Dec | 1948 | 365 | 3286 |
| 11 | Dec | 1949 | 365 | 3651 |
| 12 | Dec | 1950 | 365 | 4016 |
| 13 | Dec | 1951 | 365 | 4381 |
| 14 | Dec | 1952 | 365 | 4746 |
| 15 | Dec | 1953 | 365 | 5111 |
| 16 | Dec | 1954 | 365 | 5476 |
| 17 | Dec | 1955 | 365 | 5841 |
| 18 | Dec | 1956 | 365 | 6206 |
| 19 | Dec | 1957 | 365 | 6571 |
| 20 | Dec | 1958 | 365 | 6936 |
| 21 | Dec | 1959 | 365 | 7301 |
| 22 | Dec | 1960 | 365 | 7666 |
| 23 | Dec | 1961 | 365 | 8031 |
| 24 | Dec | 1962 | 365 | 8396 |
| 25 | Dec | 1963 | 365 | 8761 |
| 26 | Dec | 1964 | 365 | 9126 |
| 27 | Dec | 1965 | 365 | 9491 |
| 28 | Dec | 1966 | 365 | 9856 |
| 29 | Dec | 1967 | 365 | 10221 |
| 30 | Dec | 1968 | 365 | 10586 |
| 31 | Dec | 1969 | 365 | 10951 |
| 32 | Dec | 1970 | 365 | 11316 |
| 33 | Dec | 1971 | 365 | 11681 |
| 34 | Dec | 1972 | 365 | 12046 |
| 35 | Dec | 1973 | 365 | 12411 |
| 36 | Dec | 1974 | 365 | 12776 |
| 37 | Dec | 1975 | 365 | 13141 |
| 38 | Dec | 1976 | 365 | 13506 |
| 39 | Dec | 1977 | 365 | 13871 |
| 40 | Dec | 1978 | 365 | 14236 |
| 41 | Dec | 1979 | 365 | 14601 |
| 42 | Dec | 1980 | 365 | 14966 |
| 43 | Dec | 1981 | 365 | 15331 |
| 44 | Dec | 1982 | 365 | 15696 |

| | | | | |
|---|---|---|---|---|
| 45 | Dec | 1983 | 365 | 16061 |
| 46 | Dec | 1984 | 365 | 16426 |
| 47 | Dec | 1985 | 365 | 16791 |
| 48 | January | 1986 | 30.417 | 16821 |
| 49 | February | 1986 | 30.417 | 16852 |
| 50 | March | 1986 | 30.417 | 16882 |
| 51 | April | 1986 | 30.417 | 16913 |
| 52 | May | 1986 | 30.417 | 16943 |
| 53 | June | 1986 | 30.417 | 16974 |
| 54 | July | 1986 | 30.417 | 17004 |
| 55 | Aug | 1986 | 30.417 | 17034 |
| 56 | Sept | 1986 | 30.417 | 17065 |
| 57 | Oct | 1986 | 30.417 | 17095 |
| 58 | Nov | 1986 | 30.417 | 17126 |
| 59 | Dec | 1986 | 30.417 | 17156 |
| 60 | January | 1987 | 30.417 | 17186 |
| 61 | February | 1987 | 30.417 | 17217 |
| 62 | March | 1987 | 30.417 | 17247 |
| 63 | April | 1987 | 30.417 | 17278 |
| 64 | May | 1987 | 30.417 | 17308 |
| 65 | June | 1987 | 30.417 | 17339 |
| 66 | July | 1987 | 30.417 | 17369 |
| 67 | Aug | 1987 | 30.417 | 17399 |
| 68 | Sept | 1987 | 30.417 | 17430 |
| 69 | Oct | 1987 | 30.417 | 17460 |
| 70 | Nov | 1987 | 30.417 | 17491 |
| 71 | Dec | 1987 | 30.417 | 17521 |
| 72 | January | 1988 | 30.417 | 17551 |
| 73 | February | 1988 | 30.417 | 17582 |
| 74 | March | 1988 | 30.417 | 17612 |
| 75 | April | 1988 | 30.417 | 17643 |
| 76 | May | 1988 | 30.417 | 17673 |
| 77 | June | 1988 | 30.417 | 17704 |
| 78 | July | 1988 | 30.417 | 17734 |
| 79 | Aug | 1988 | 30.417 | 17764 |
| 80 | Sept | 1988 | 30.417 | 17795 |
| 81 | Oct | 1988 | 30.417 | 17825 |
| 82 | Nov | 1988 | 30.417 | 17856 |
| 83 | Dec | 1988 | 30.417 | 17886 |
| 84 | January | 1989 | 30.417 | 17916 |
| 85 | February | 1989 | 30.417 | 17947 |
| 86 | March | 1989 | 30.417 | 17977 |
| 87 | April | 1989 | 30.417 | 18008 |
| 88 | May | 1989 | 30.417 | 18038 |
| 89 | June | 1989 | 30.417 | 18069 |
| 90 | July | 1989 | 30.417 | 18099 |
| 91 | Aug | 1989 | 30.417 | 18129 |

| | | | | |
|---|---|---|---|---|
| 92 | Sept | 1989 | 30.417 | 18160 |
| 93 | Oct | 1989 | 30.417 | 18190 |
| 94 | Nov | 1989 | 30.417 | 18221 |
| 95 | Dec | 1989 | 30.417 | 18251 |
| 96 | January | 1990 | 30.417 | 18281 |
| 97 | February | 1990 | 30.417 | 18312 |
| 98 | March | 1990 | 30.417 | 18342 |
| 99 | April | 1990 | 30.417 | 18373 |
| 100 | May | 1990 | 30.417 | 18403 |
| 101 | June | 1990 | 30.417 | 18434 |
| 102 | July | 1990 | 30.417 | 18464 |
| 103 | Aug | 1990 | 30.417 | 18494 |
| 104 | Sept | 1990 | 30.417 | 18525 |
| 105 | Oct | 1990 | 30.417 | 18555 |
| 106 | Nov | 1990 | 30.417 | 18586 |
| 107 | Dec | 1990 | 30.417 | 18616 |
| 108 | January | 1991 | 30.417 | 18646 |
| 109 | February | 1991 | 30.417 | 18677 |
| 110 | March | 1991 | 30.417 | 18707 |
| 111 | April | 1991 | 30.417 | 18738 |
| 112 | May | 1991 | 30.417 | 18768 |
| 113 | June | 1991 | 30.417 | 18799 |
| 114 | July | 1991 | 30.417 | 18829 |
| 115 | Aug | 1991 | 30.417 | 18859 |
| 116 | Sept | 1991 | 30.417 | 18890 |
| 117 | Oct | 1991 | 30.417 | 18920 |
| 118 | Nov | 1991 | 30.417 | 18951 |
| 119 | Dec | 1991 | 30.417 | 18981 |
| 120 | January | 1992 | 30.417 | 19011 |
| 121 | February | 1992 | 30.417 | 19042 |
| 122 | March | 1992 | 30.417 | 19072 |
| 123 | April | 1992 | 30.417 | 19103 |
| 124 | May | 1992 | 30.417 | 19133 |
| 125 | June | 1992 | 30.417 | 19164 |
| 126 | July | 1992 | 30.417 | 19194 |
| 127 | Aug | 1992 | 30.417 | 19224 |
| 128 | Sept | 1992 | 30.417 | 19255 |
| 129 | Oct | 1992 | 30.417 | 19285 |
| 130 | Nov | 1992 | 30.417 | 19316 |
| 131 | Dec | 1992 | 30.417 | 19346 |
| 132 | January | 1993 | 30.417 | 19376 |
| 133 | February | 1993 | 30.417 | 19407 |
| 134 | March | 1993 | 30.417 | 19437 |
| 135 | April | 1993 | 30.417 | 19468 |
| 136 | May | 1993 | 30.417 | 19498 |
| 137 | June | 1993 | 30.417 | 19529 |
| 138 | July | 1993 | 30.417 | 19559 |

| | | | | |
|---|---|---|---|---|
| 139 | Aug | 1993 | 30.417 | 19589 |
| 140 | Sept | 1993 | 30.417 | 19620 |
| 141 | Oct | 1993 | 30.417 | 19650 |
| 142 | Nov | 1993 | 30.417 | 19681 |
| 143 | Dec | 1993 | 30.417 | 19711 |
| 144 | January | 1994 | 30.417 | 19741 |
| 145 | February | 1994 | 30.417 | 19772 |
| 146 | March | 1994 | 30.417 | 19802 |
| 147 | April | 1994 | 30.417 | 19833 |
| 148 | May | 1994 | 30.417 | 19863 |
| 149 | June | 1994 | 30.417 | 19894 |
| 150 | July | 1994 | 30.417 | 19924 |
| 151 | Aug | 1994 | 30.417 | 19954 |
| 152 | Sept | 1994 | 30.417 | 19985 |
| 153 | Oct | 1994 | 30.417 | 20015 |
| 154 | Nov | 1994 | 30.417 | 20046 |
| 155 | Dec | 1994 | 30.417 | 20076 |
| 156 | January | 1995 | 30.417 | 20106 |
| 157 | February | 1995 | 30.417 | 20137 |
| 158 | March | 1995 | 30.417 | 20167 |
| 159 | April | 1995 | 30.417 | 20198 |
| 160 | May | 1995 | 30.417 | 20228 |
| 161 | June | 1995 | 30.417 | 20259 |
| 162 | July | 1995 | 30.417 | 20289 |
| 163 | Aug | 1995 | 30.417 | 20319 |
| 164 | Sept | 1995 | 30.417 | 20350 |
| 165 | Oct | 1995 | 30.417 | 20380 |
| 166 | Nov | 1995 | 30.417 | 20411 |
| 167 | Dec | 1995 | 30.417 | 20441 |
| 168 | January | 1996 | 30.417 | 20471 |
| 169 | February | 1996 | 30.417 | 20502 |
| 170 | March | 1996 | 30.417 | 20532 |
| 171 | April | 1996 | 30.417 | 20563 |
| 172 | May | 1996 | 30.417 | 20593 |
| 173 | June | 1996 | 30.417 | 20624 |
| 174 | July | 1996 | 30.417 | 20654 |
| 175 | Aug | 1996 | 30.417 | 20684 |
| 176 | Sept | 1996 | 30.417 | 20715 |
| 177 | Oct | 1996 | 30.417 | 20745 |
| 178 | Nov | 1996 | 30.417 | 20776 |
| 179 | Dec | 1996 | 30.417 | 20806 |
| 180 | January | 1997 | 30.417 | 20836 |
| 181 | February | 1997 | 30.417 | 20867 |
| 182 | March | 1997 | 30.417 | 20897 |
| 183 | April | 1997 | 30.417 | 20928 |
| 184 | May | 1997 | 30.417 | 20958 |
| 185 | June | 1997 | 30.417 | 20989 |

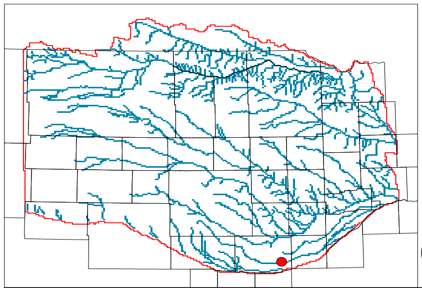
| | | | | |
|---|---|---|---|---|
| 186 | July | 1997 | 30.417 | 21019 |
| 187 | Aug | 1997 | 30.417 | 21049 |
| 188 | Sept | 1997 | 30.417 | 21080 |
| 189 | Oct | 1997 | 30.417 | 21110 |
| 190 | Nov | 1997 | 30.417 | 21141 |
| 191 | Dec | 1997 | 30.417 | 21171 |
| 192 | January | 1998 | 30.417 | 21201 |
| 193 | February | 1998 | 30.417 | 21232 |
| 194 | March | 1998 | 30.417 | 21262 |
| 195 | April | 1998 | 30.417 | 21293 |
| 196 | May | 1998 | 30.417 | 21323 |
| 197 | June | 1998 | 30.417 | 21354 |
| 198 | July | 1998 | 30.417 | 21384 |
| 199 | Aug | 1998 | 30.417 | 21414 |
| 200 | Sept | 1998 | 30.417 | 21445 |
| 201 | Oct | 1998 | 30.417 | 21475 |
| 202 | Nov | 1998 | 30.417 | 21506 |
| 203 | Dec | 1998 | 30.417 | 21536 |
| 204 | January | 1999 | 30.417 | 21566 |
| 205 | February | 1999 | 30.417 | 21597 |
| 206 | March | 1999 | 30.417 | 21627 |
| 207 | April | 1999 | 30.417 | 21658 |
| 208 | May | 1999 | 30.417 | 21688 |
| 209 | June | 1999 | 30.417 | 21719 |
| 210 | July | 1999 | 30.417 | 21749 |
| 211 | Aug | 1999 | 30.417 | 21779 |
| 212 | Sept | 1999 | 30.417 | 21810 |
| 213 | Oct | 1999 | 30.417 | 21840 |
| 214 | Nov | 1999 | 30.417 | 21871 |
| 215 | Dec | 1999 | 30.417 | 21901 |
| 216 | January | 2000 | 30.417 | 21931 |
| 217 | February | 2000 | 30.417 | 21962 |
| 218 | March | 2000 | 30.417 | 21992 |
| 219 | April | 2000 | 30.417 | 22023 |
| 220 | May | 2000 | 30.417 | 22053 |
| 221 | June | 2000 | 30.417 | 22084 |
| 222 | July | 2000 | 30.417 | 22114 |
| 223 | Aug | 2000 | 30.417 | 22144 |
| 224 | Sept | 2000 | 30.417 | 22175 |
| 225 | Oct | 2000 | 30.417 | 22205 |
| 226 | Nov | 2000 | 30.417 | 22236 |
| 227 | Dec | 2000 | 30.417 | 22266 |
| 228 | January | 2001 | 30.417 | 22296 |
| 229 | February | 2001 | 30.417 | 22327 |
| 230 | March | 2001 | 30.417 | 22357 |
| 231 | April | 2001 | 30.417 | 22388 |
| 232 | May | 2001 | 30.417 | 22418 |

| | | | | |
|---|---|---|---|---|
| 233 | June | 2001 | 30.417 | 22449 |
| 234 | July | 2001 | 30.417 | 22479 |
| 235 | Aug | 2001 | 30.417 | 22509 |
| 236 | Sept | 2001 | 30.417 | 22540 |
| 237 | Oct | 2001 | 30.417 | 22570 |
| 238 | Nov | 2001 | 30.417 | 22601 |
| 239 | Dec | 2001 | 30.417 | 22631 |
| 240 | January | 2002 | 30.417 | 22661 |
| 241 | February | 2002 | 30.417 | 22692 |
| 242 | March | 2002 | 30.417 | 22722 |
| 243 | April | 2002 | 30.417 | 22753 |
| 244 | May | 2002 | 30.417 | 22783 |
| 245 | June | 2002 | 30.417 | 22814 |
| 246 | July | 2002 | 30.417 | 22844 |
| 247 | Aug | 2002 | 30.417 | 22874 |
| 248 | Sept | 2002 | 30.417 | 22905 |
| 249 | Oct | 2002 | 30.417 | 22935 |
| 250 | Nov | 2002 | 30.417 | 22966 |
| 251 | Dec | 2002 | 30.417 | 22996 |
| 252 | January | 2003 | 30.417 | 23026 |
| 253 | February | 2003 | 30.417 | 23057 |
| 254 | March | 2003 | 30.417 | 23087 |
| 255 | April | 2003 | 30.417 | 23118 |
| 256 | May | 2003 | 30.417 | 23148 |
| 257 | June | 2003 | 30.417 | 23179 |
| 258 | July | 2003 | 30.417 | 23209 |
| 259 | Aug | 2003 | 30.417 | 23239 |
| 260 | Sept | 2003 | 30.417 | 23270 |
| 261 | Oct | 2003 | 30.417 | 23300 |
| 262 | Nov | 2003 | 30.417 | 23331 |
| 263 | Dec | 2003 | 30.417 | 23361 |
| 264 | January | 2004 | 30.417 | 23391 |
| 265 | February | 2004 | 30.417 | 23422 |
| 266 | March | 2004 | 30.417 | 23452 |
| 267 | April | 2004 | 30.417 | 23483 |
| 268 | May | 2004 | 30.417 | 23513 |
| 269 | June | 2004 | 30.417 | 23544 |
| 270 | July | 2004 | 30.417 | 23574 |
| 271 | Aug | 2004 | 30.417 | 23604 |
| 272 | Sept | 2004 | 30.417 | 23635 |
| 273 | Oct | 2004 | 30.417 | 23665 |
| 274 | Nov | 2004 | 30.417 | 23696 |
| 275 | Dec | 2004 | 30.417 | 23726 |
| 276 | January | 2005 | 30.417 | 23756 |
| 277 | February | 2005 | 30.417 | 23787 |
| 278 | March | 2005 | 30.417 | 23817 |
| 279 | April | 2005 | 30.417 | 23848 |

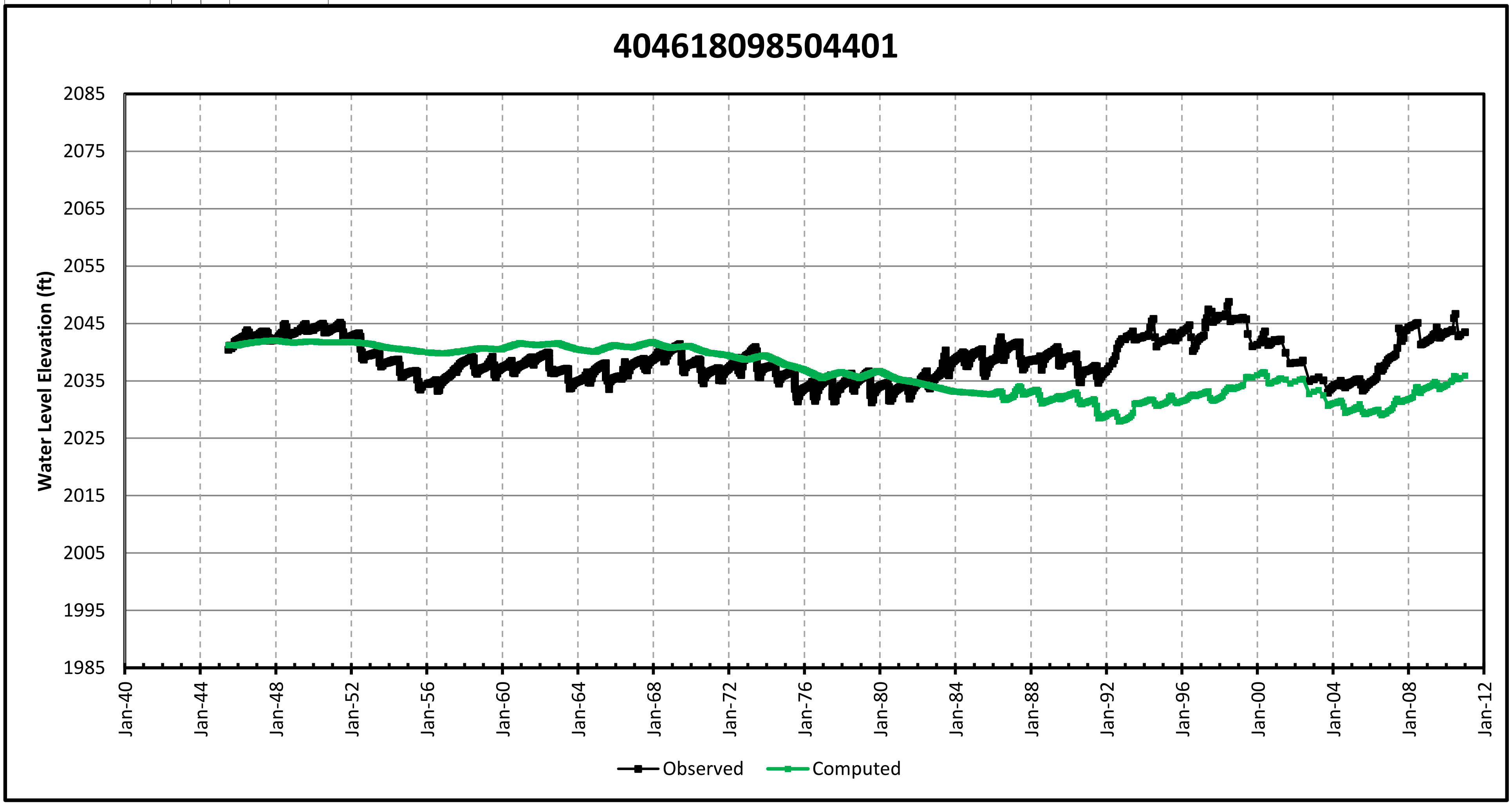
| | | | | |
|---|---|---|---|---|
| 280 | May | 2005 | 30.417 | 23878 |
| 281 | June | 2005 | 30.417 | 23909 |
| 282 | July | 2005 | 30.417 | 23939 |
| 283 | Aug | 2005 | 30.417 | 23969 |
| 284 | Sept | 2005 | 30.417 | 24000 |
| 285 | Oct | 2005 | 30.417 | 24030 |
| 286 | Nov | 2005 | 30.417 | 24061 |
| 287 | Dec | 2005 | 30.417 | 24091 |
| 288 | January | 2006 | 30.417 | 24121 |
| 289 | February | 2006 | 30.417 | 24152 |
| 290 | March | 2006 | 30.417 | 24182 |
| 291 | April | 2006 | 30.417 | 24213 |
| 292 | May | 2006 | 30.417 | 24243 |
| 293 | June | 2006 | 30.417 | 24274 |
| 294 | July | 2006 | 30.417 | 24304 |
| 295 | Aug | 2006 | 30.417 | 24334 |
| 296 | Sept | 2006 | 30.417 | 24365 |
| 297 | Oct | 2006 | 30.417 | 24395 |
| 298 | Nov | 2006 | 30.417 | 24426 |
| 299 | Dec | 2006 | 30.417 | 24456 |
| 300 | January | 2007 | 30.417 | 24487 |
| 301 | February | 2007 | 30.417 | 24517 |
| 302 | March | 2007 | 30.417 | 24547 |
| 303 | April | 2007 | 30.417 | 24578 |
| 304 | May | 2007 | 30.417 | 24608 |
| 305 | June | 2007 | 30.417 | 24639 |
| 306 | July | 2007 | 30.417 | 24669 |
| 307 | Aug | 2007 | 30.417 | 24699 |
| 308 | Sept | 2007 | 30.417 | 24730 |
| 309 | Oct | 2007 | 30.417 | 24760 |
| 310 | Nov | 2007 | 30.417 | 24791 |
| 311 | Dec | 2007 | 30.417 | 24821 |
| 312 | January | 2008 | 30.417 | 24852 |
| 313 | February | 2008 | 30.417 | 24882 |
| 314 | March | 2008 | 30.417 | 24912 |
| 315 | April | 2008 | 30.417 | 24943 |
| 316 | May | 2008 | 30.417 | 24973 |
| 317 | June | 2008 | 30.417 | 25004 |
| 318 | July | 2008 | 30.417 | 25034 |
| 319 | Aug | 2008 | 30.417 | 25064 |
| 320 | Sept | 2008 | 30.417 | 25095 |
| 321 | Oct | 2008 | 30.417 | 25125 |
| 322 | Nov | 2008 | 30.417 | 25156 |
| 323 | Dec | 2008 | 30.417 | 25186 |
| 324 | January | 2009 | 30.417 | 25217 |
| 325 | February | 2009 | 30.417 | 25247 |
| 326 | March | 2009 | 30.417 | 25277 |

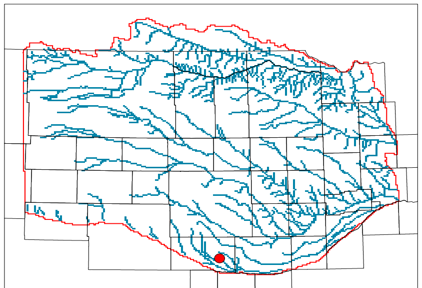
| | | | | |
|---|---|---|---|---|
| 327 | April | 2009 | 30.417 | 25308 |
| 328 | May | 2009 | 30.417 | 25338 |
| 329 | June | 2009 | 30.417 | 25369 |
| 330 | July | 2009 | 30.417 | 25399 |
| 331 | Aug | 2009 | 30.417 | 25429 |
| 332 | Sept | 2009 | 30.417 | 25460 |
| 333 | Oct | 2009 | 30.417 | 25490 |
| 334 | Nov | 2009 | 30.417 | 25521 |
| 335 | Dec | 2009 | 30.417 | 25551 |
| 336 | January | 2010 | 30.417 | 25582 |
| 337 | February | 2010 | 30.417 | 25612 |
| 338 | March | 2010 | 30.417 | 25642 |
| 339 | April | 2010 | 30.417 | 25673 |
| 340 | May | 2010 | 30.417 | 25703 |
| 341 | June | 2010 | 30.417 | 25734 |
| 342 | July | 2010 | 30.417 | 25764 |
| 343 | Aug | 2010 | 30.417 | 25794 |
| 344 | Sept | 2010 | 30.417 | 25825 |
| 345 | Oct | 2010 | 30.417 | 25855 |
| 346 | Nov | 2010 | 30.417 | 25886 |
| 347 | Dec | 2010 | 30.417 | 25916 |
| 348 | January | 2011 | 30.417 | 25947 |
| 349 | February | 2011 | 30.417 | 25977 |
| 350 | March | 2011 | 30.417 | 26007 |
| 351 | April | 2011 | 30.417 | 26038 |
| 352 | May | 2011 | 30.417 | 26068 |
| 353 | June | 2011 | 30.417 | 26099 |
| 354 | July | 2011 | 30.417 | 26129 |
| 355 | Aug | 2011 | 30.417 | 26159 |
| 356 | Sept | 2011 | 30.417 | 26190 |
| 357 | Oct | 2011 | 30.417 | 26220 |
| 358 | Nov | 2011 | 30.417 | 26251 |
| 359 | Dec | 2011 | 30.417 | 26281 |

# Appendix C: Water Level Hydrographs

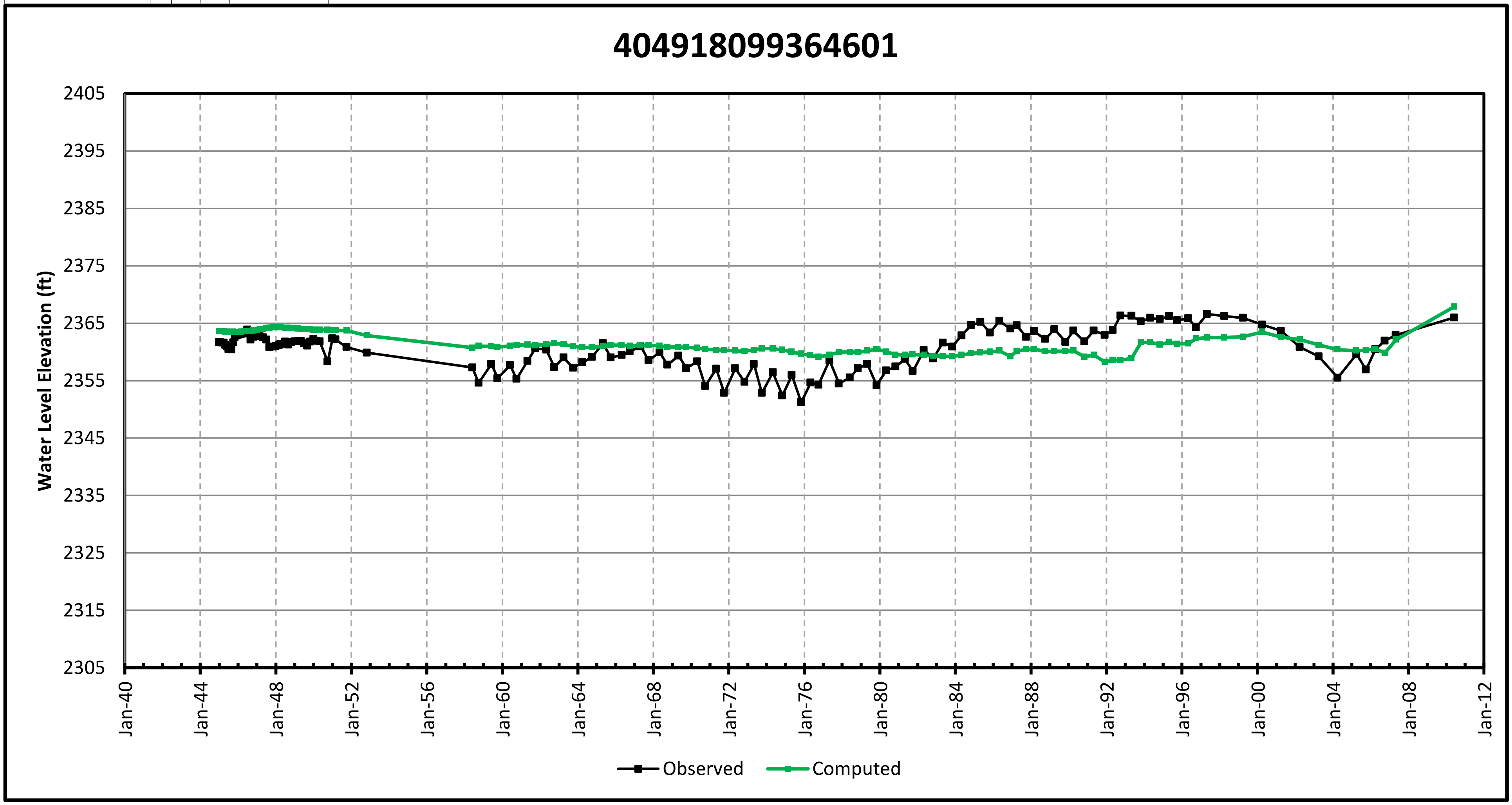


09N14W01DC

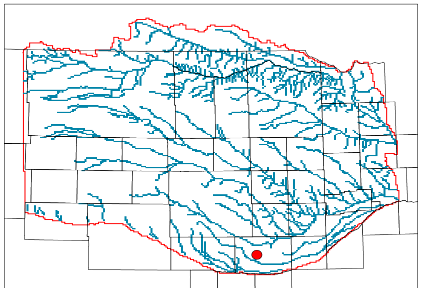

404618098504401
Water Level Elevation (ft)
2085
2075
2065
2055
2045
2035
2025
2015
2005
1995
1985
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



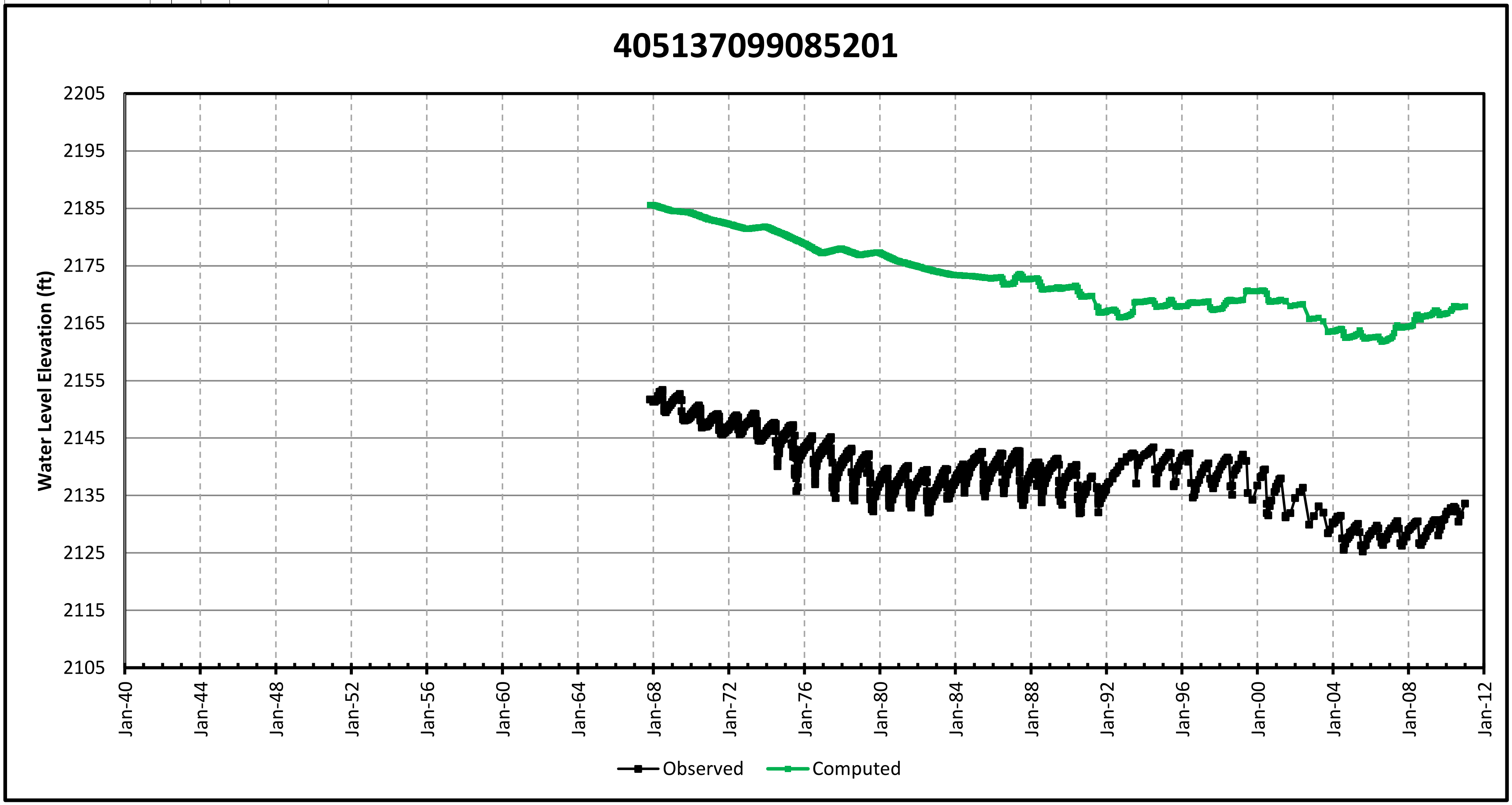
10N20W21CB

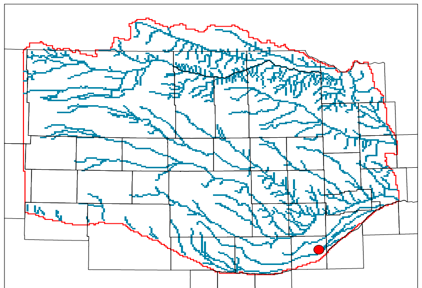


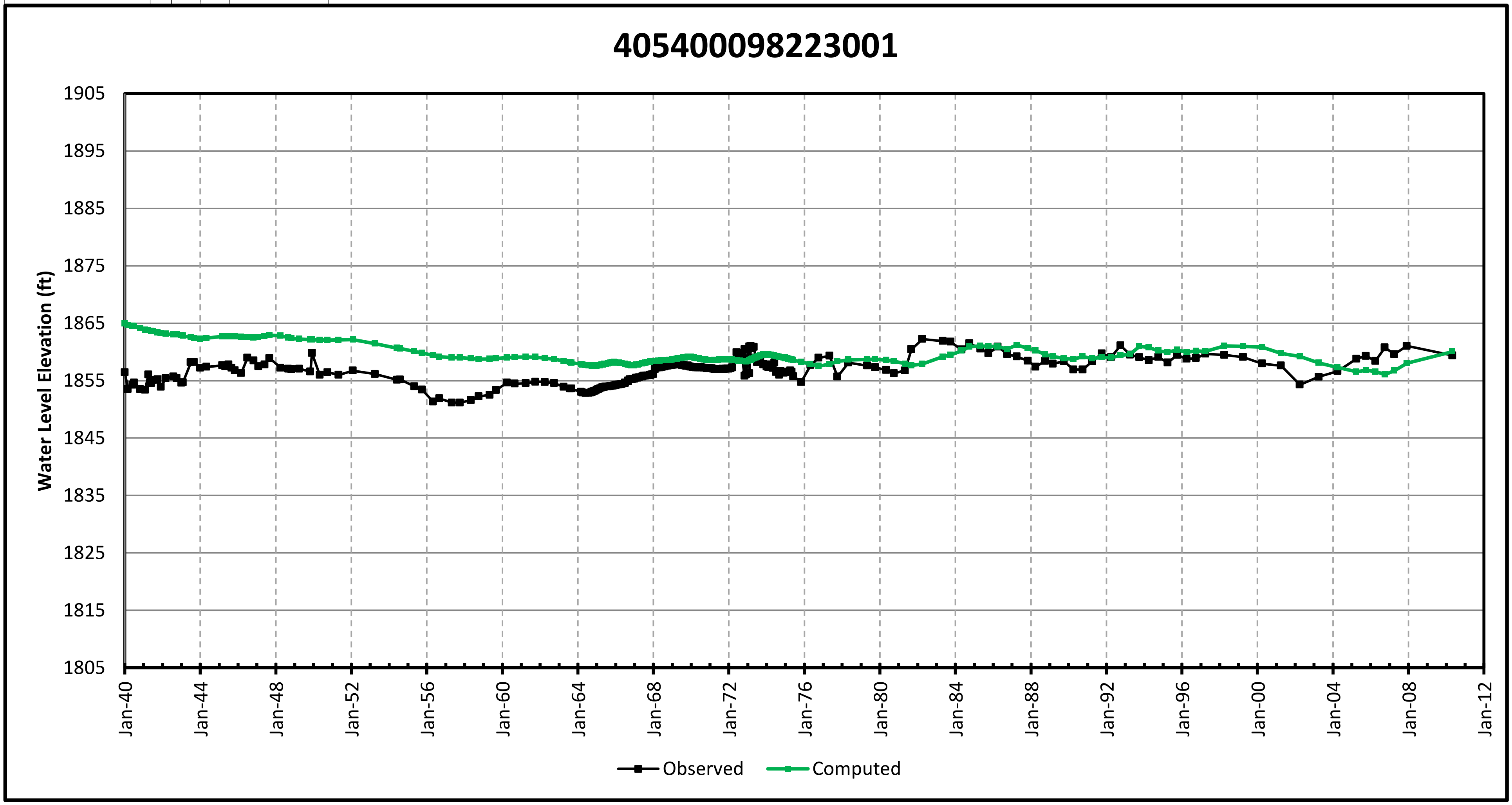
404918099364601
Water Level Elevation (ft)
2405
2395
2385
2375
2365
2355
2345
2335
2325
2315
2305
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

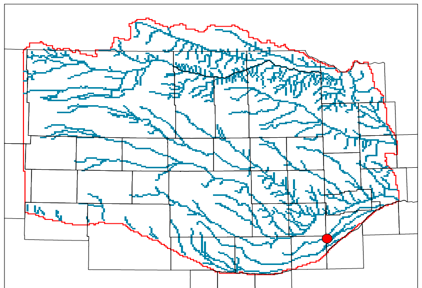


10N16W05DC

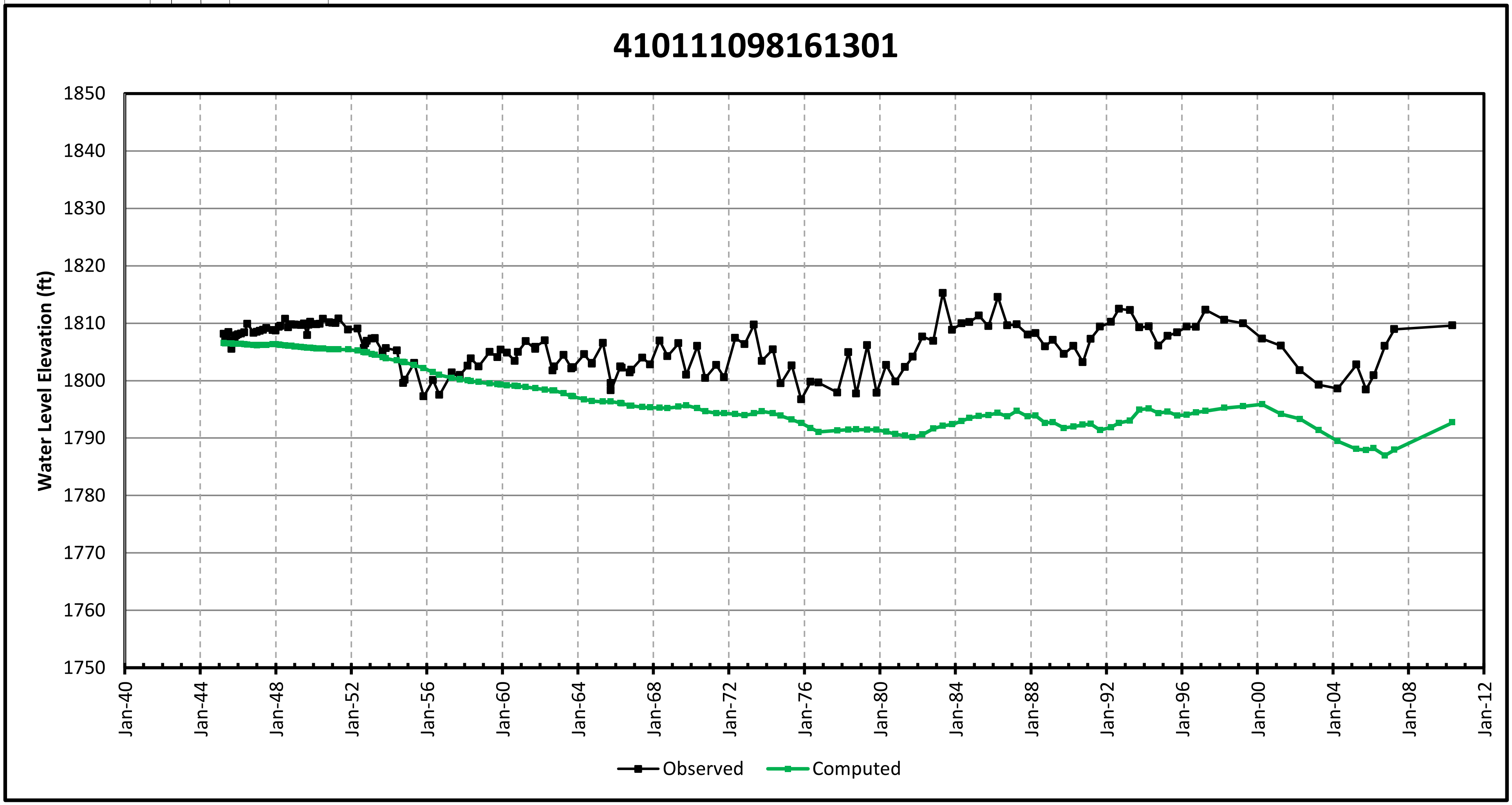

405137099085201
Water Level Elevation (ft)
2205
2195
2185
2175
2165
2155
2145
2135
2125
2115
2105
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed


11N09W29BB

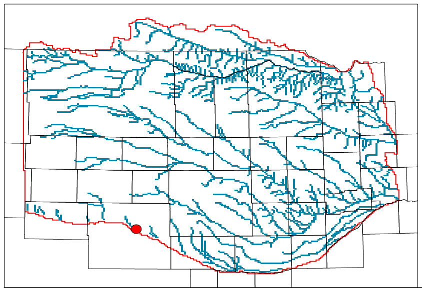

405400098223001
1905
1895
1885
1875
1865
1855
1845
1835
1825
1815
1805
Water Level Elevation (ft)
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



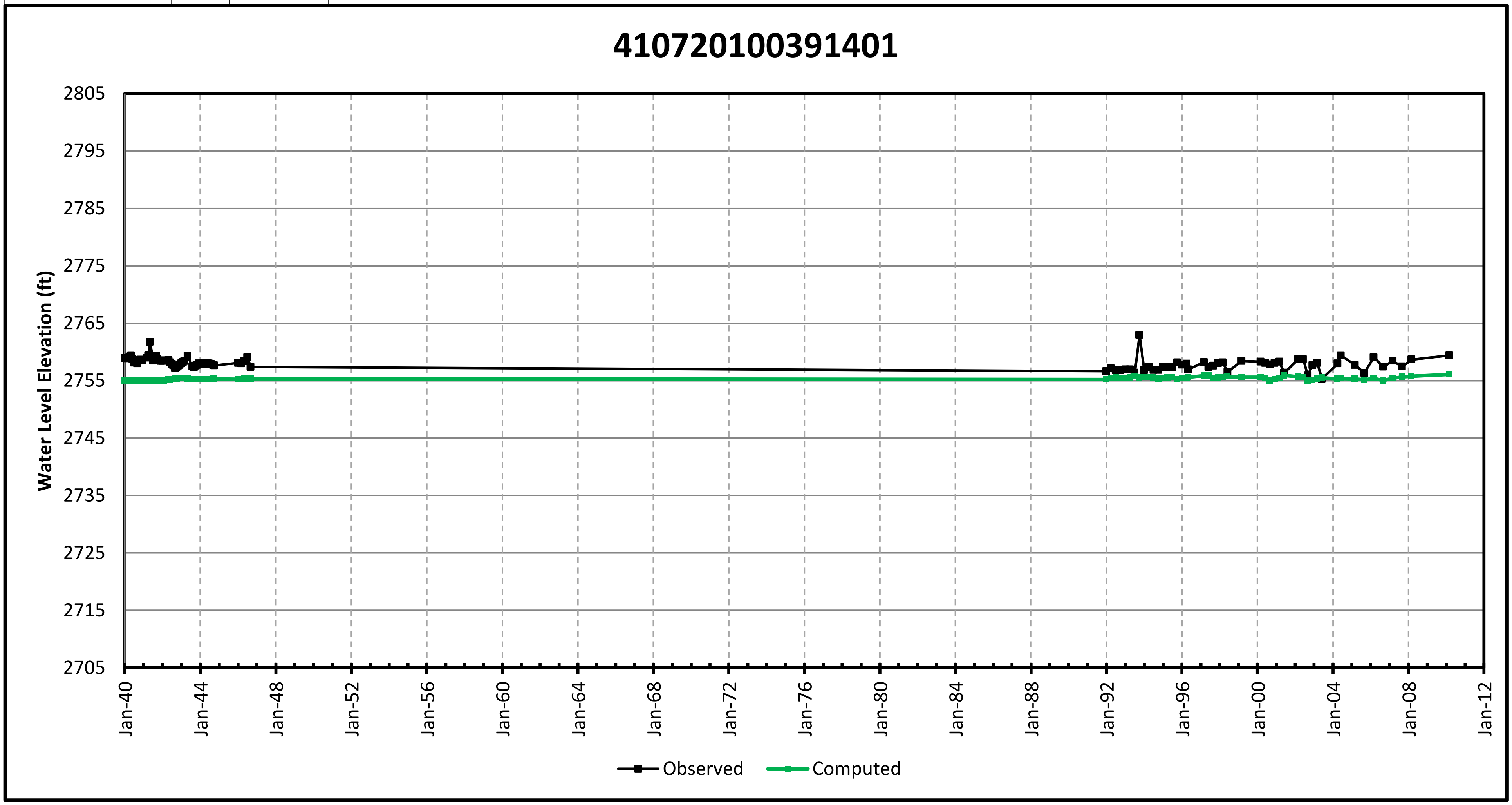
12N08W7DC



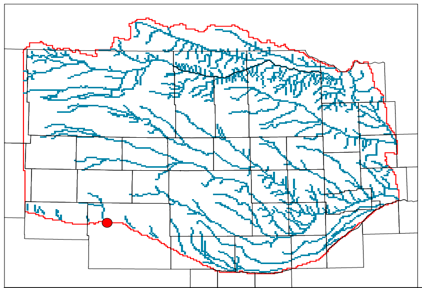
410111098161301
Water Level Elevation (ft)
1850
1840
1830
1820
1810
1800
1790
1780
1770
1760
1750
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



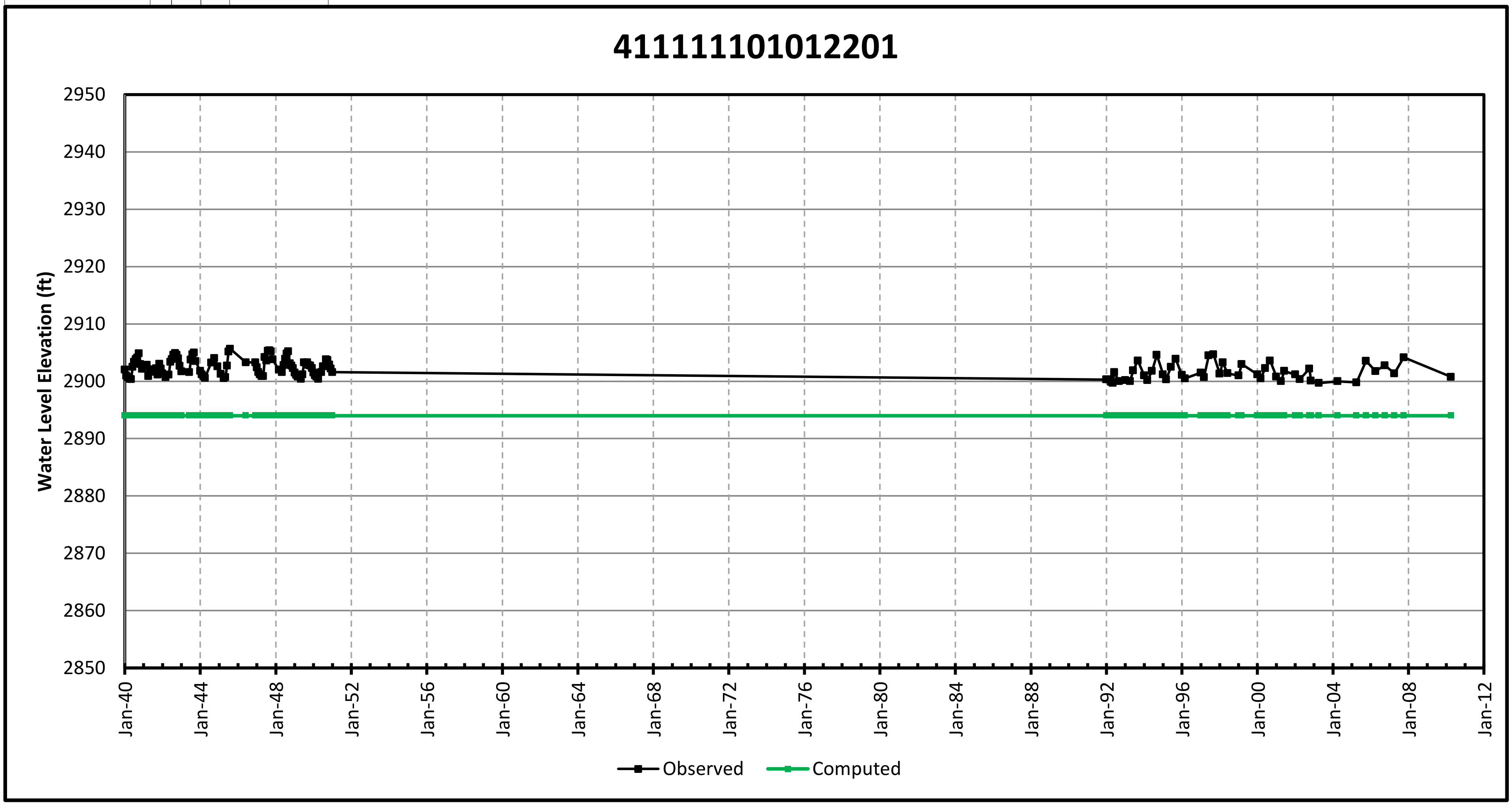
13N29W04CC



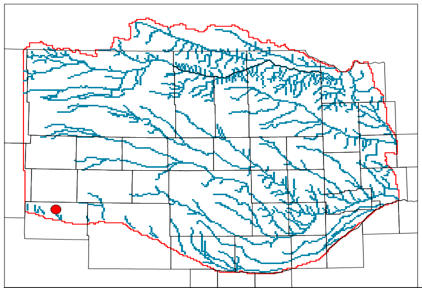
410720100391401
Water Level Elevation (ft)
2805
2795
2785
2775
2765
2755
2745
2735
2725
2715
2705
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



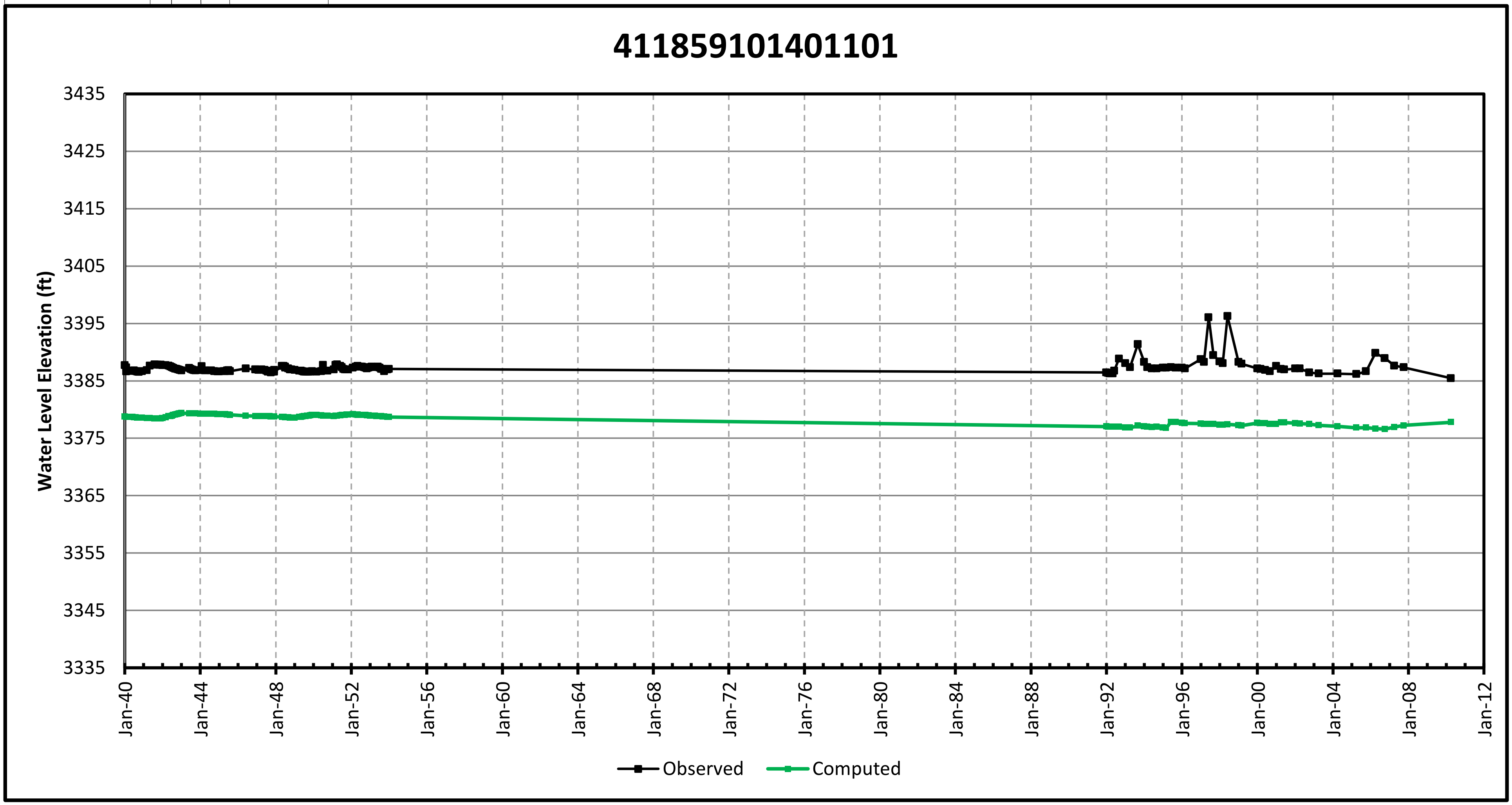
14N32W18AD



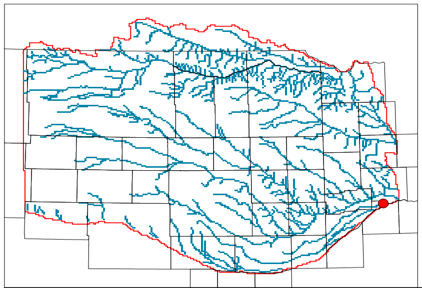
411111101012201
Water Level Elevation (ft)
2950
2940
2930
2920
2910
2900
2890
2880
2870
2860
2850
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



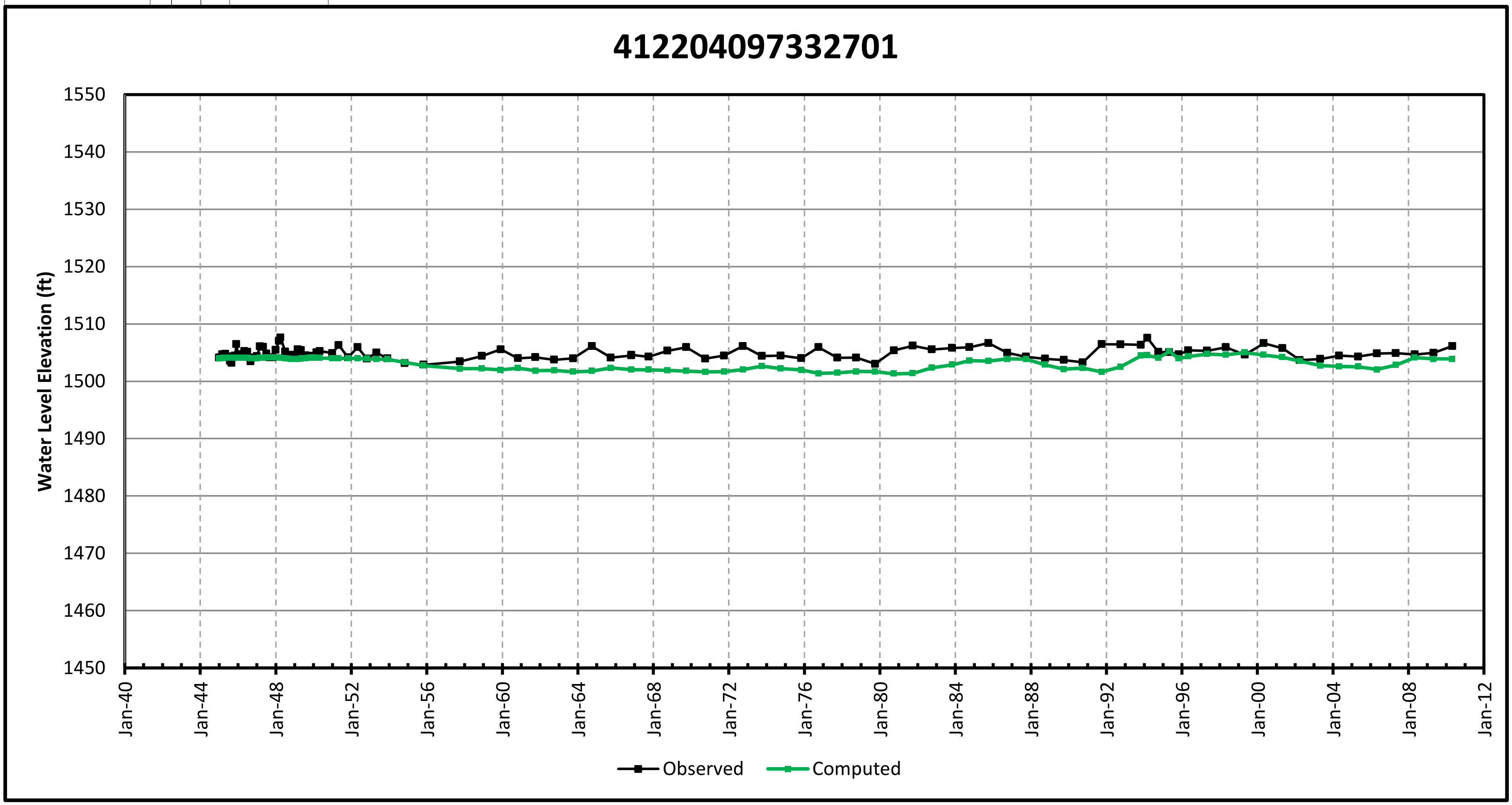
16N38W34BC



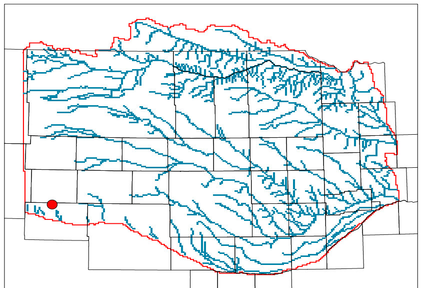
411859101401101
Water Level Elevation (ft)
3435
3425
3415
3405
3395
3385
3375
3365
3355
3345
3335
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



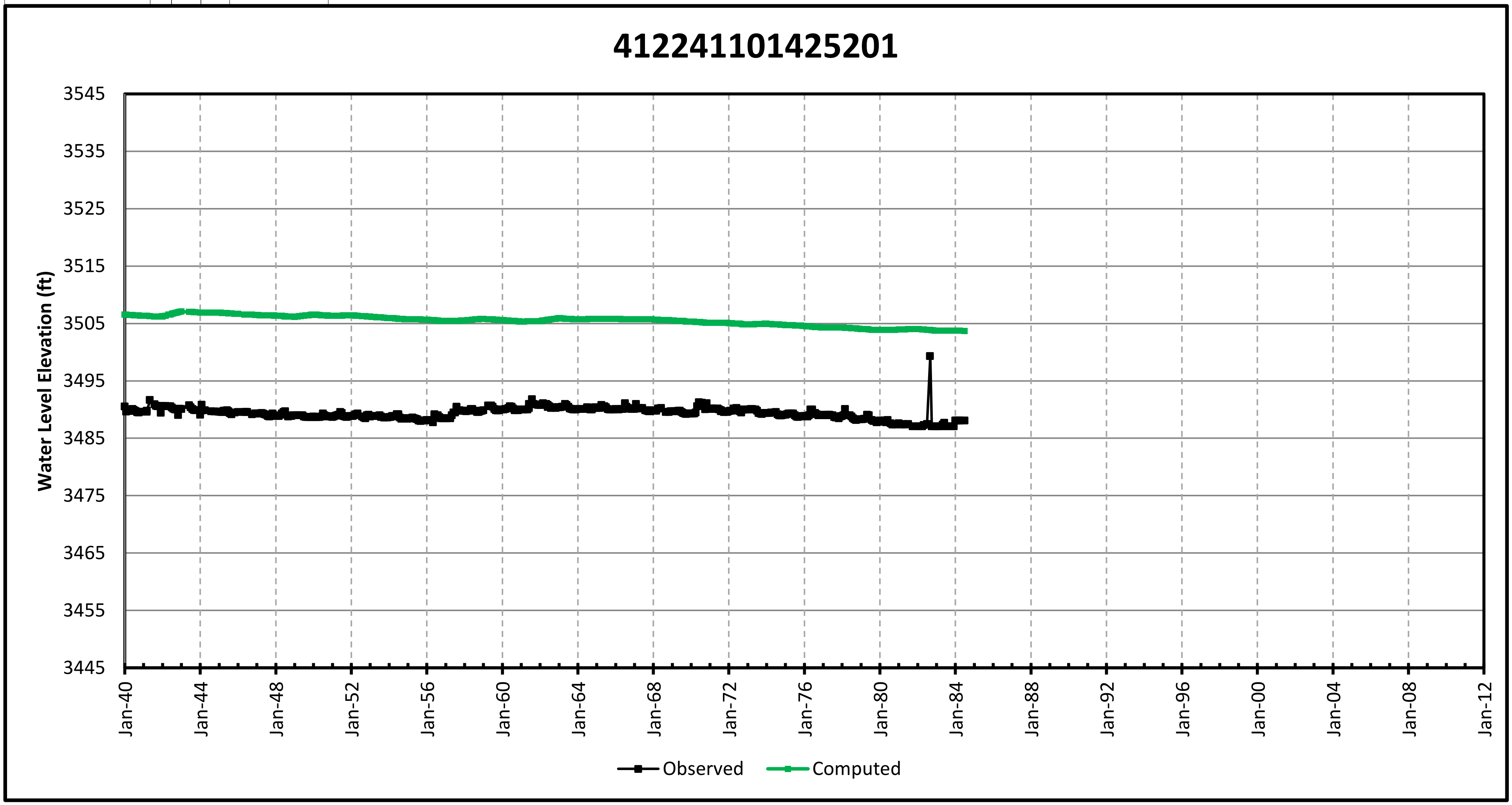
16N02W09CC



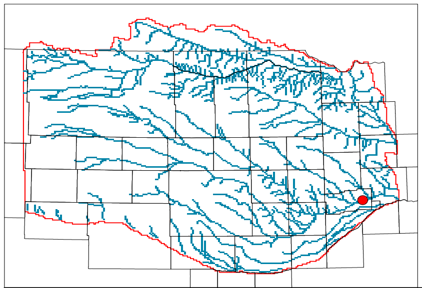
412204097332701
Water Level Elevation (ft)
1550
1540
1530
1520
1510
1500
1490
1480
1470
1460
1450
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



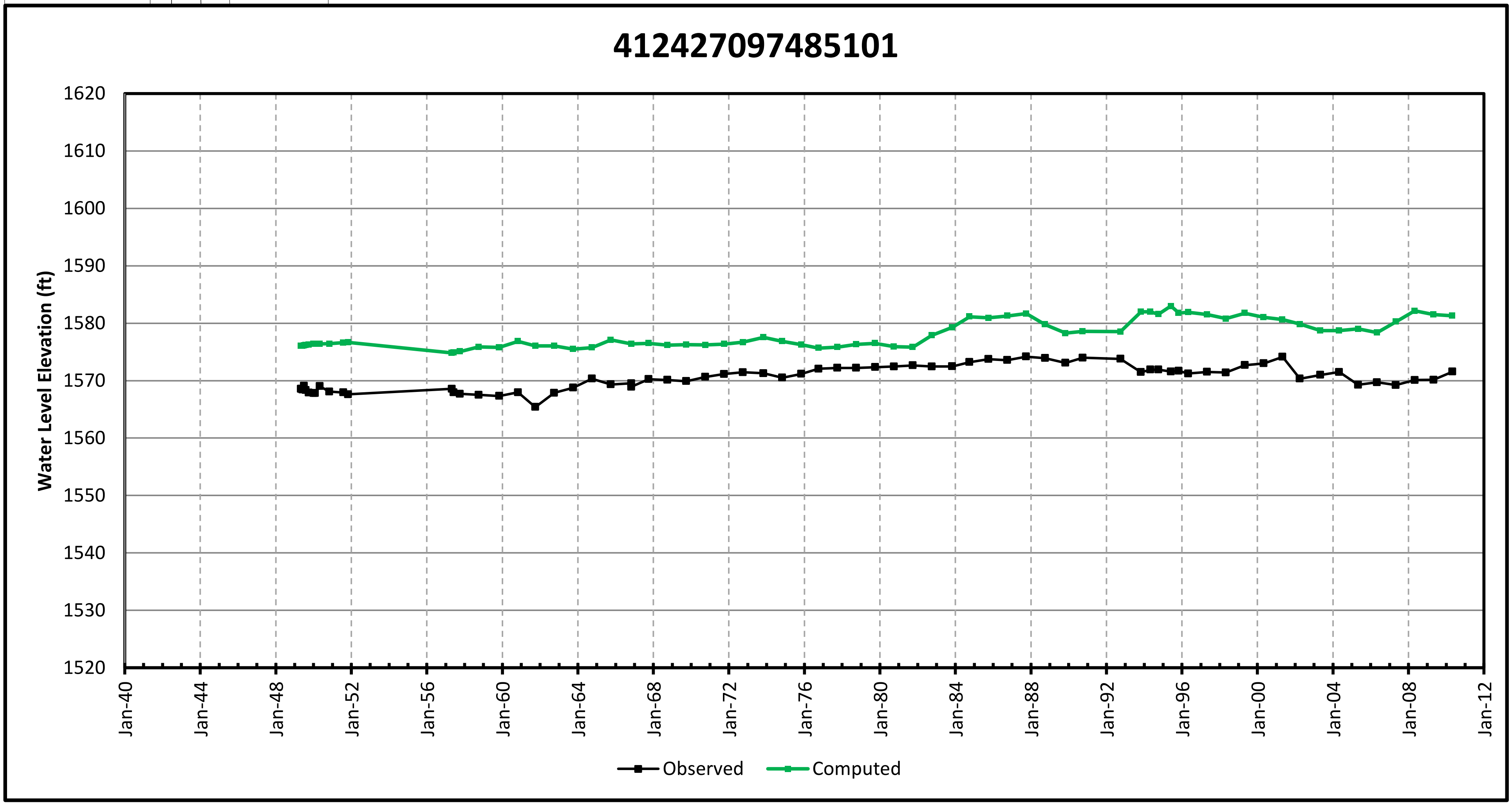
16N38W07AA



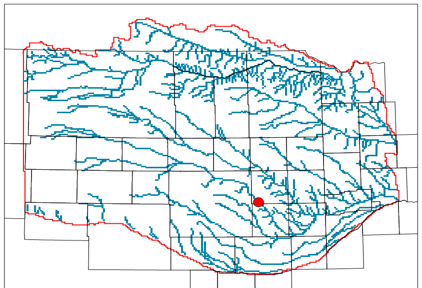
412241101425201
Water Level Elevation (ft)
3545
3535
3525
3515
3505
3495
3485
3475
3465
3455
3445
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



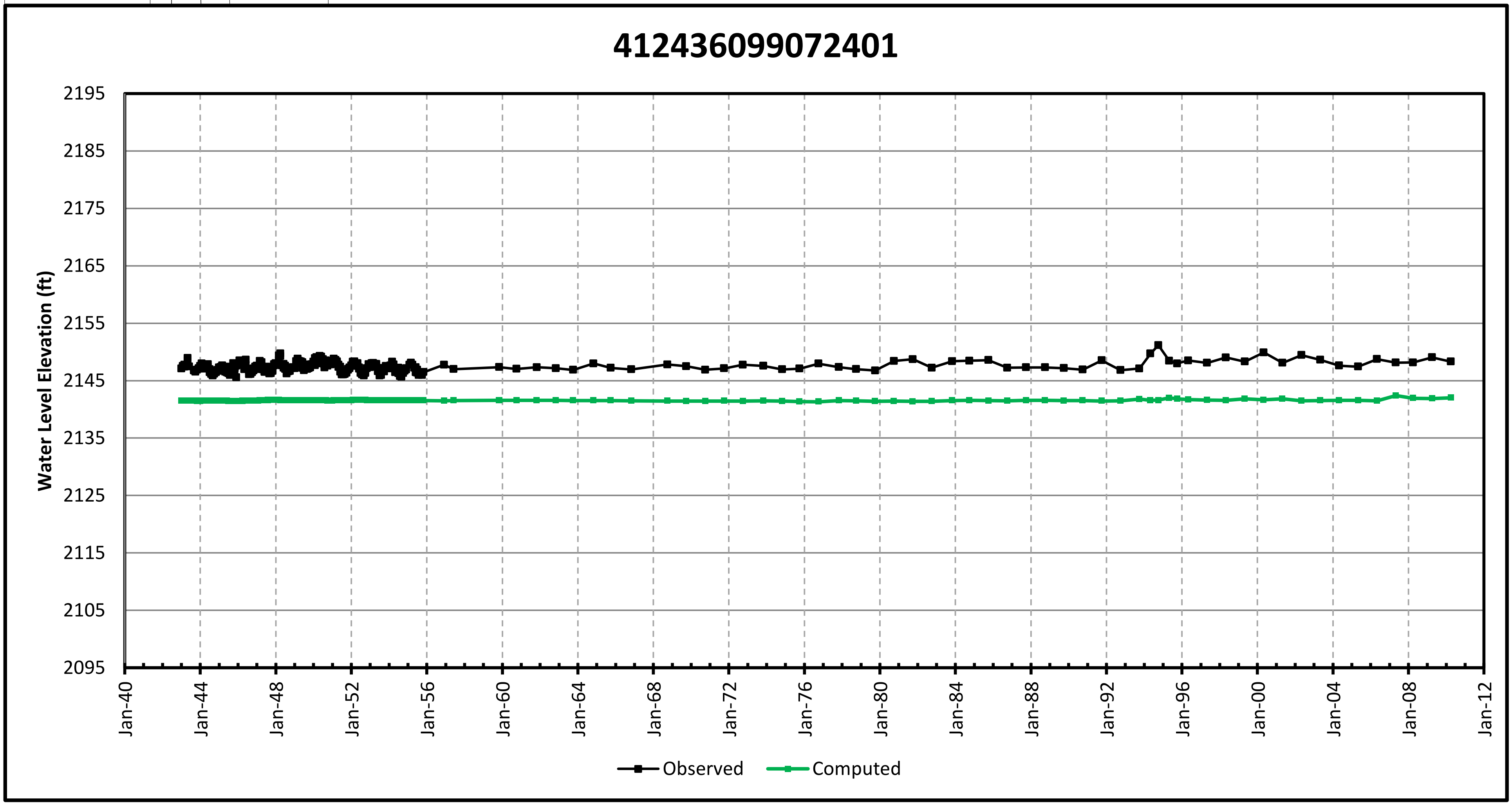
17N04W31AA



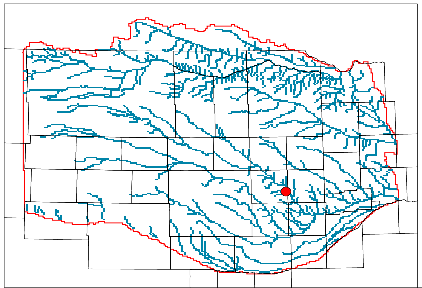
412427097485101
Water Level Elevation (ft)
1620
1610
1600
1590
1580
1570
1560
1550
1540
1530
1520
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



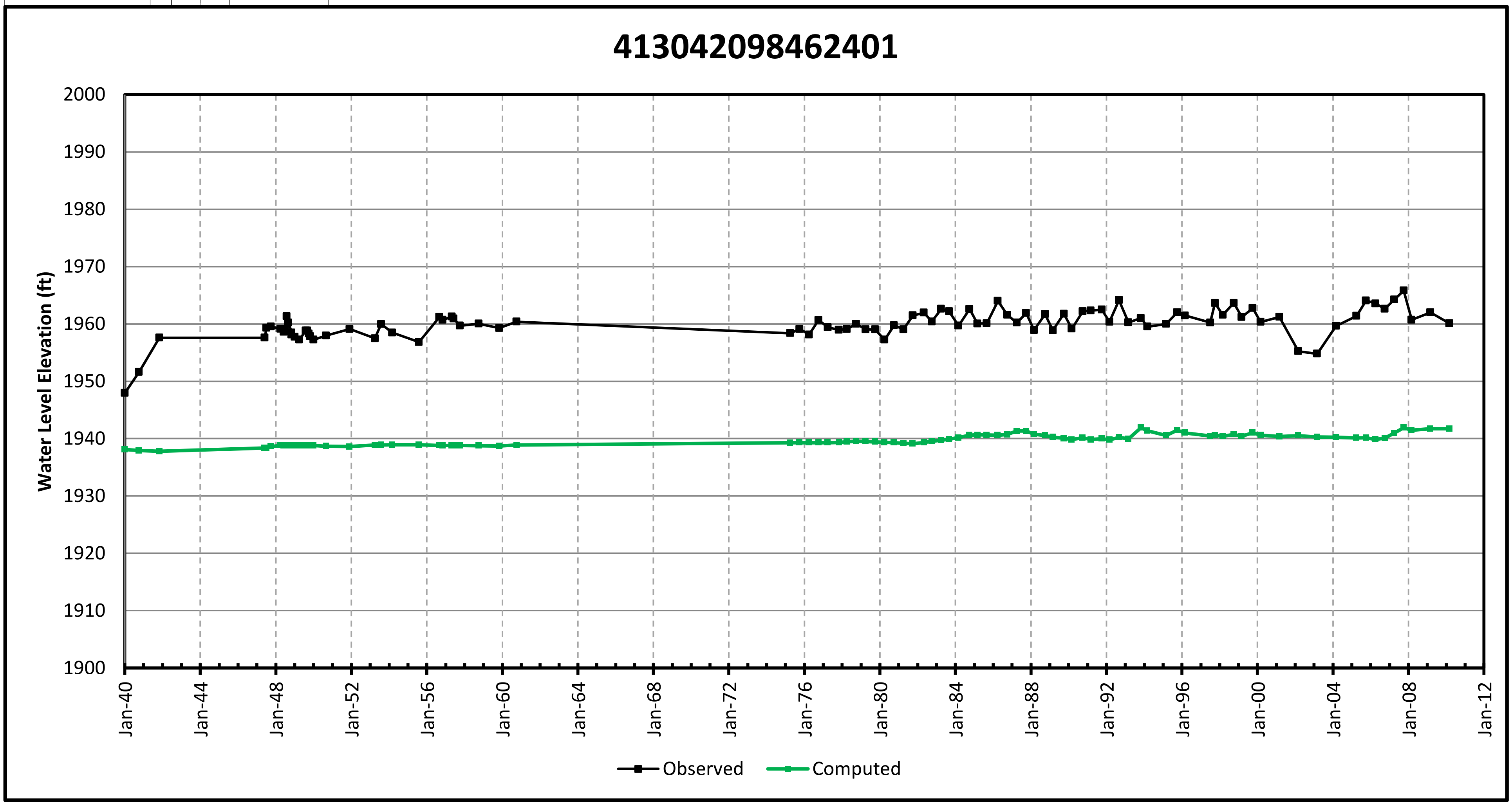
17N16W26DC



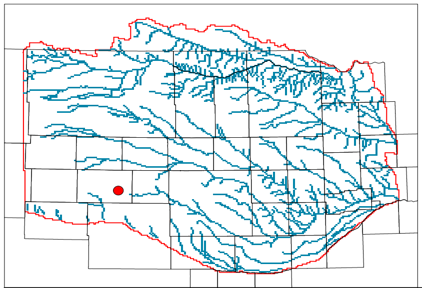
412436099072401
Water Level Elevation (ft)
2195
2185
2175
2165
2155
2145
2135
2125
2115
2105
2095
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



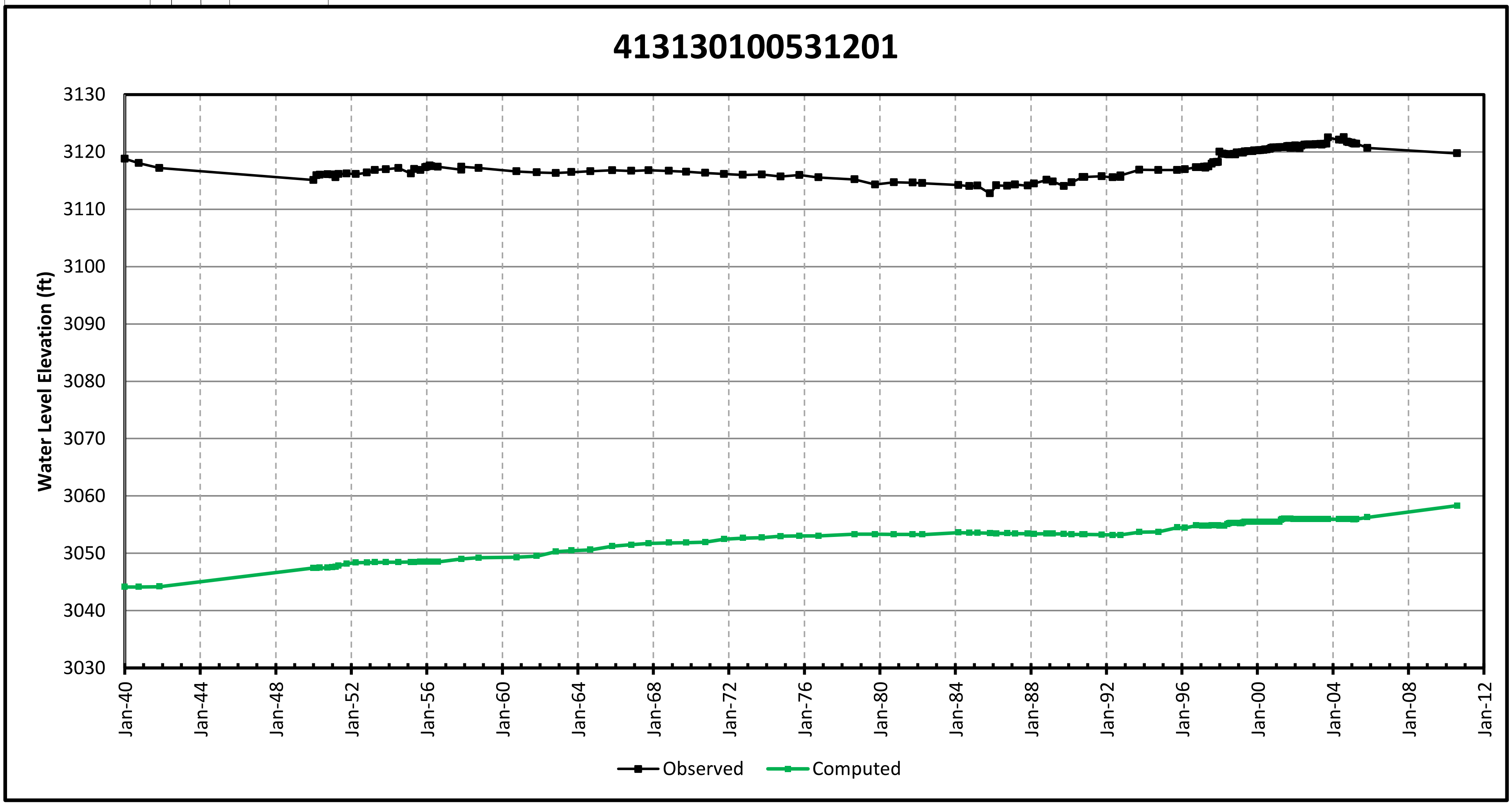
18N13W23DD



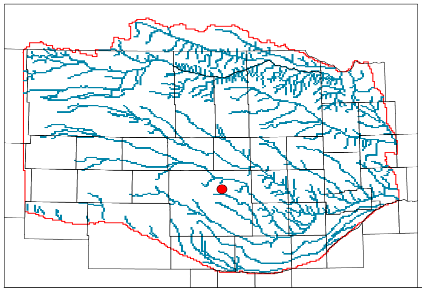
413042098462401
Water Level Elevation (ft)
2000
1990
1980
1970
1960
1950
1940
1930
1920
1910
1900
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



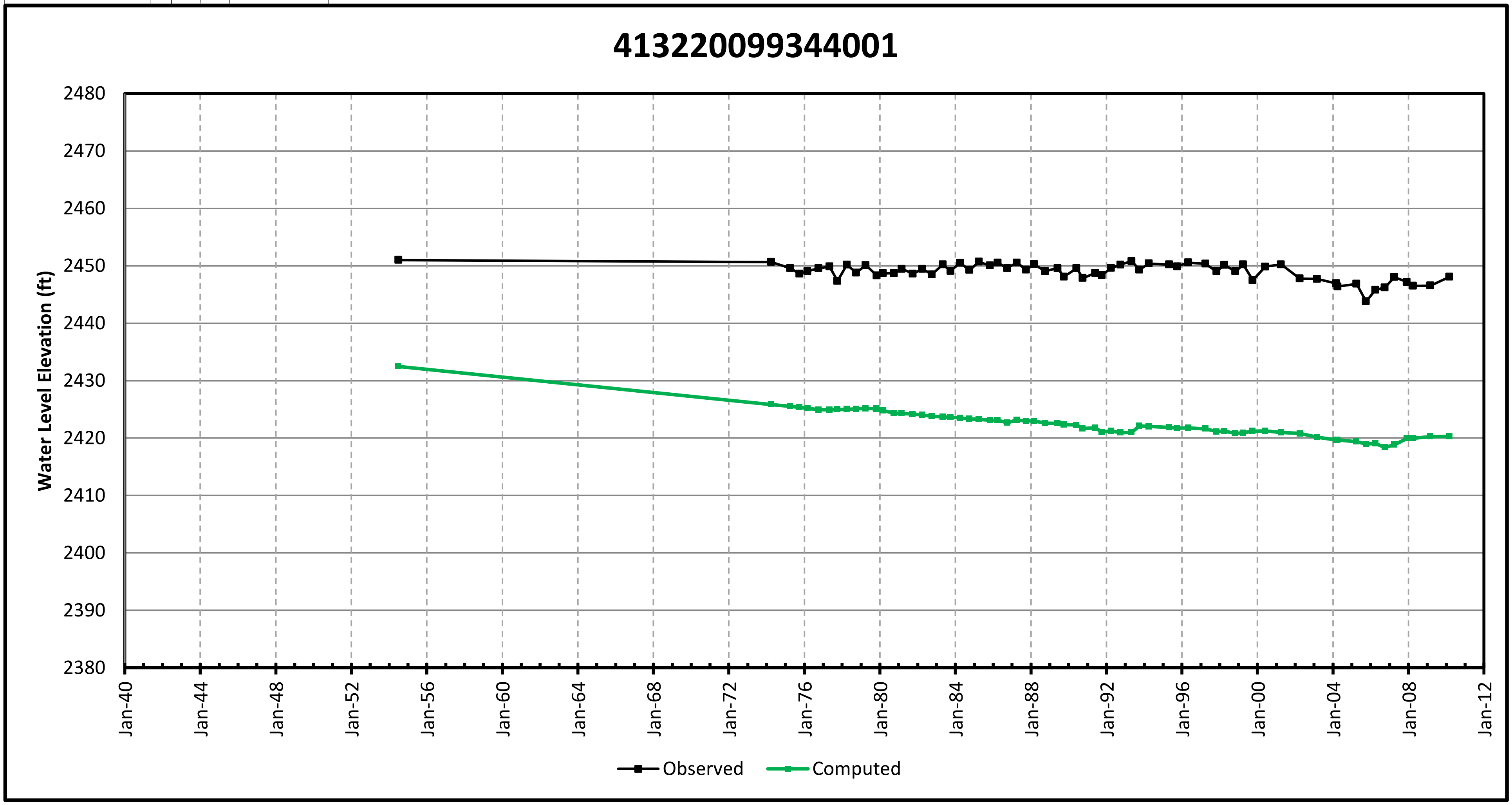
18N31W16DD

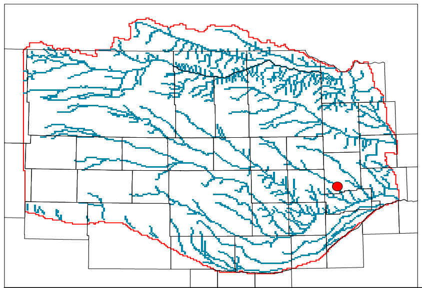


413130100531201
Water Level Elevation (ft)
3130
3120
3110
3100
3090
3080
3070
3060
3050
3040
3030
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

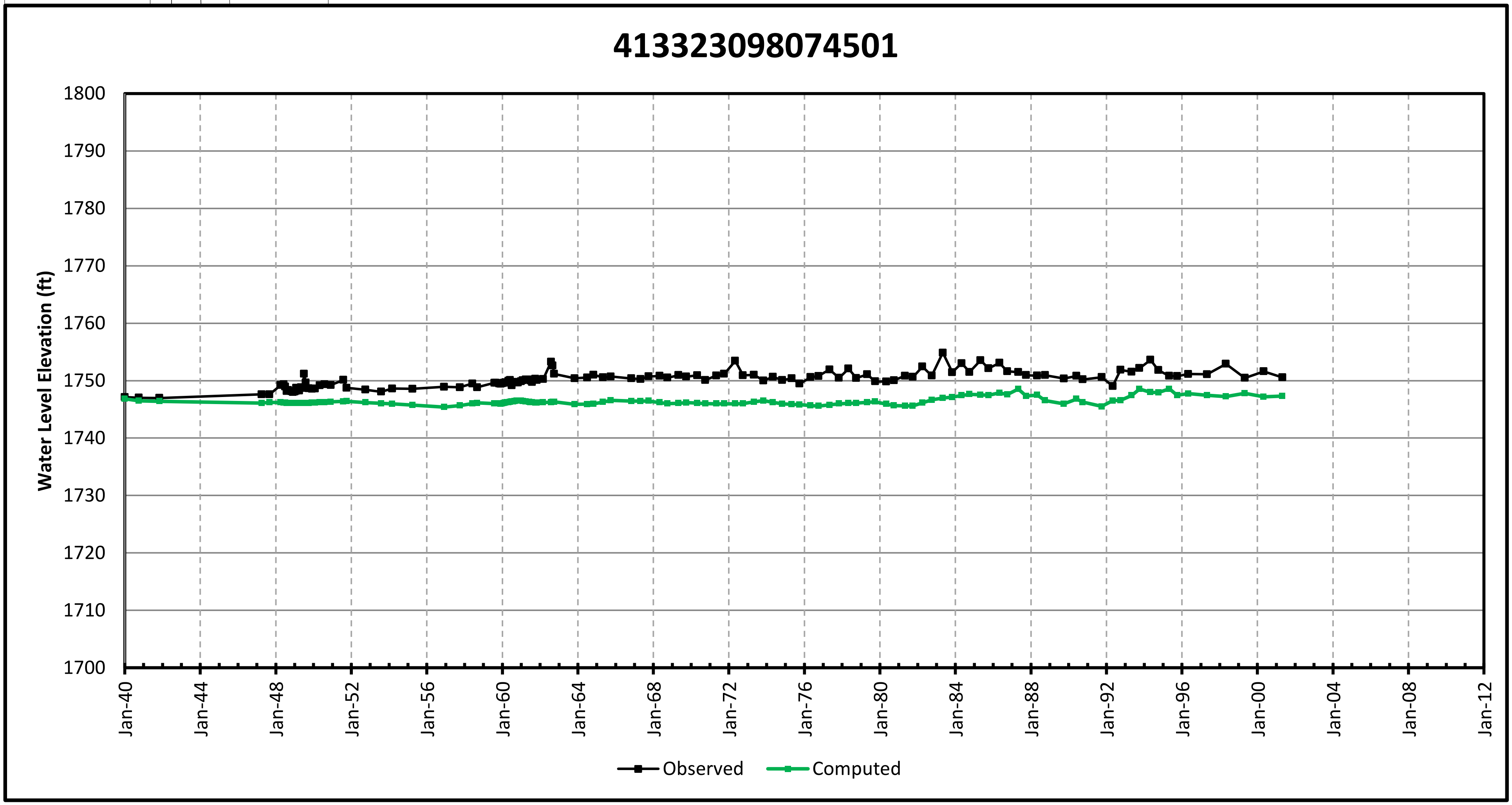


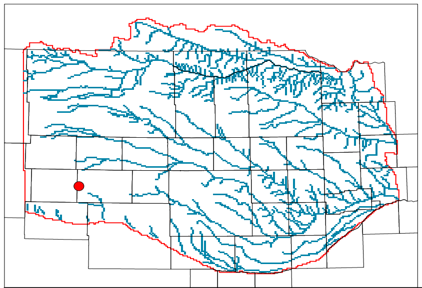
18N20W11DDDD



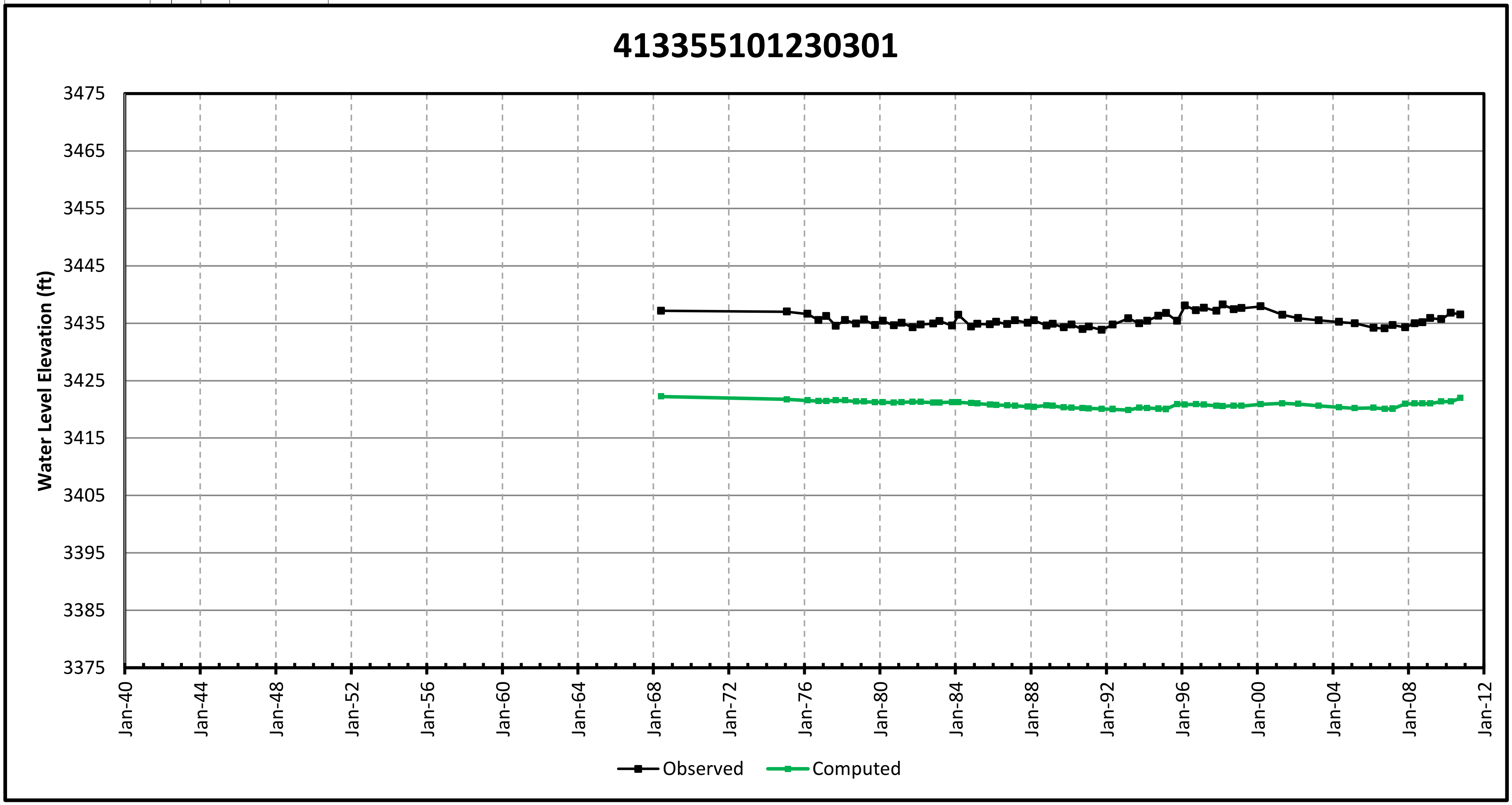


18N07W04CA

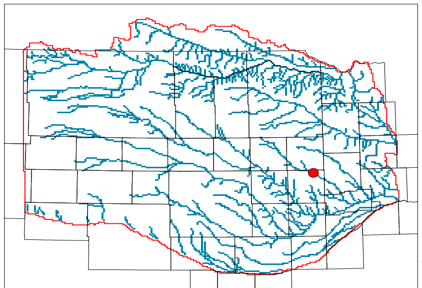

413323098074501
Water Level Elevation (ft)
1800
1790
1780
1770
1760
1750
1740
1730
1720
1710
1700
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



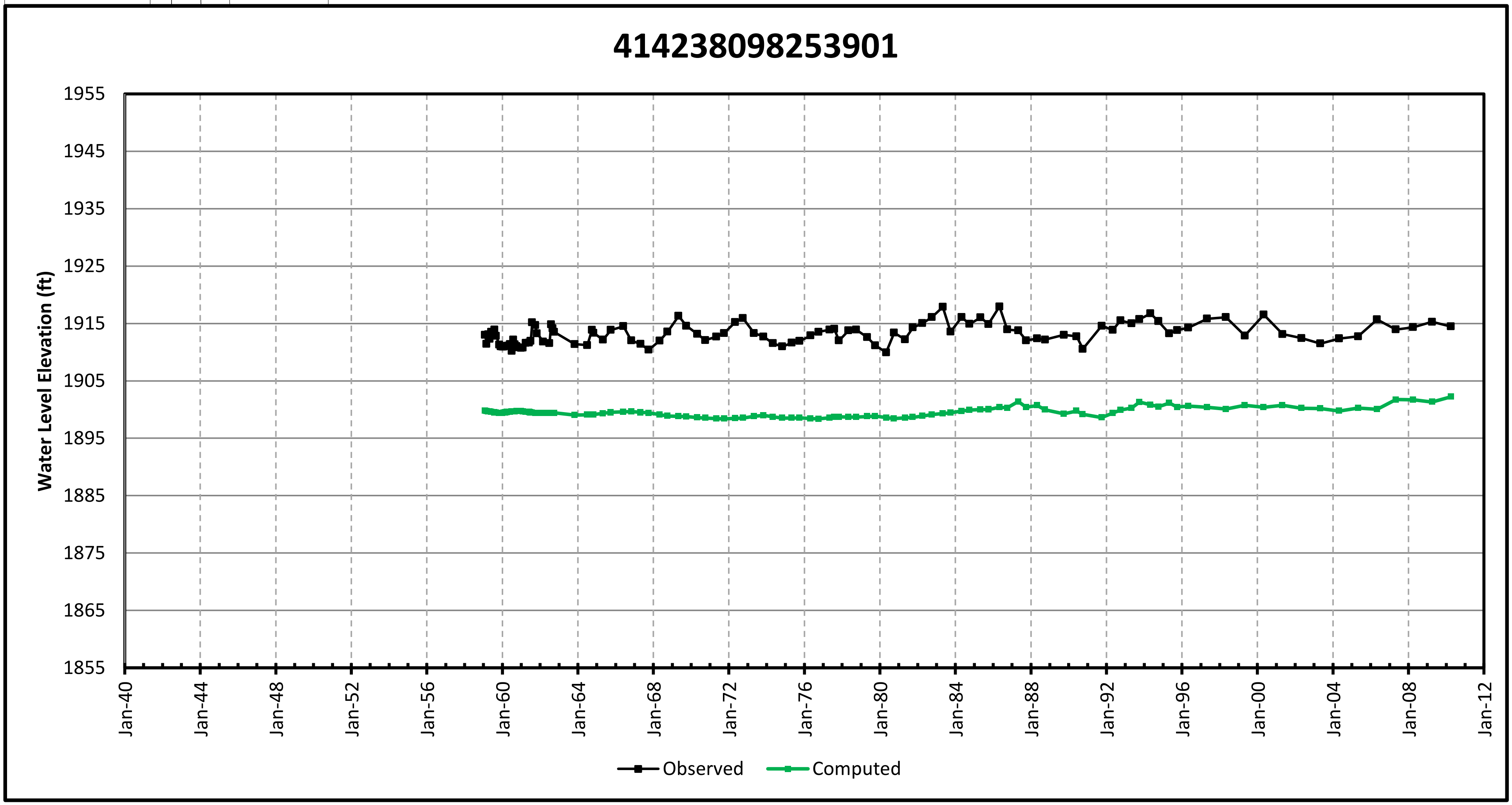
18N35W05BB



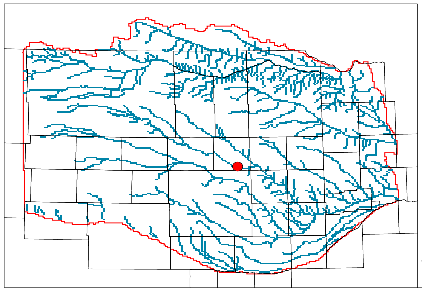
413355101230301
Water Level Elevation (ft)
3475
3465
3455
3445
3435
3425
3415
3405
3395
3385
3375
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



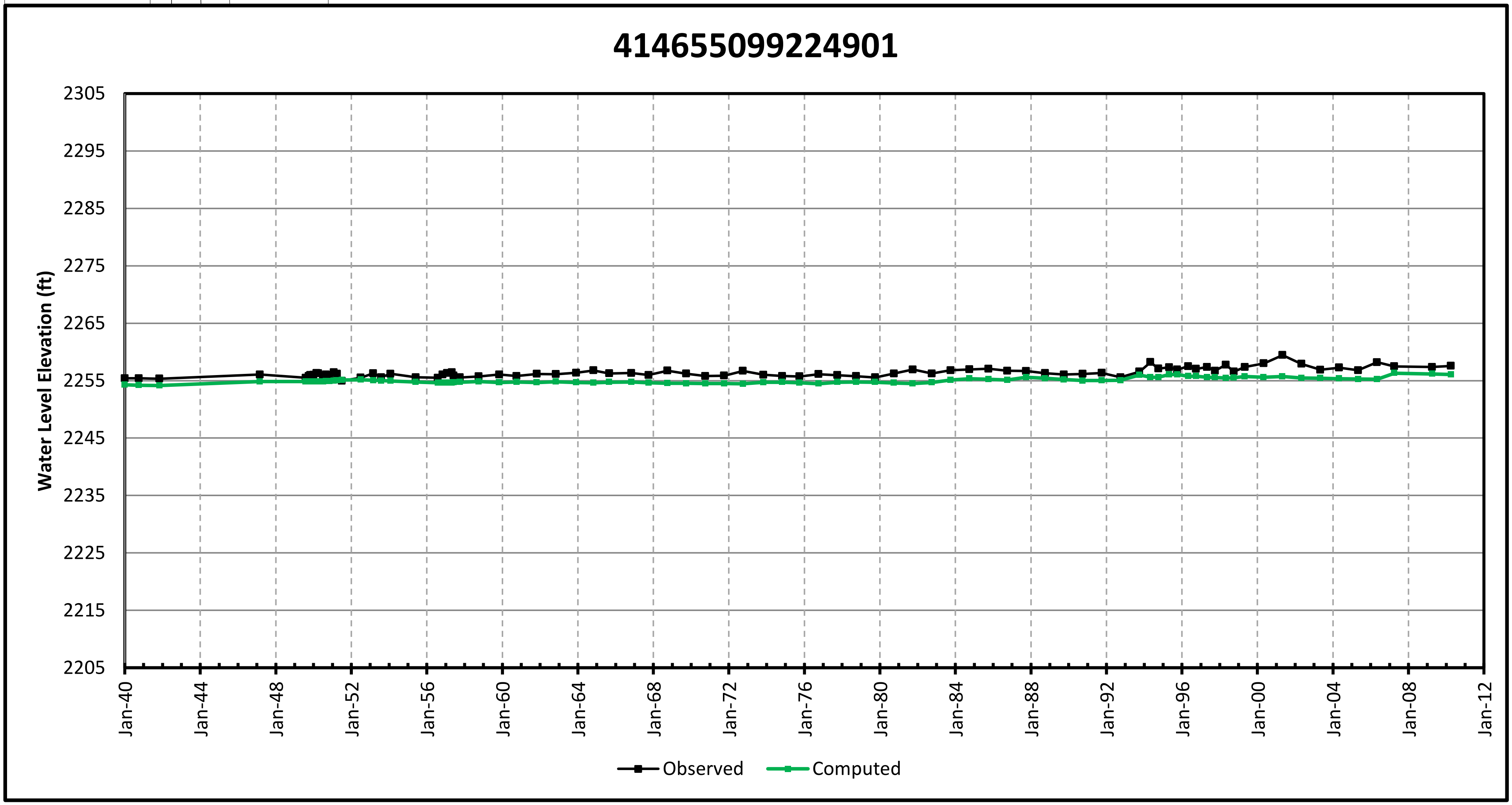
20N10W14AA



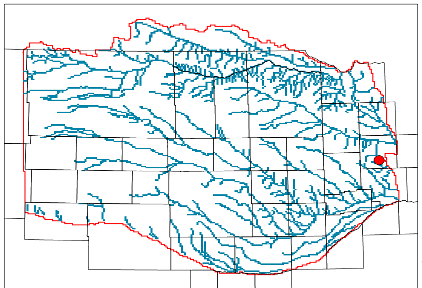
414238098253901
Water Level Elevation (ft)
1955
1945
1935
1925
1915
1905
1895
1885
1875
1865
1855
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

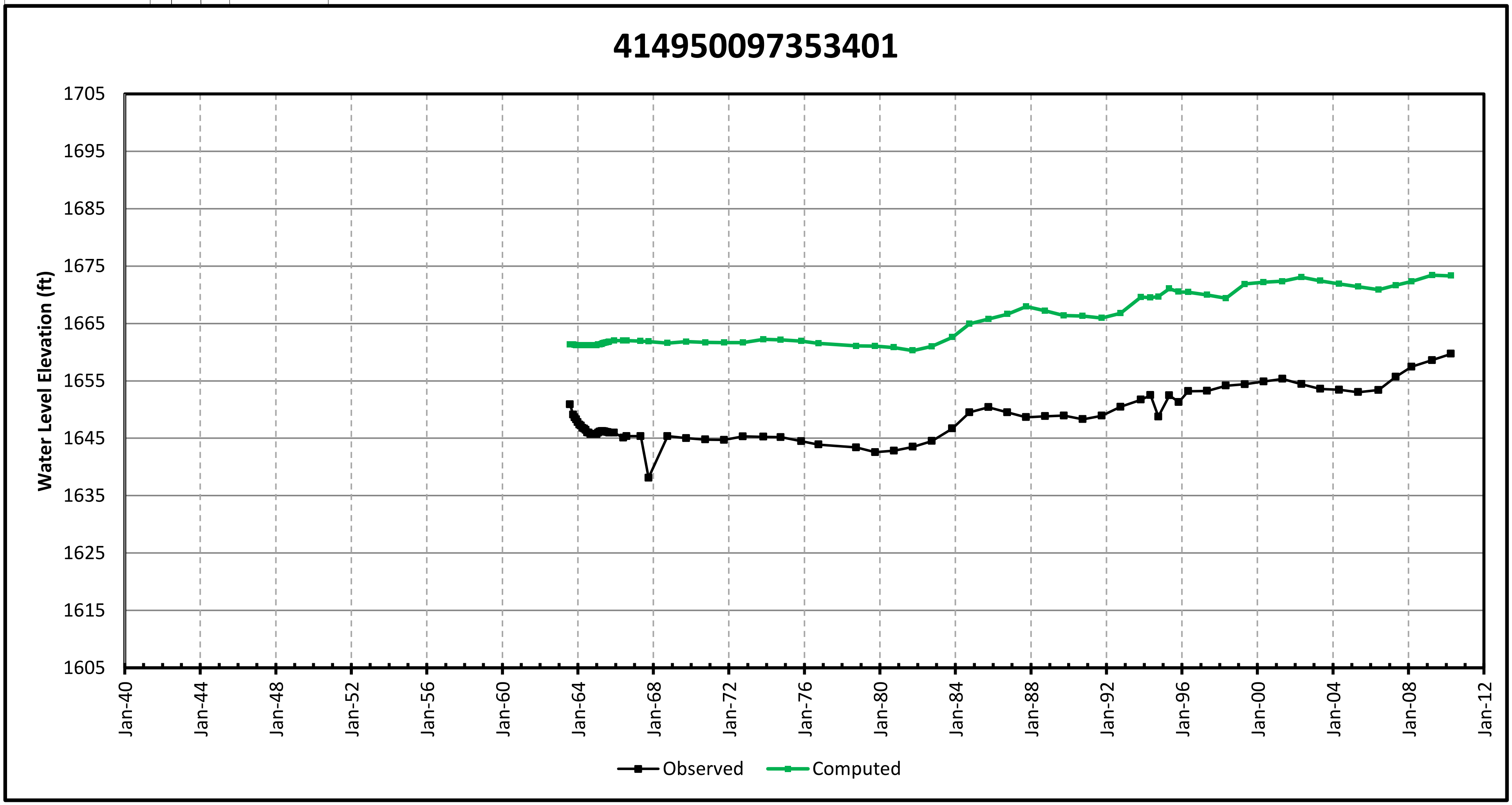


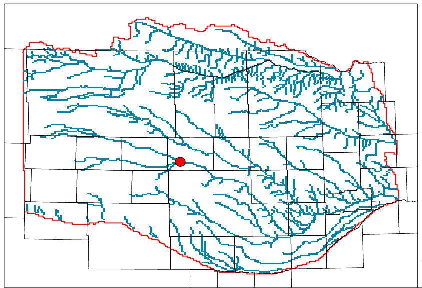
21N18W22AA



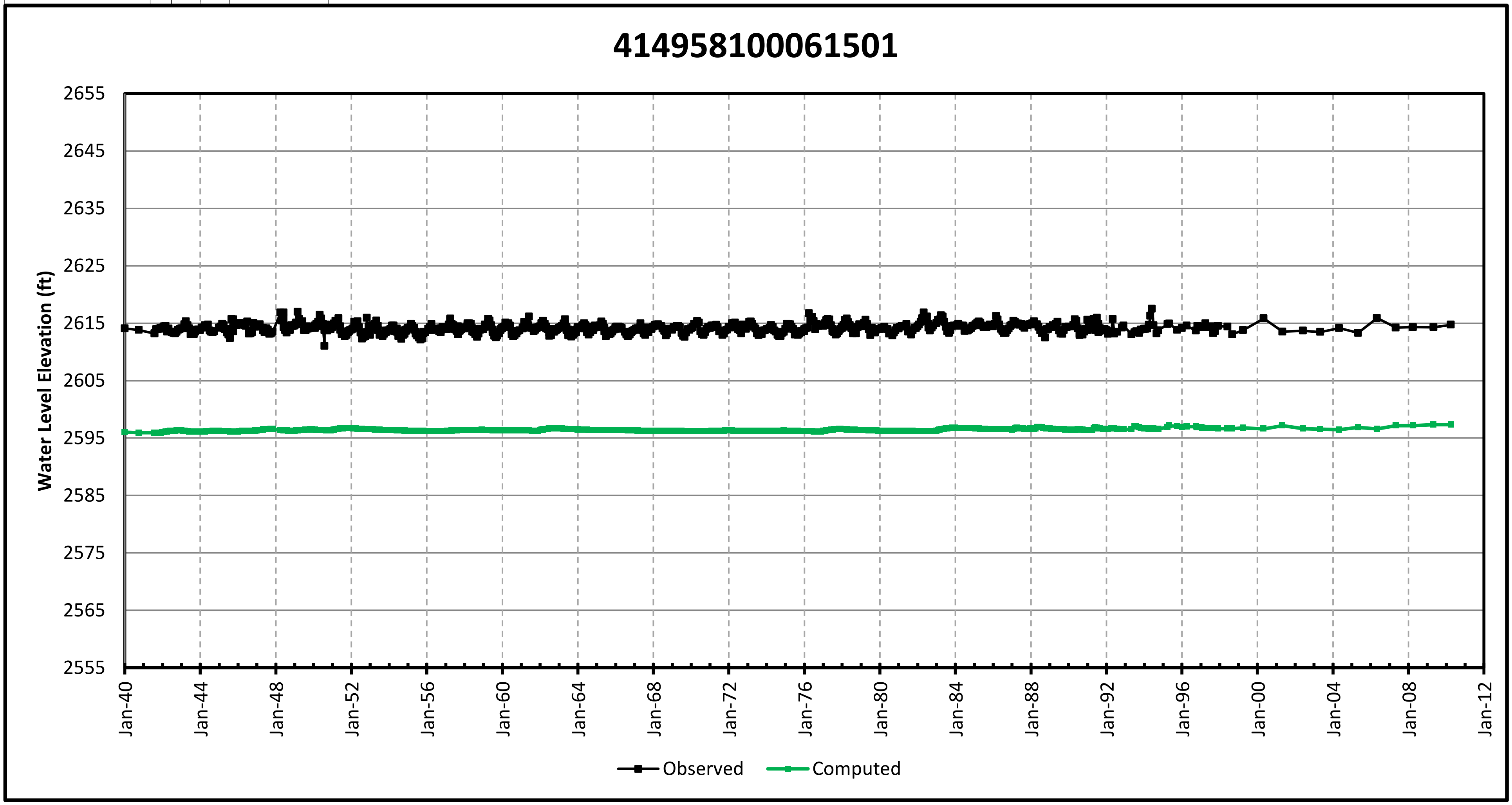
414655099224901
Water Level Elevation (ft)
2305
2295
2285
2275
2265
2255
2245
2235
2225
2215
2205
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed


22N02W31CDD

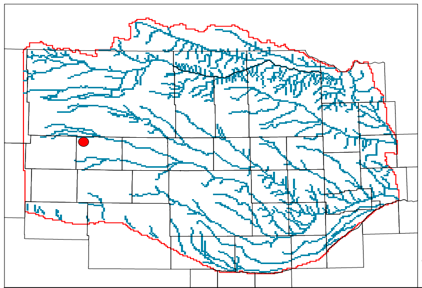

414950097353401
Water Level Elevation (ft)
1705
1695
1685
1675
1665
1655
1645
1635
1625
1615
1605
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



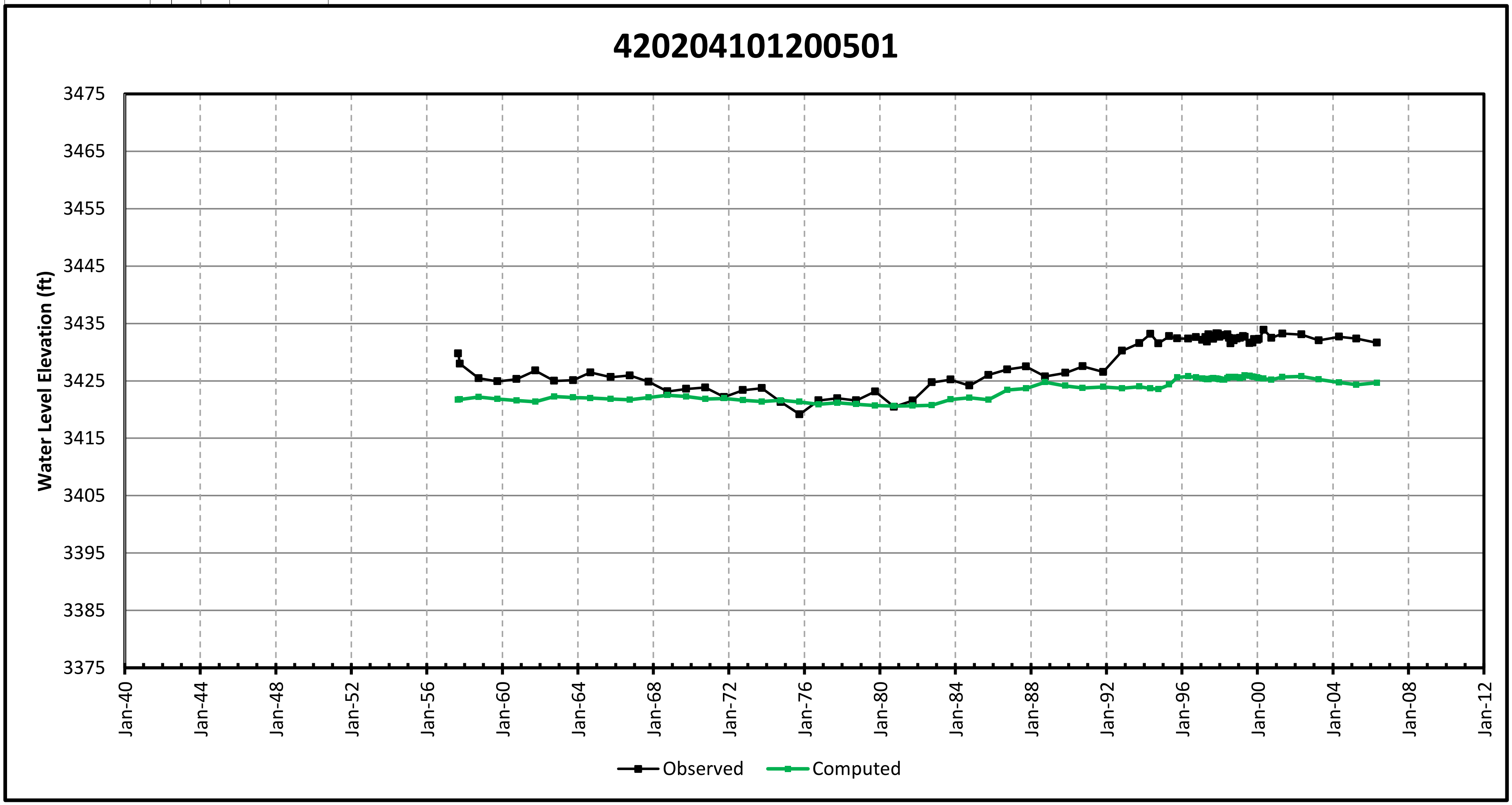
22N24W33CA

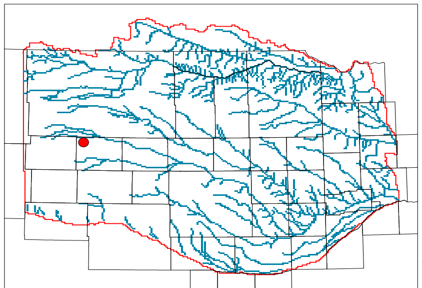


414958100061501
Water Level Elevation (ft)
2655
2645
2635
2625
2615
2605
2595
2585
2575
2565
2555
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

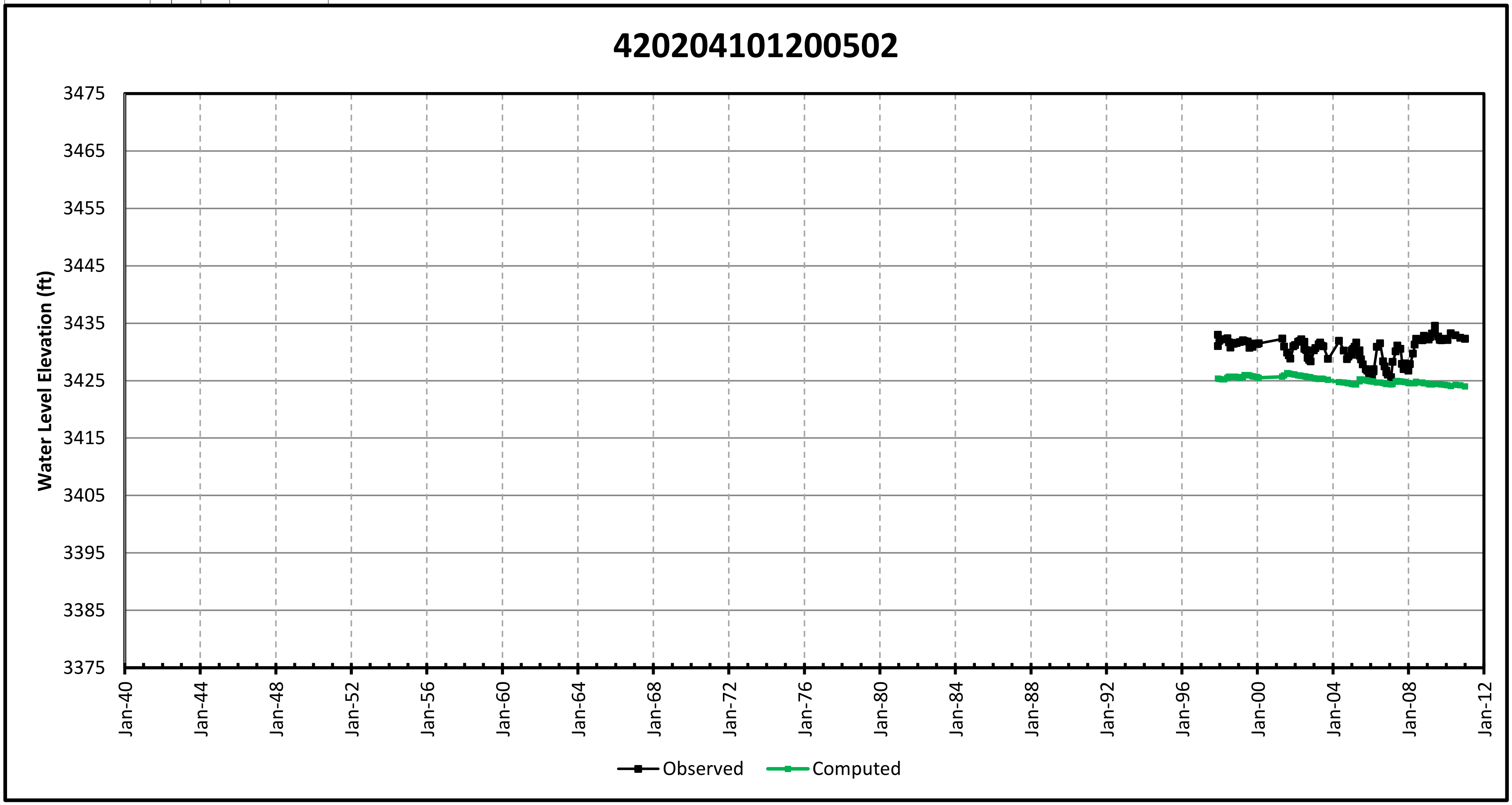


24N35W23DC

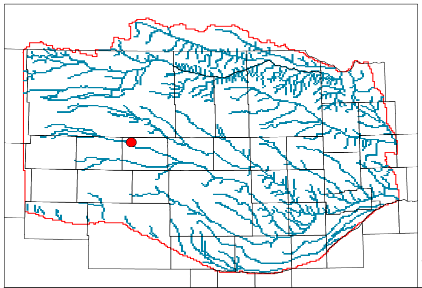

420204101200501
Water Level Elevation (ft)
3475
3465
3455
3445
3435
3425
3415
3405
3395
3385
3375
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



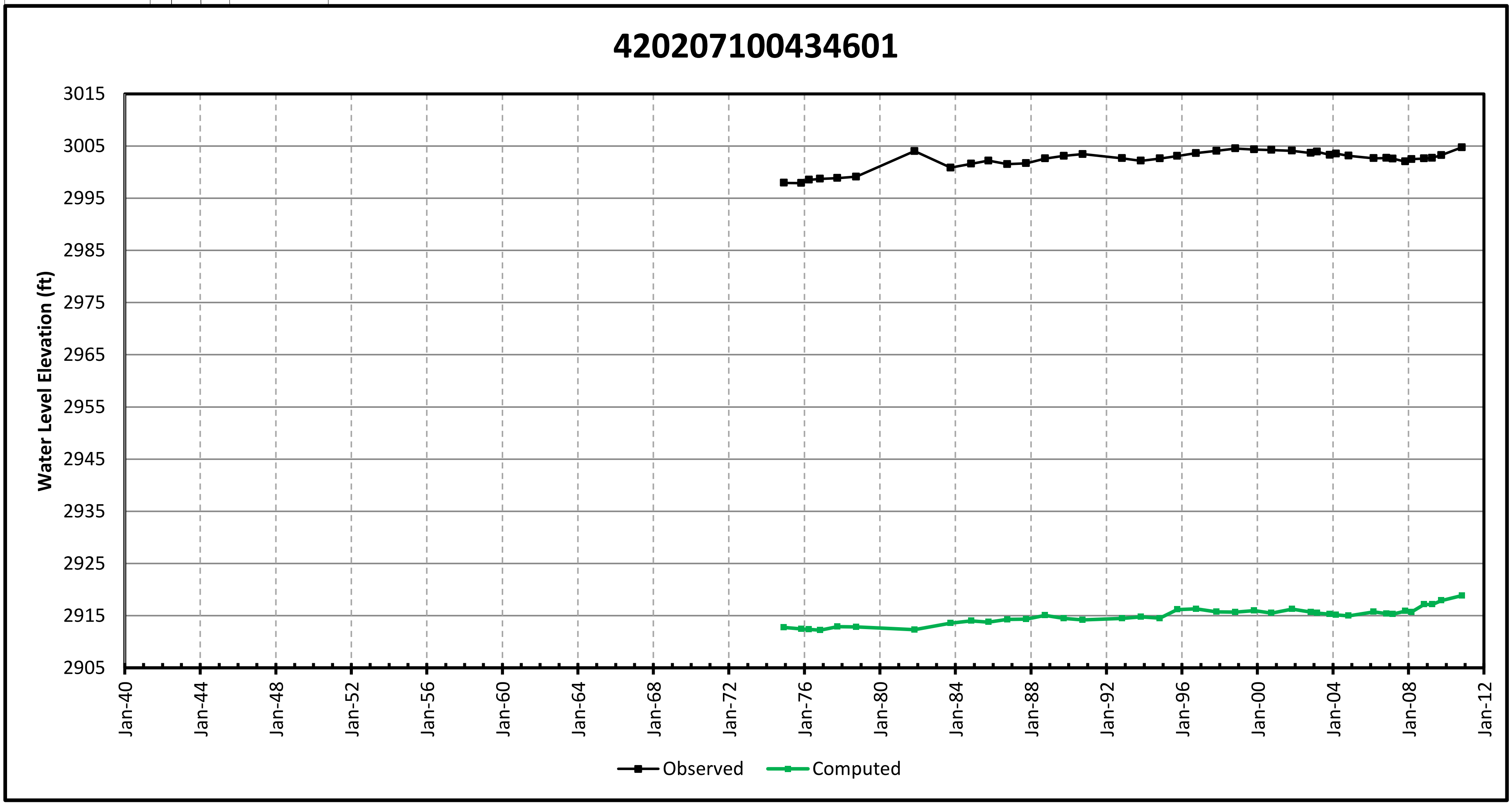
24N35W23DC



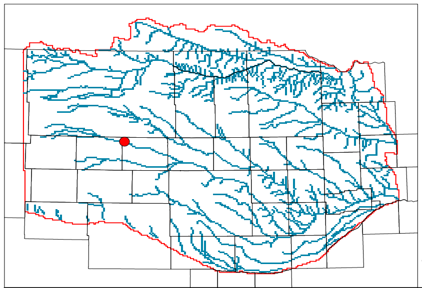
420204101200502
Water Level Elevation (ft)
3475
3465
3455
3445
3435
3425
3415
3405
3395
3385
3375
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



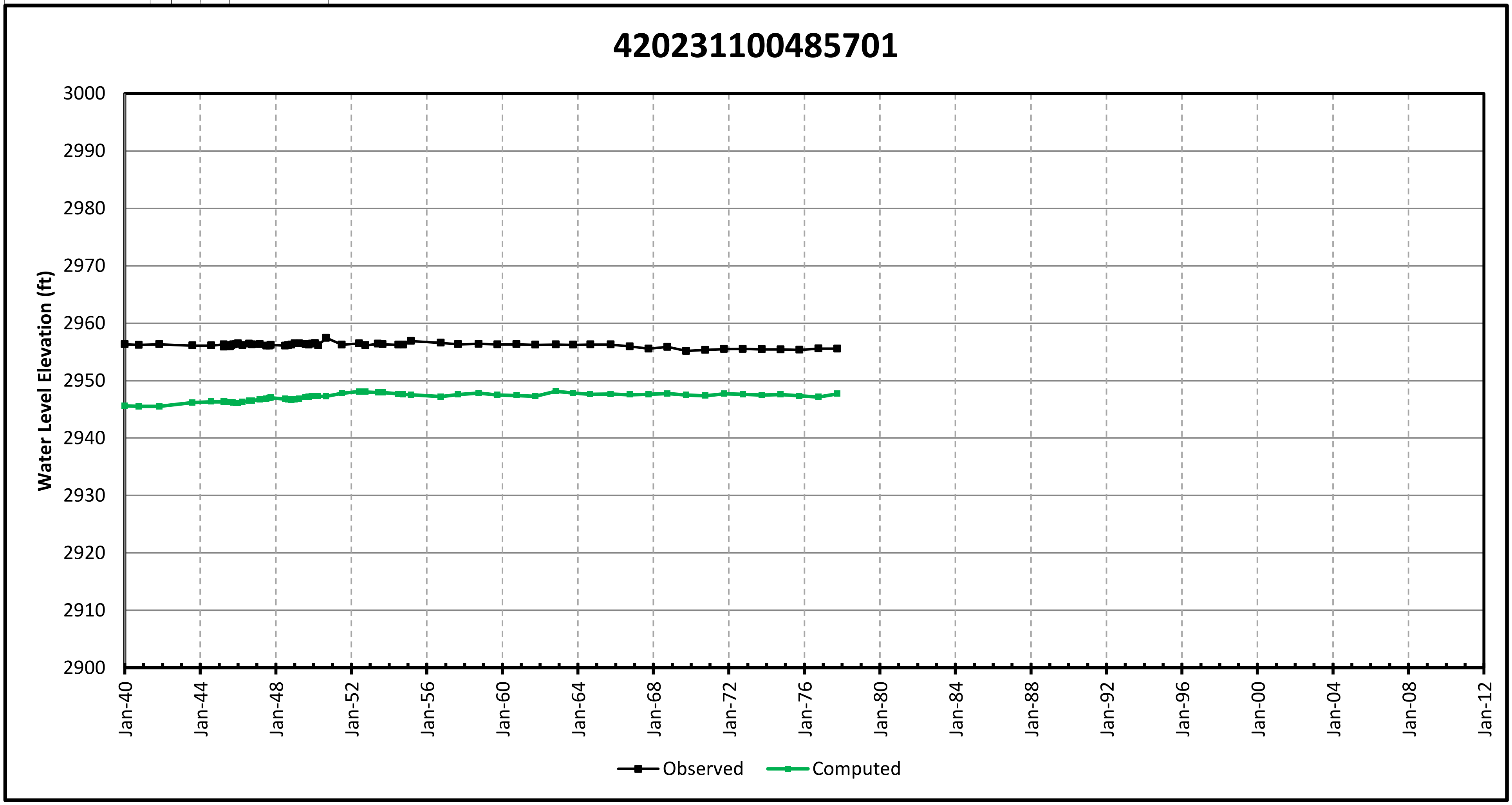
24N29W19CB



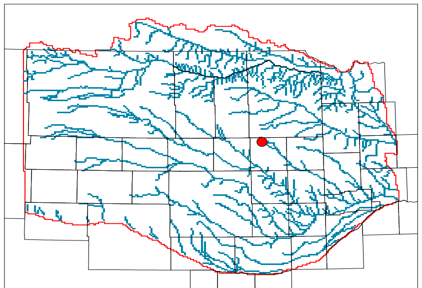
420207100434601
Water Level Elevation (ft)
3015
3005
2995
2985
2975
2965
2955
2945
2935
2925
2915
2905
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



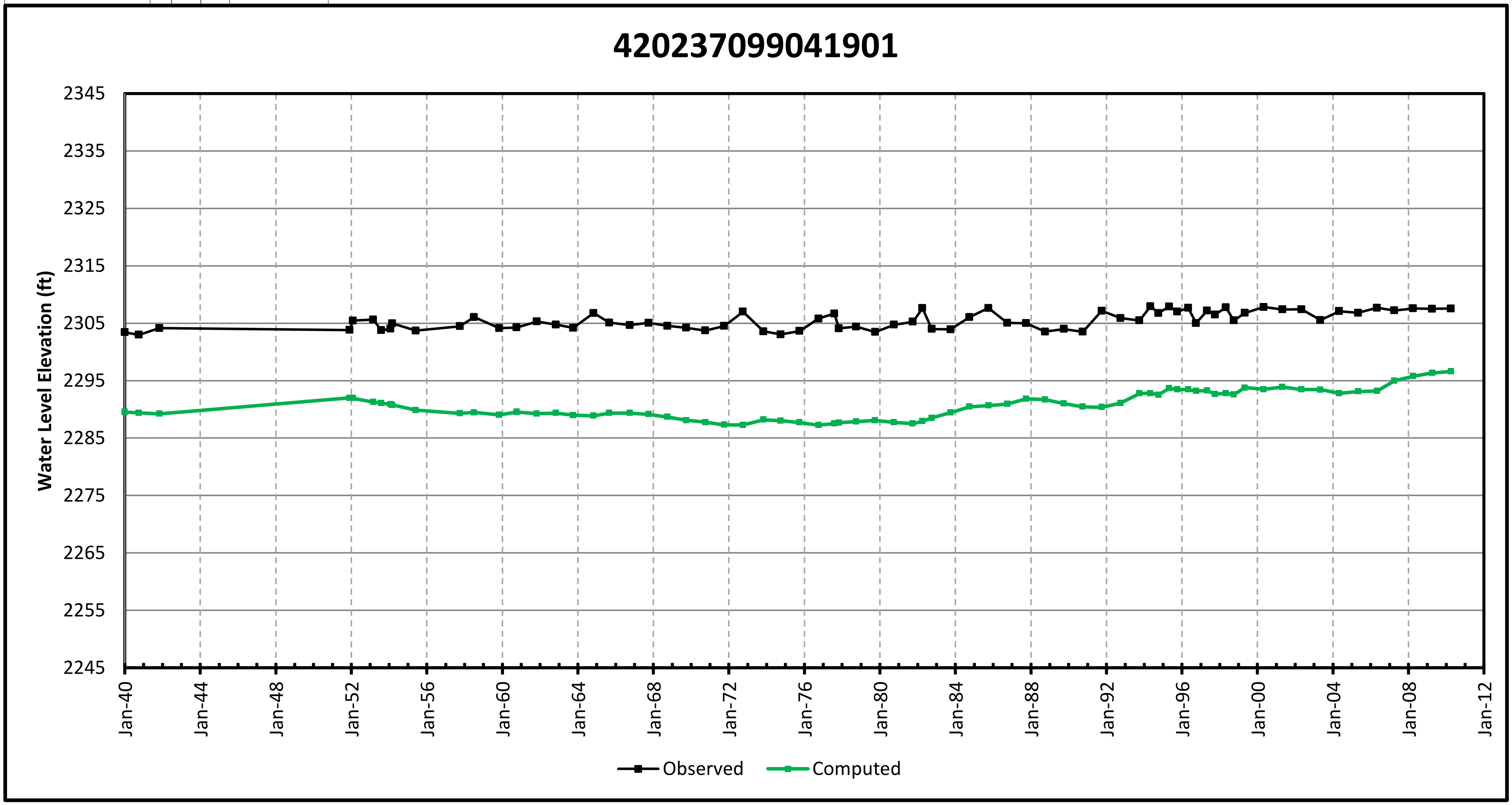
24N30W20AB

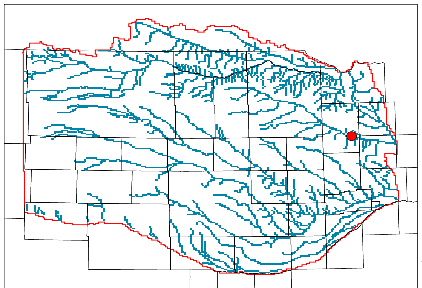


420231100485701
Water Level Elevation (ft)
3000
2990
2980
2970
2960
2950
2940
2930
2920
2910
2900
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

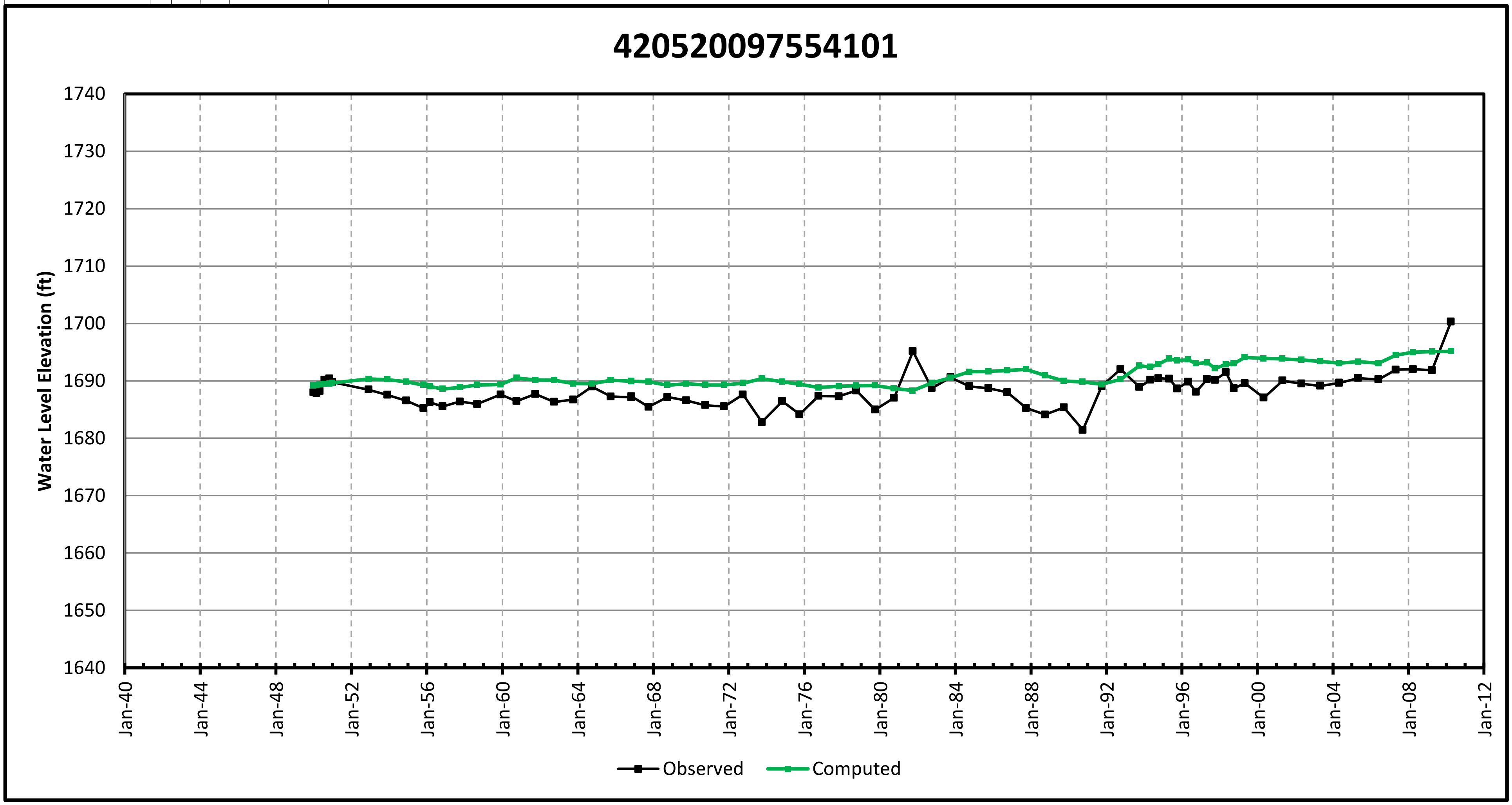


24N15W20AA

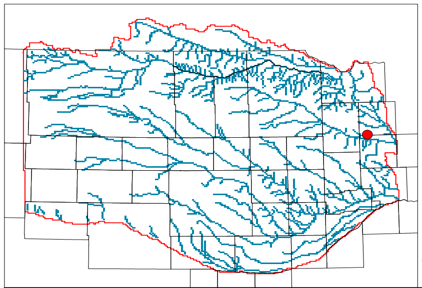

420237099041901
Water Level Elevation (ft)
2345
2335
2325
2315
2305
2295
2285
2275
2265
2255
2245
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



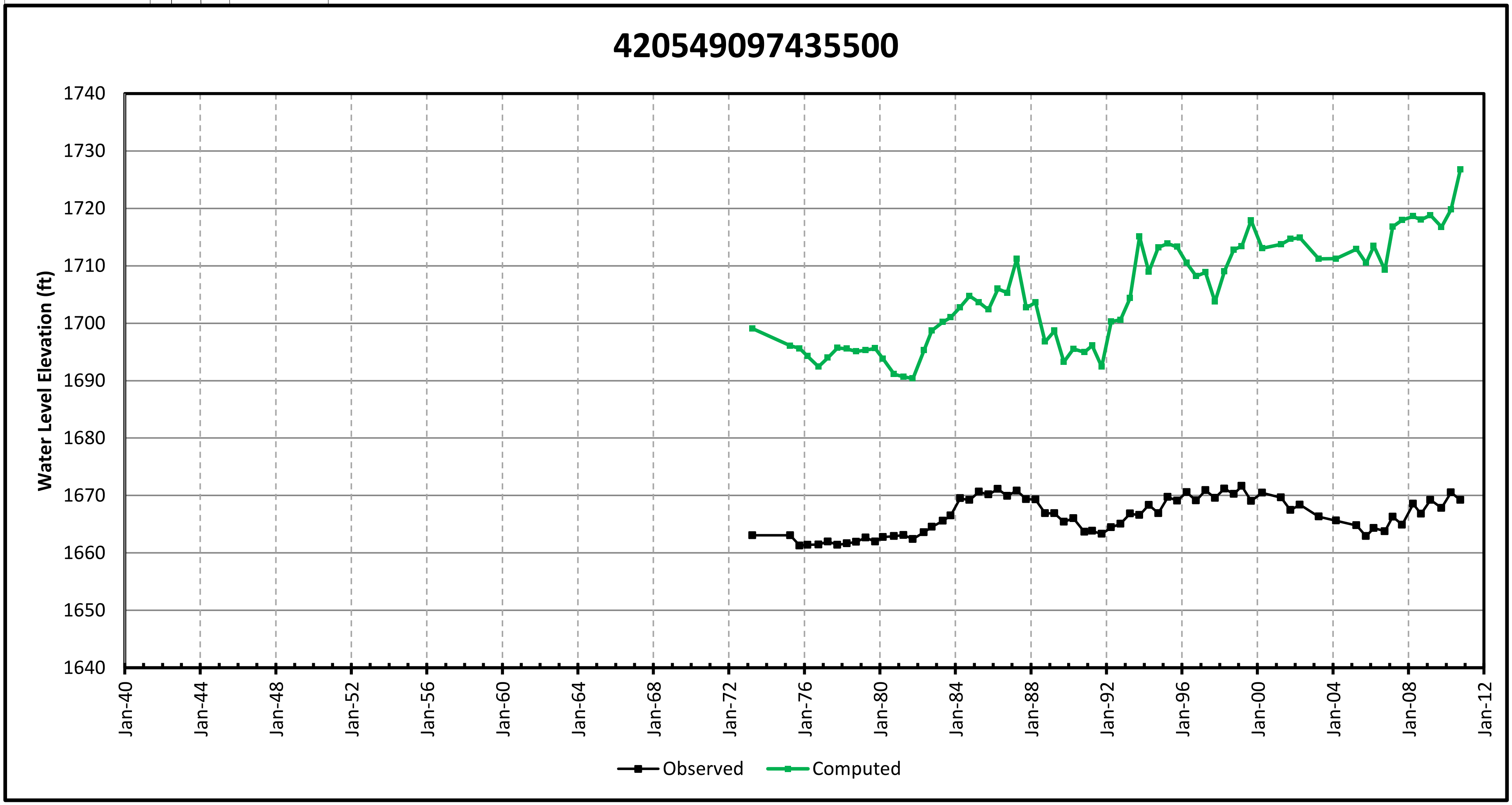
24N05W05BB

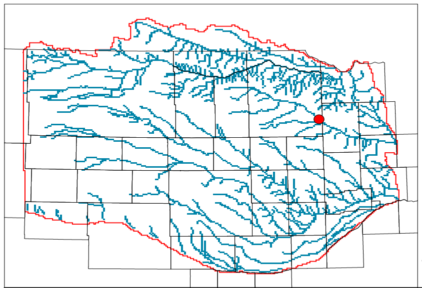


420520097554101
Water Level Elevation (ft)
1740
1730
1720
1710
1700
1690
1680
1670
1660
1650
1640
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

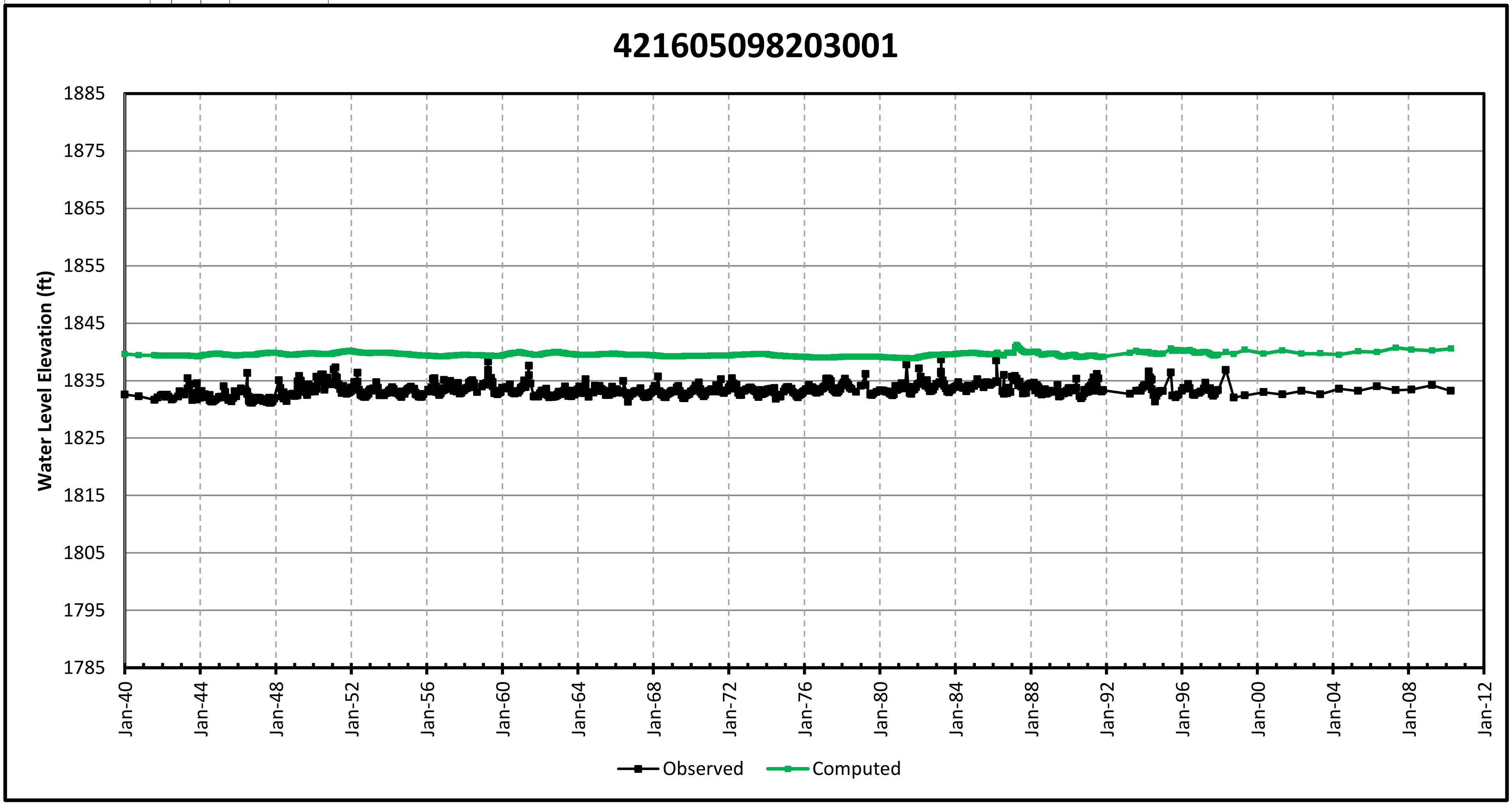


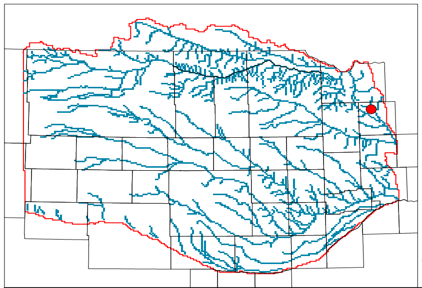
25N04W36CBAA



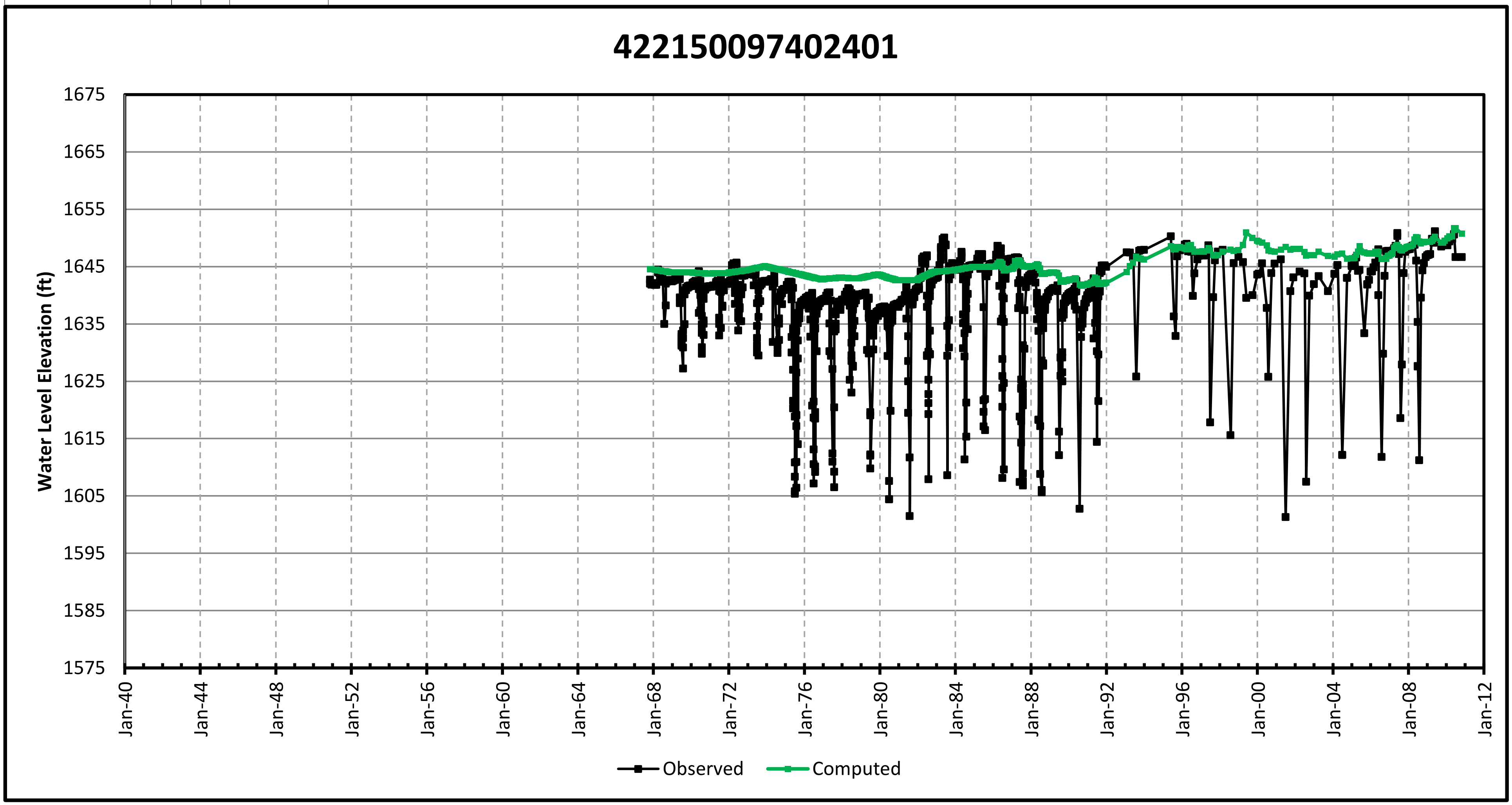


27N09W34DA

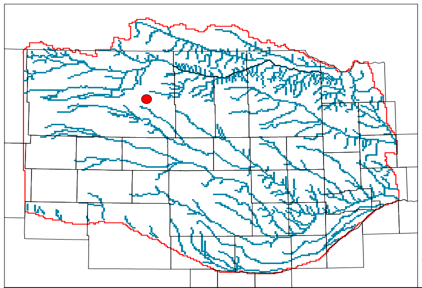

421605098203001
Water Level Elevation (ft)
1885
1875
1865
1855
1845
1835
1825
1815
1805
1795
1785
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



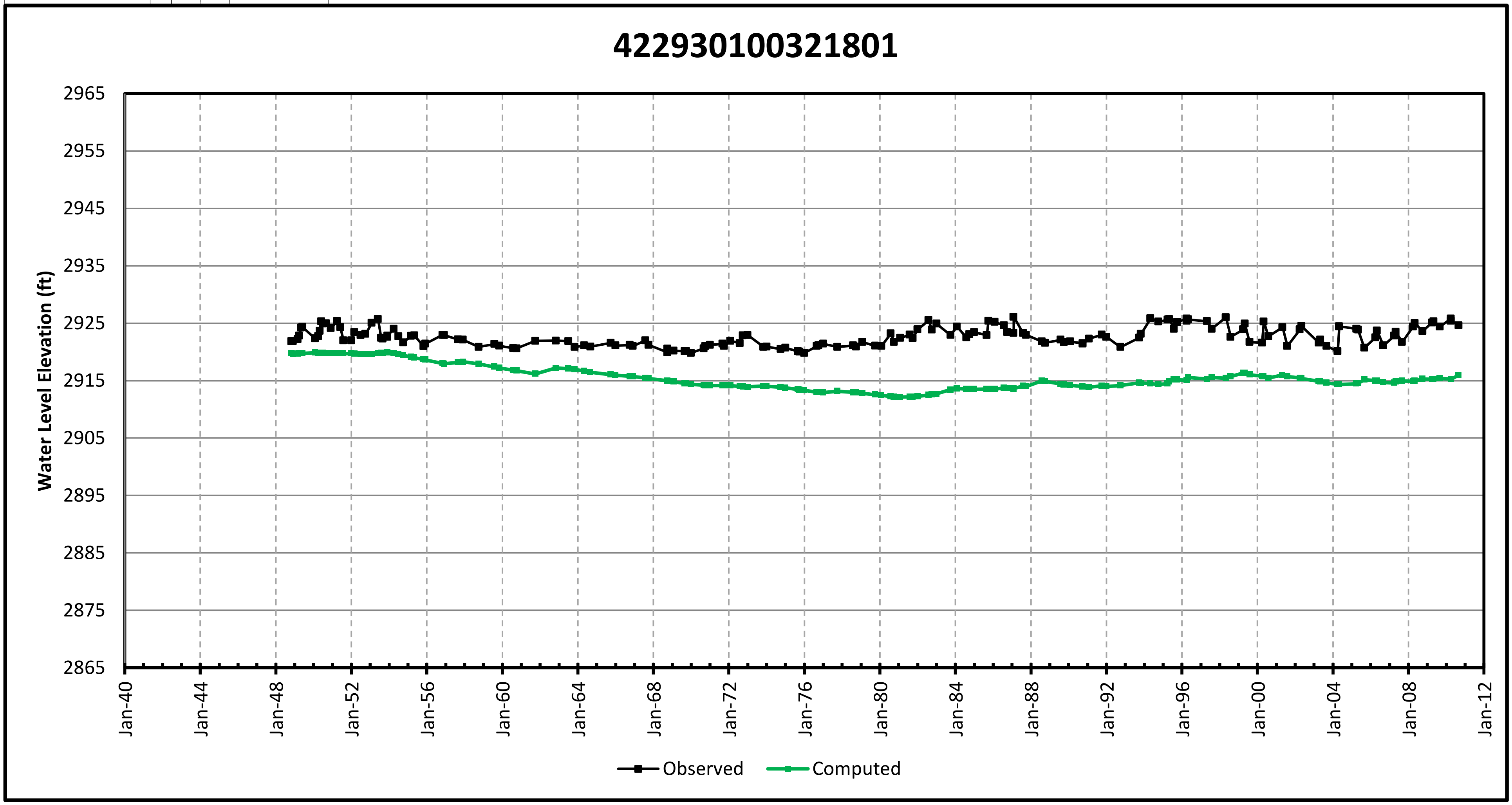
28N03W33BA

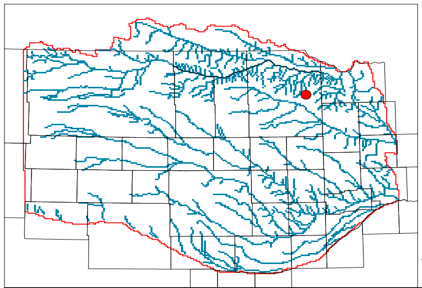


422150097402401
Water Level Elevation (ft)
1675
1665
1655
1645
1635
1625
1615
1605
1595
1585
1575
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

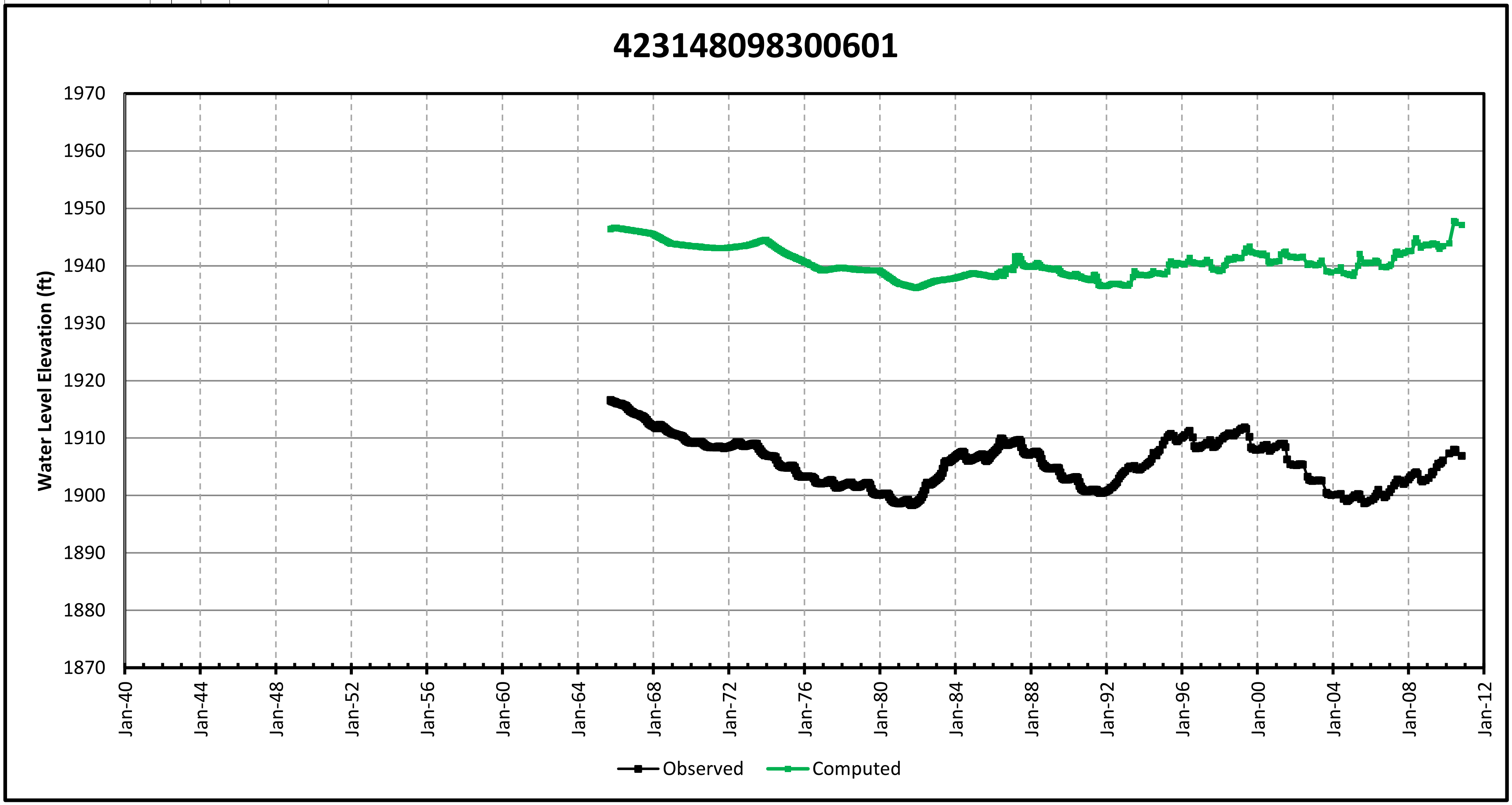


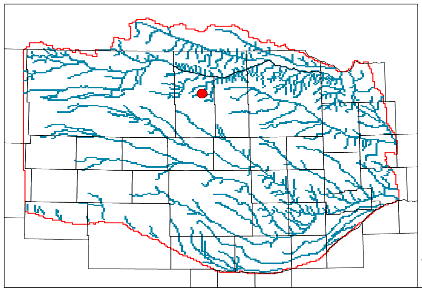
29N28W13AA


422930100321801
Water Level Elevation (ft)
2965
2955
2945
2935
2925
2915
2905
2895
2885
2875
2865
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

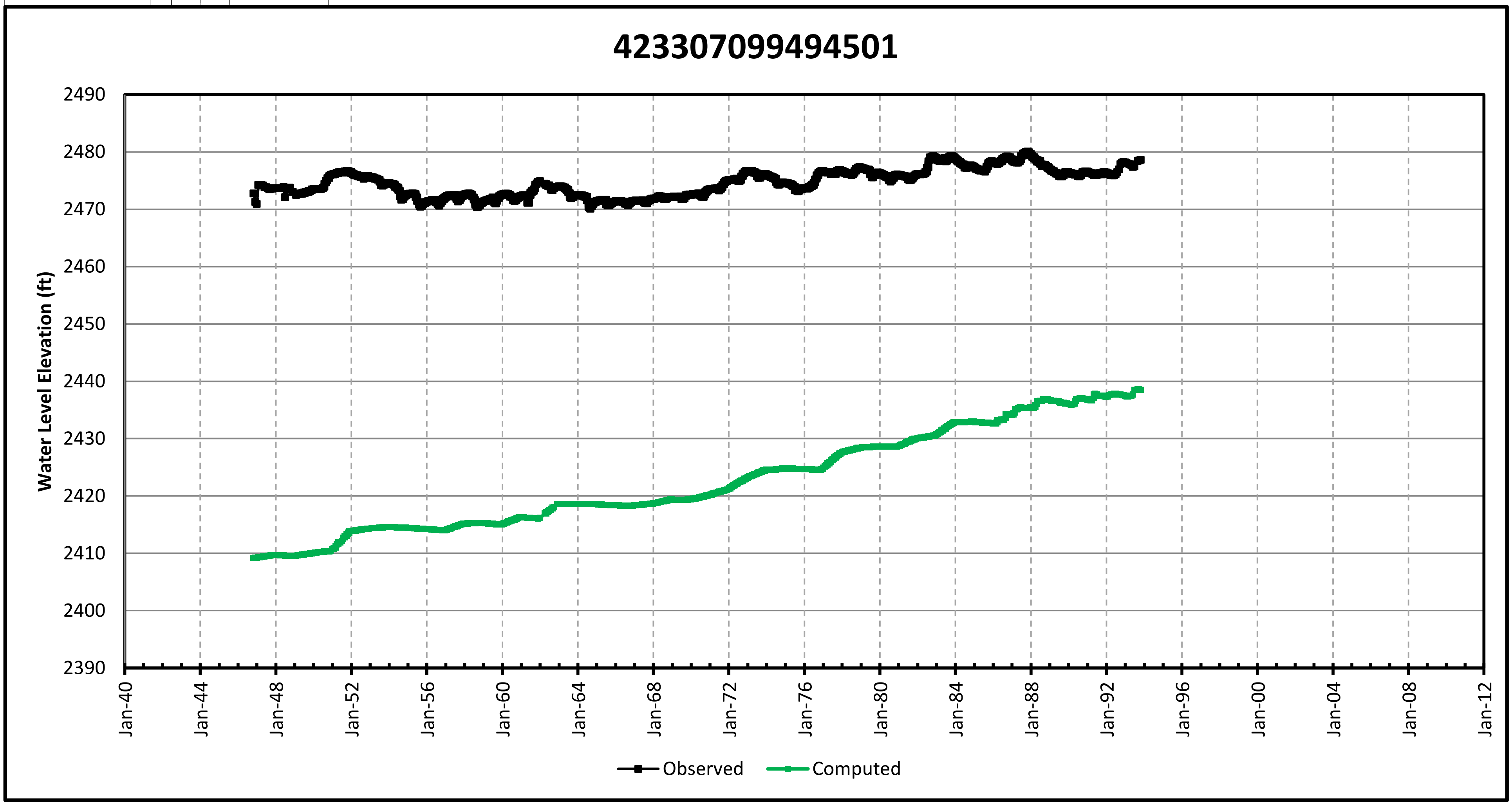


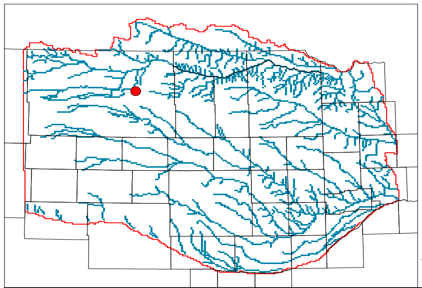
30N10W32DAA



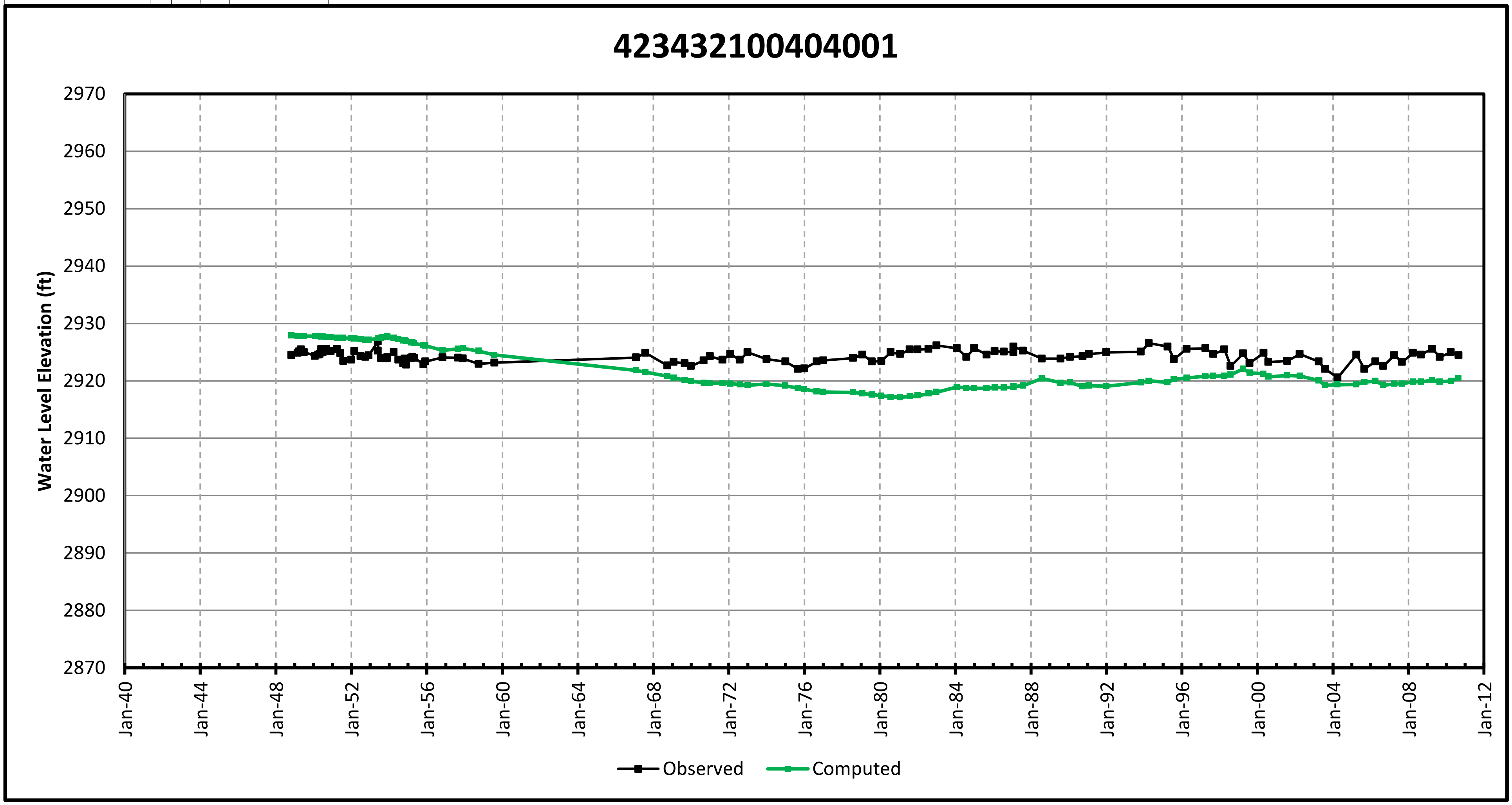


30N21W19CC

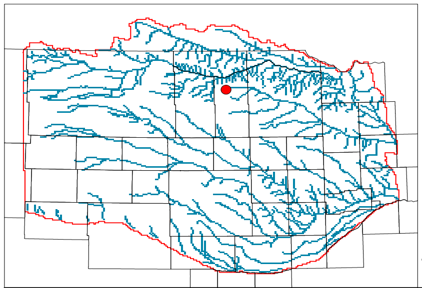

423307099494501
Water Level Elevation (ft)
2490
2480
2470
2460
2450
2440
2430
2420
2410
2400
2390
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

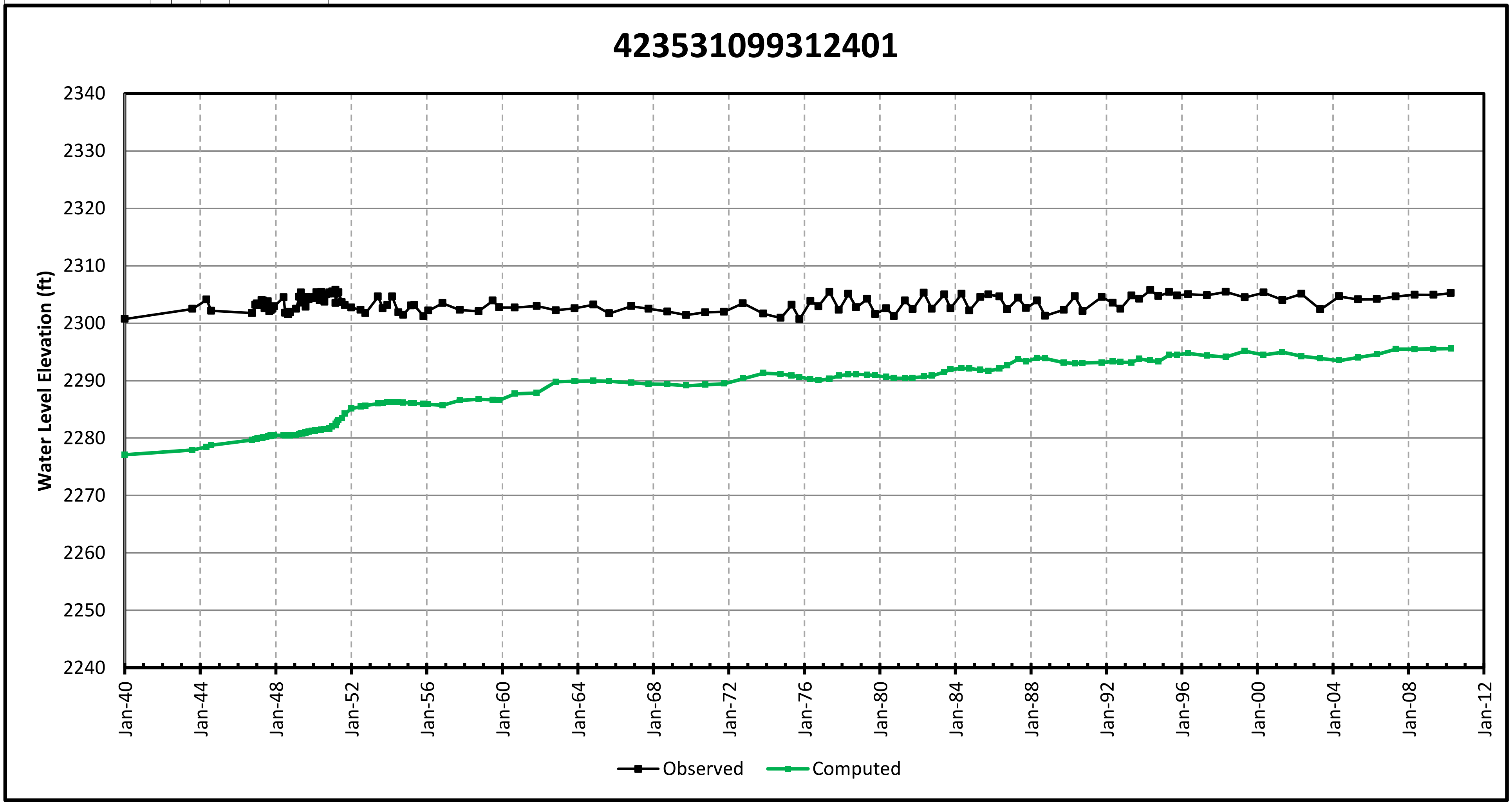


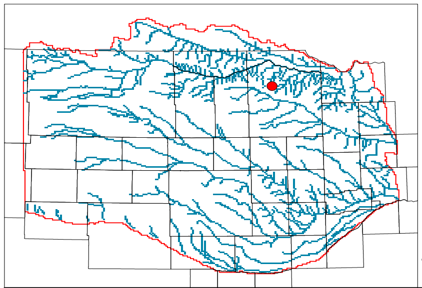
30N29W14AC



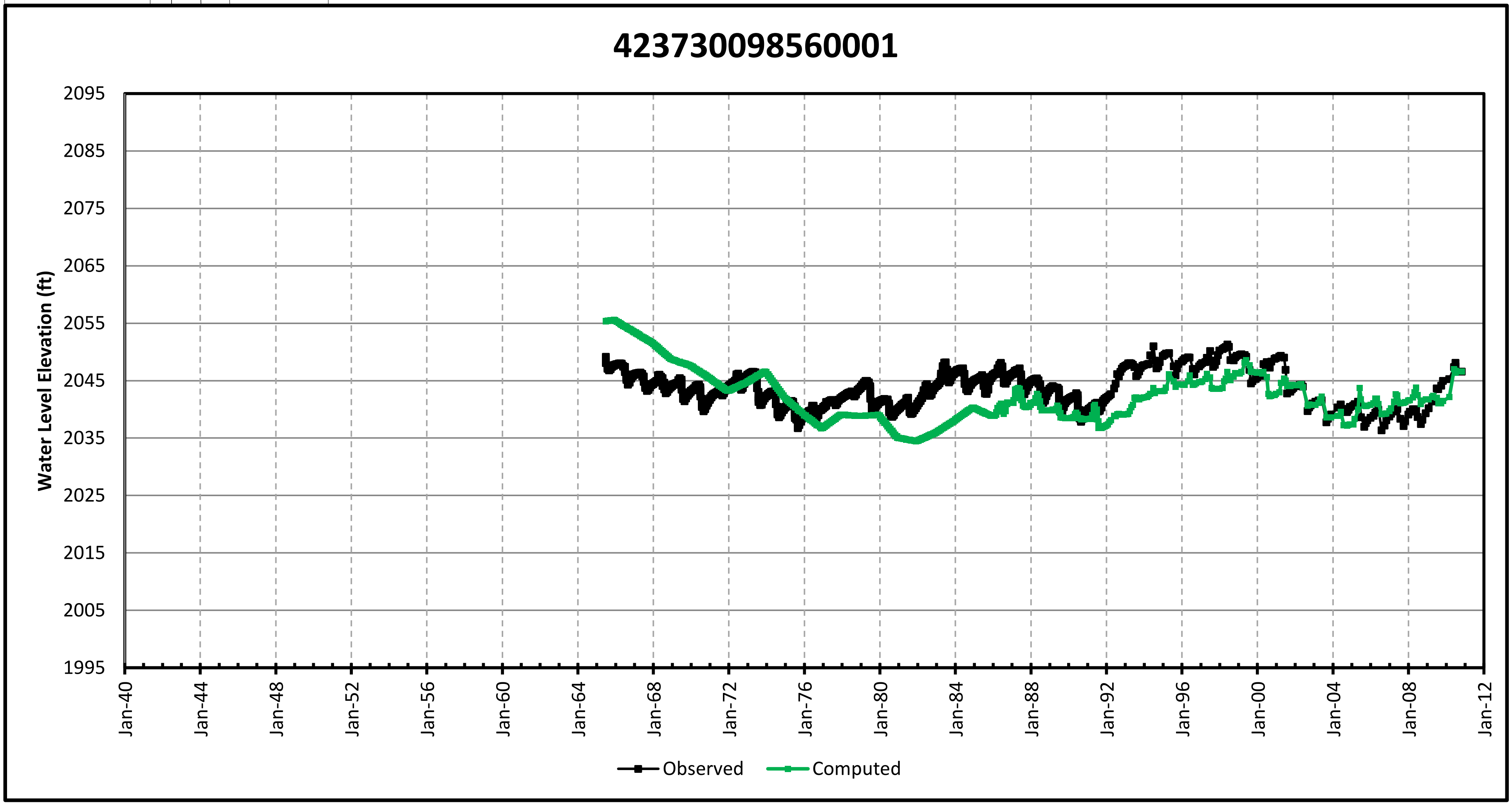
423432100404001
Water Level Elevation (ft)
2970
2960
2950
2940
2930
2920
2910
2900
2890
2880
2870
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

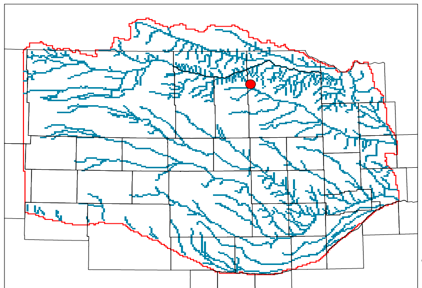

30N19W10AA


423531099312401
Water Level Elevation (ft)
2340
2330
2320
2310
2300
2290
2280
2270
2260
2250
2240
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

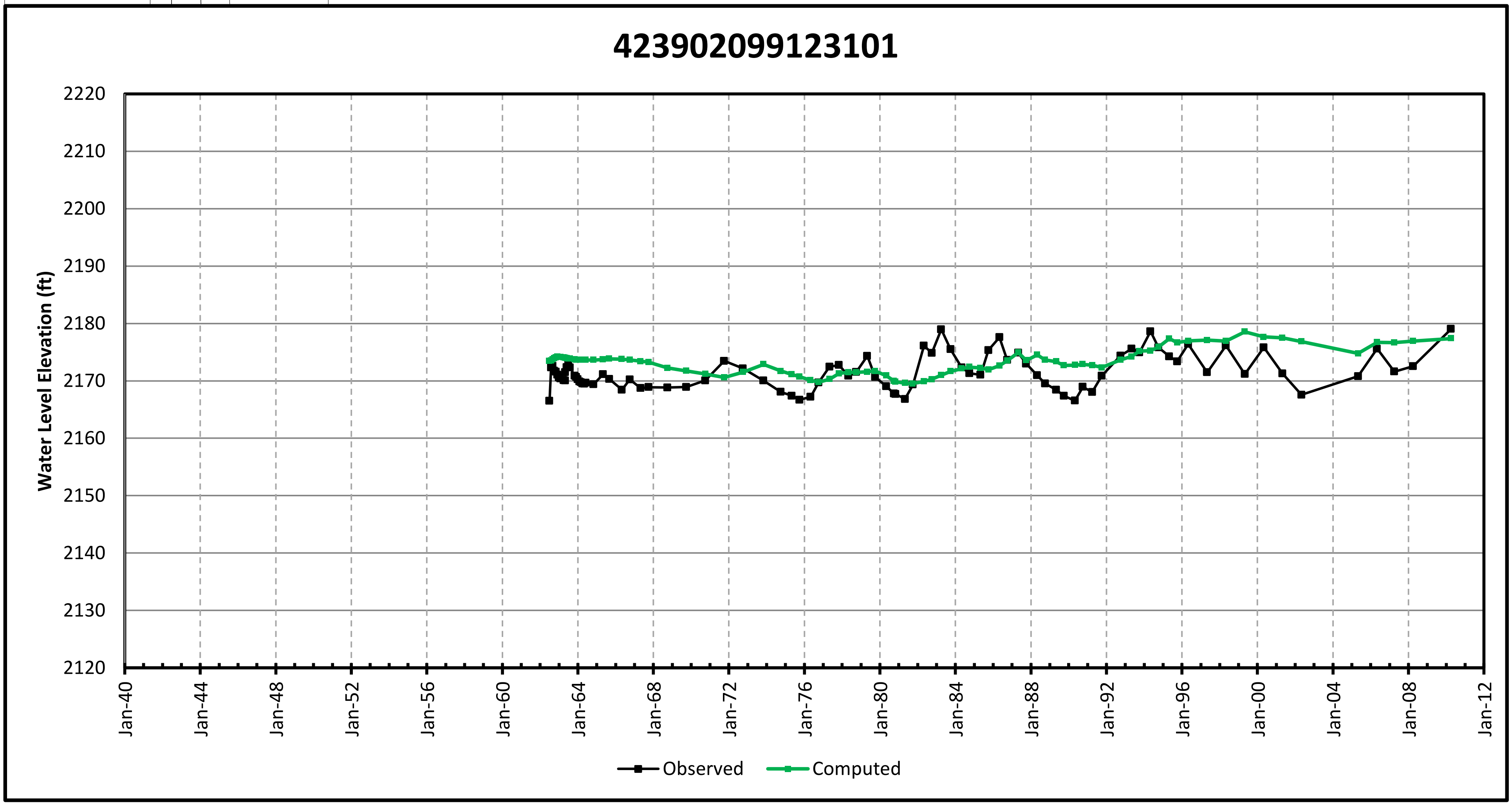


31N14W27DDD

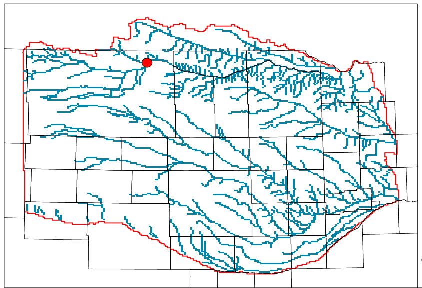




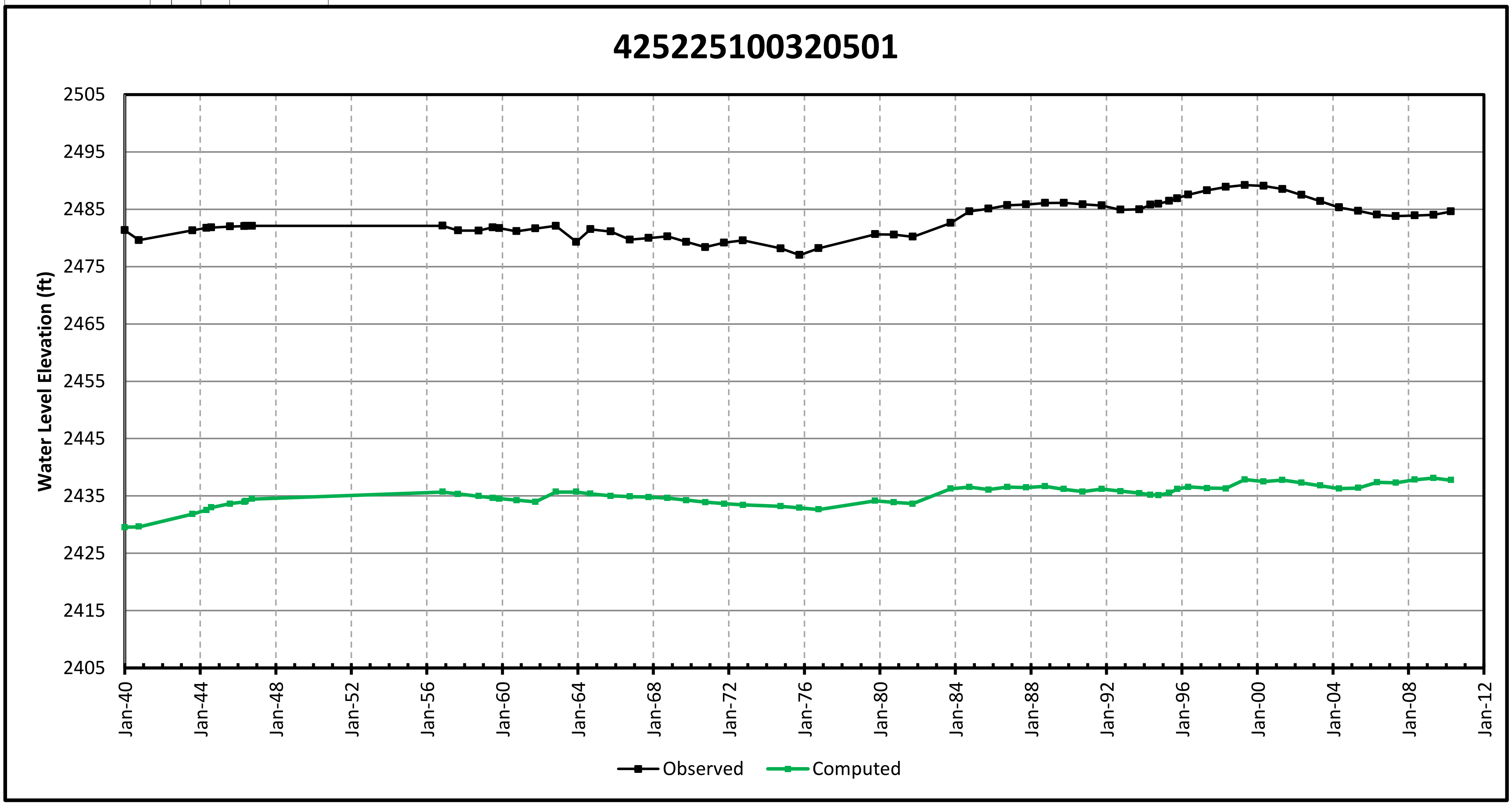
31N16W20AA



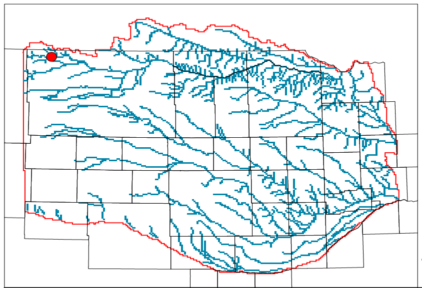
423902099123101
Water Level Elevation (ft)
2220
2210
2200
2190
2180
2170
2160
2150
2140
2130
2120
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



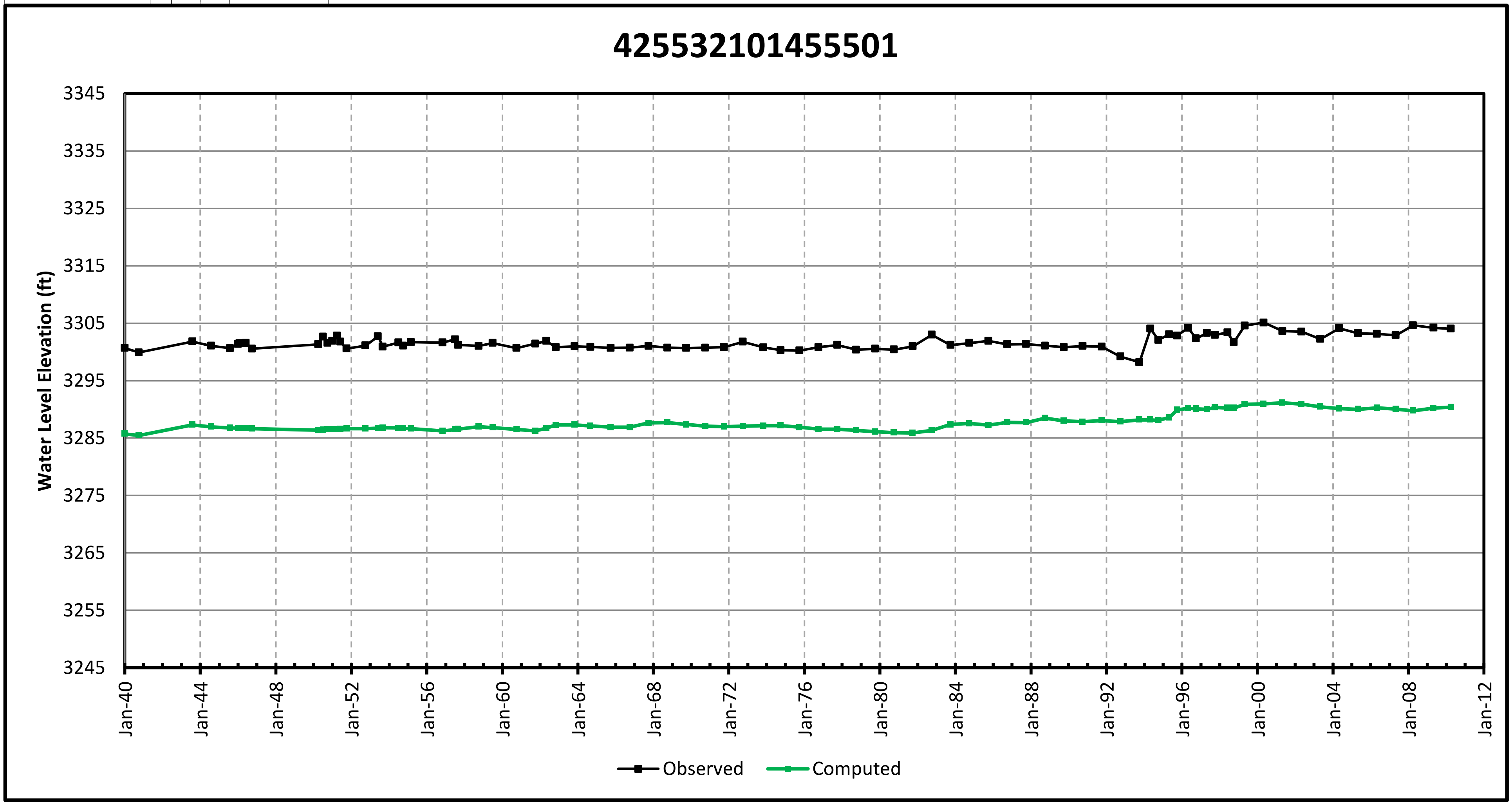
34N27W31DA



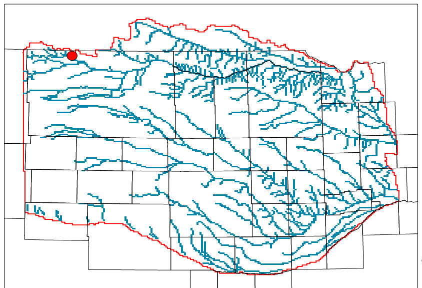
425225100320501
Water Level Elevation (ft)
2505
2495
2485
2475
2465
2455
2445
2435
2425
2415
2405
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



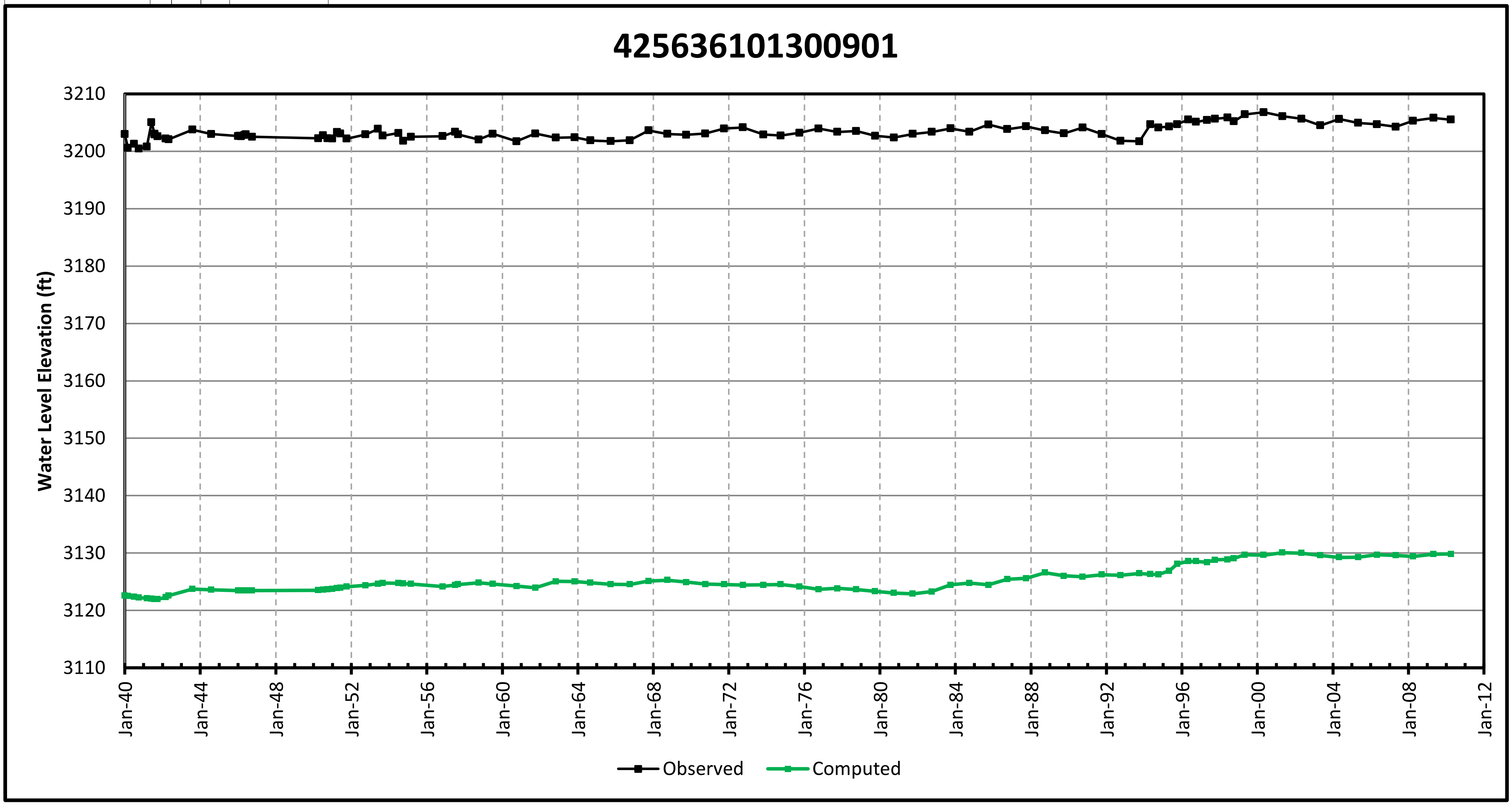
34N38W14BC



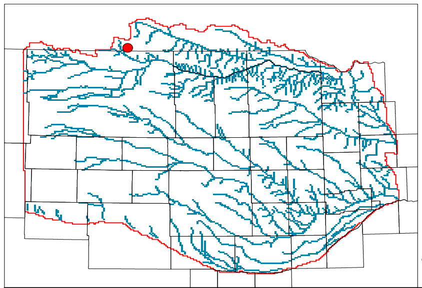
425532101455501
Water Level Elevation (ft)
3345
3335
3325
3315
3305
3295
3285
3275
3265
3255
3245
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



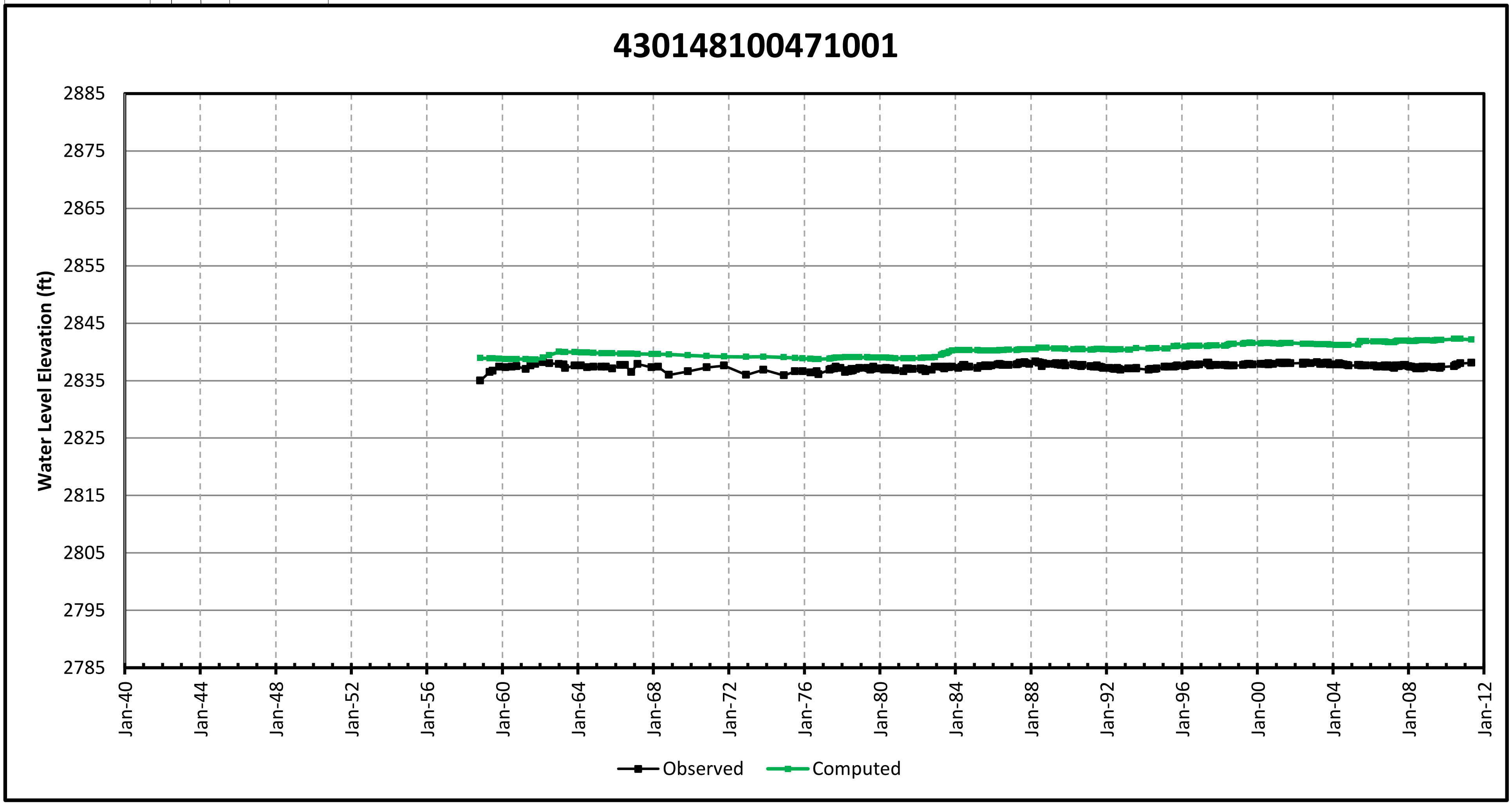
34N36W01DC

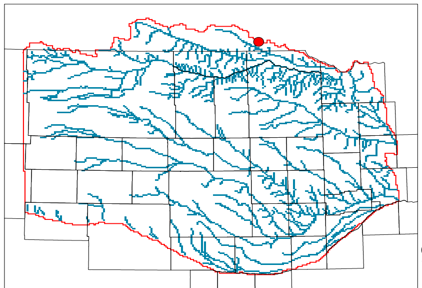


425636101300901
Water Level Elevation (ft)
3210
3200
3190
3180
3170
3160
3150
3140
3130
3120
3110
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

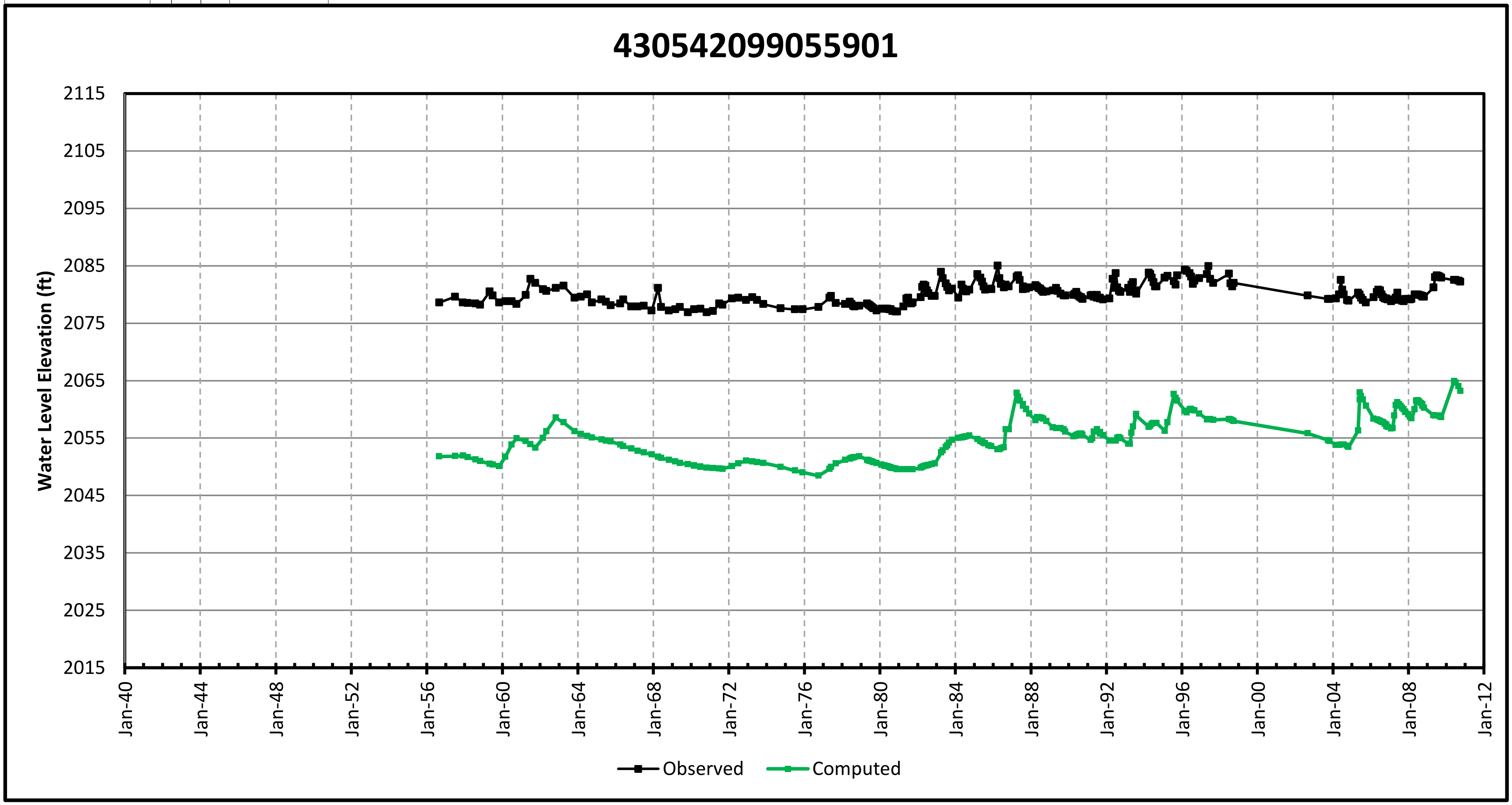


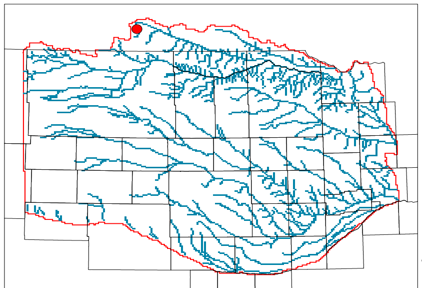
35N29W 7BBBB



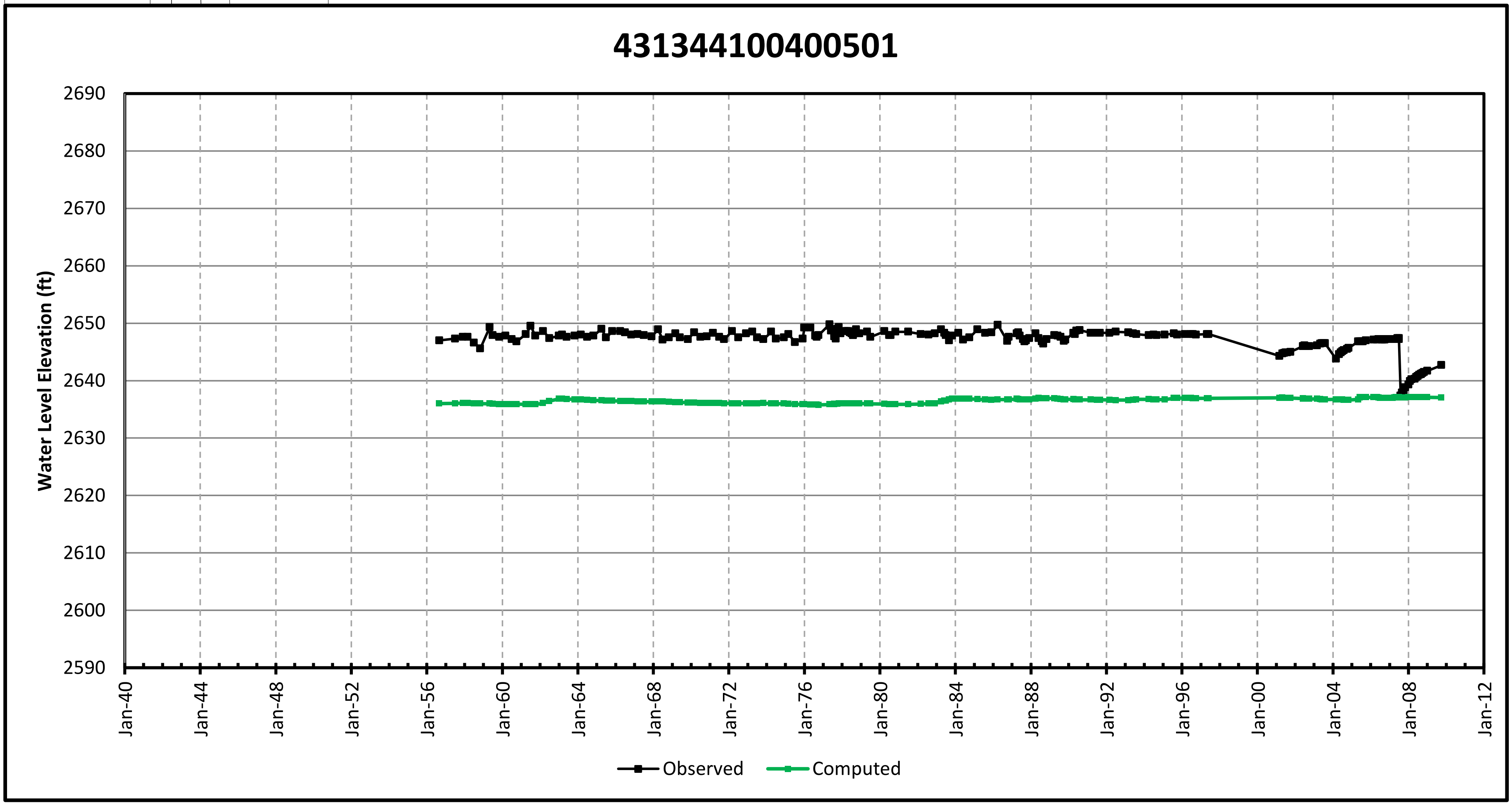


96N70W34AAAD

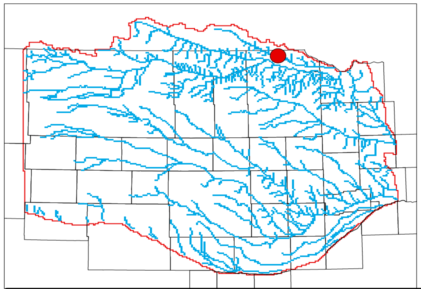


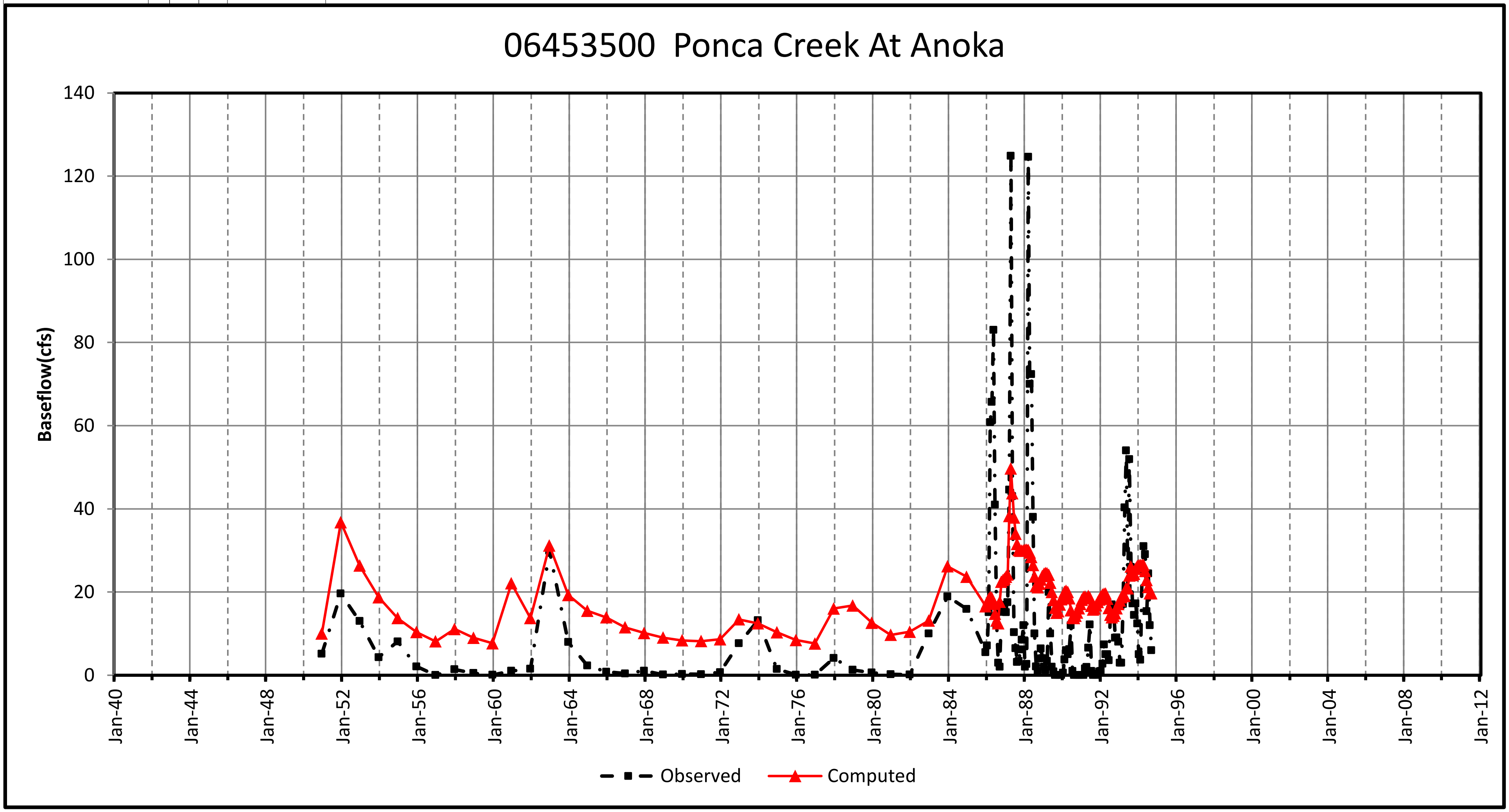


38N28W32BBBB

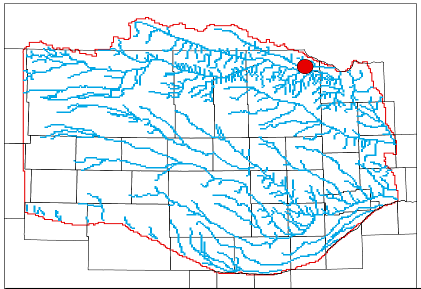


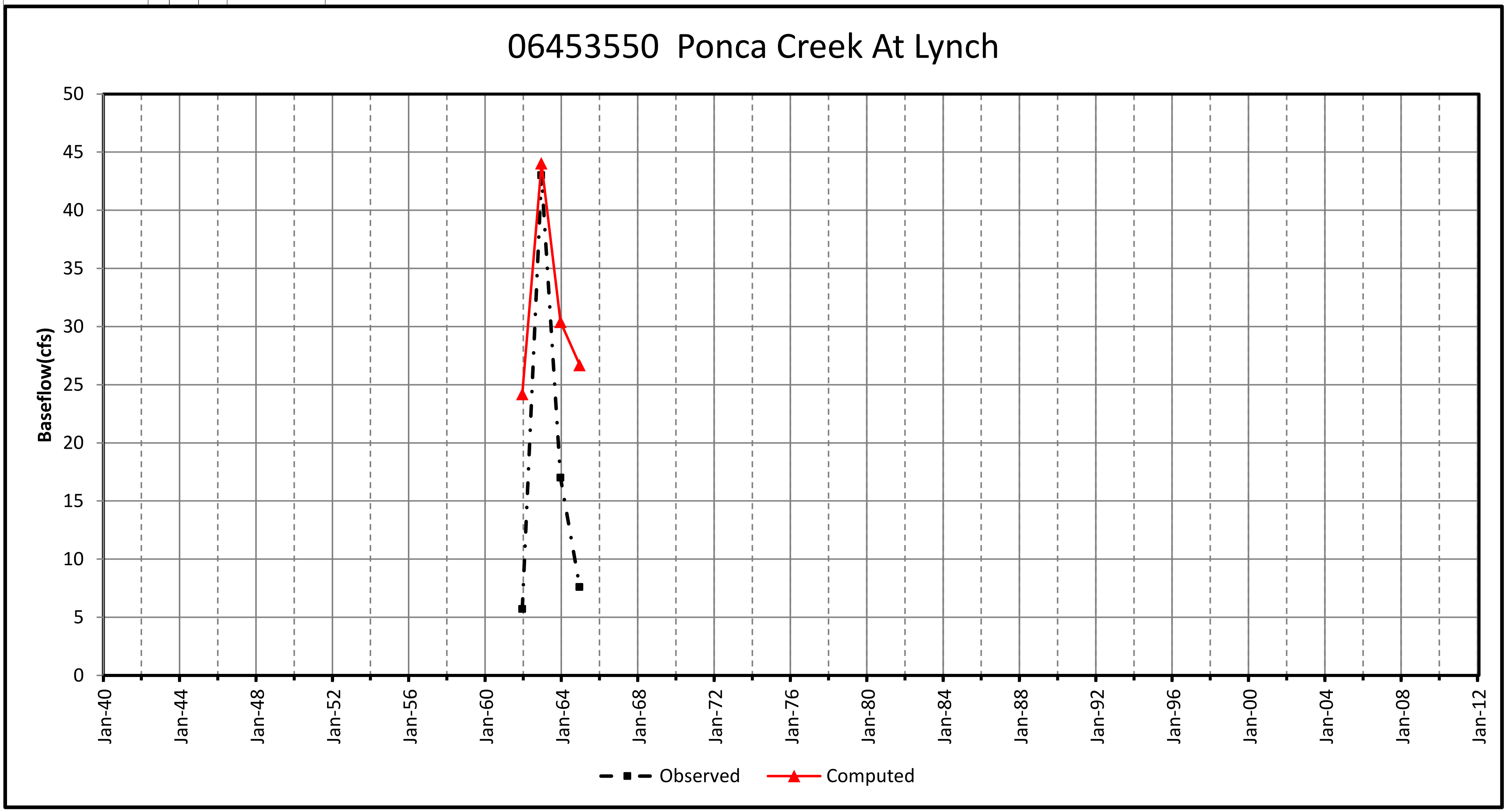
# Appendix D: Baseflow Hydrographs

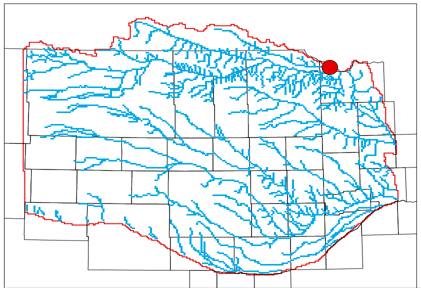


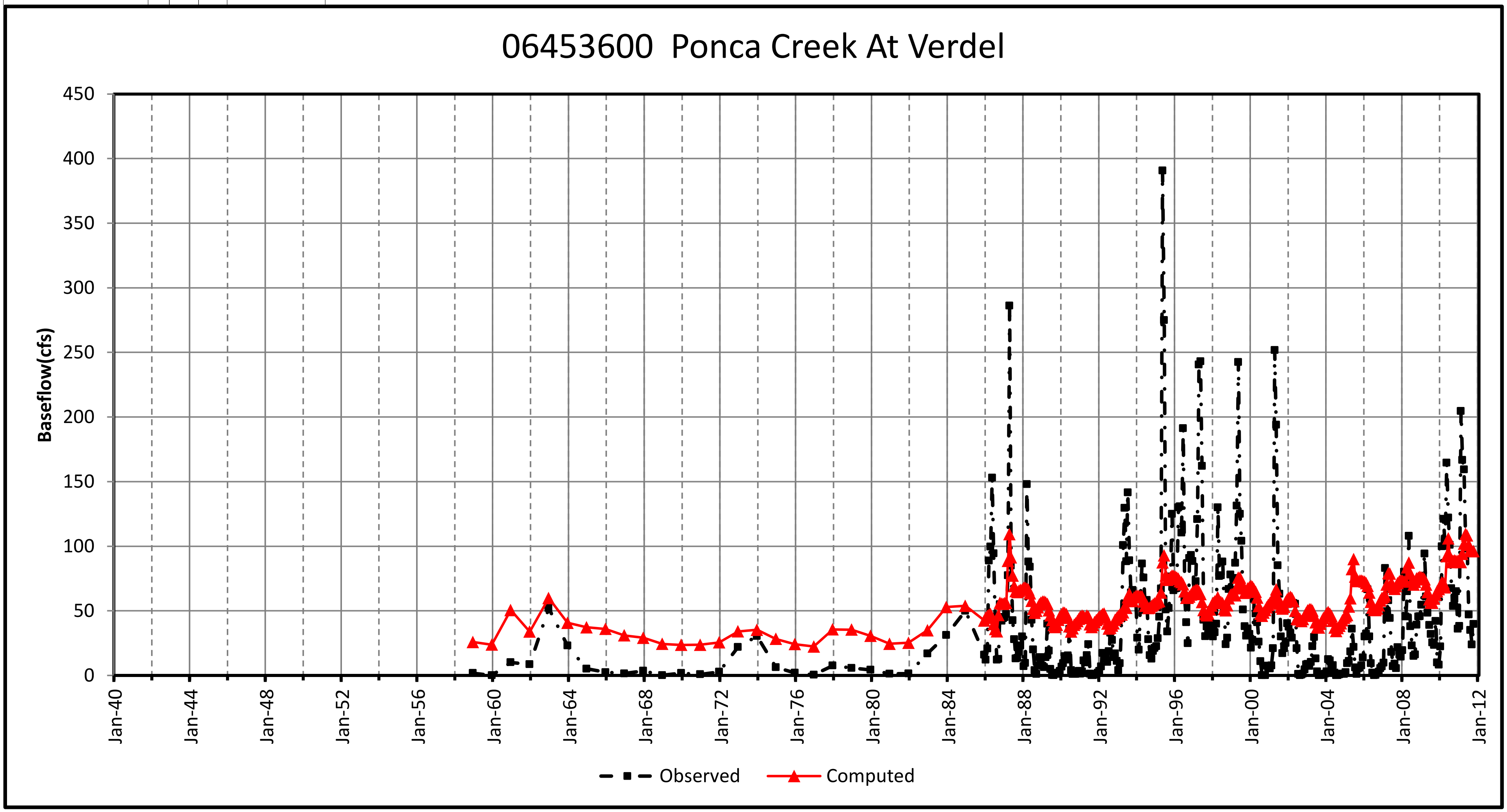


06453500 Ponca Creek At Anoka
Baseflow(cfs)
140
120
100
80
60
40
20
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

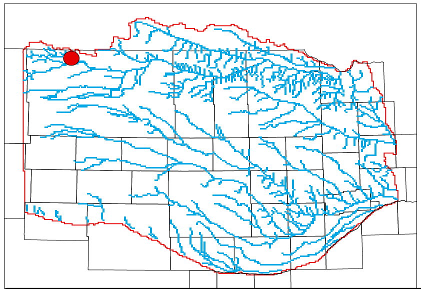


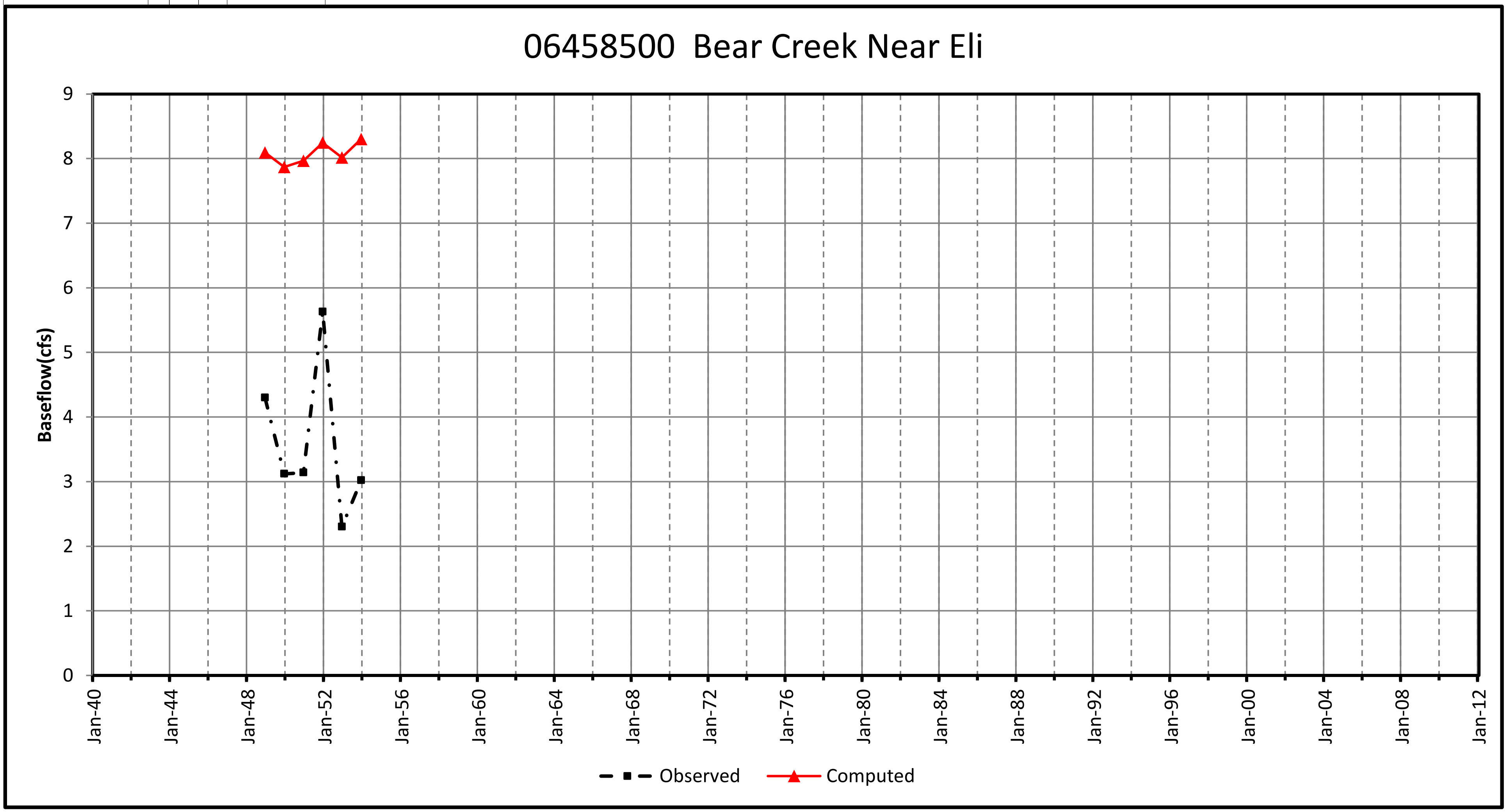

06453550 Ponca Creek At Lynch
Baseflow(cfs)
0
5
10
15
20
25
30
35
40
45
50
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

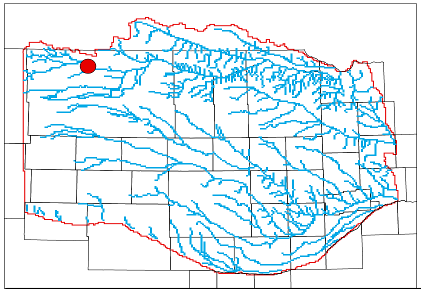


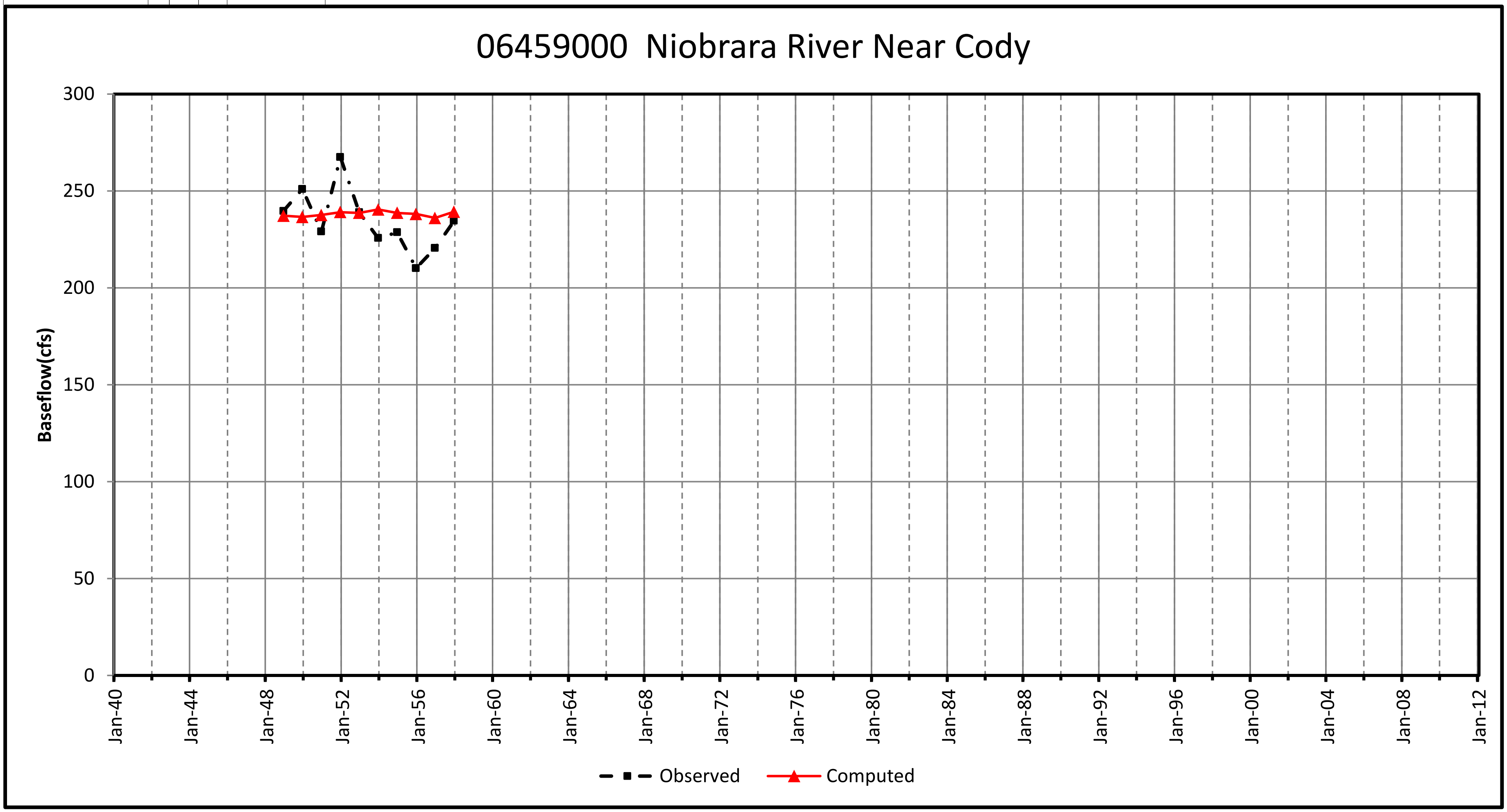


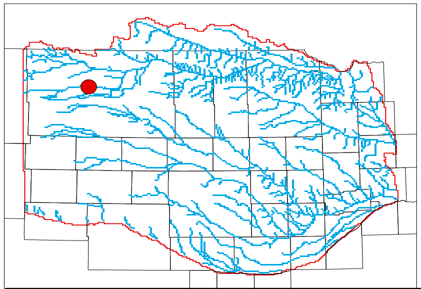
06453600 Ponca Creek At Verdel
Baseflow(cfs)
450
400
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

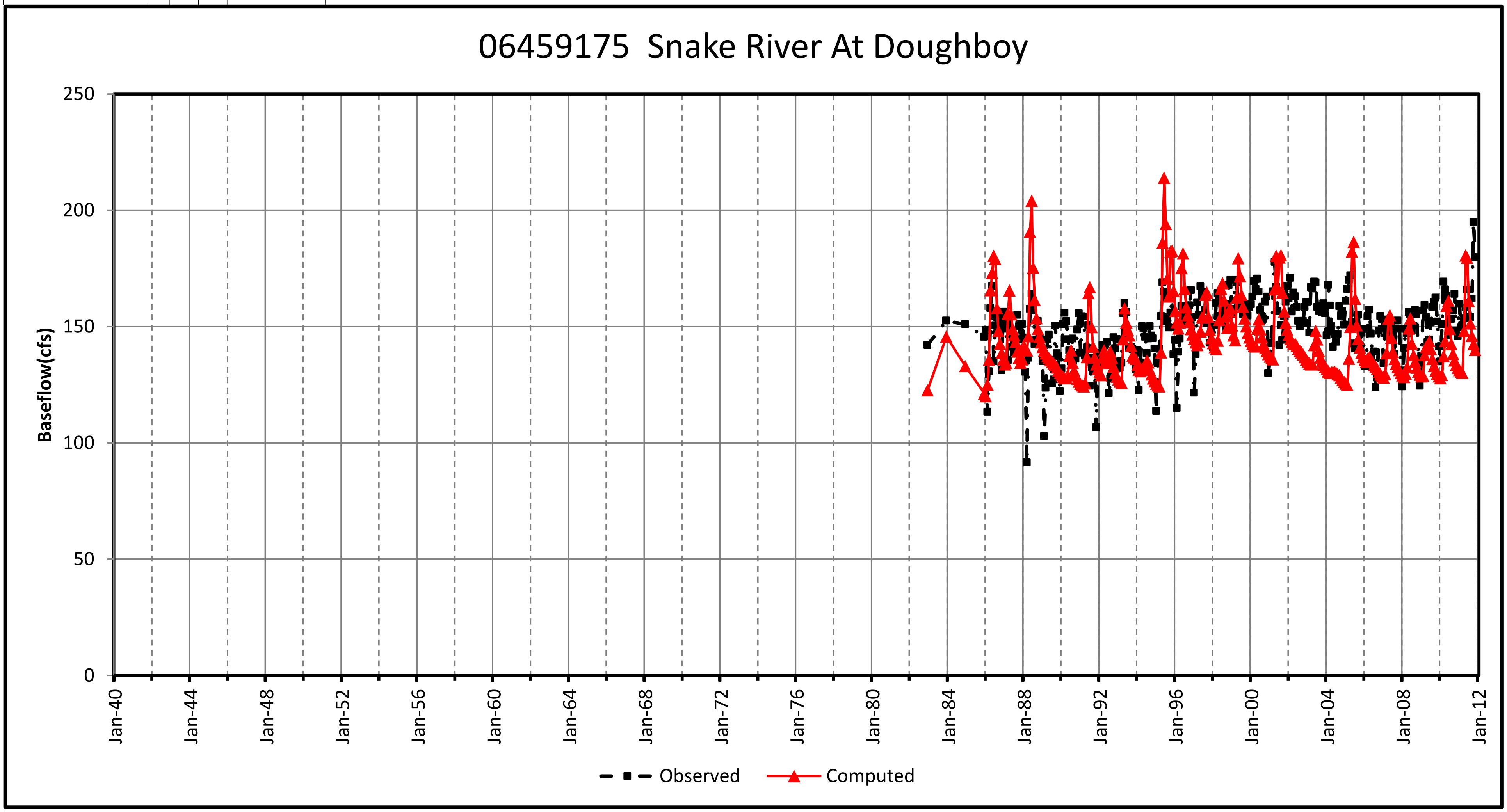



06458500 Bear Creek Near Eli
Baseflow(cfs)
0
1
2
3
4
5
6
7
8
9
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

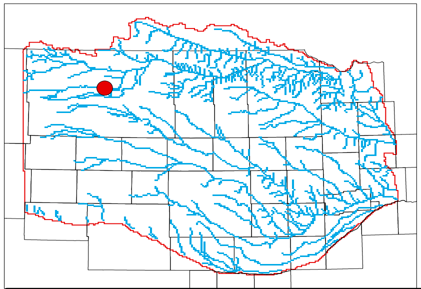


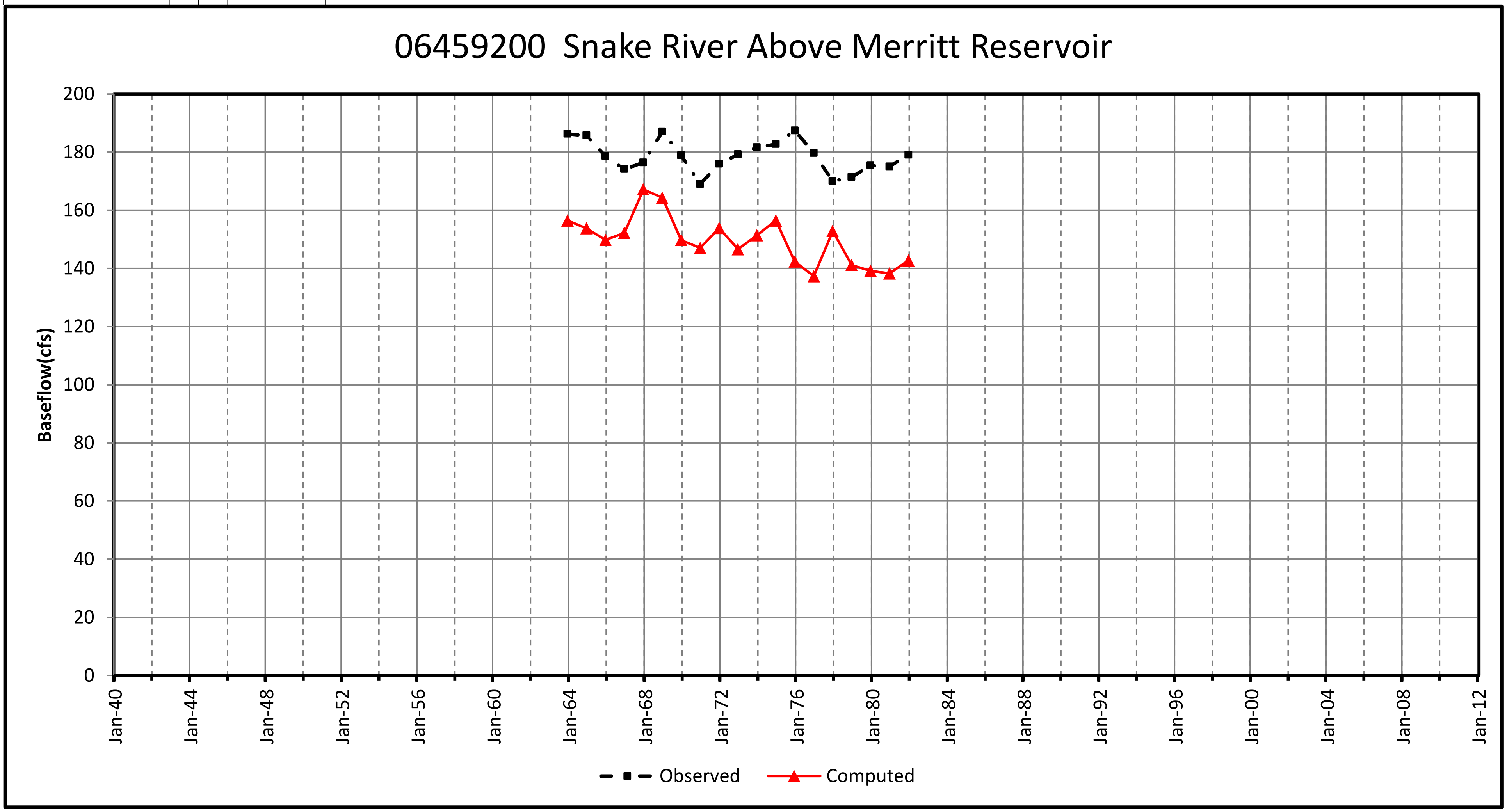

06459000 Niobrara River Near Cody
Baseflow(cfs)
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



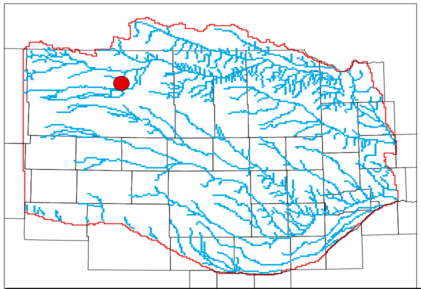


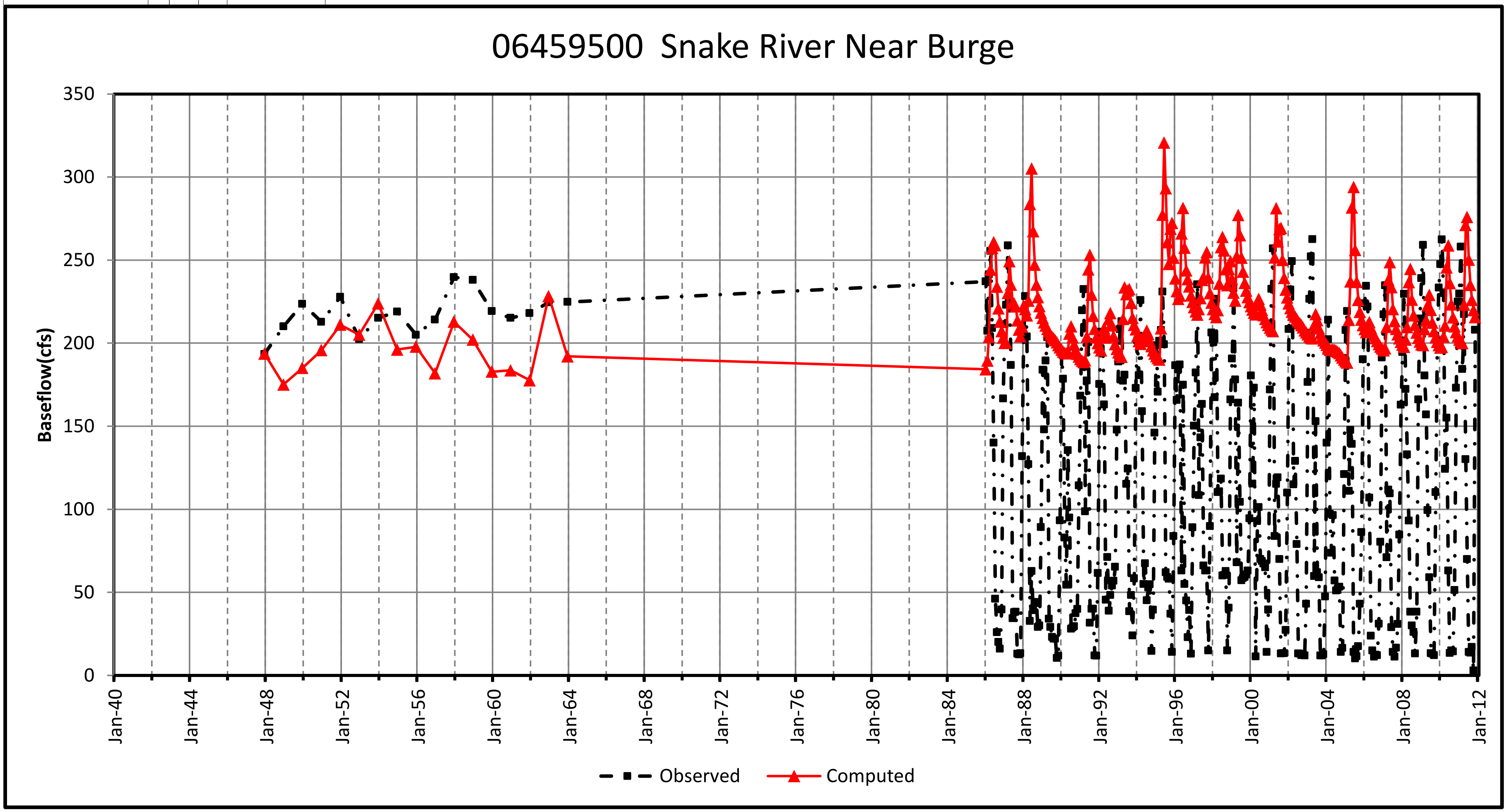
06459175 Snake River At Doughboy
Baseflow(cfs)
0
50
100
150
200
250
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

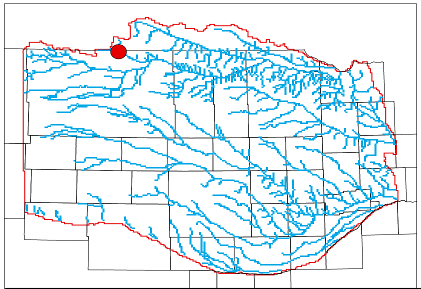


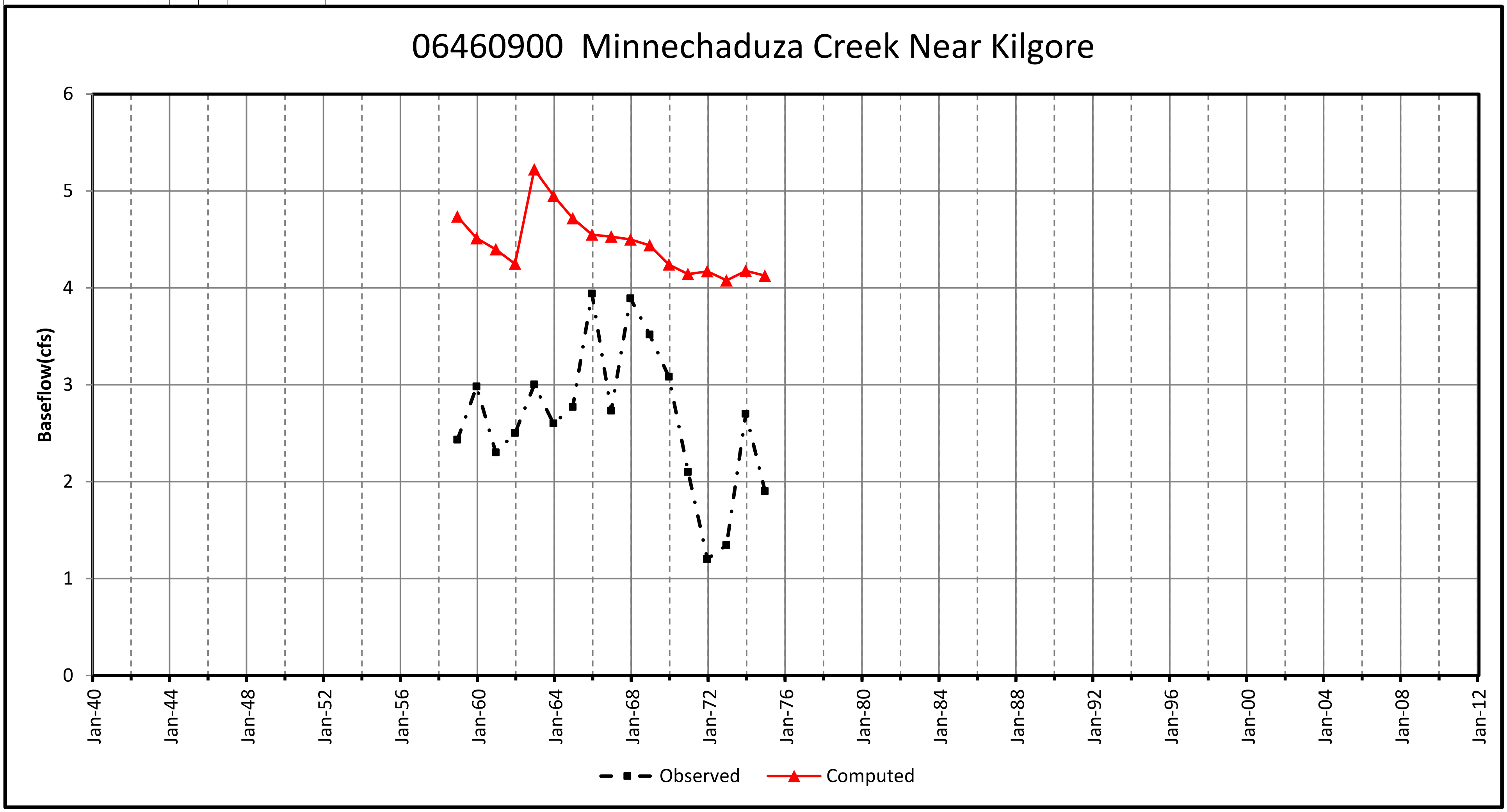


06459200 Snake River Above Merritt Reservoir
Baseflow(cfs)
200
180
160
140
120
100
80
60
40
20
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

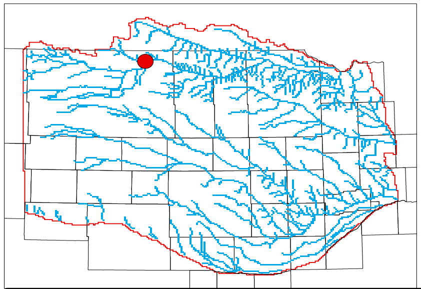


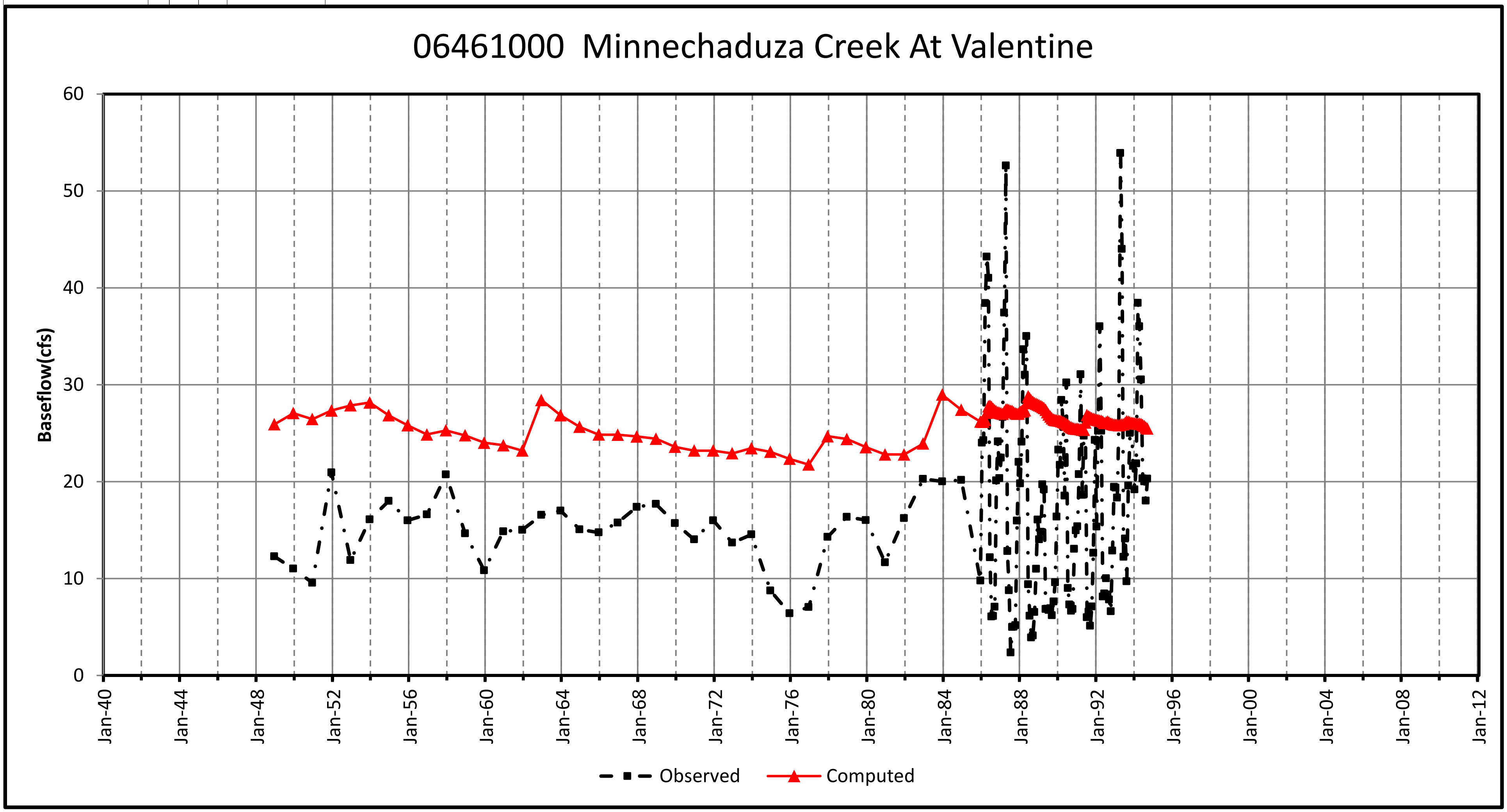

06459500 Snake River Near Burge
Baseflow(cfs)
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



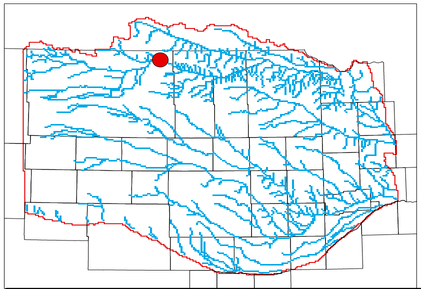


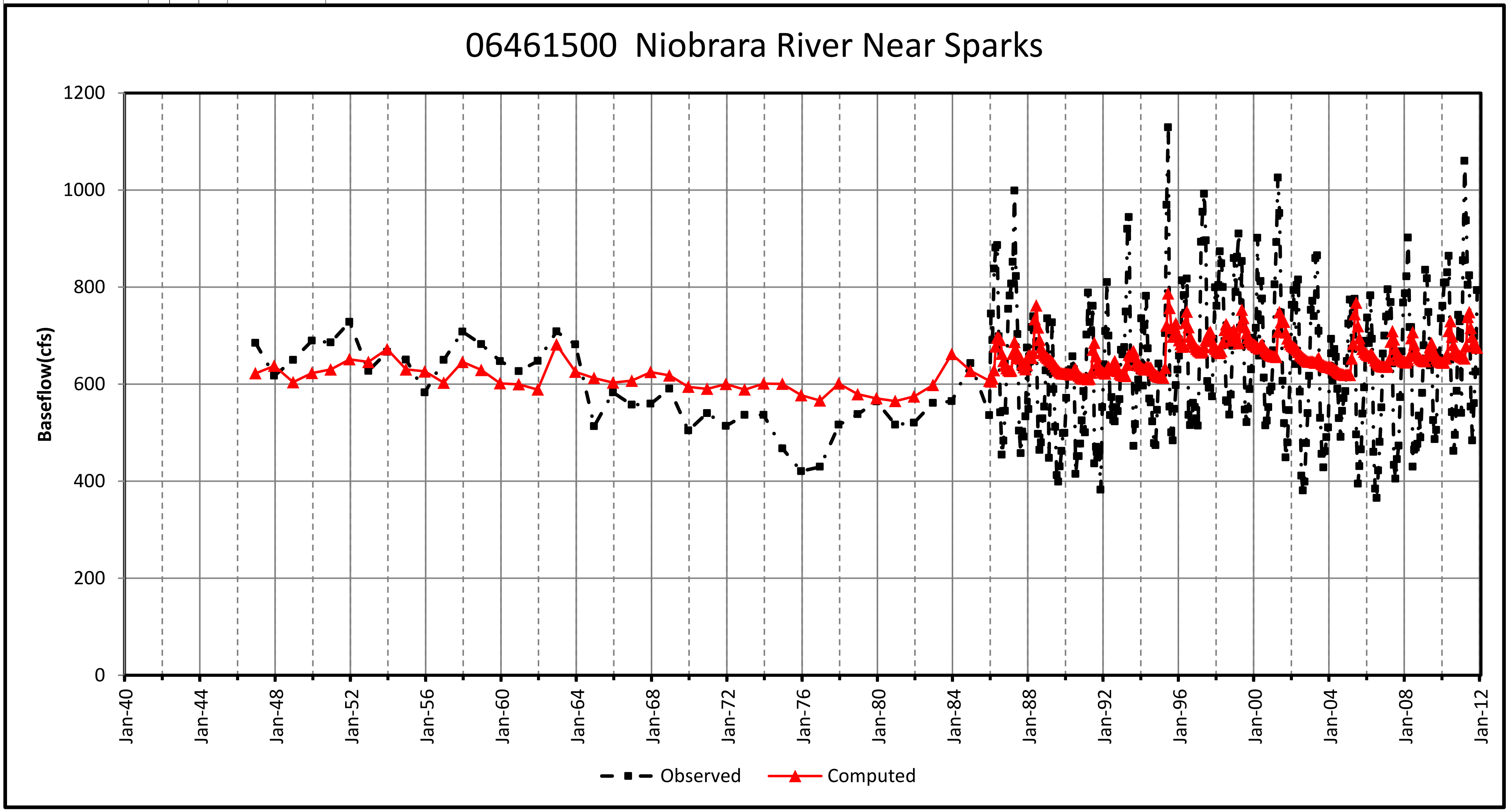
06460900 Minnechaduza Creek Near Kilgore
Baseflow(cfs)
0
1
2
3
4
5
6
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

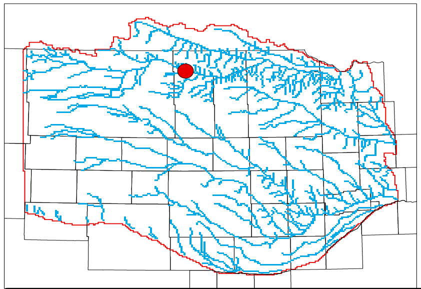


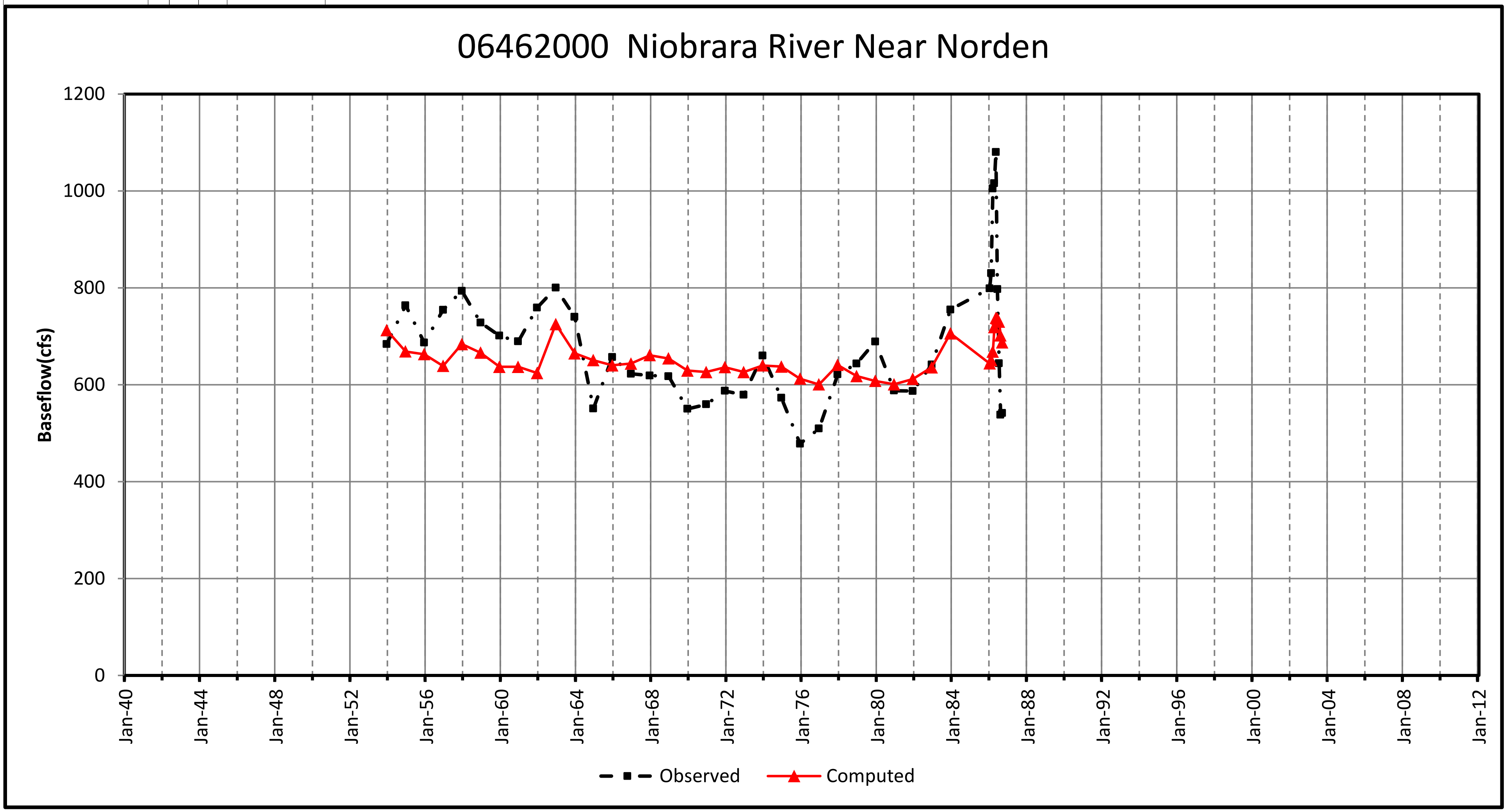


06461000 Minnechaduza Creek At Valentine
Baseflow(cfs)
60
50
40
30
20
10
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

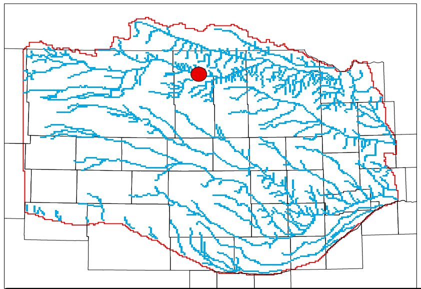


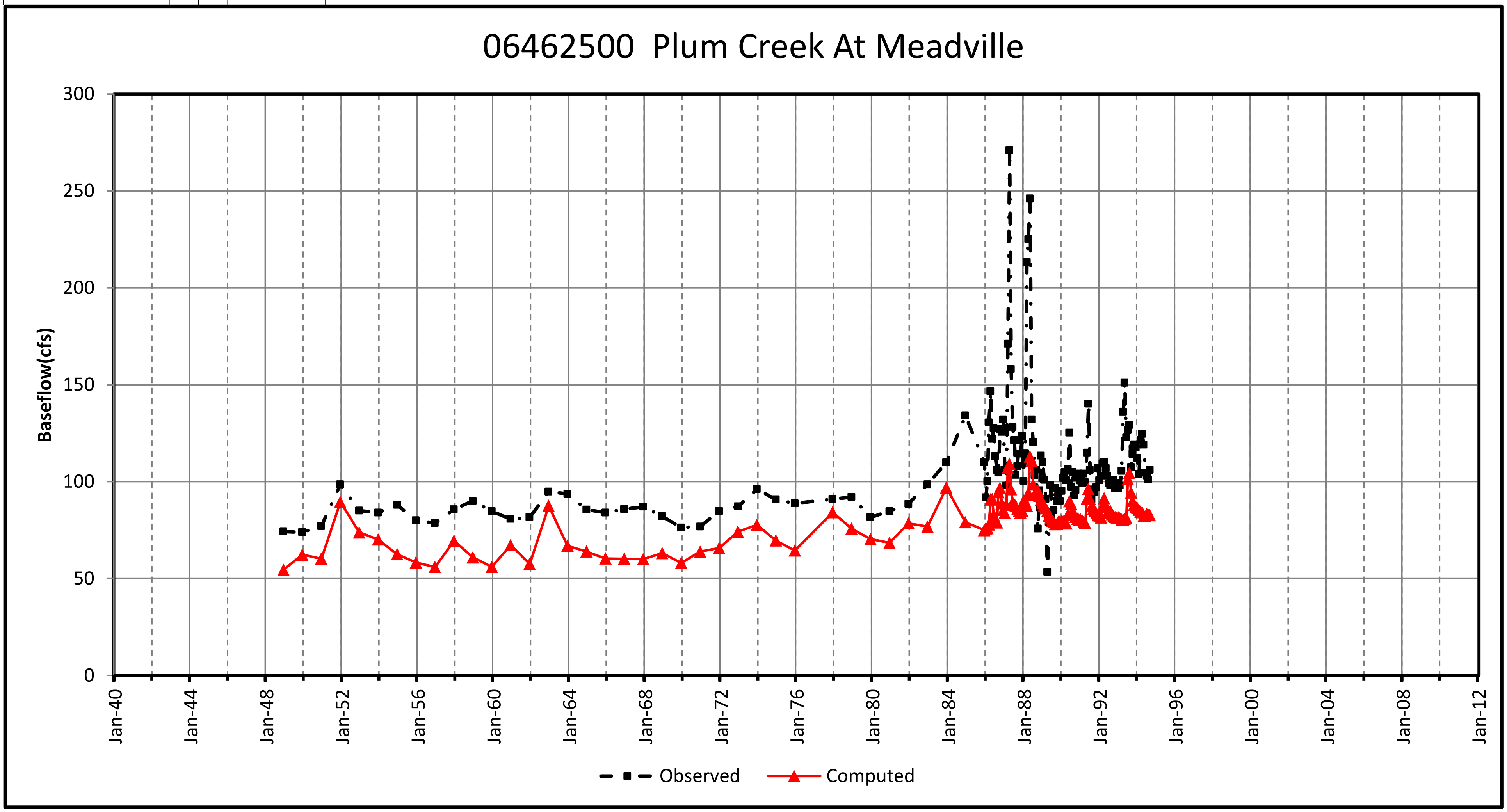

06461500 Niobrara River Near Sparks
Baseflow(cfs)
1200
1000
800
600
400
200
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

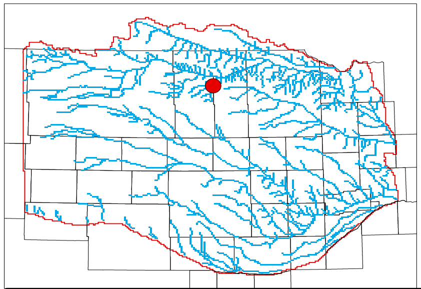


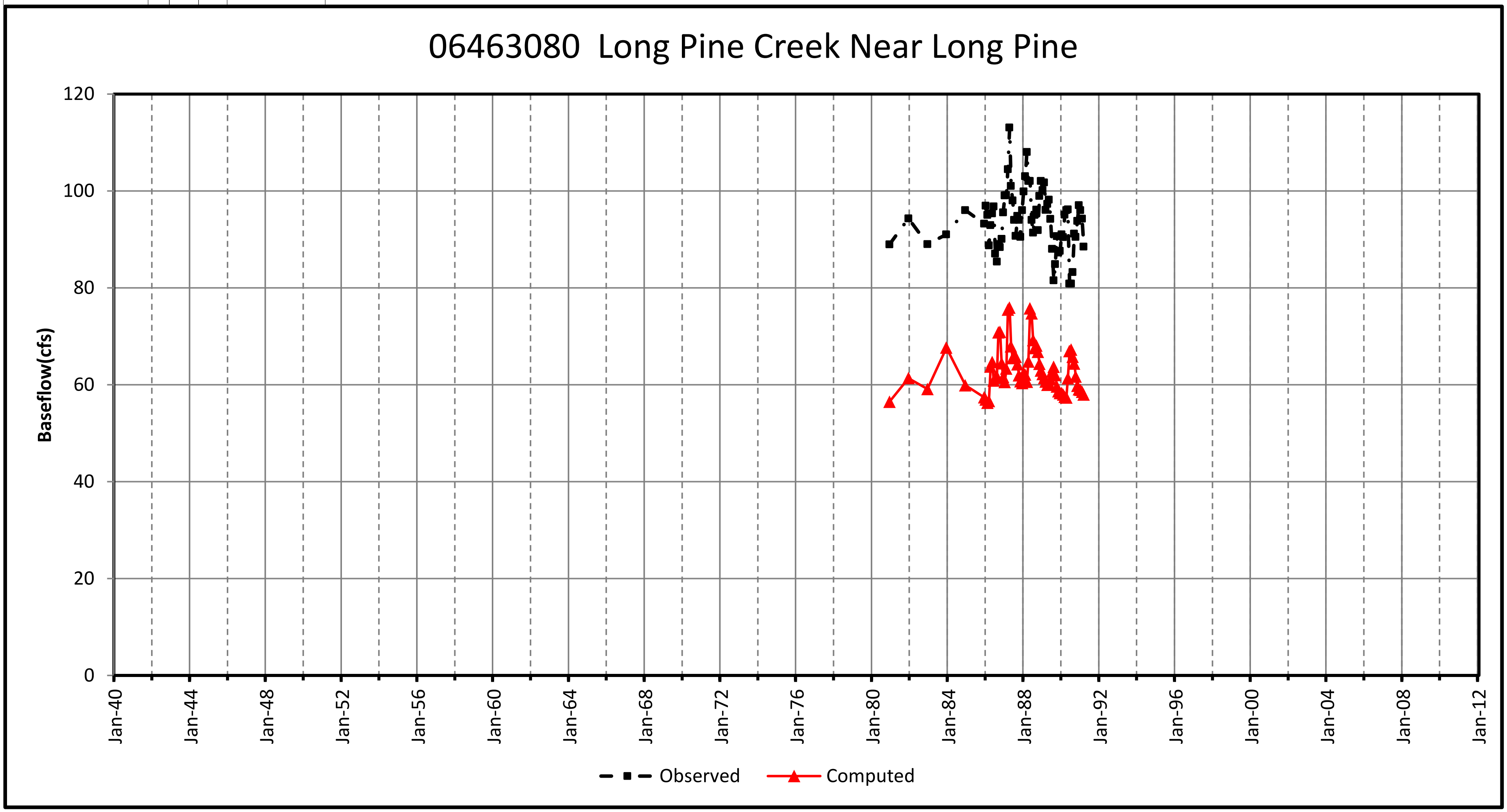


06462000 Niobrara River Near Norden
Baseflow(cfs)
1200
1000
800
600
400
200
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

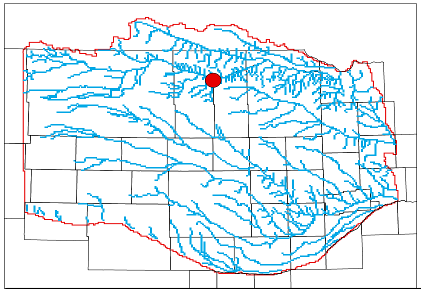


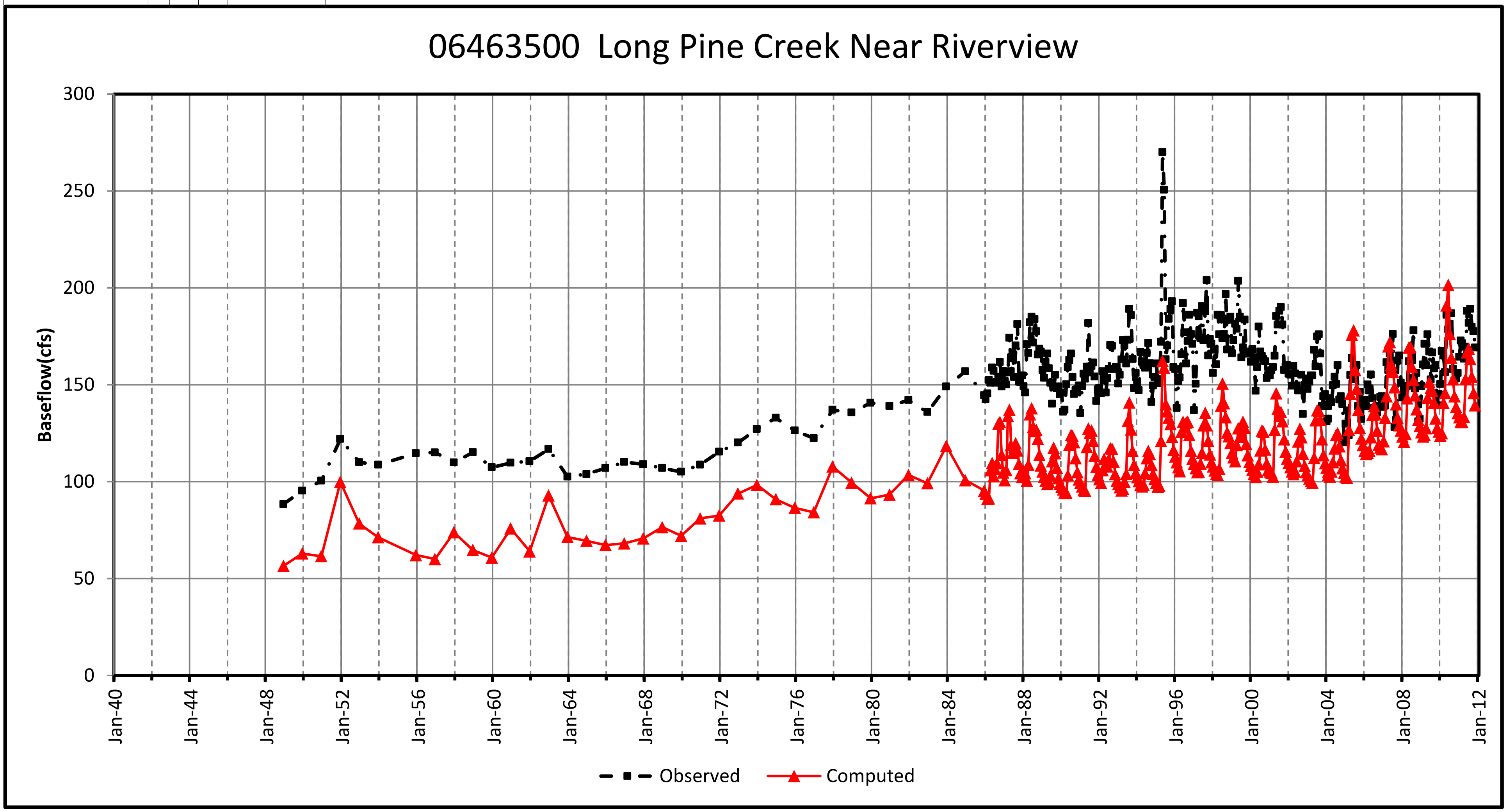

06462500 Plum Creek At Meadville
Baseflow(cfs)
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

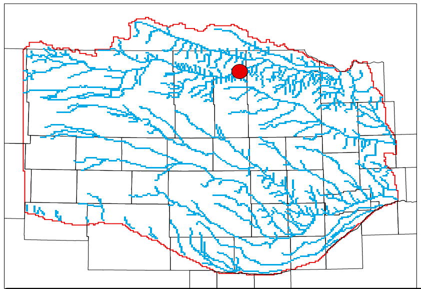


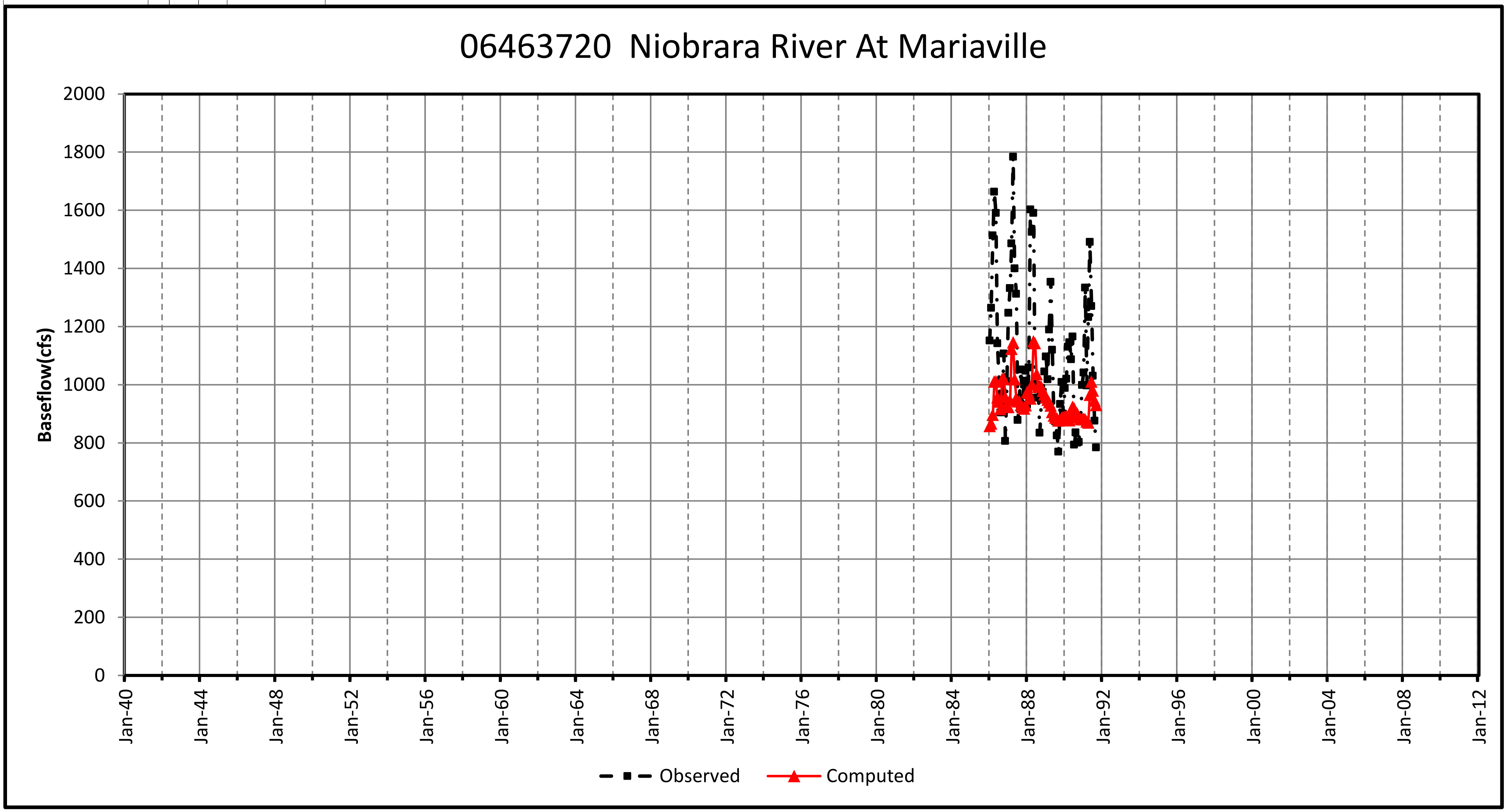


06463080 Long Pine Creek Near Long Pine
Baseflow(cfs)
0
20
40
60
80
100
120
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

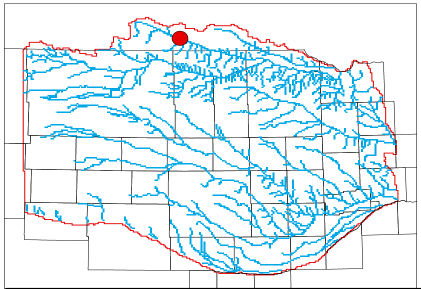


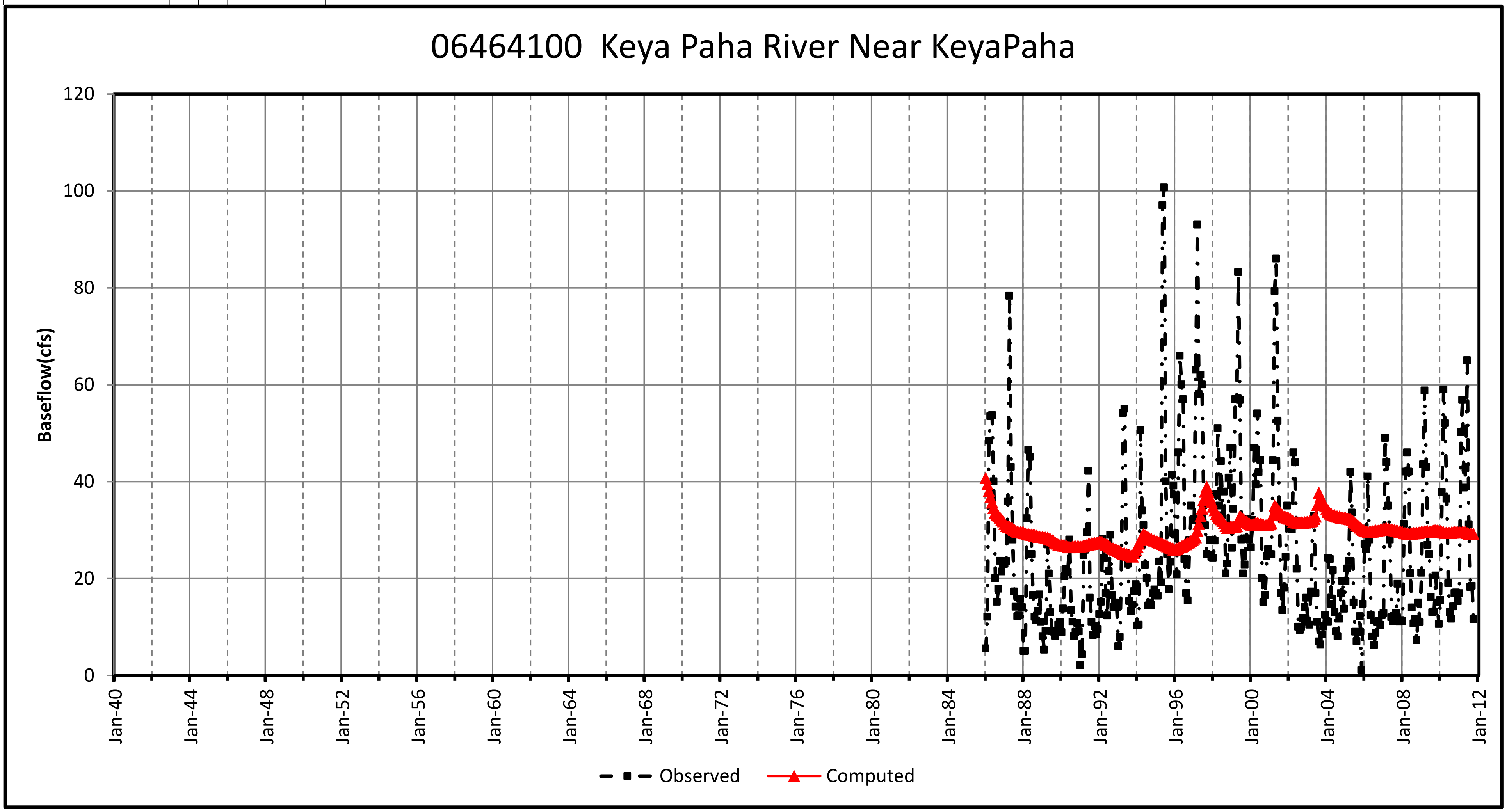

06463500 Long Pine Creek Near Riverview
300
250
200
150
100
50
0
Baseflow(cfs)
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



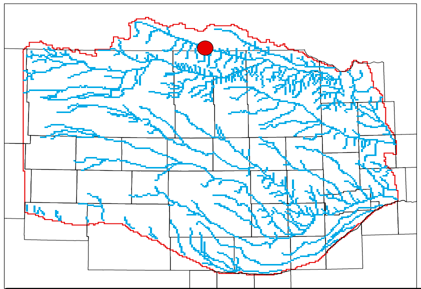


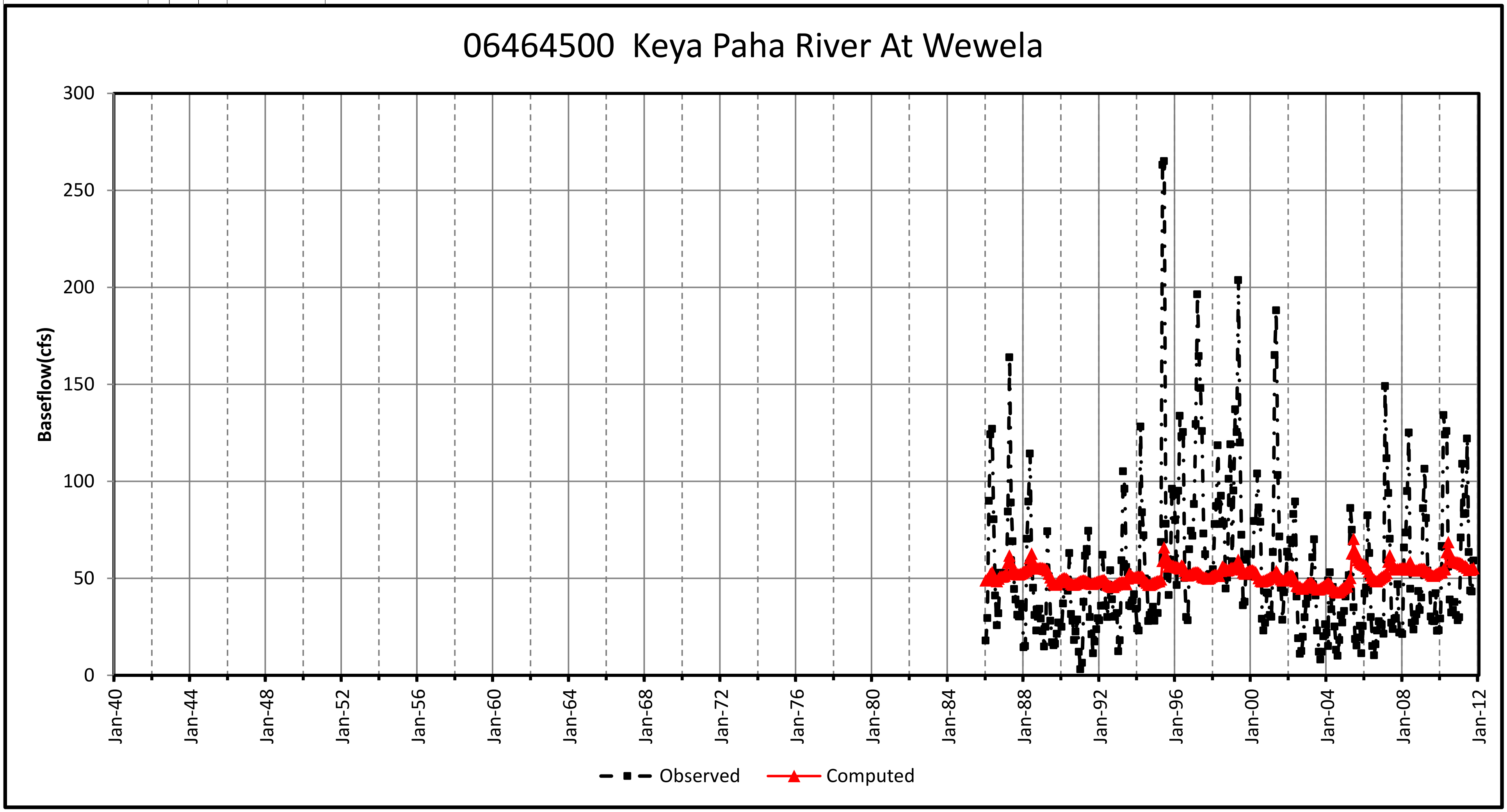
06463720 Niobrara River At Mariaville
Baseflow(cfs)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



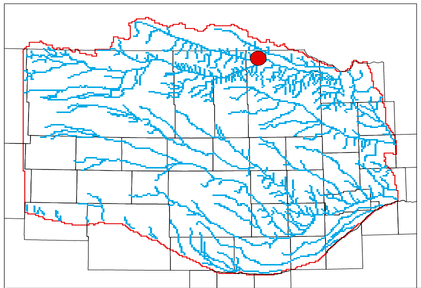


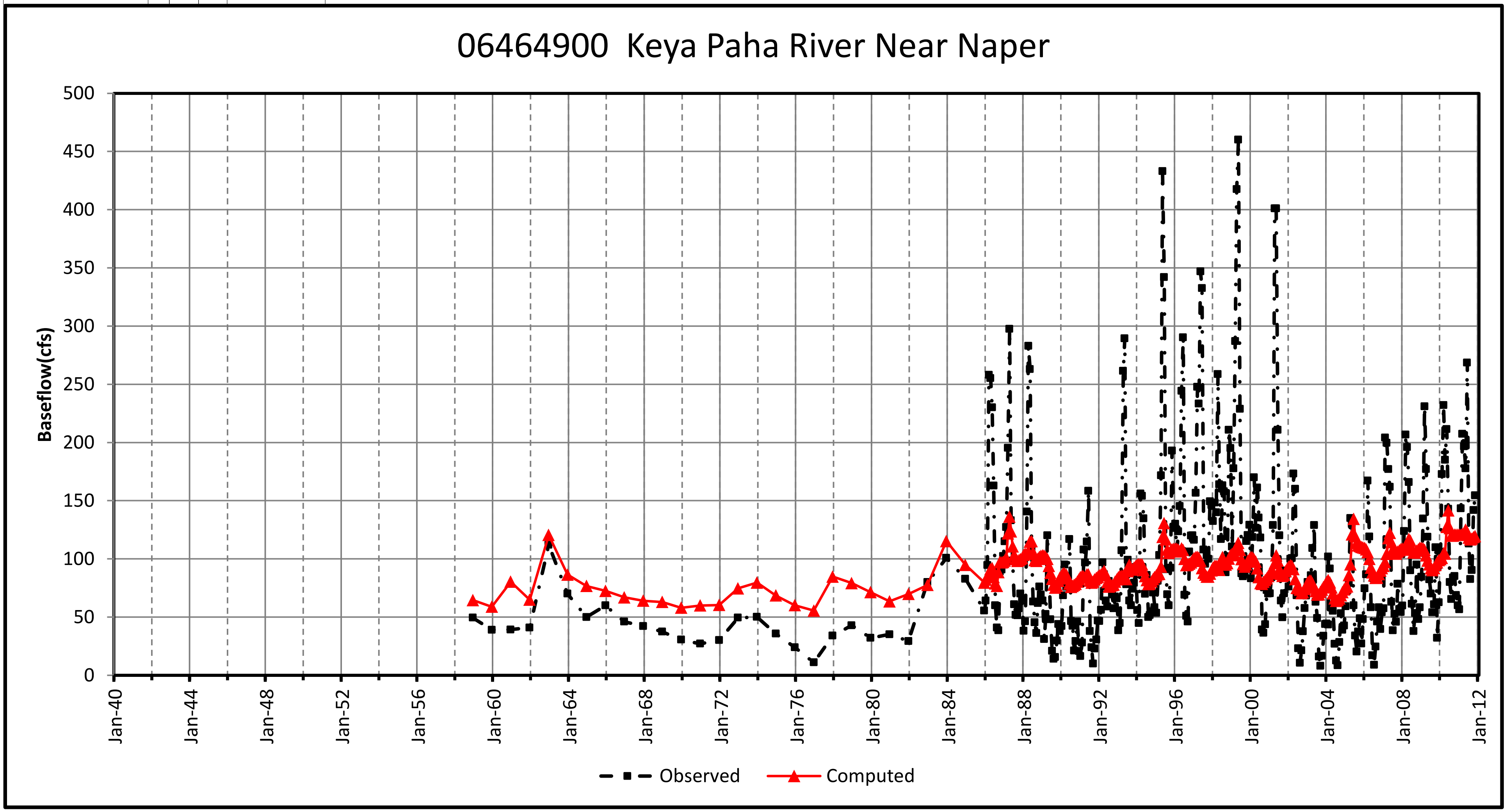
06464100 Keya Paha River Near KeyaPaha
Baseflow(cfs)
0
20
40
60
80
100
120
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



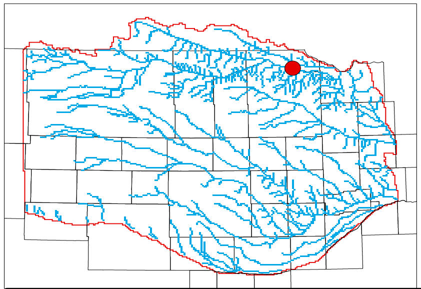


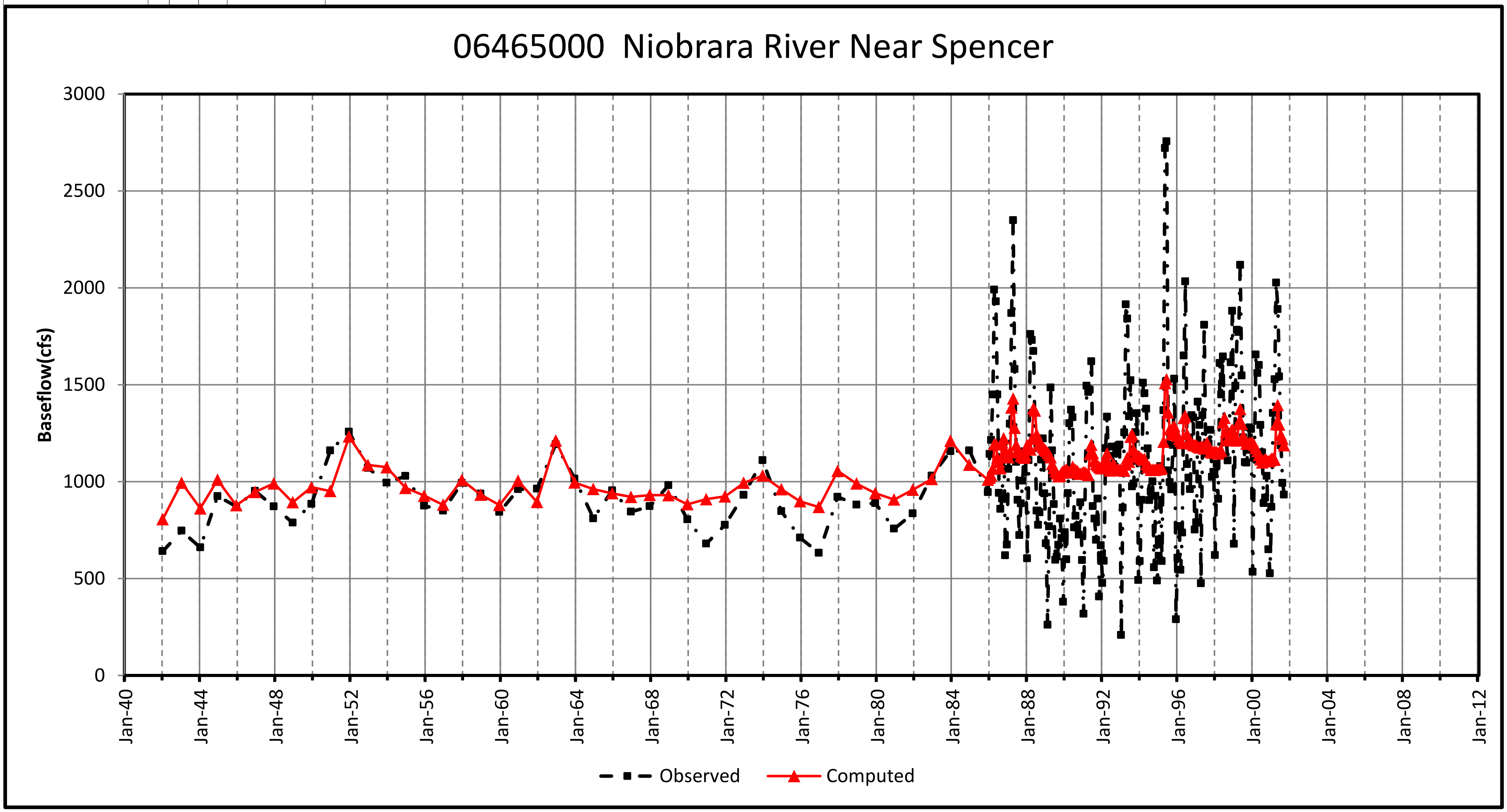
06464500 Keya Paha River At Wewela
Baseflow(cfs)
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

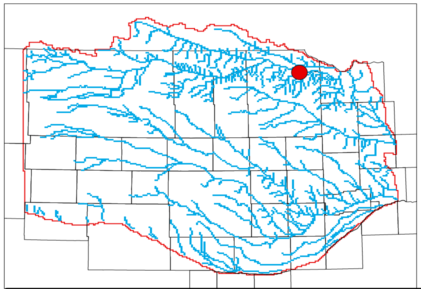


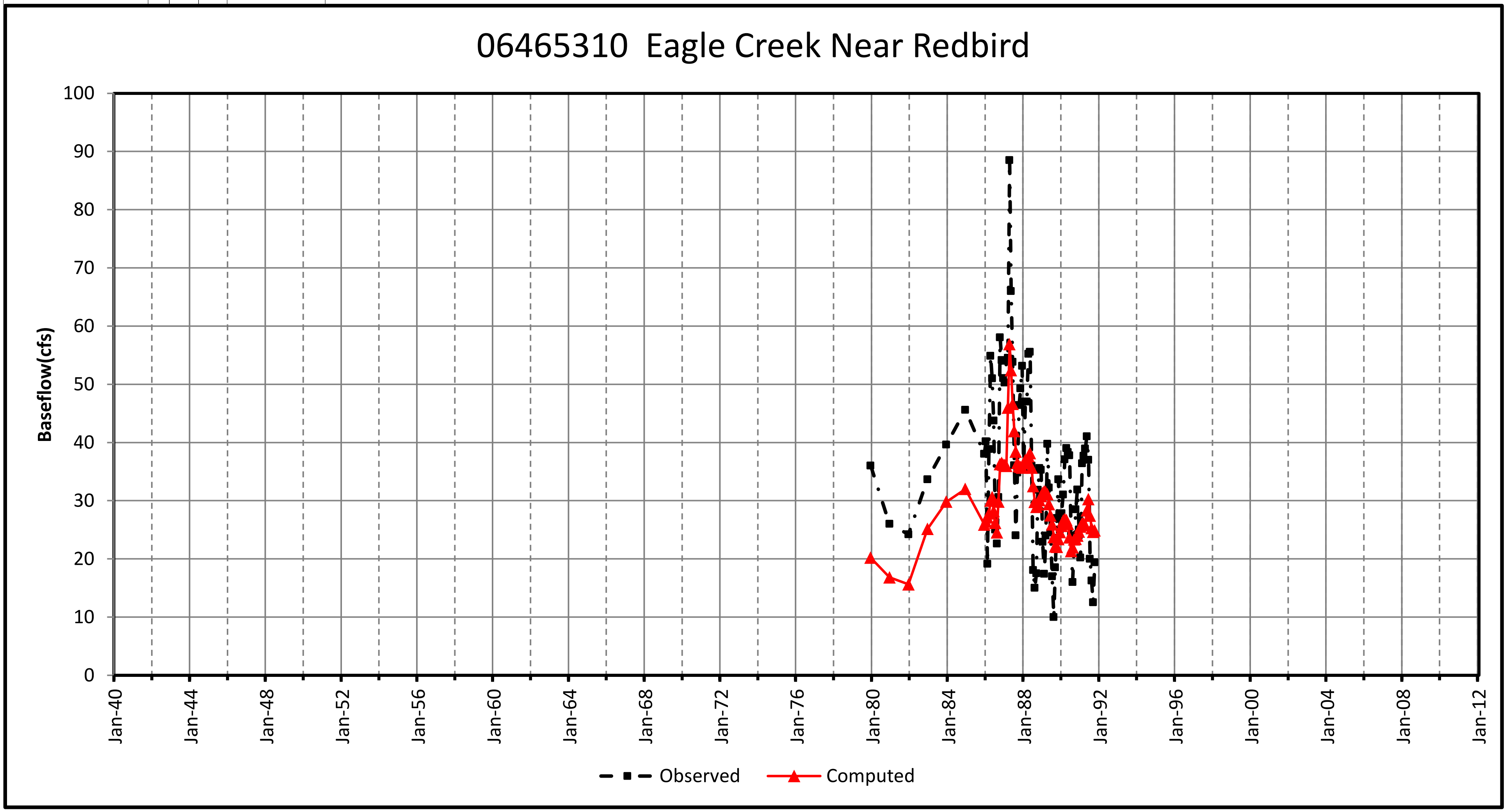


06464900 Keya Paha River Near Naper
Baseflow(cfs)
500
450
400
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

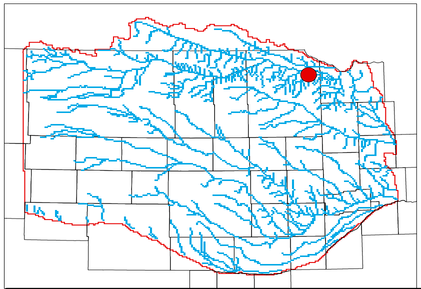


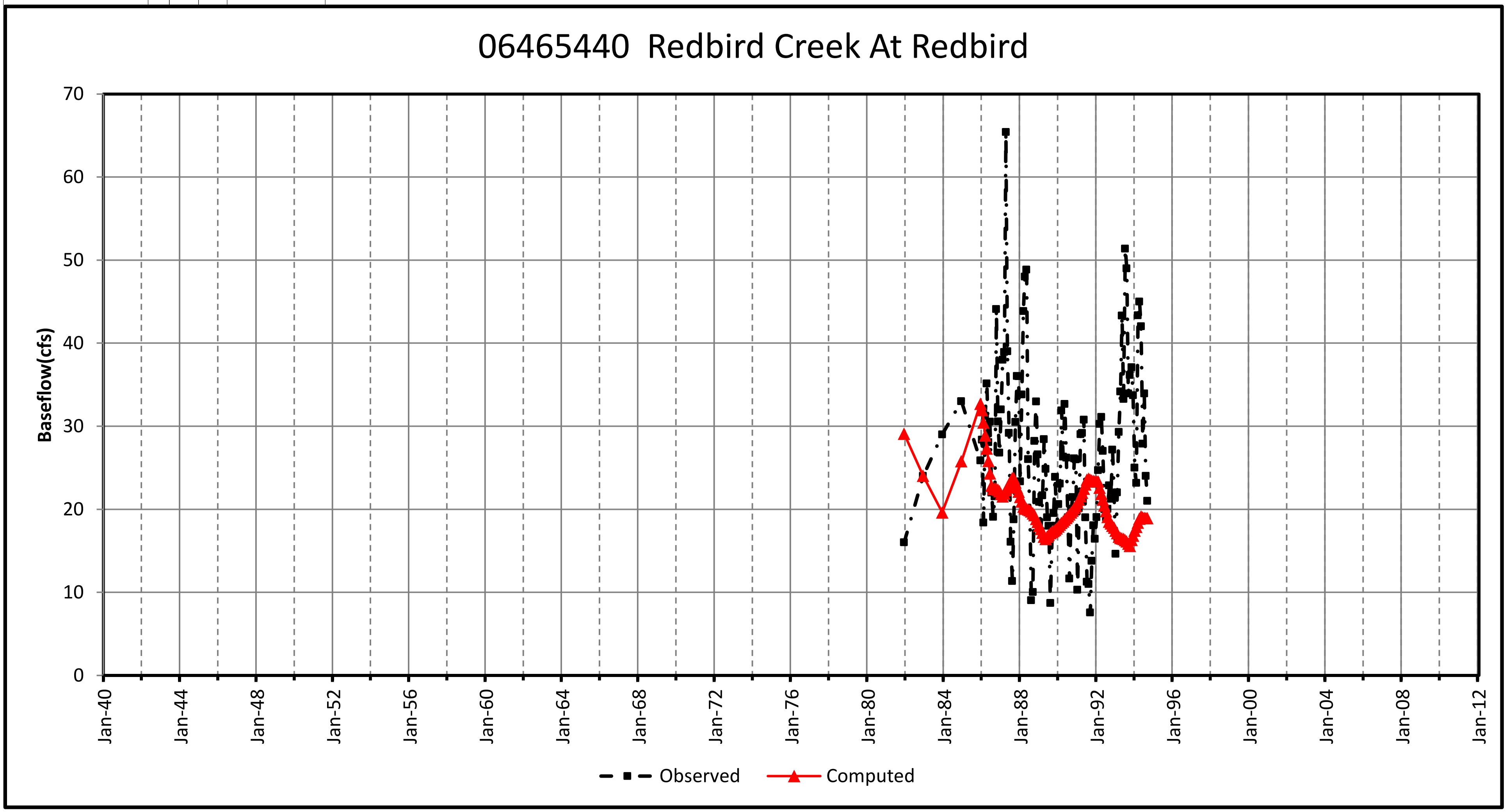

06465000 Niobrara River Near Spencer
Baseflow(cfs)
3000
2500
2000
1500
1000
500
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



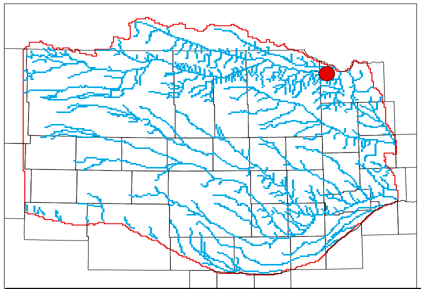


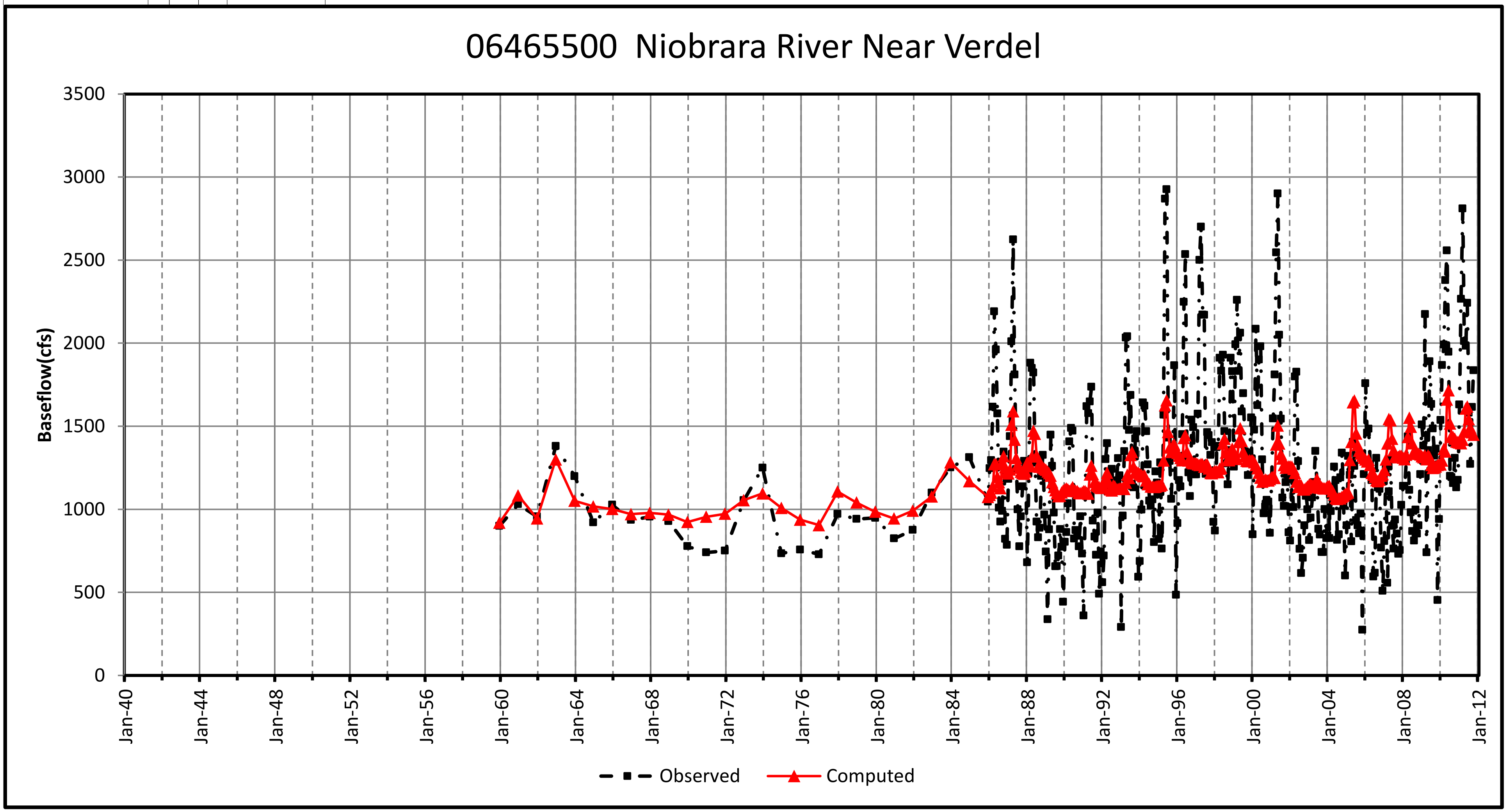
06465310 Eagle Creek Near Redbird
Baseflow(cfs)
100
90
80
70
60
50
40
30
20
10
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

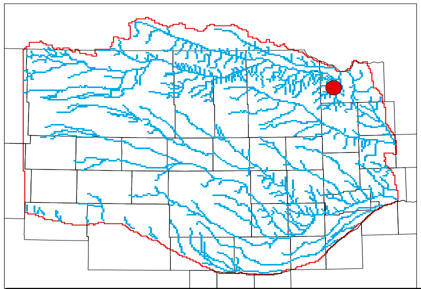


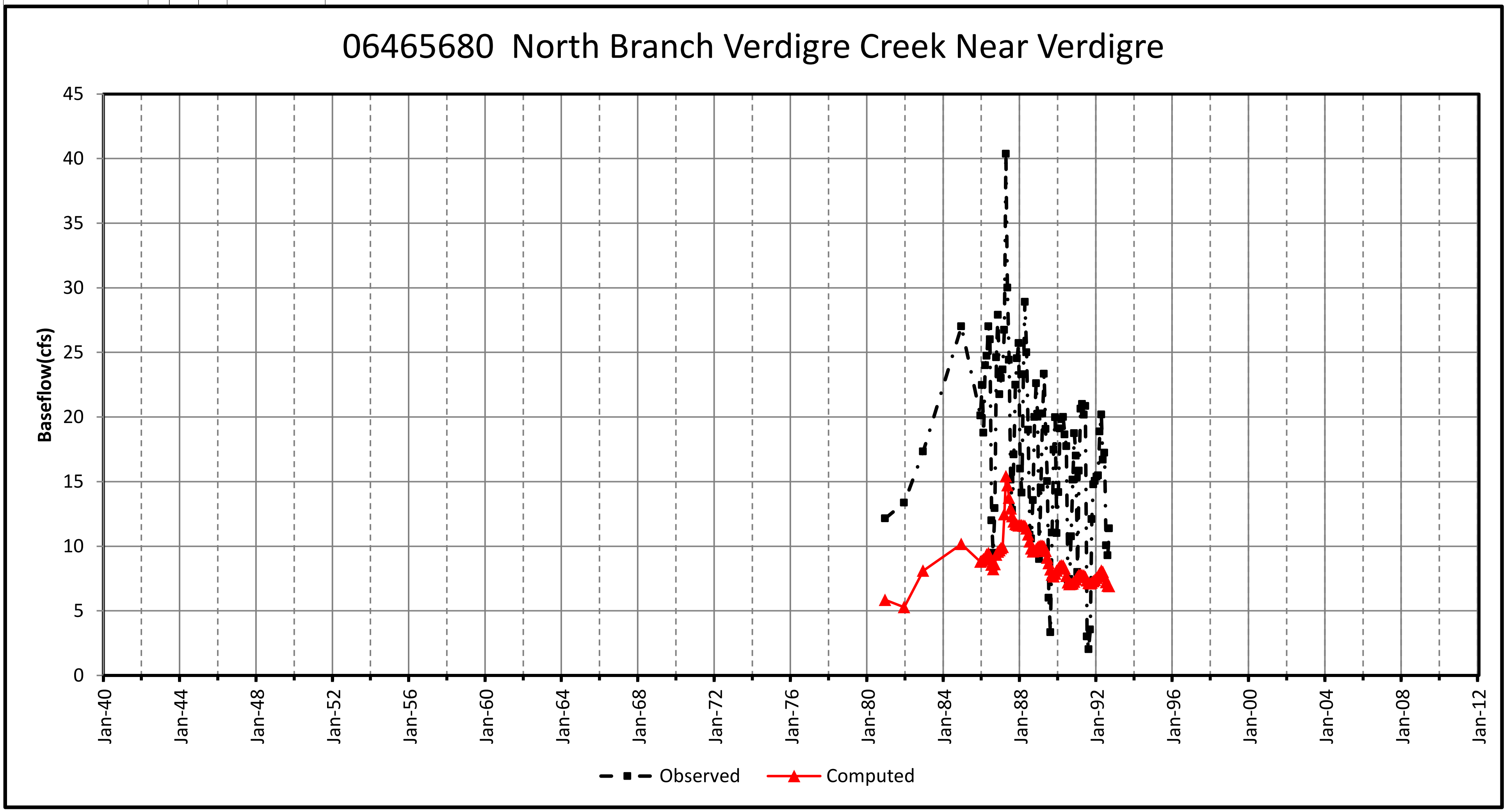


06465440 Redbird Creek At Redbird
Baseflow(cfs)
0
10
20
30
40
50
60
70
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

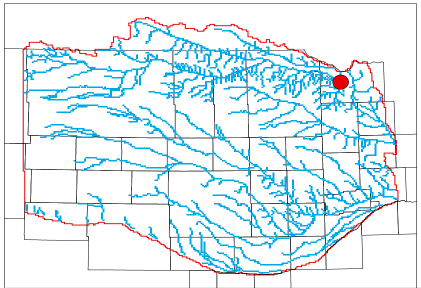


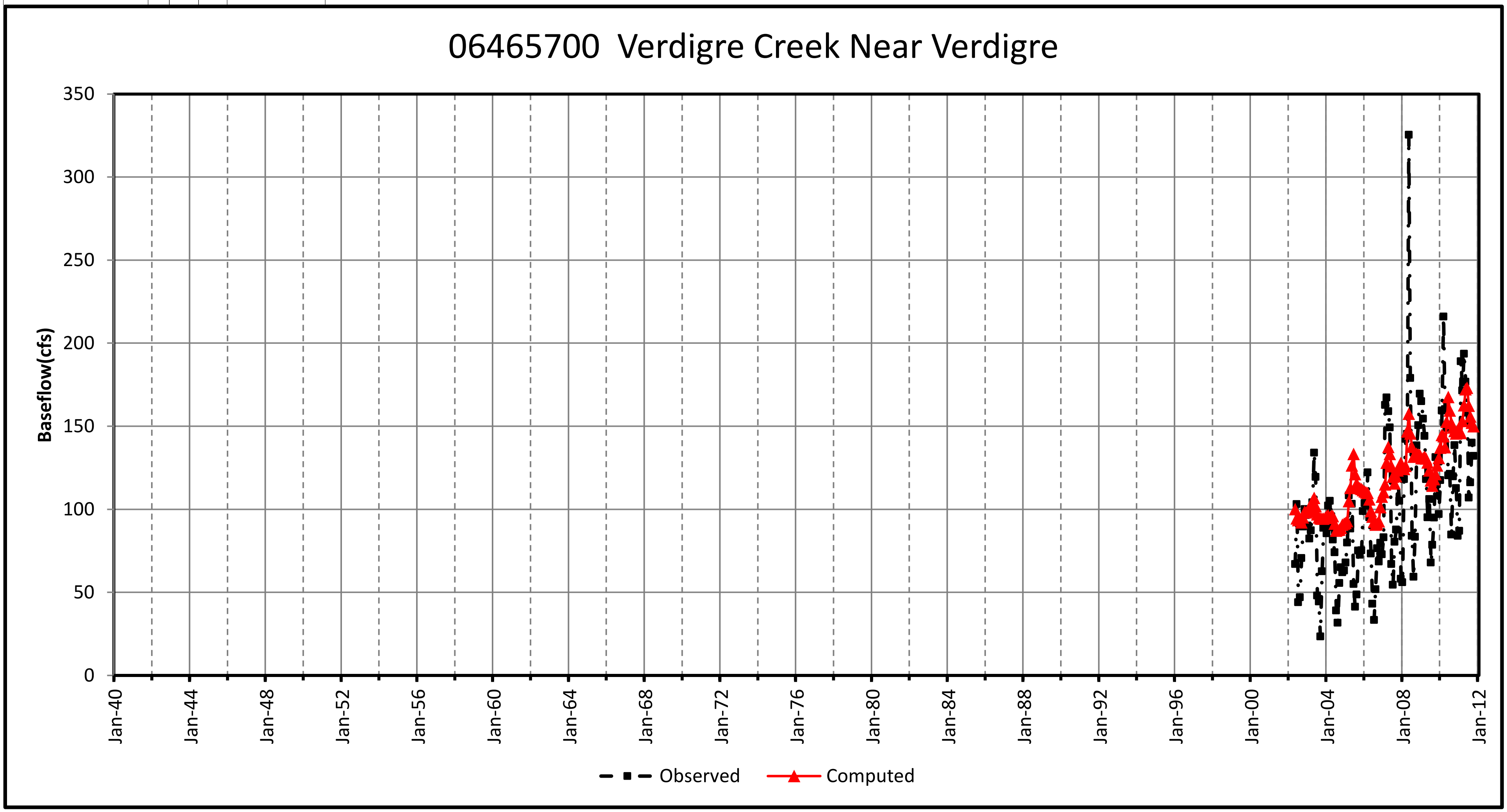

06465500 Niobrara River Near Verdel
Baseflow(cfs)
3500
3000
2500
2000
1500
1000
500
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



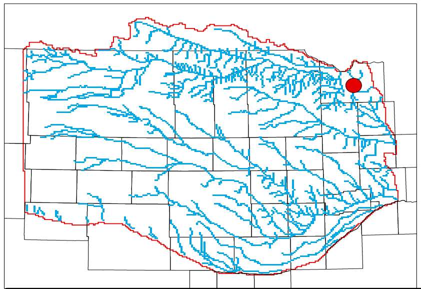


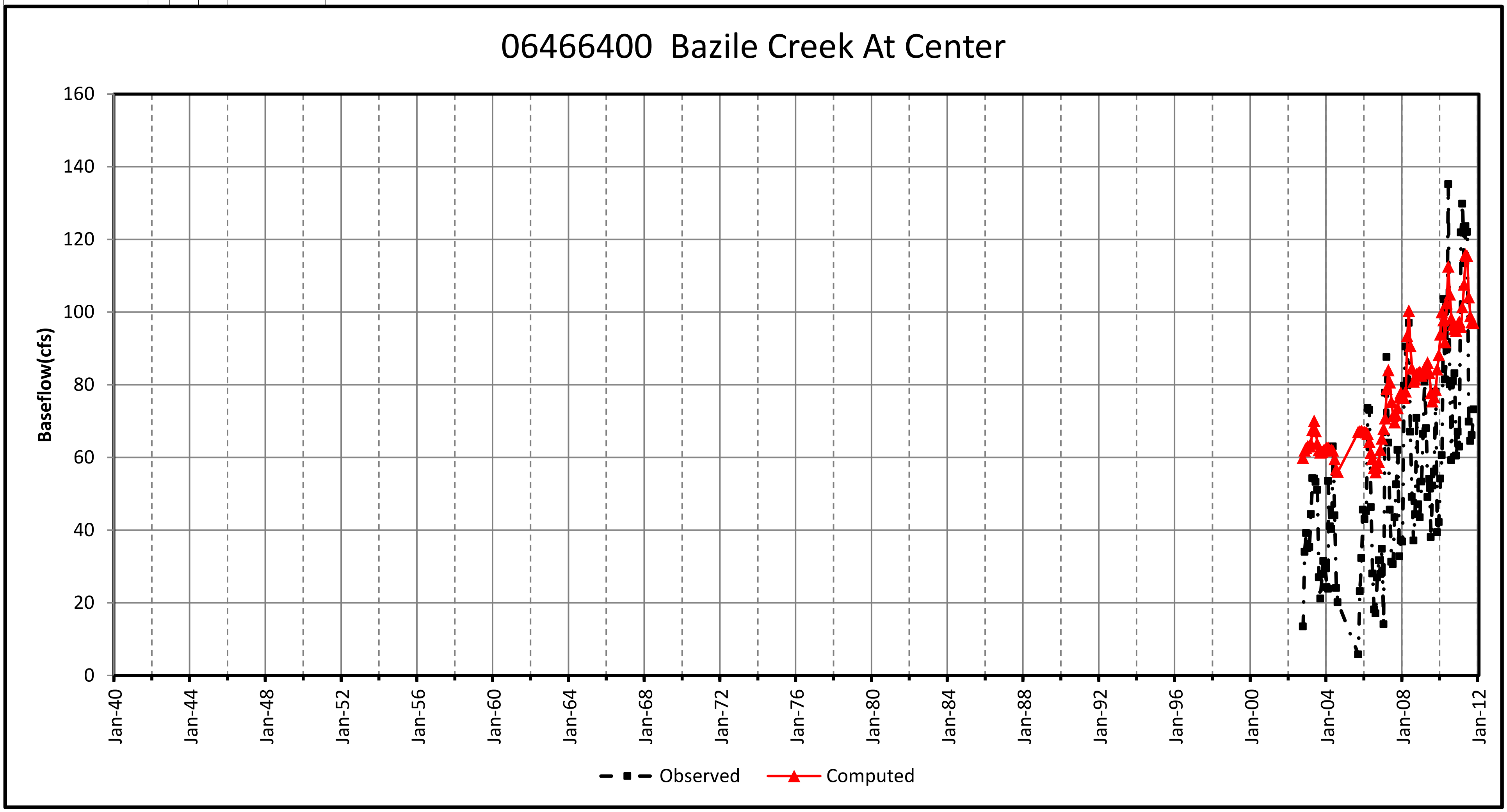
06465680 North Branch Verdigre Creek Near Verdigre
Baseflow(cfs)
45
40
35
30
25
20
15
10
5
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

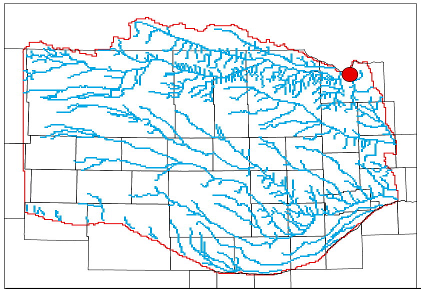


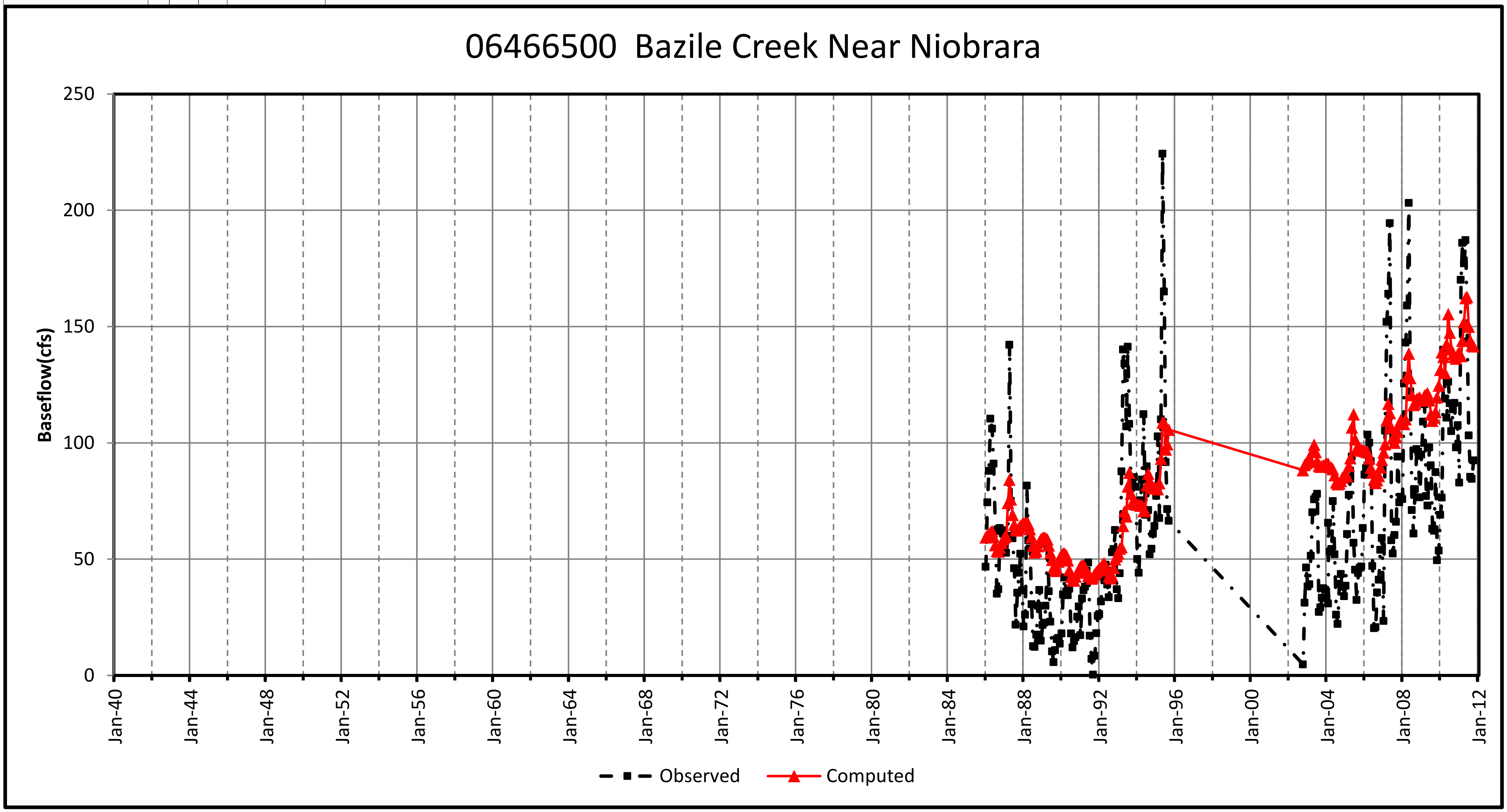


06465700 Verdigre Creek Near Verdigre
Baseflow(cfs)
0
50
100
150
200
250
300
350
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

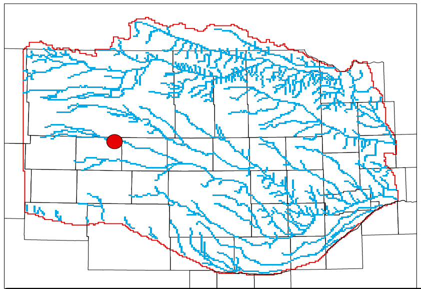


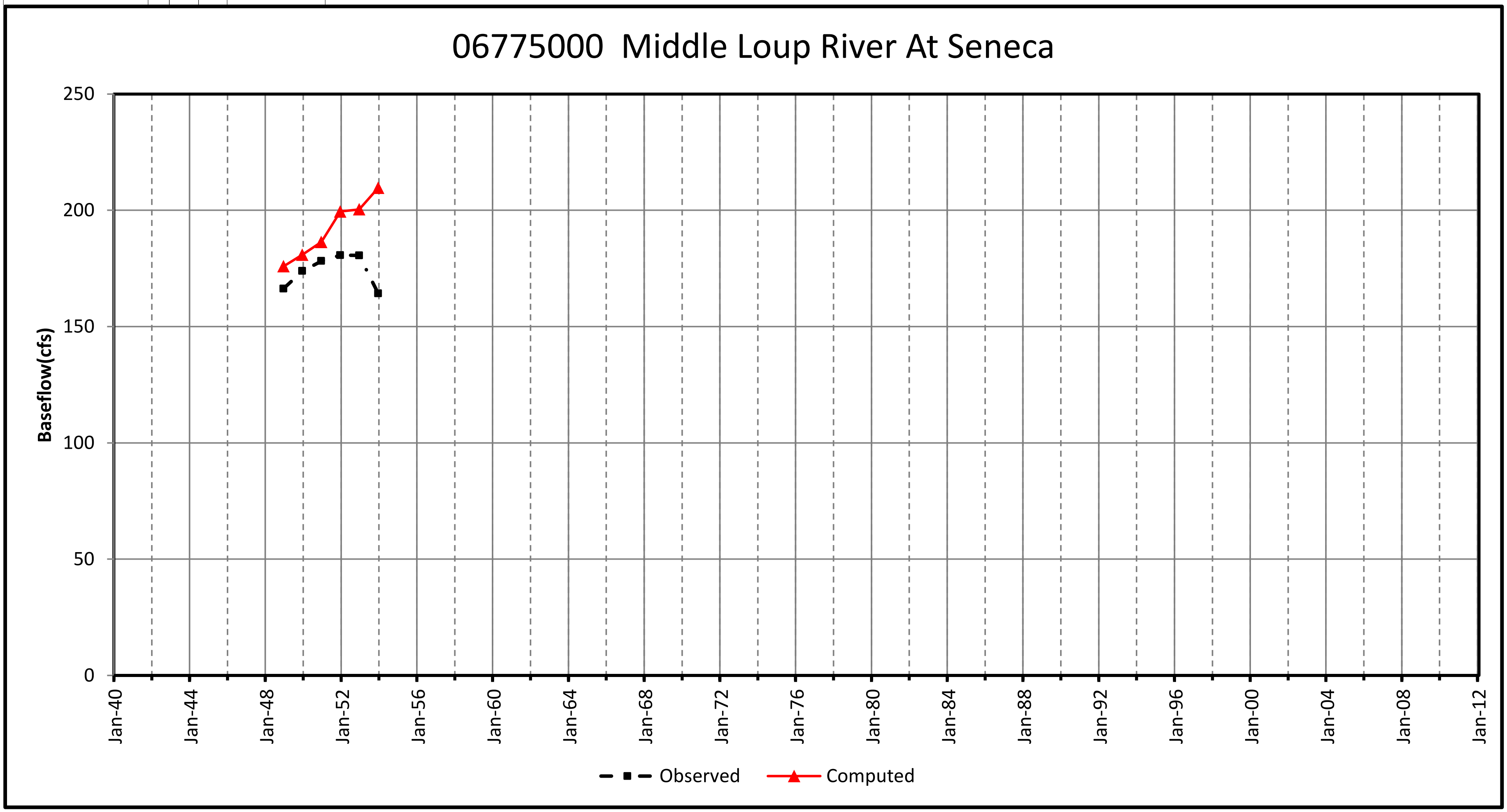

06466400 Bazile Creek At Center
Baseflow(cfs)
0
20
40
60
80
100
120
140
160
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



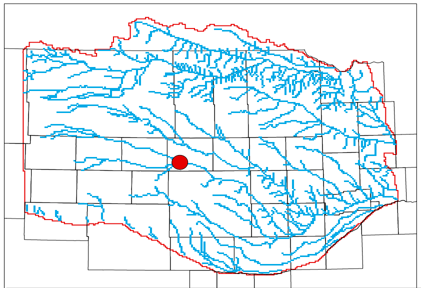


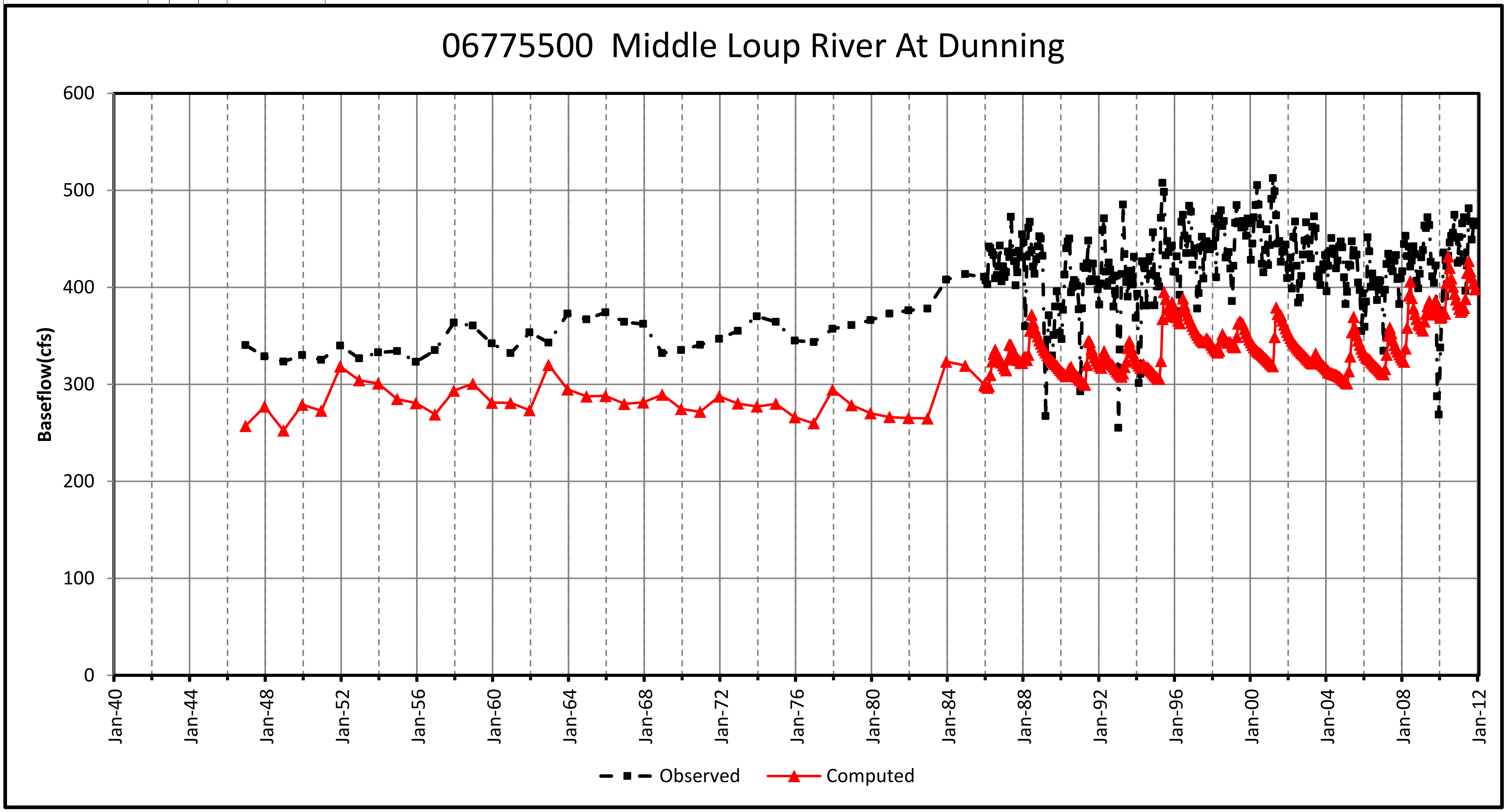
06466500 Bazile Creek Near Niobrara
Baseflow(cfs)
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



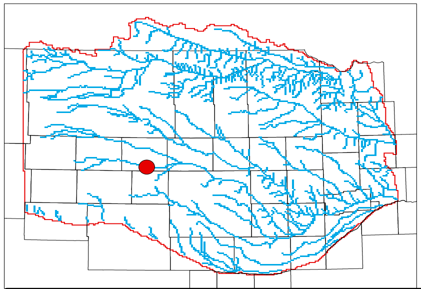


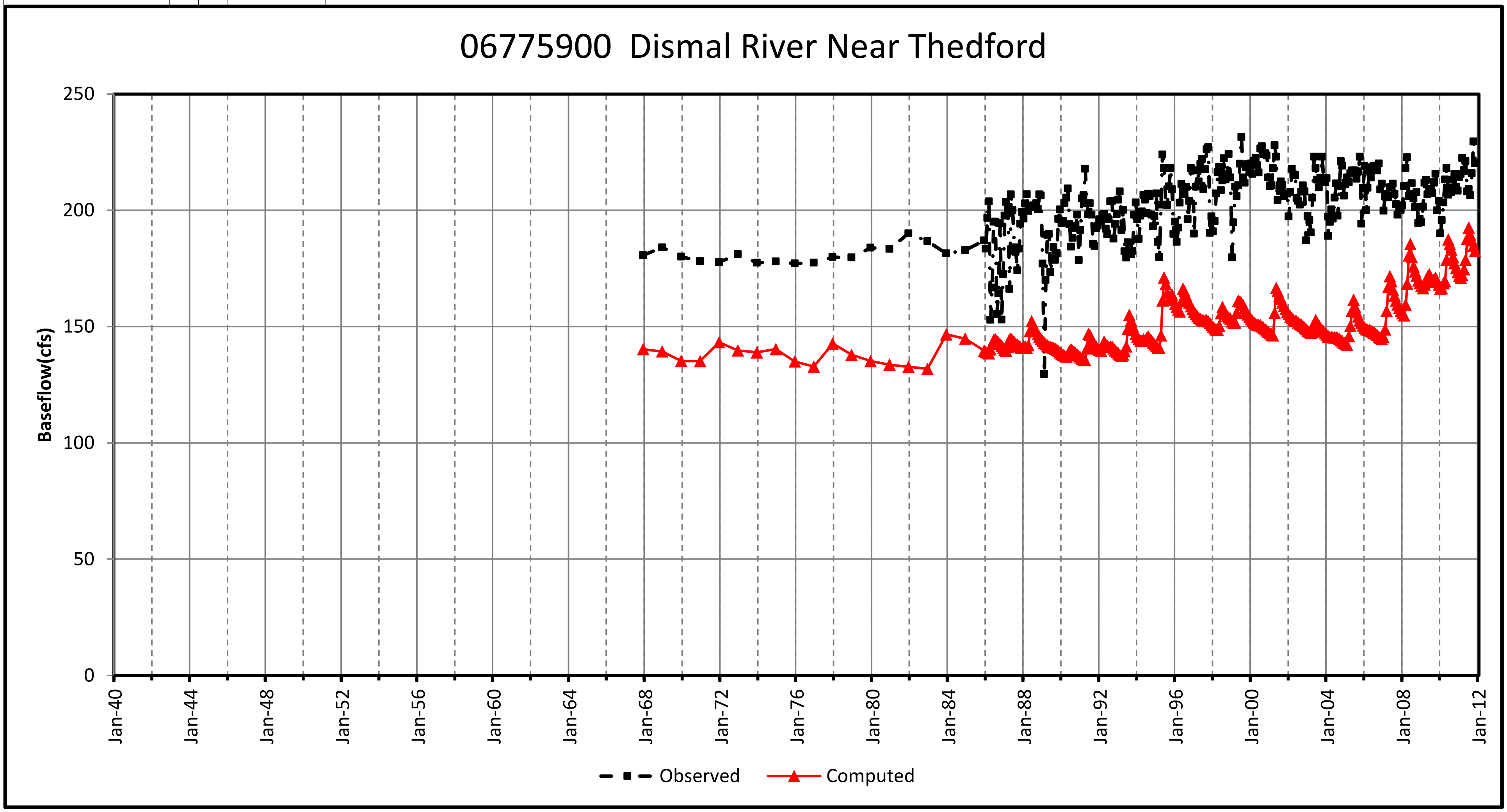
06775000 Middle Loup River At Seneca
Baseflow(cfs)
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



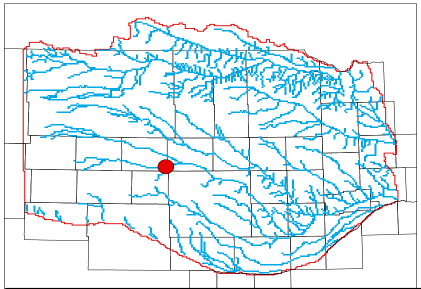


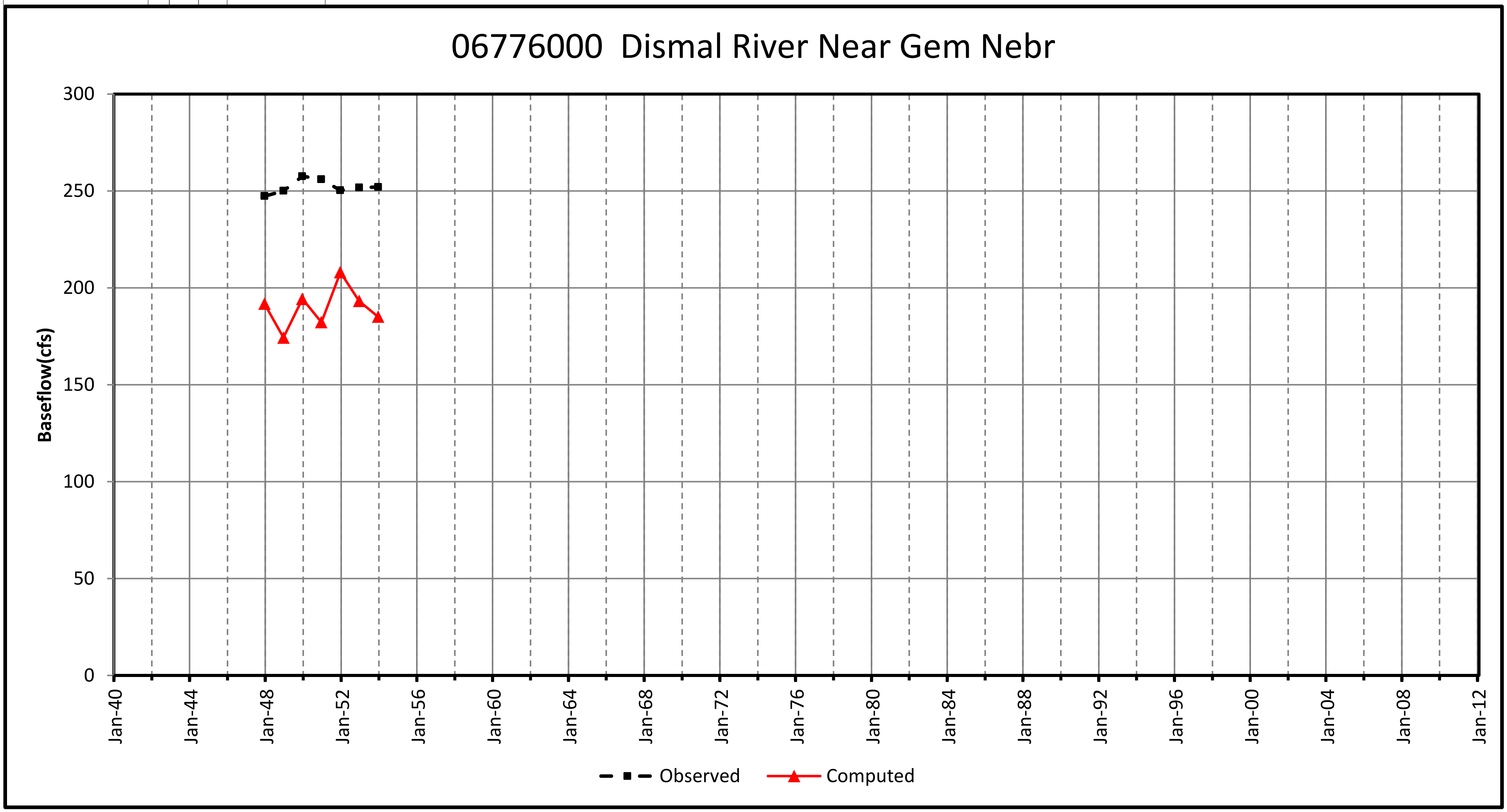
06775500 Middle Loup River At Dunning
Baseflow(cfs)
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



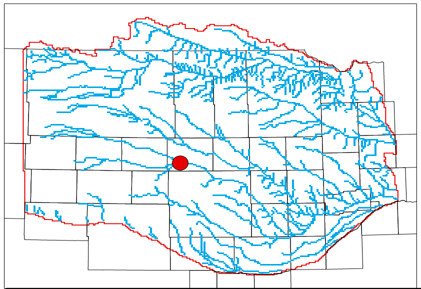


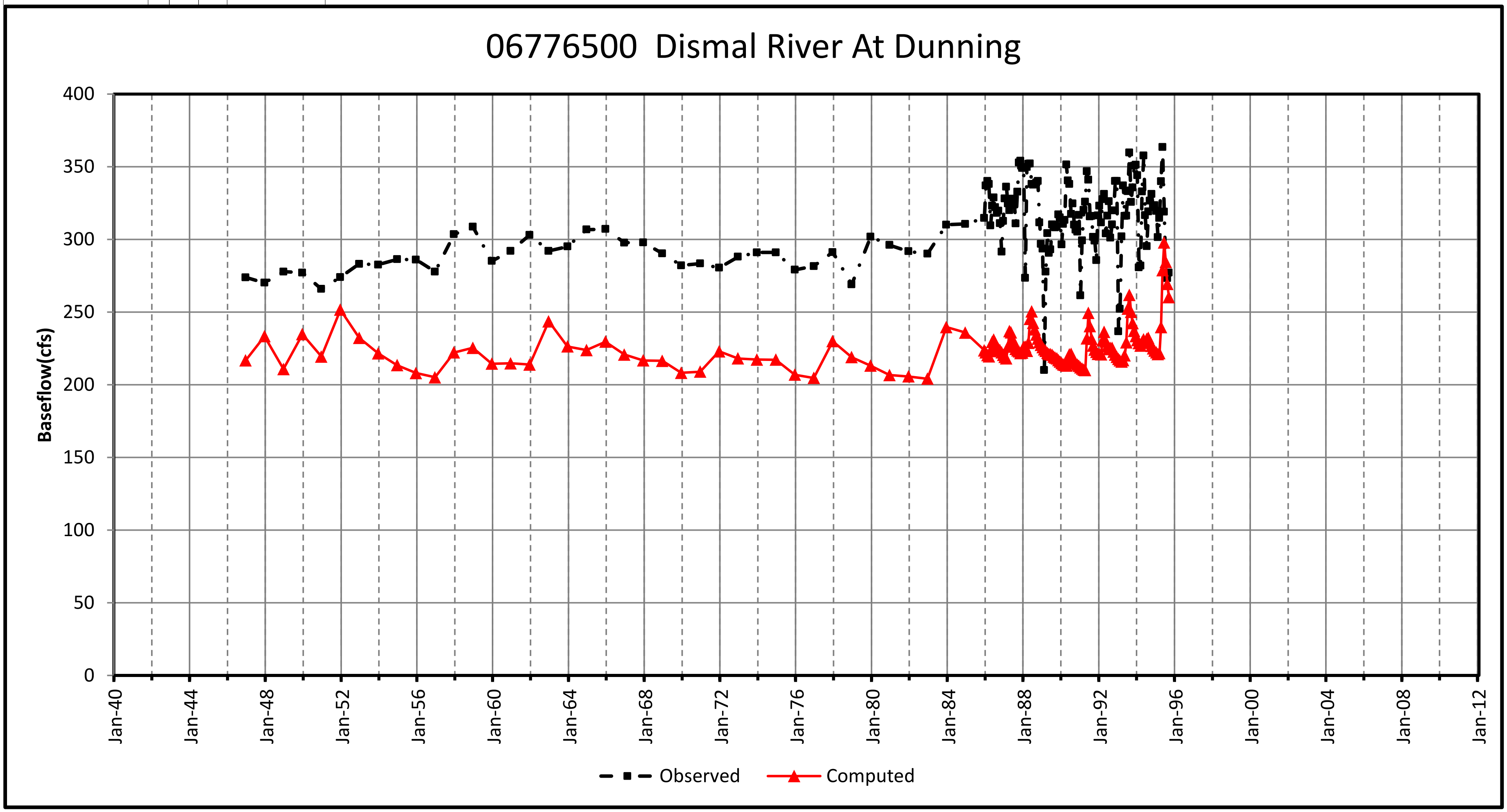
06775900 Dismal River Near Thedford
Baseflow(cfs)
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



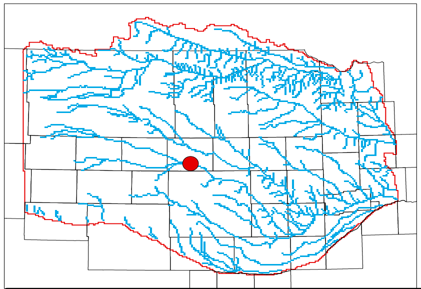


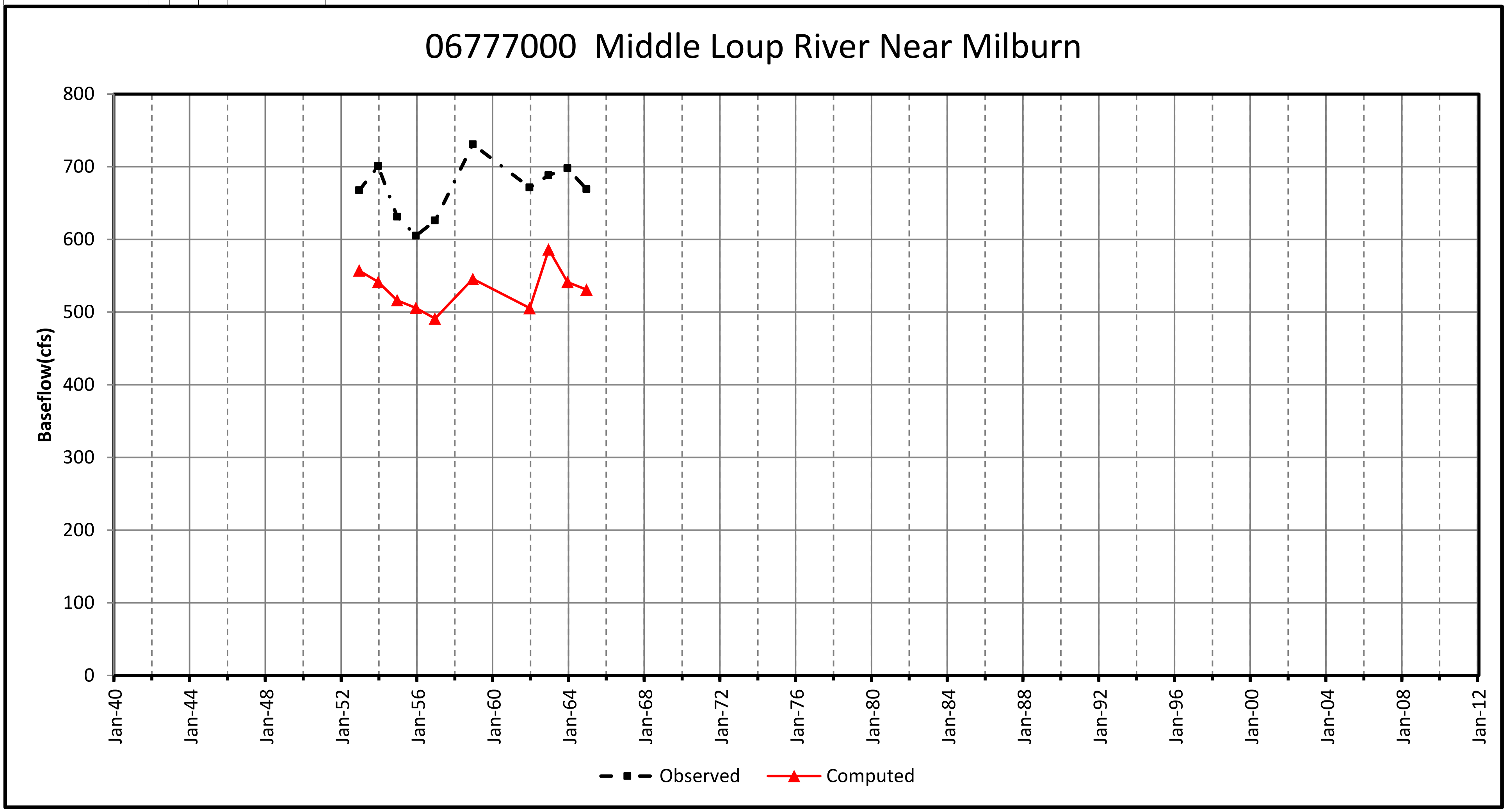
06776000 Dismal River Near Gem Nebr
Baseflow(cfs)
0
50
100
150
200
250
300
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

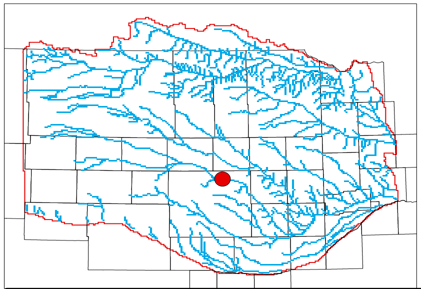


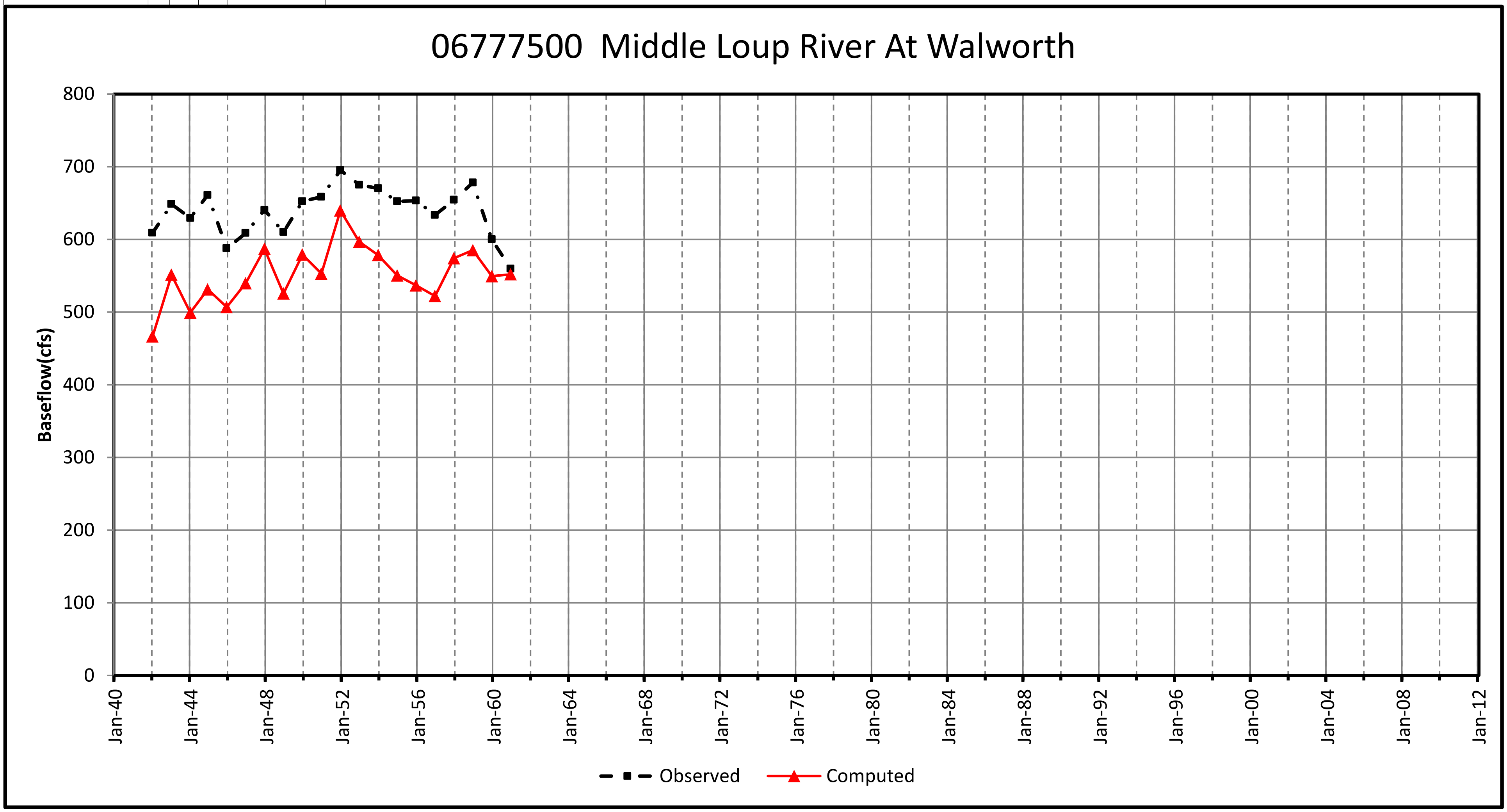


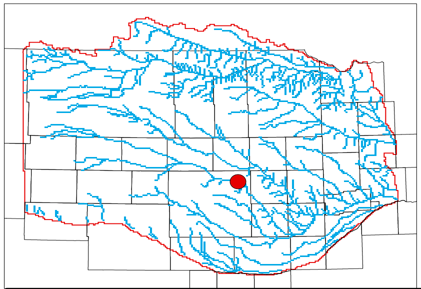
06776500 Dismal River At Dunning
Baseflow(cfs)
400
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

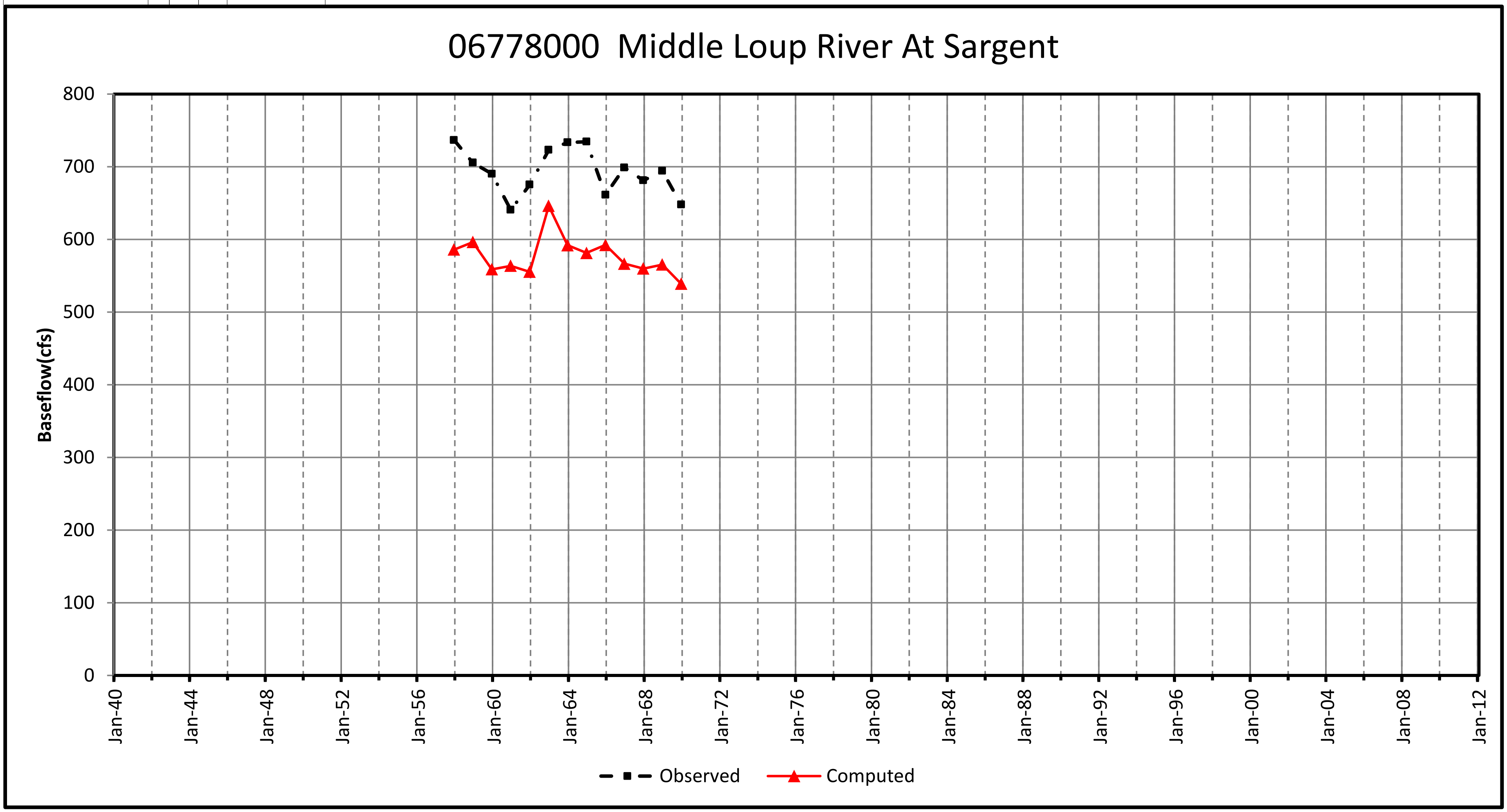



06777000 Middle Loup River Near Milburn
Baseflow(cfs)
0
100
200
300
400
500
600
700
800
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

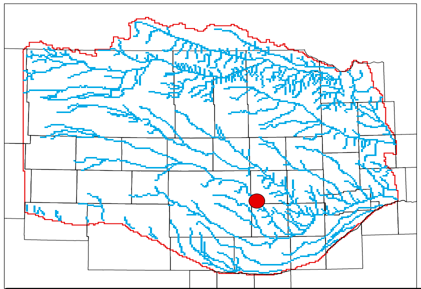


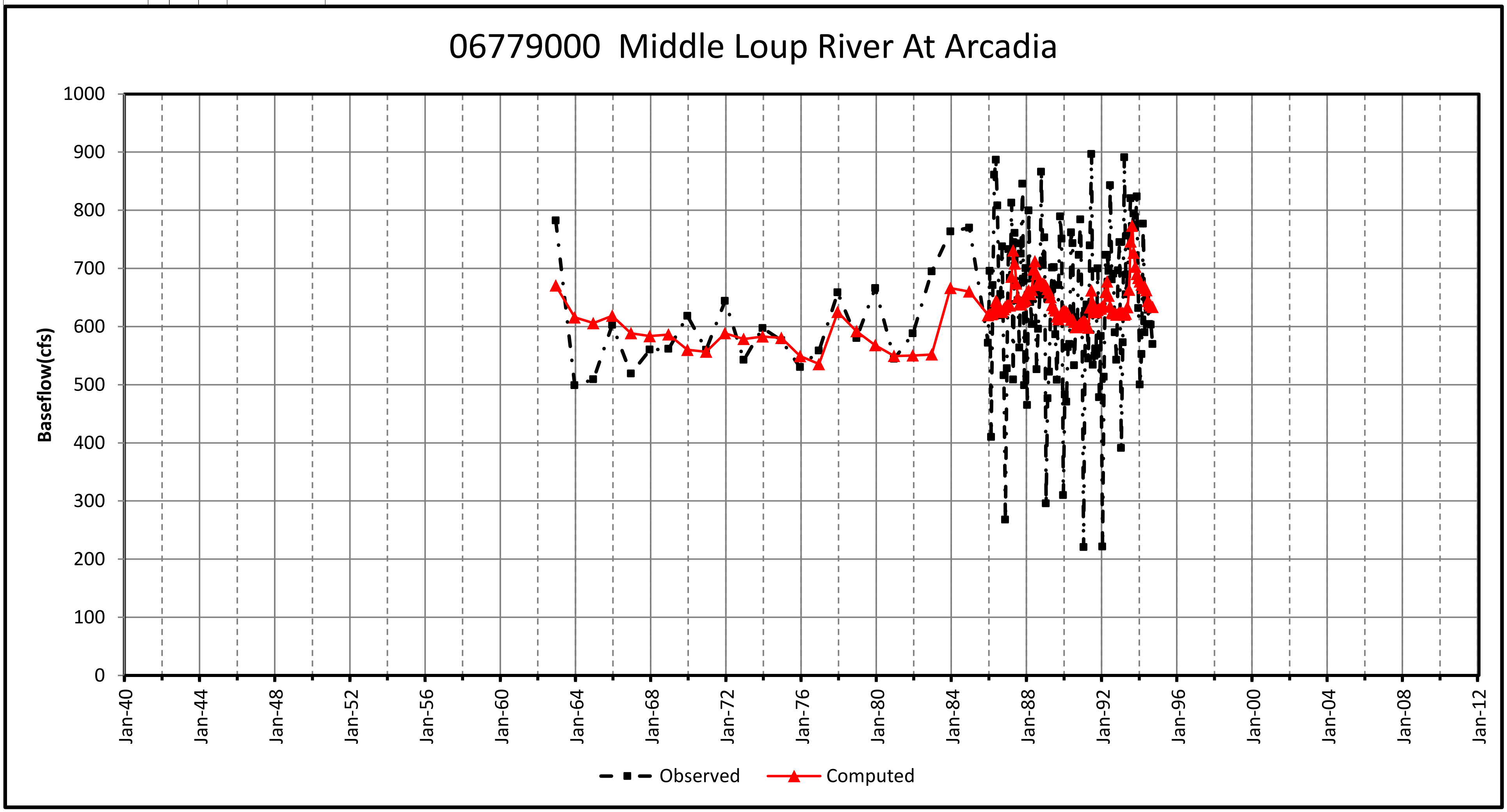

06777500 Middle Loup River At Walworth
Baseflow(cfs)
800
700
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



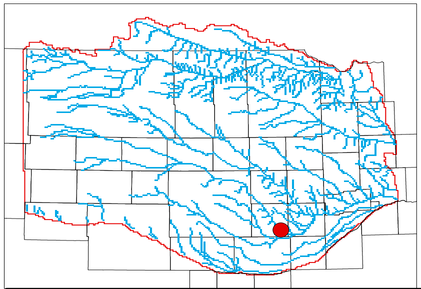


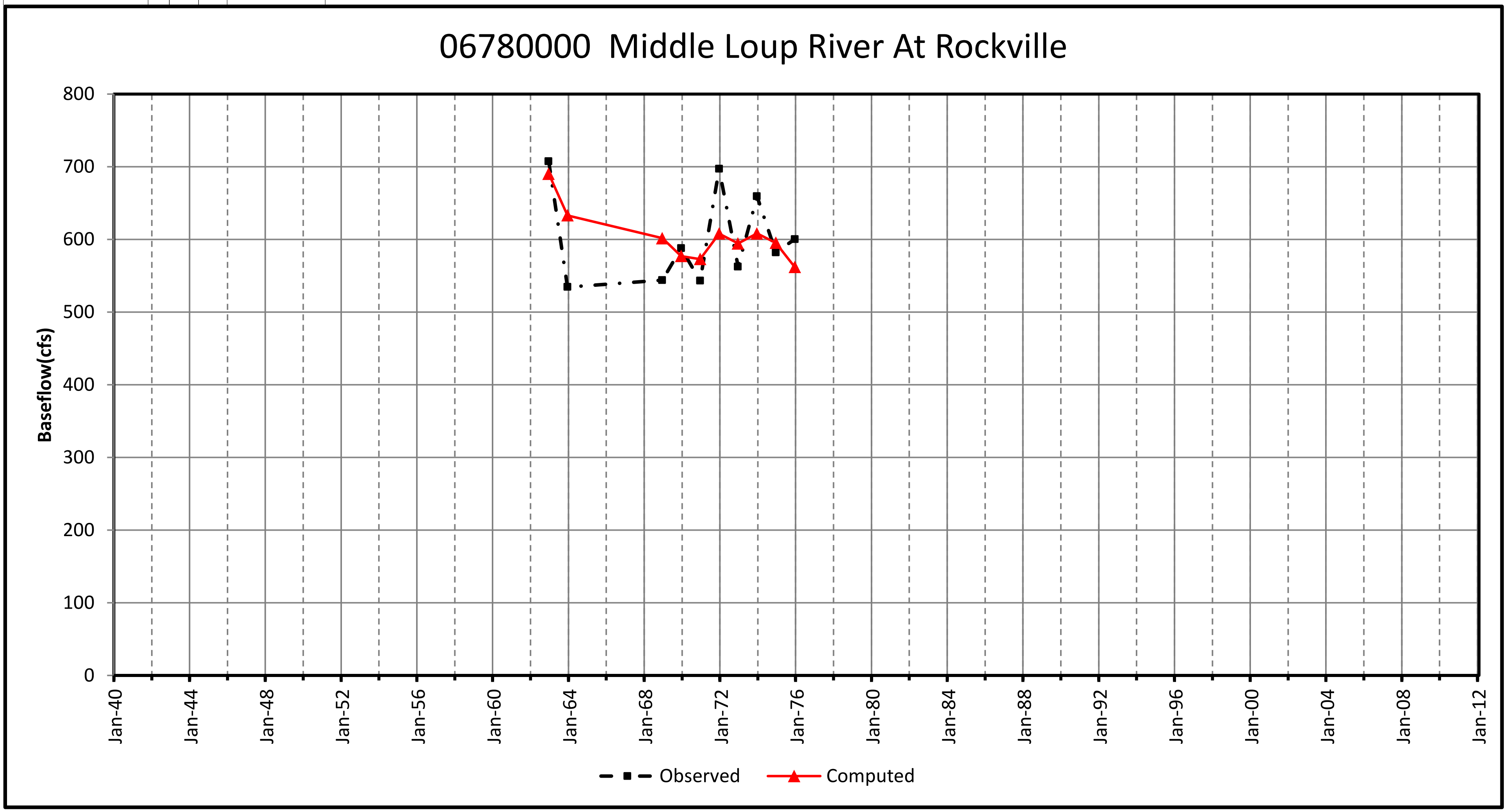
06778000 Middle Loup River At Sargent
Baseflow(cfs)
800
700
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



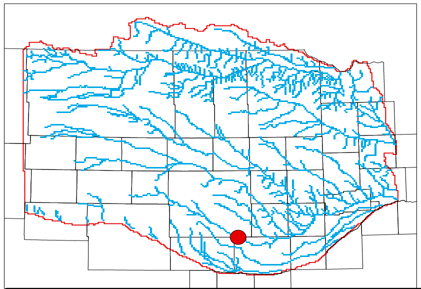


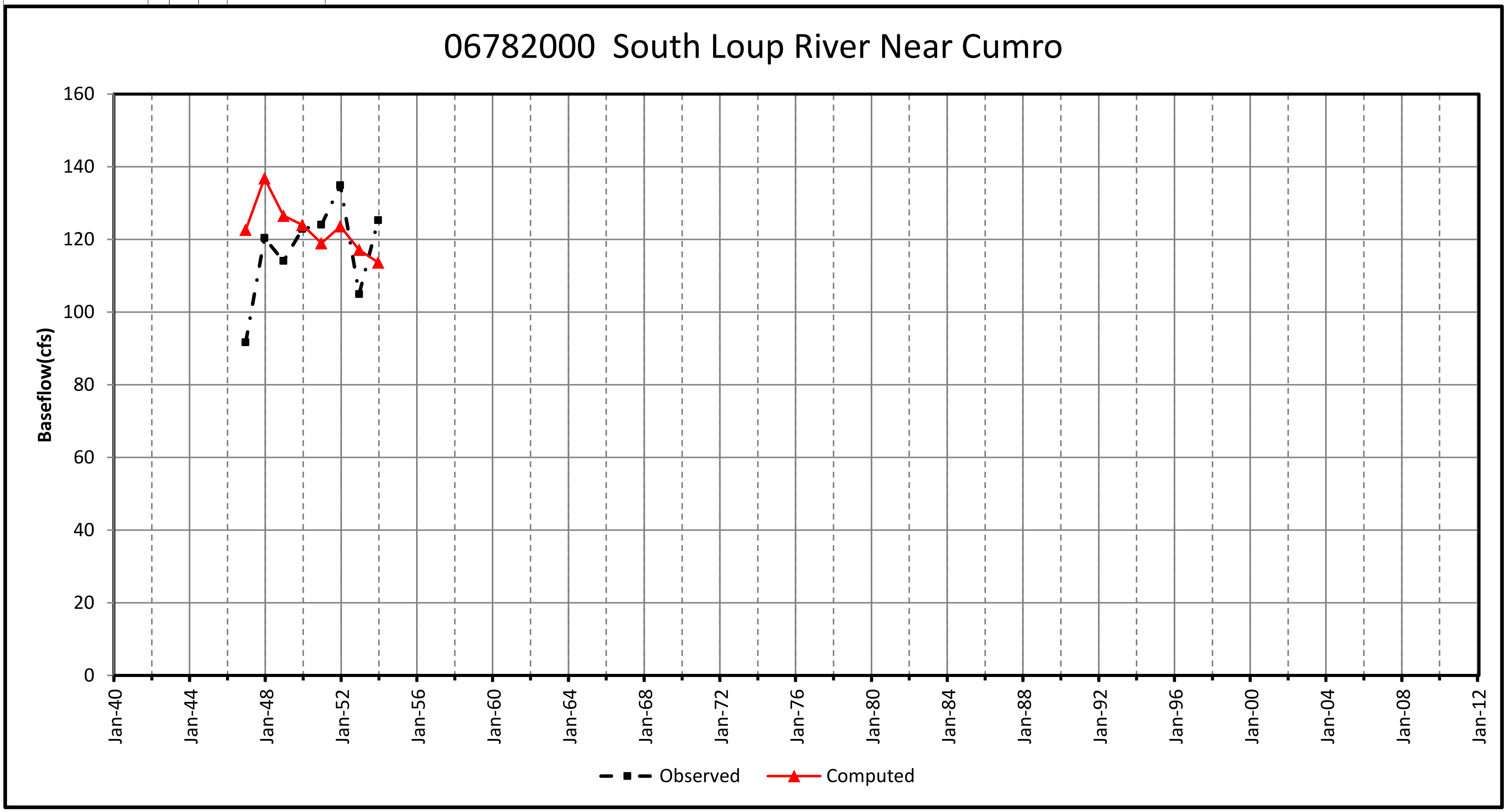
06779000 Middle Loup River At Arcadia
Baseflow(cfs)
1000
900
800
700
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



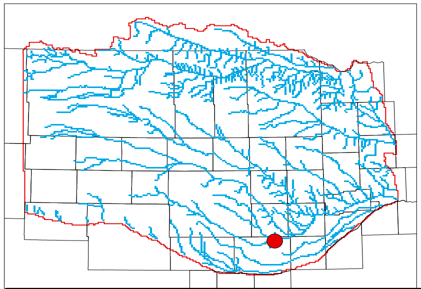


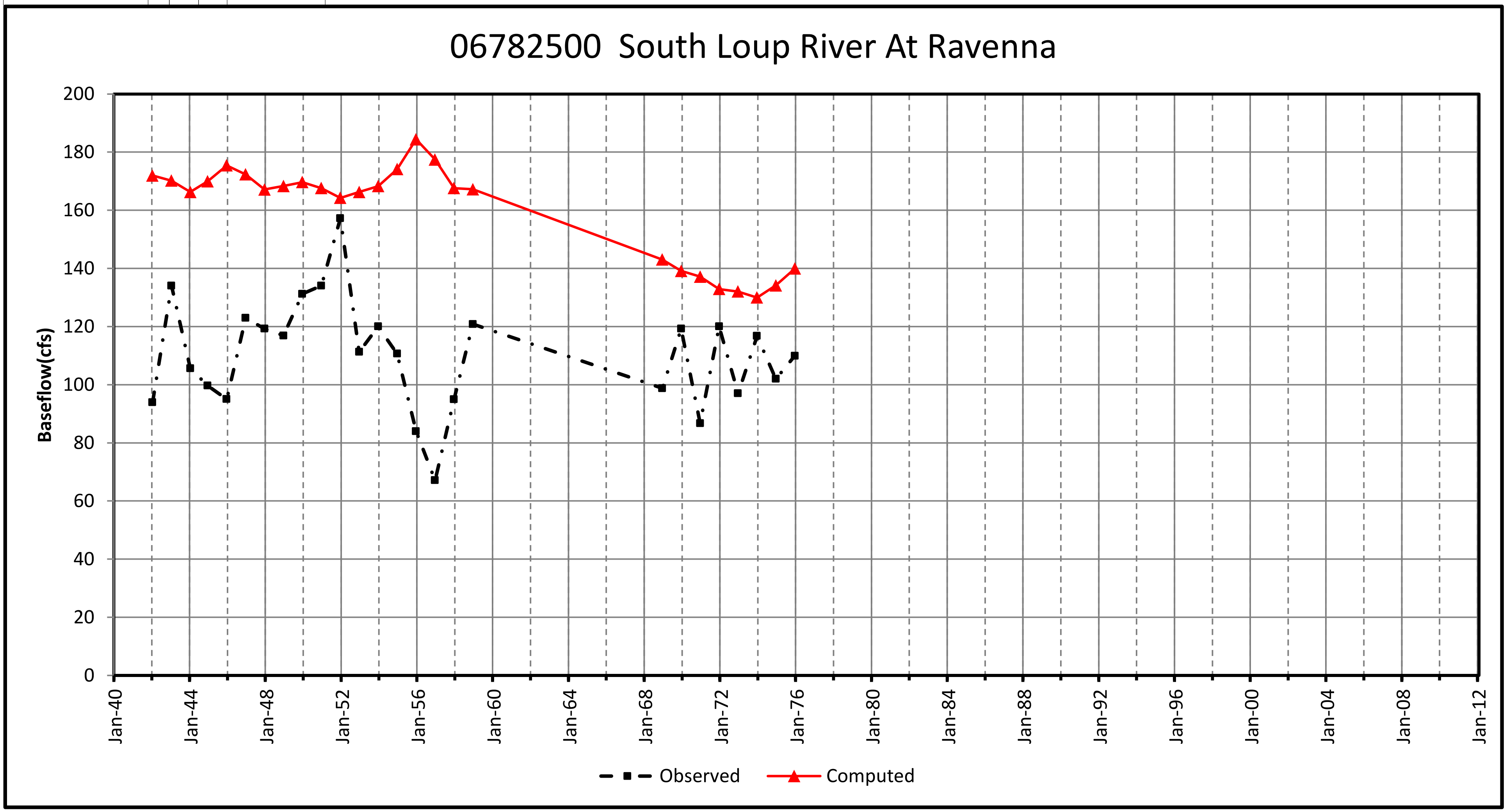
06780000 Middle Loup River At Rockville
Baseflow(cfs)
800
700
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

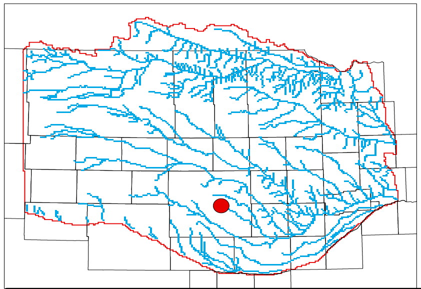


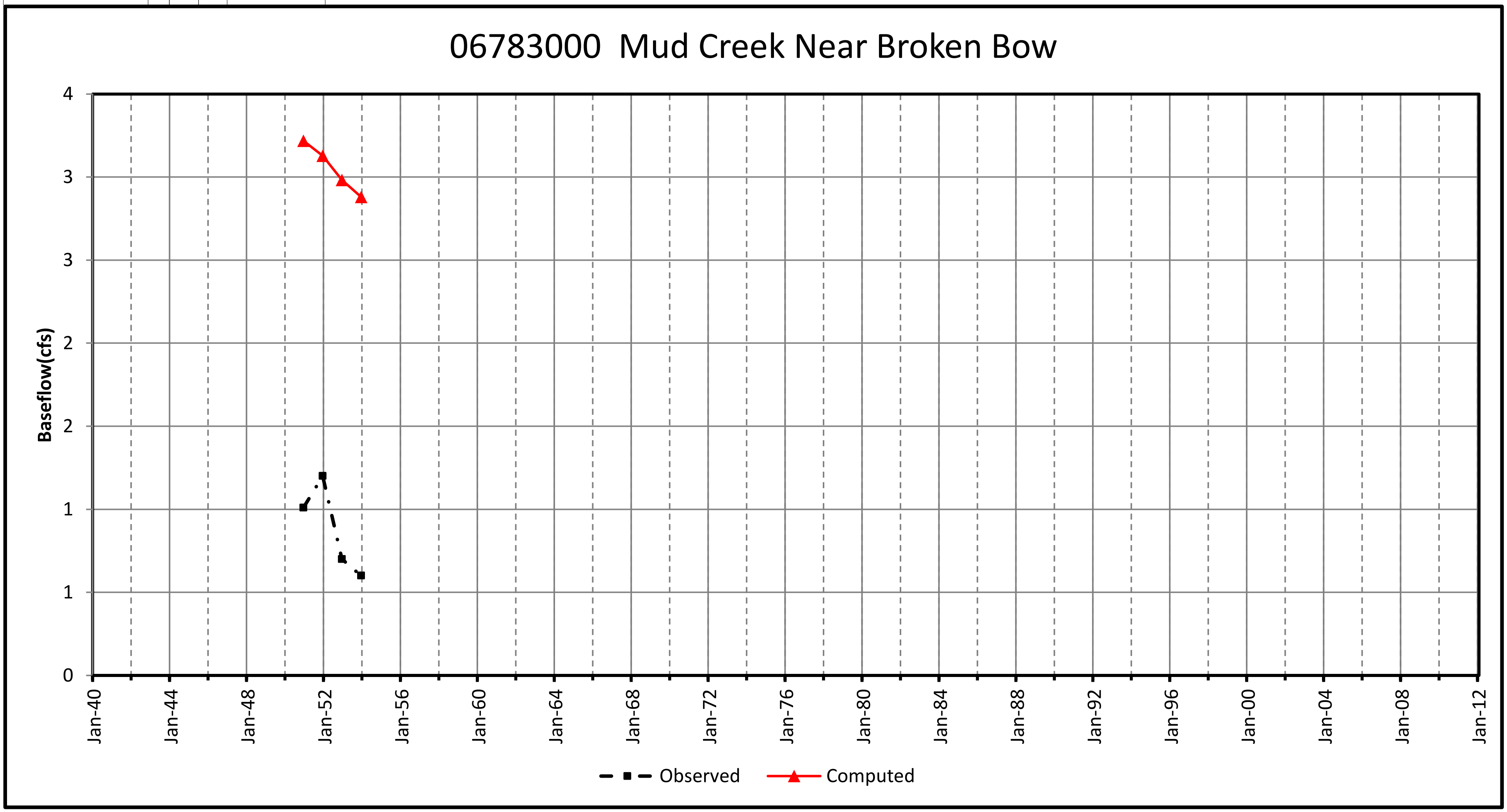


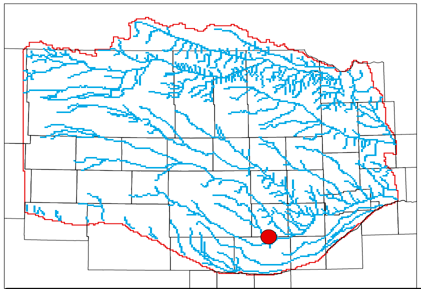
06782000 South Loup River Near Cumro
Baseflow(cfs)
0
20
40
60
80
100
120
140
160
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

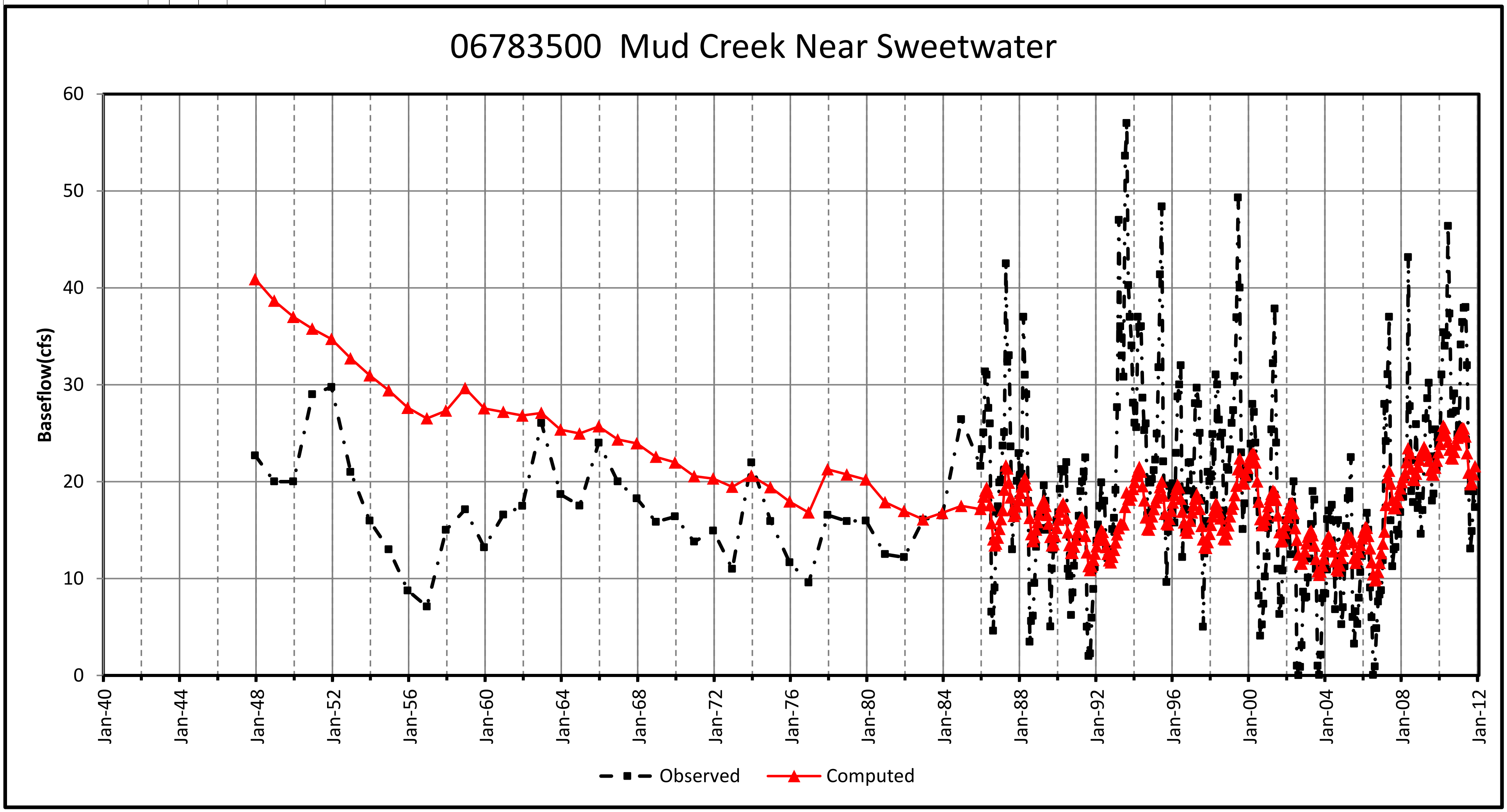



06782500 South Loup River At Ravenna
Baseflow(cfs)
0
20
40
60
80
100
120
140
160
180
200
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

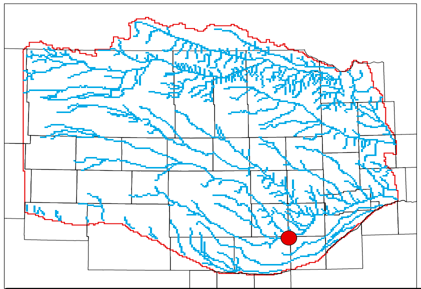


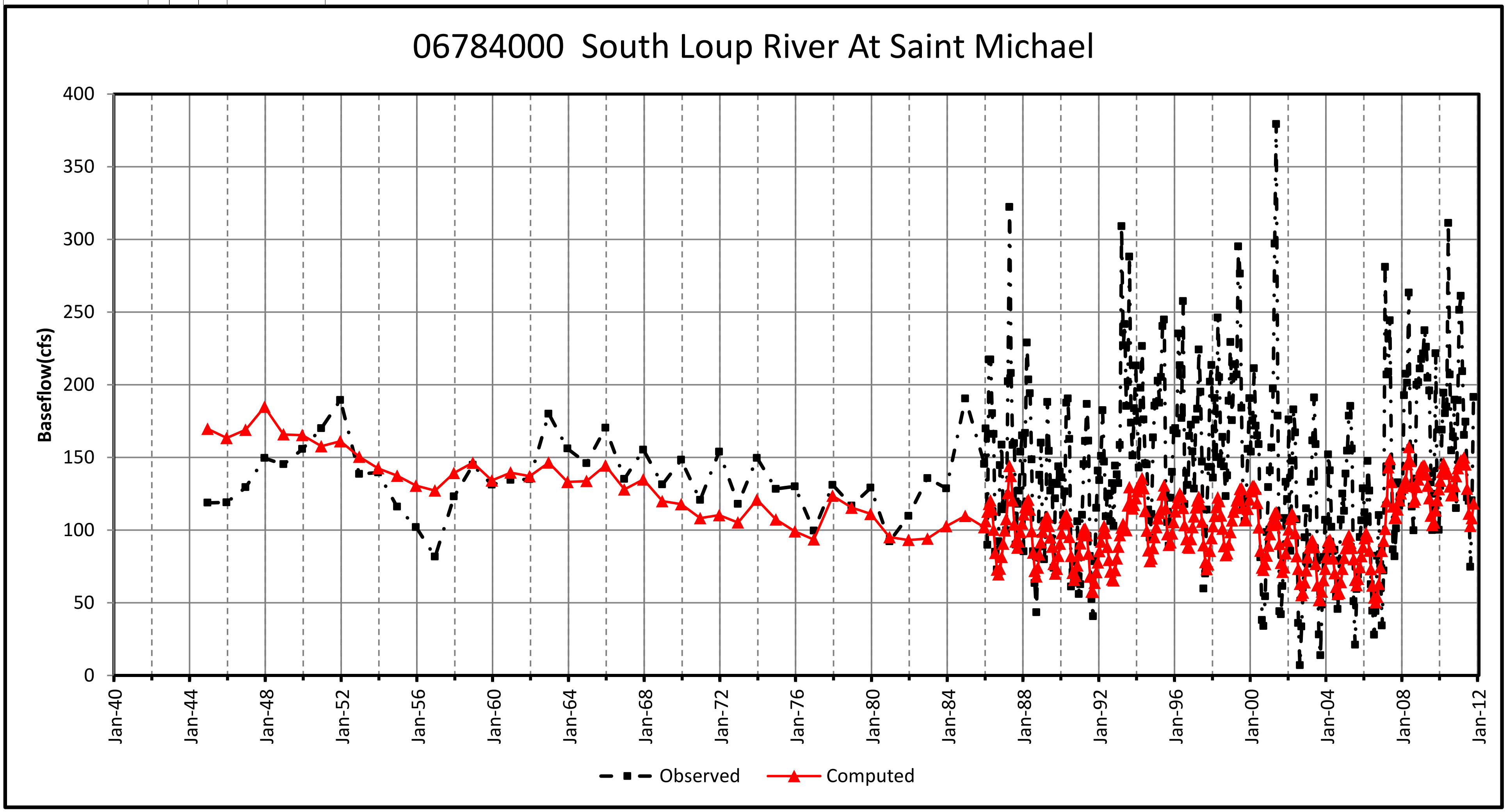

06783000 Mud Creek Near Broken Bow
Baseflow(cfs)
0
1
1
2
2
3
3
4
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



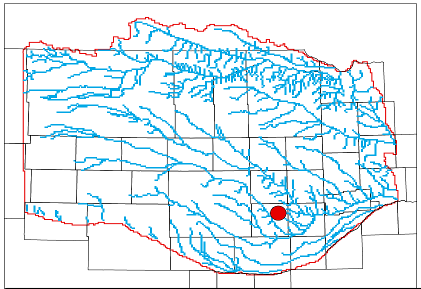


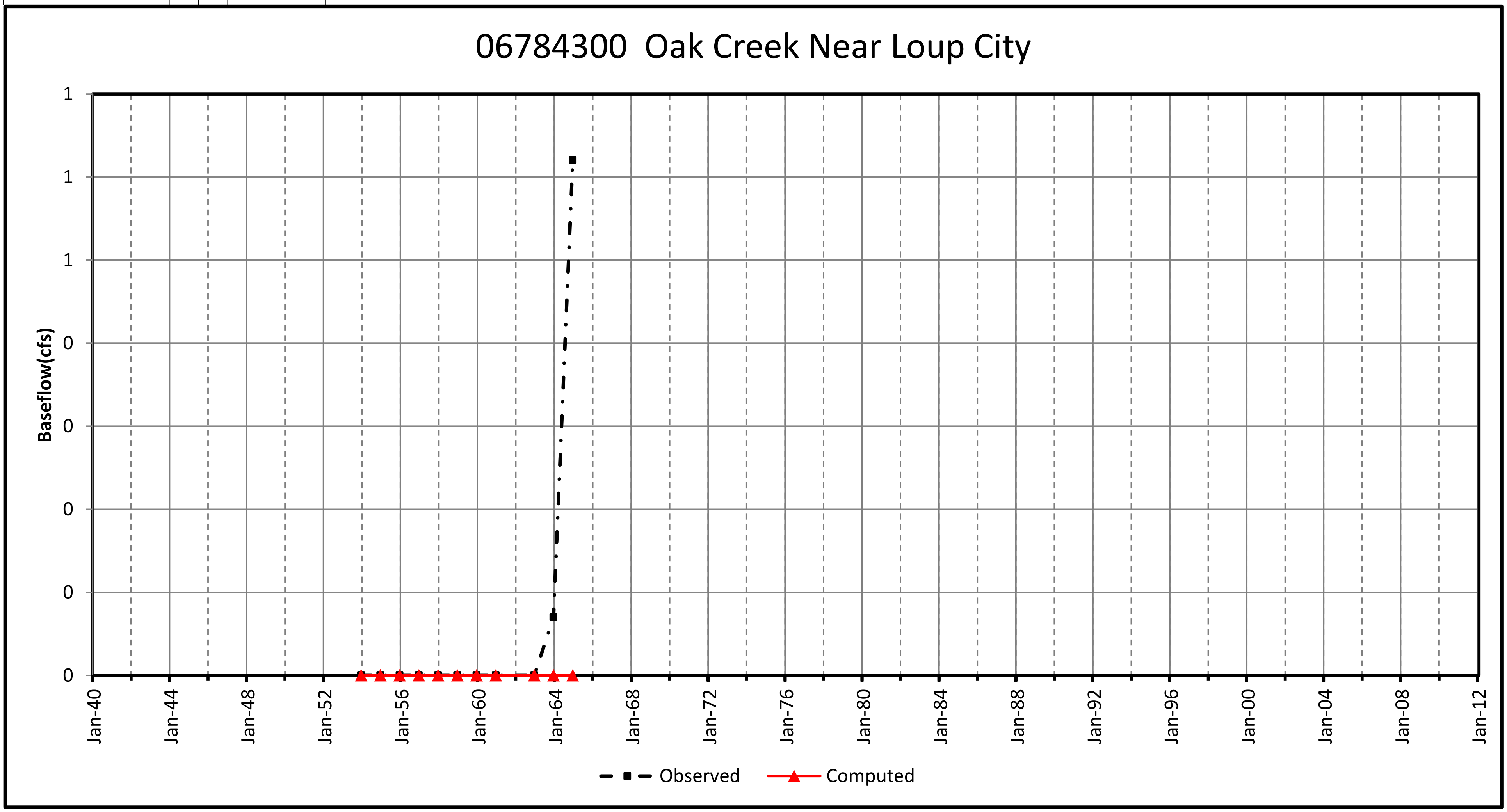
06783500 Mud Creek Near Sweetwater
Baseflow(cfs)
60
50
40
30
20
10
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



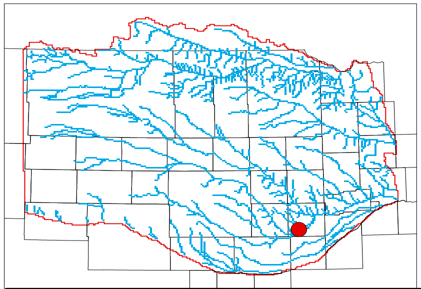


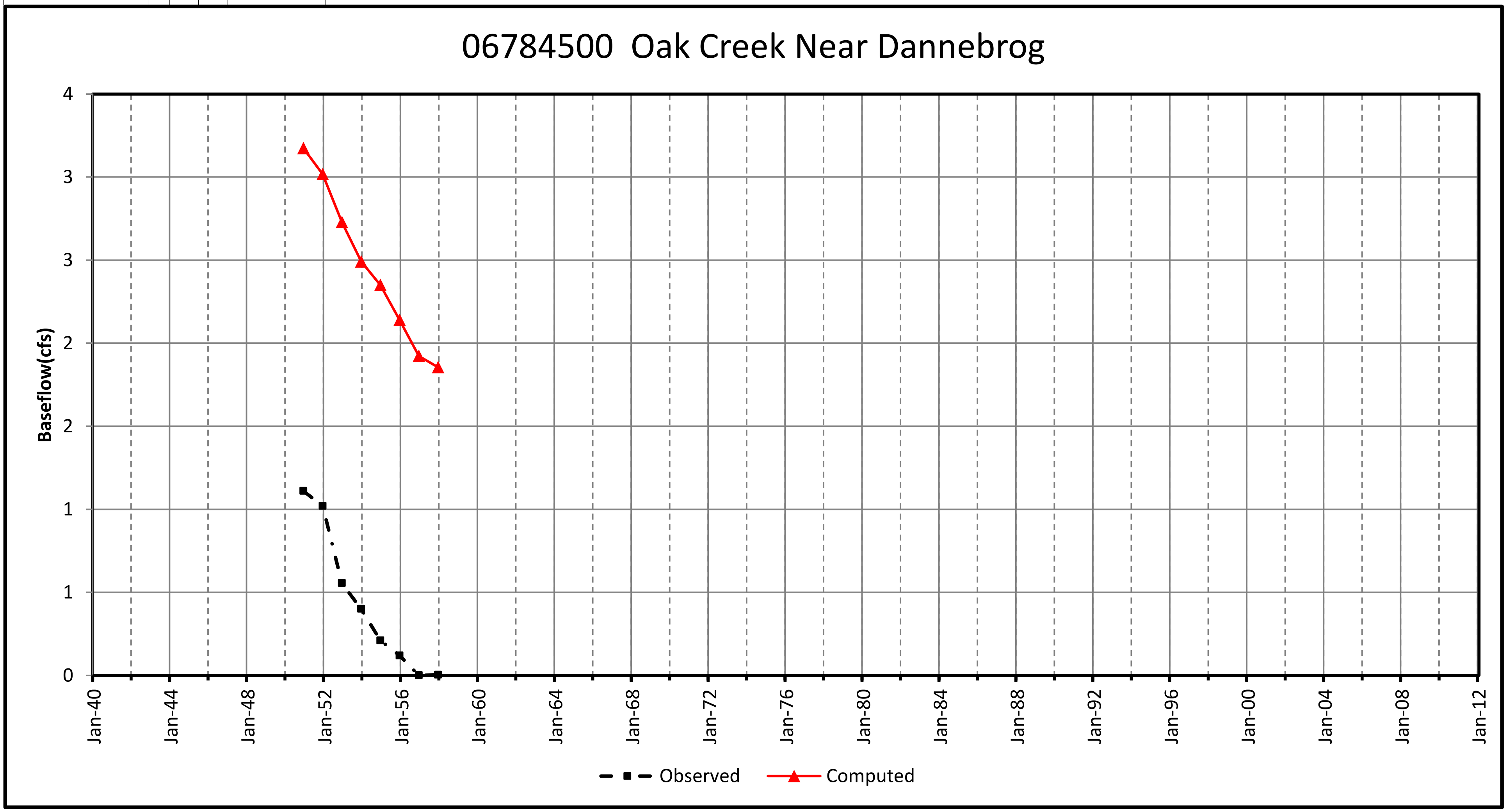
06784000 South Loup River At Saint Michael
Baseflow(cfs)
400
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



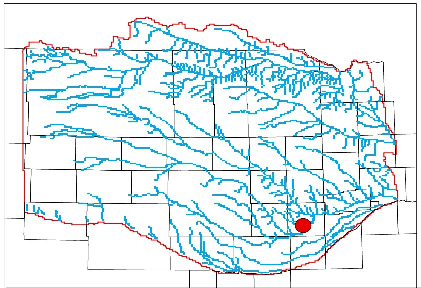


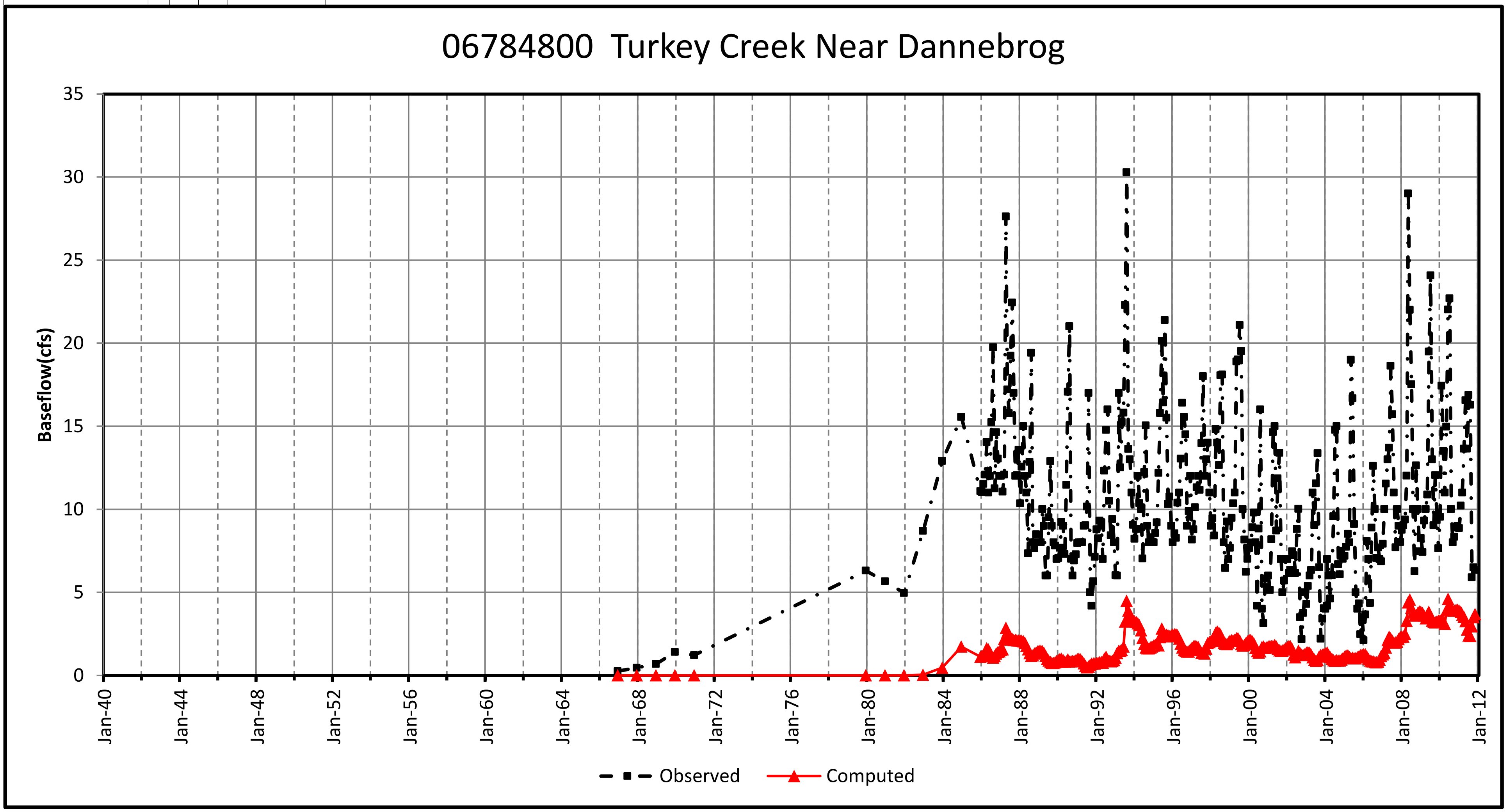
06784300 Oak Creek Near Loup City
Baseflow(cfs)
1
1
1
0
0
0
0
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



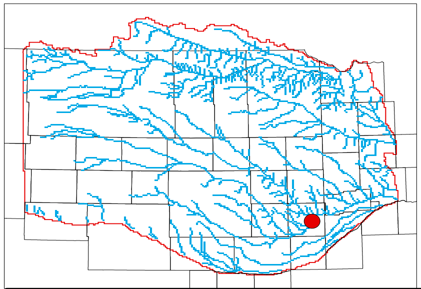


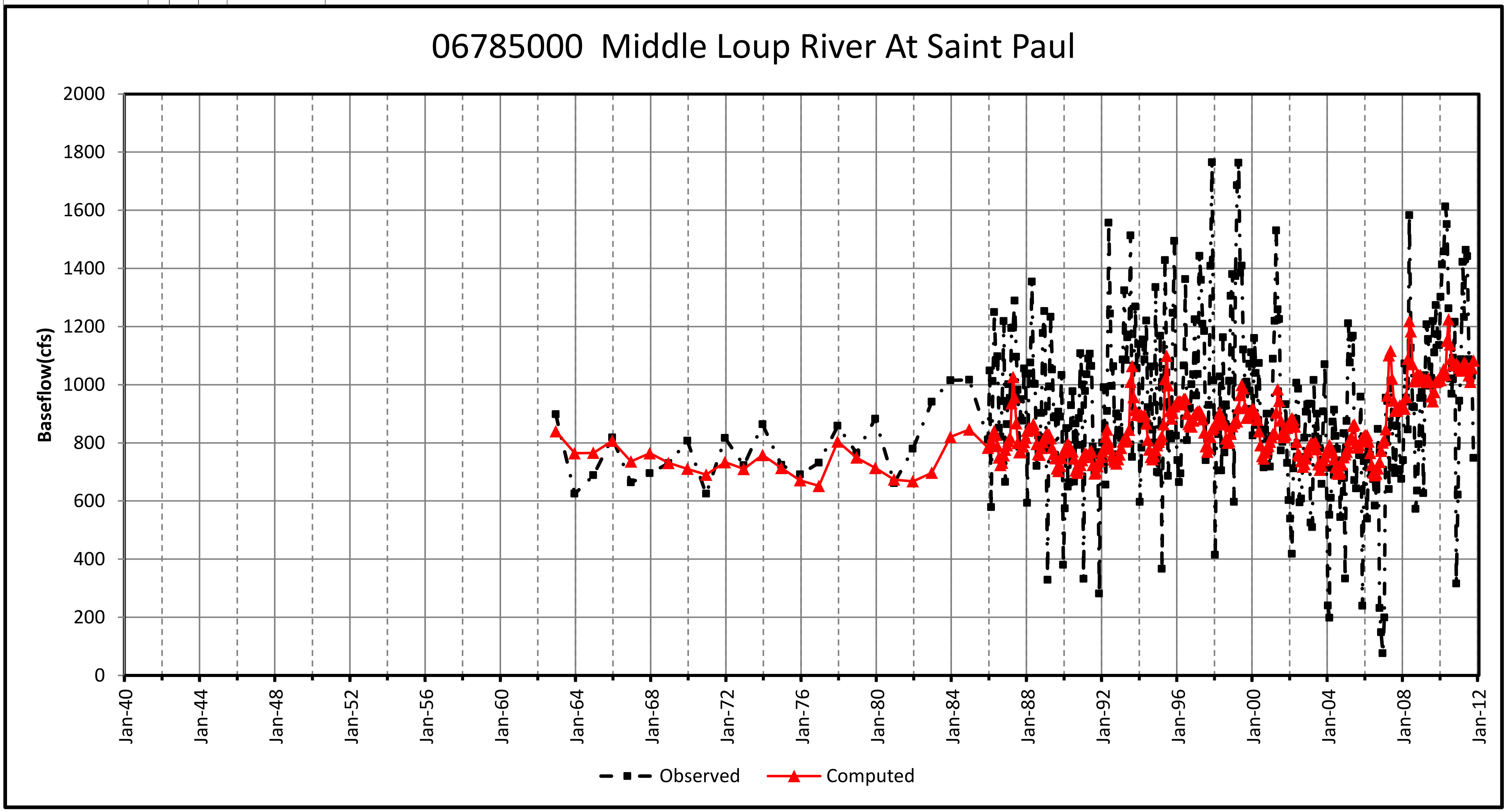
06784500 Oak Creek Near Dannebrog
Baseflow(cfs)
4
3
3
2
2
1
1
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



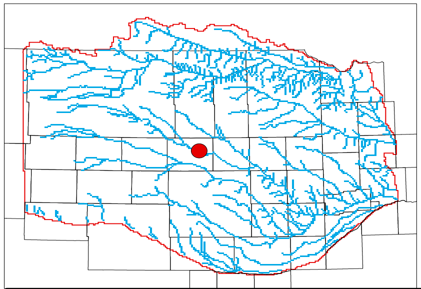


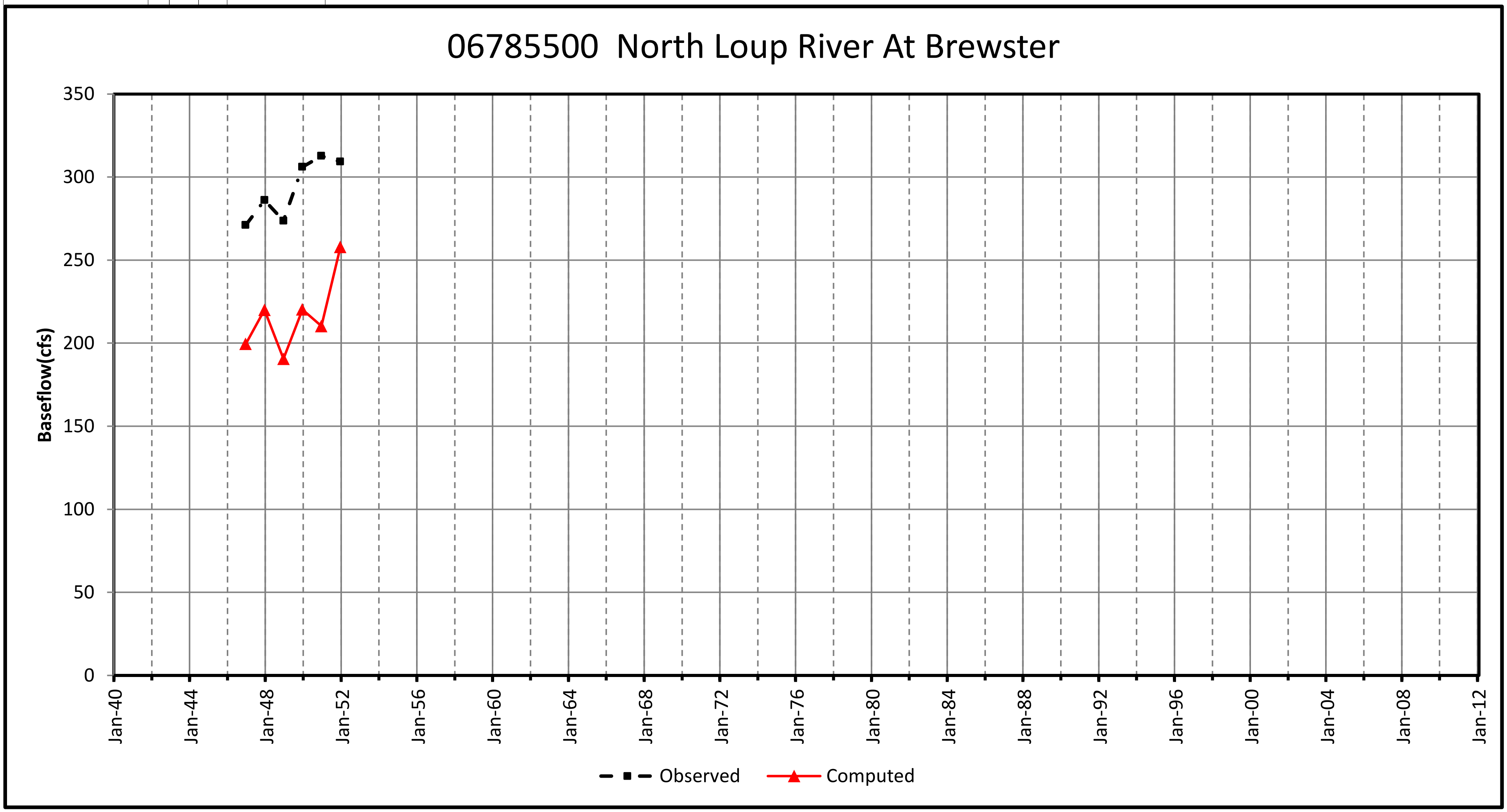
06784800 Turkey Creek Near Dannebrog
Baseflow(cfs)
35
30
25
20
15
10
5
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



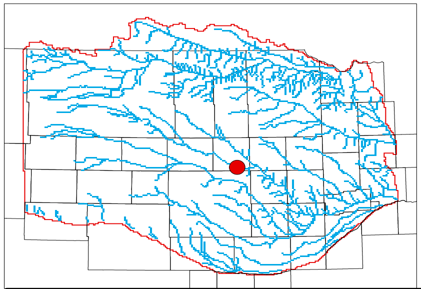


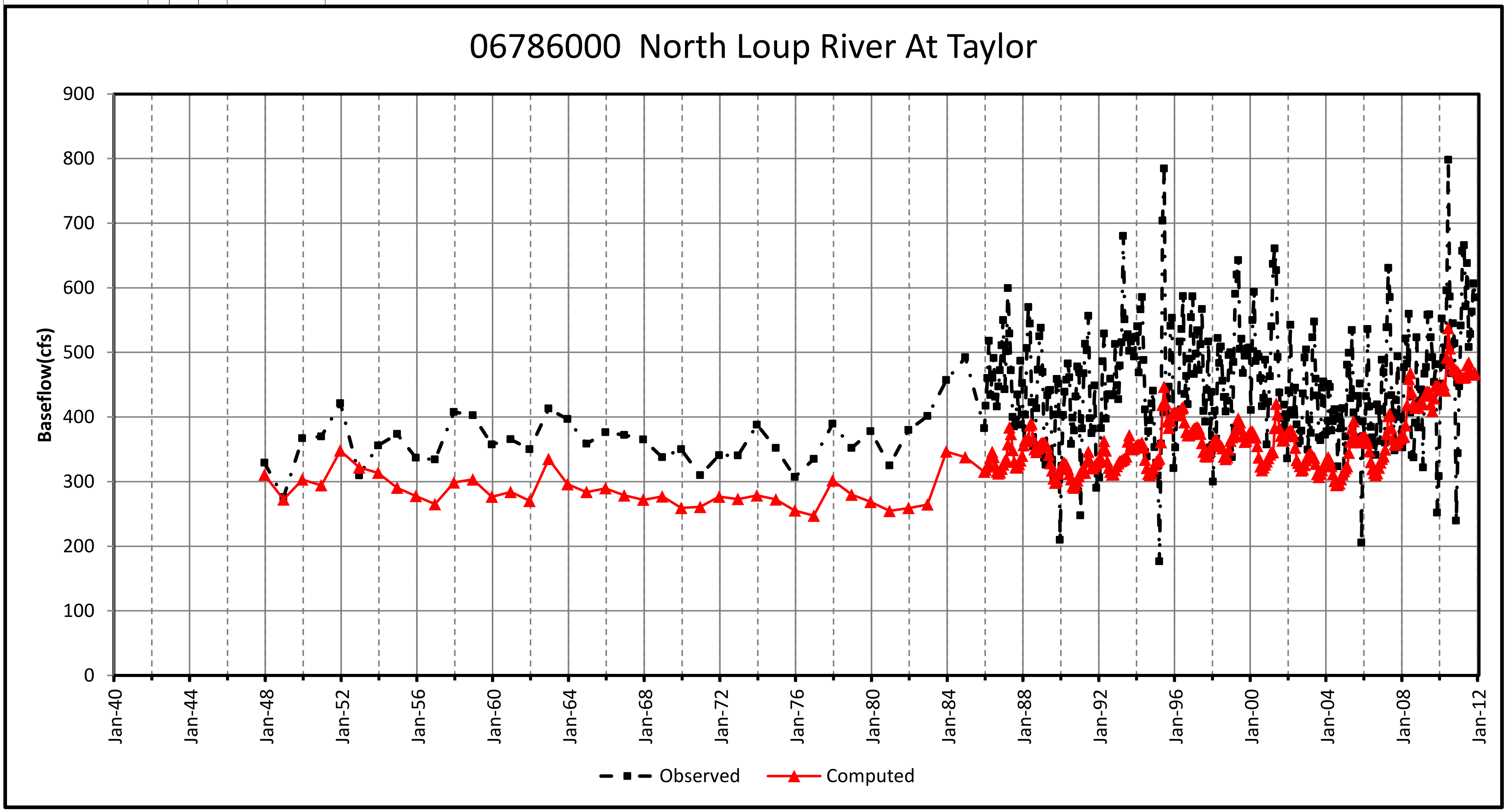
06785000 Middle Loup River At Saint Paul
Baseflow(cfs)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



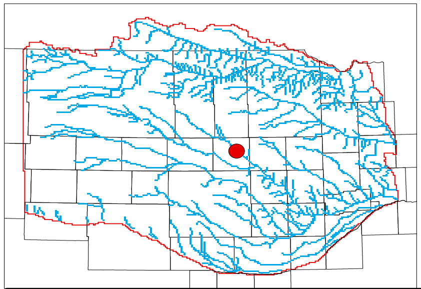


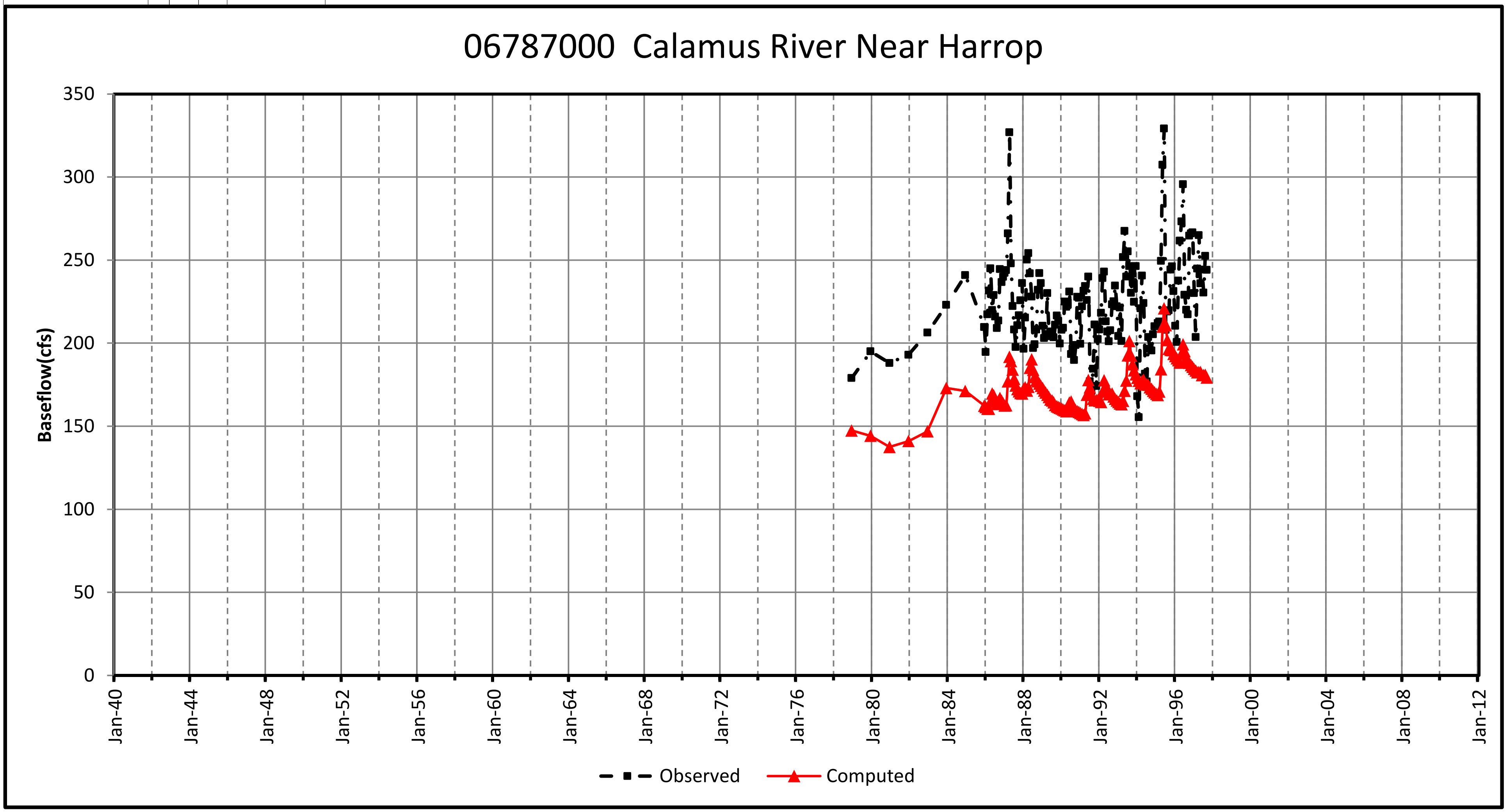
06785500 North Loup River At Brewster
Baseflow(cfs)
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



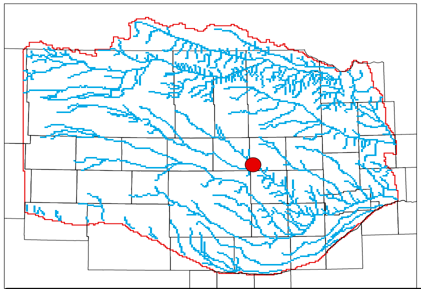


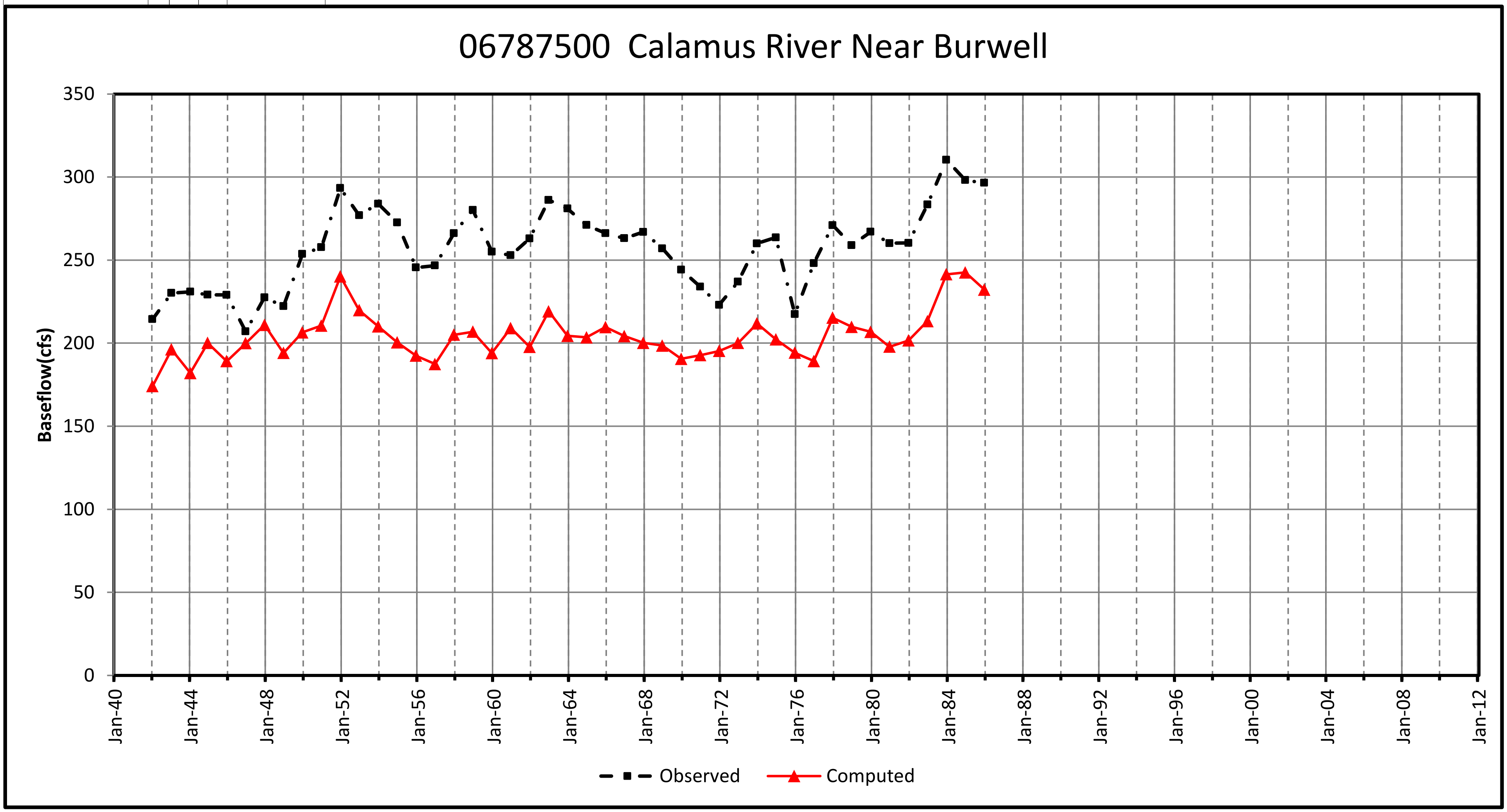
06786000 North Loup River At Taylor
Baseflow(cfs)
900
800
700
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

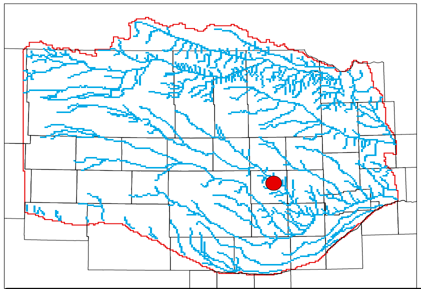


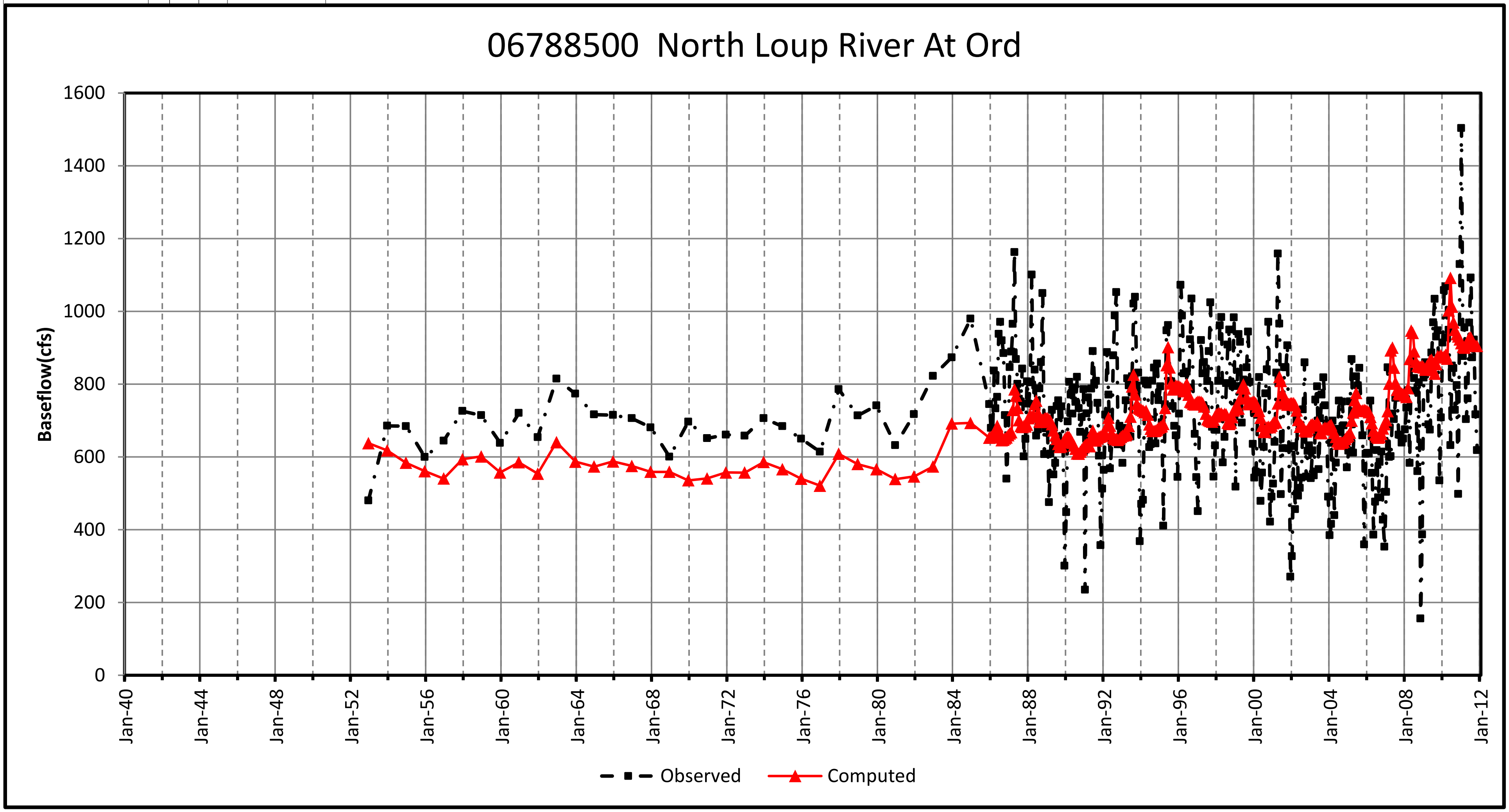


06787000 Calamus River Near Harrop
Baseflow(cfs)
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

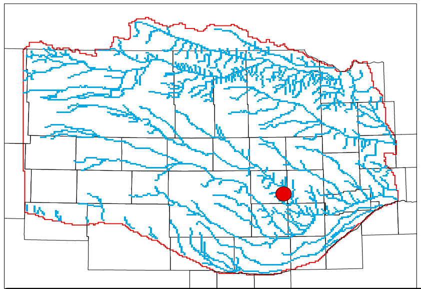


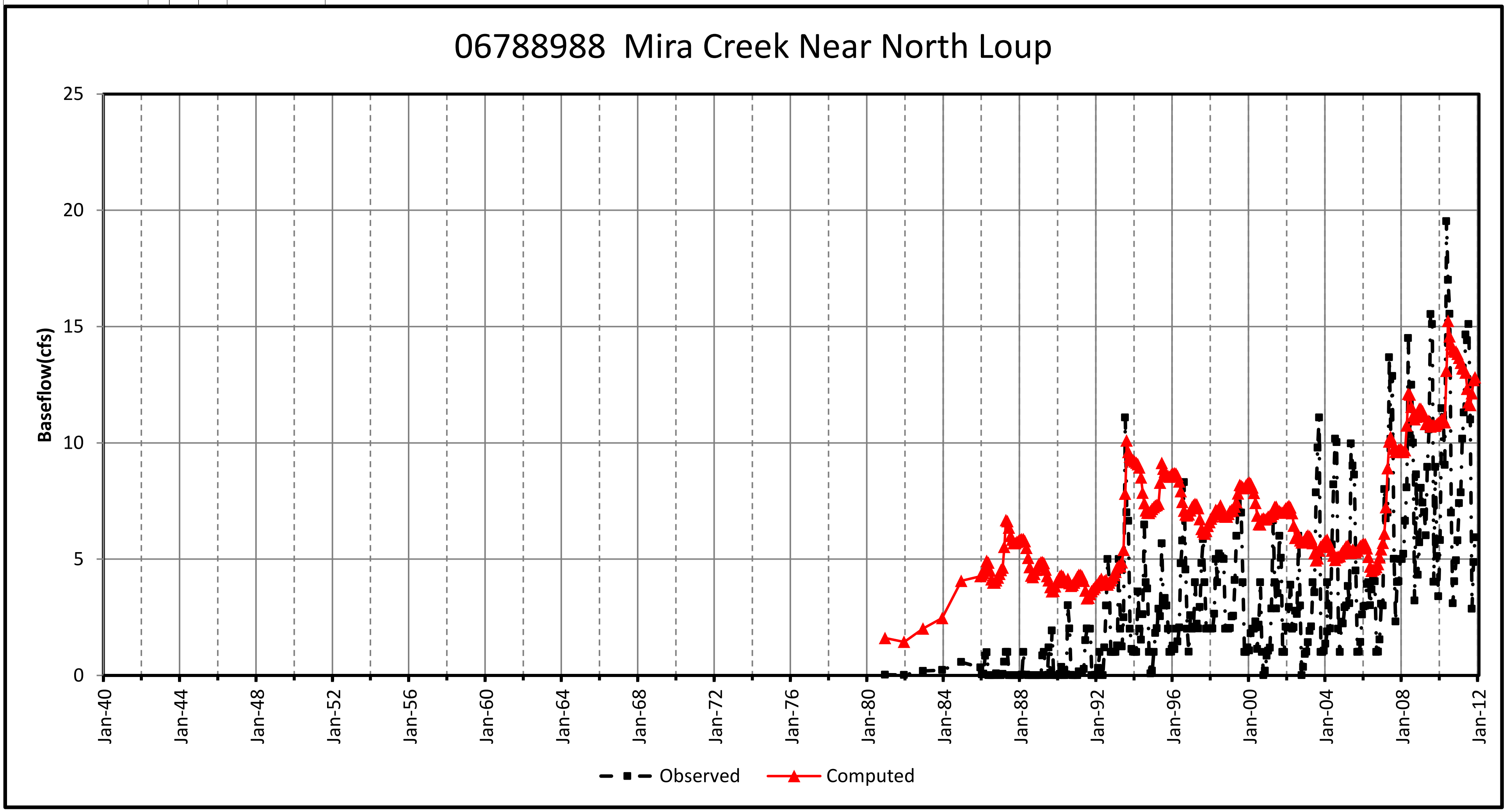

06787500 Calamus River Near Burwell
Baseflow(cfs)
0
50
100
150
200
250
300
350
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



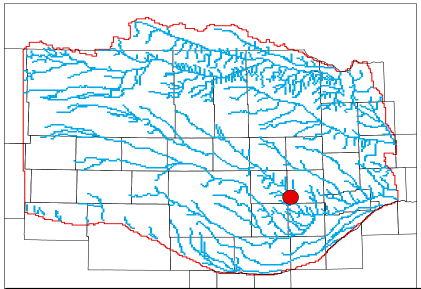


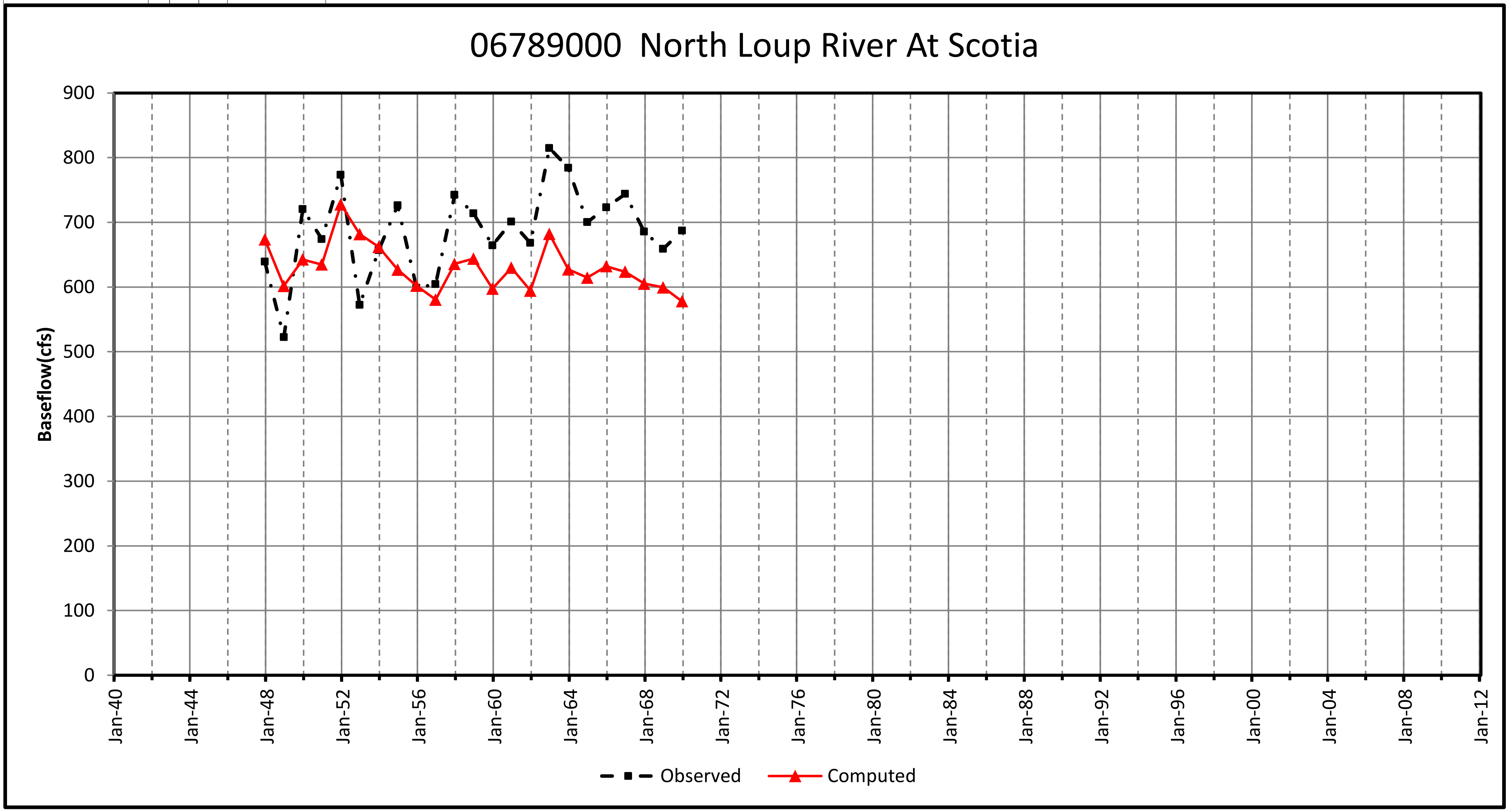
06788500 North Loup River At Ord
Baseflow(cfs)
1600
1400
1200
1000
800
600
400
200
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



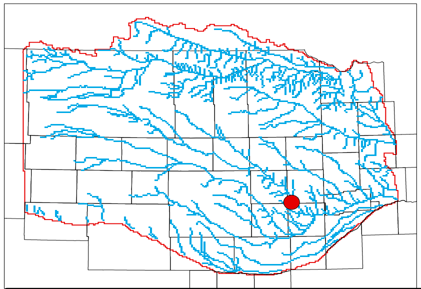


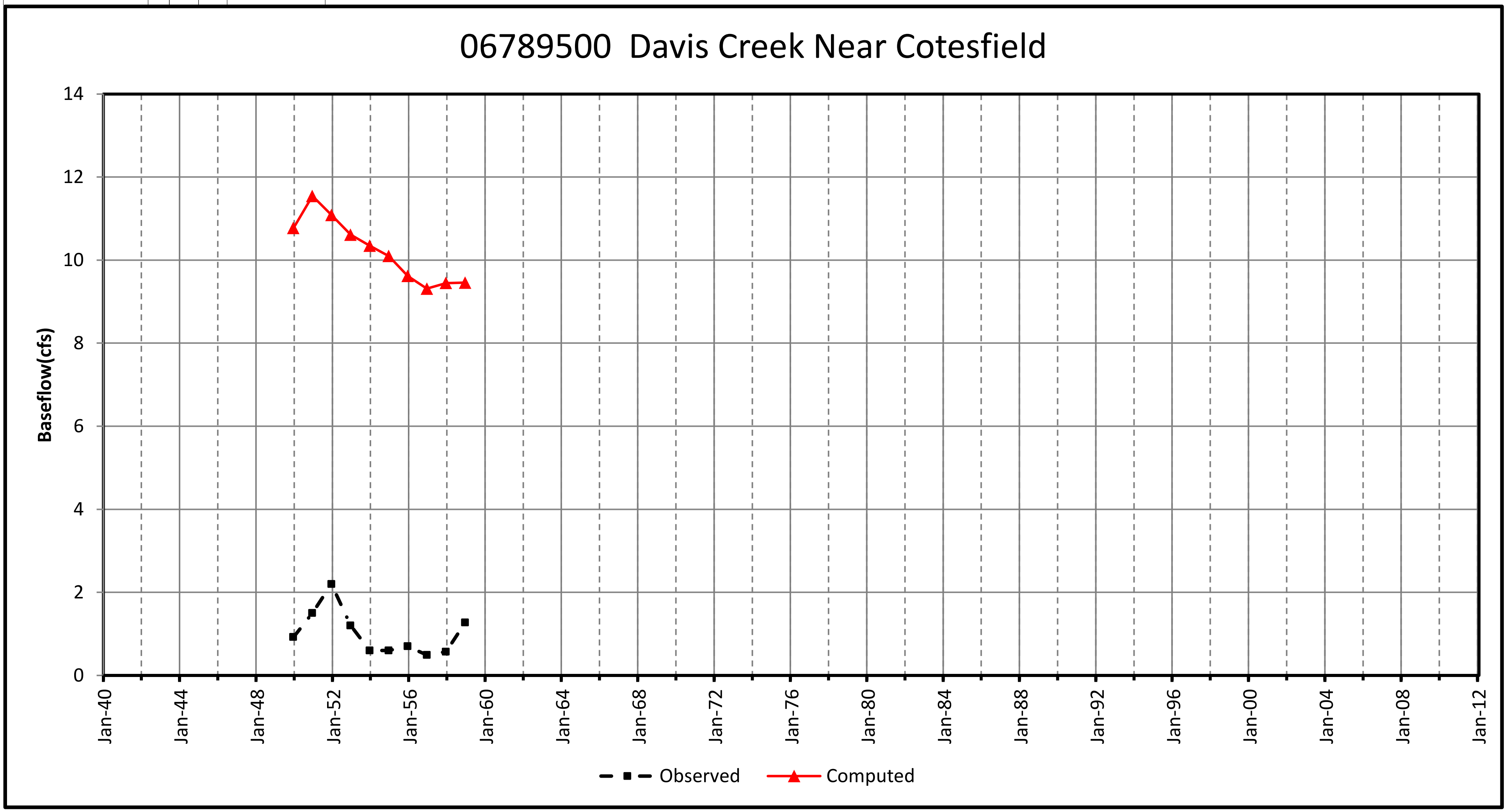
06788988 Mira Creek Near North Loup
Baseflow(cfs)
0
5
10
15
20
25
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



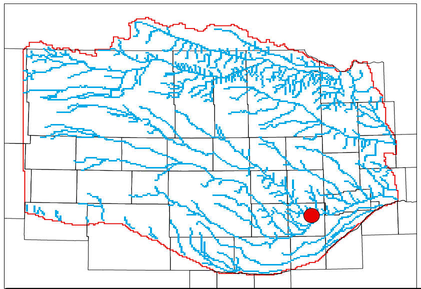


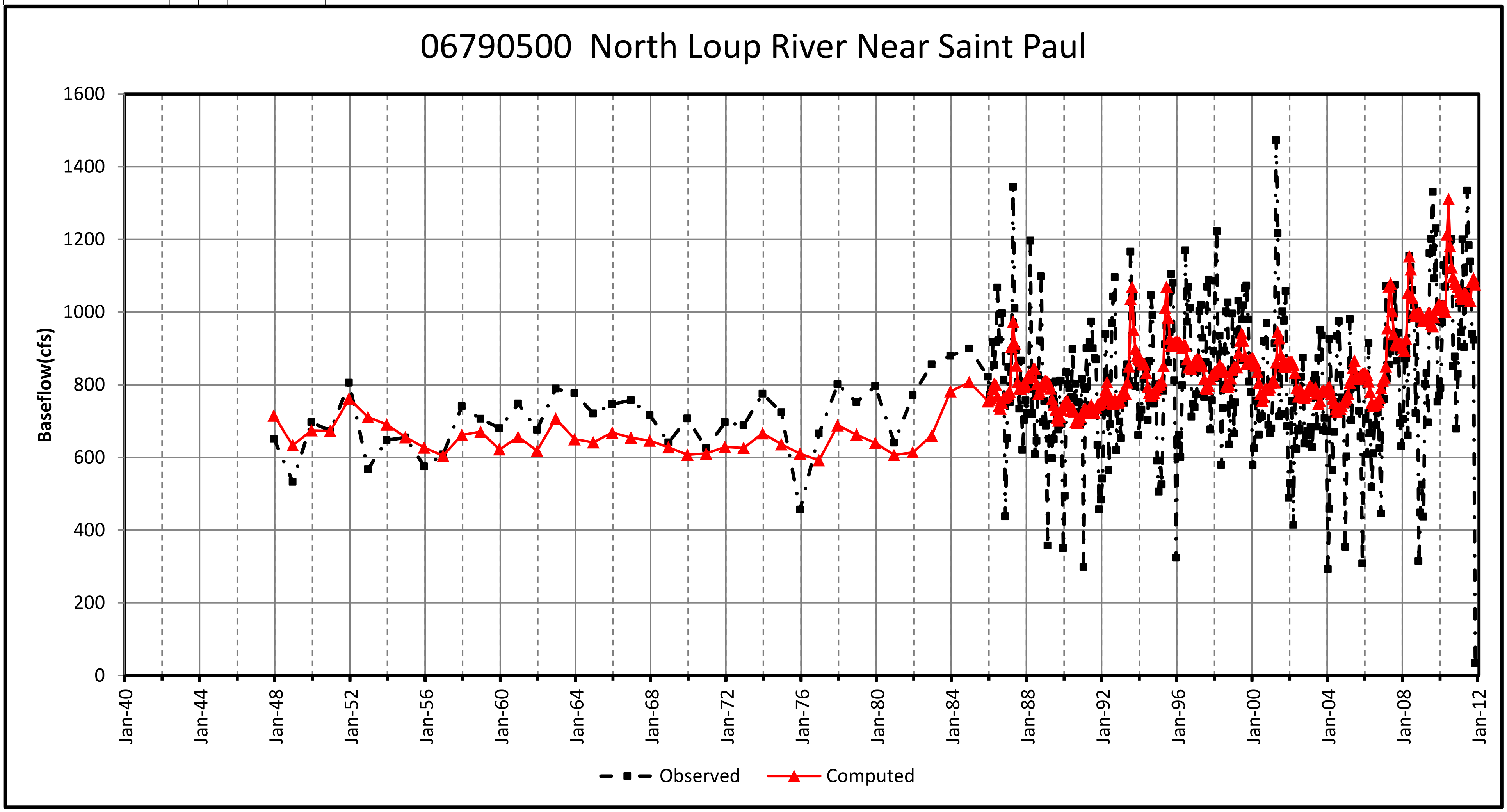
06789000 North Loup River At Scotia
Baseflow(cfs)
0
100
200
300
400
500
600
700
800
900
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



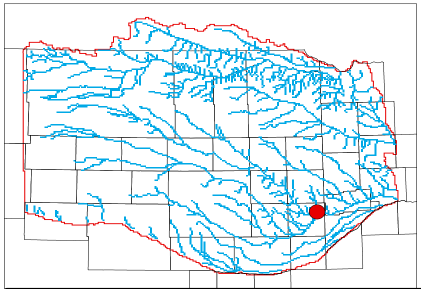


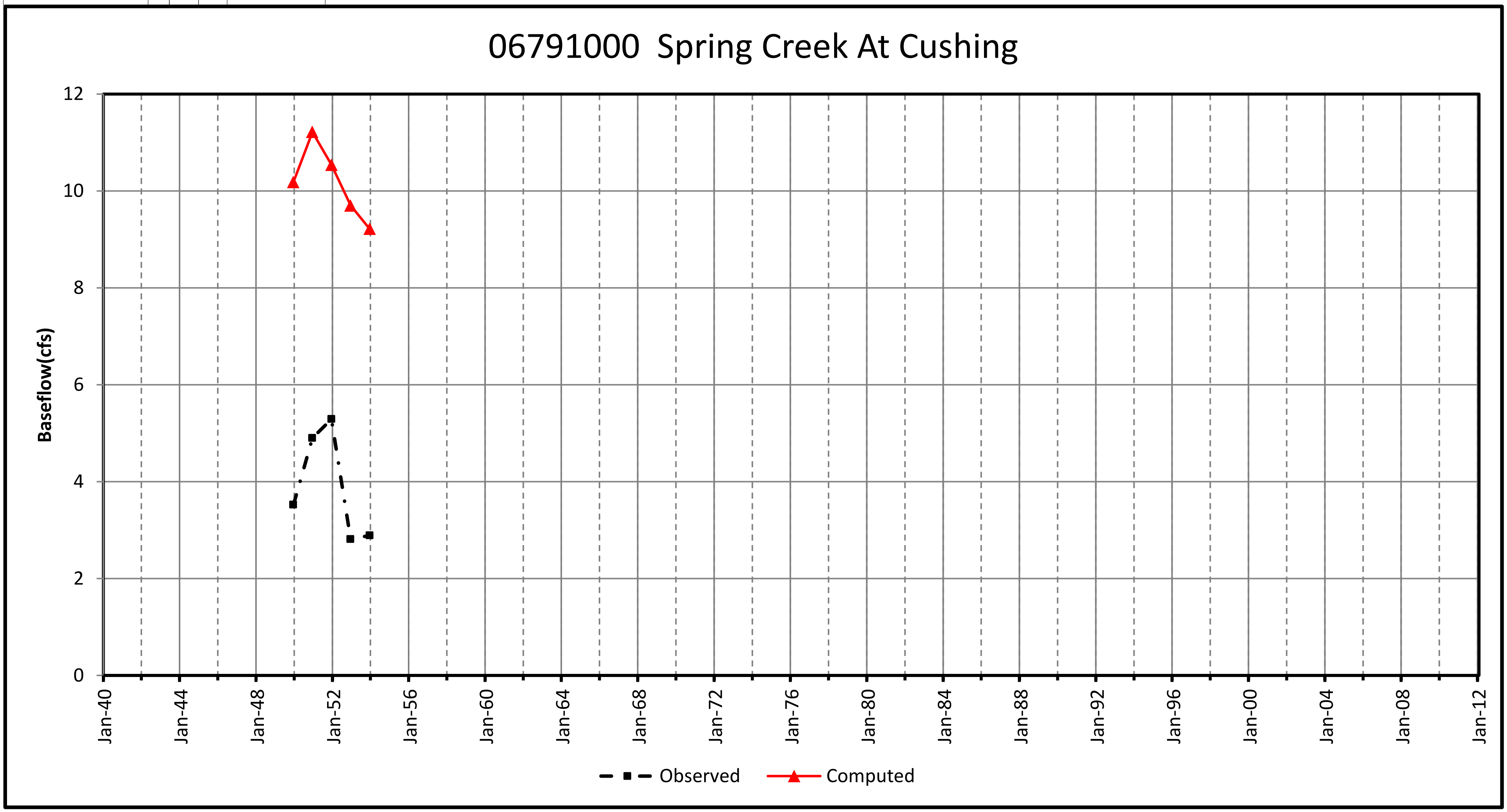
06789500 Davis Creek Near Cotesfield
Baseflow(cfs)
0
2
4
6
8
10
12
14
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



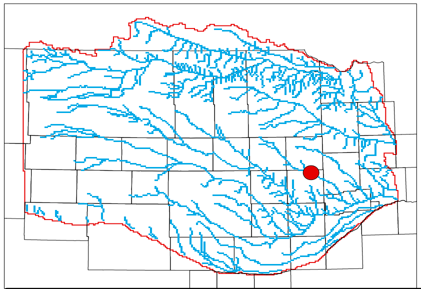


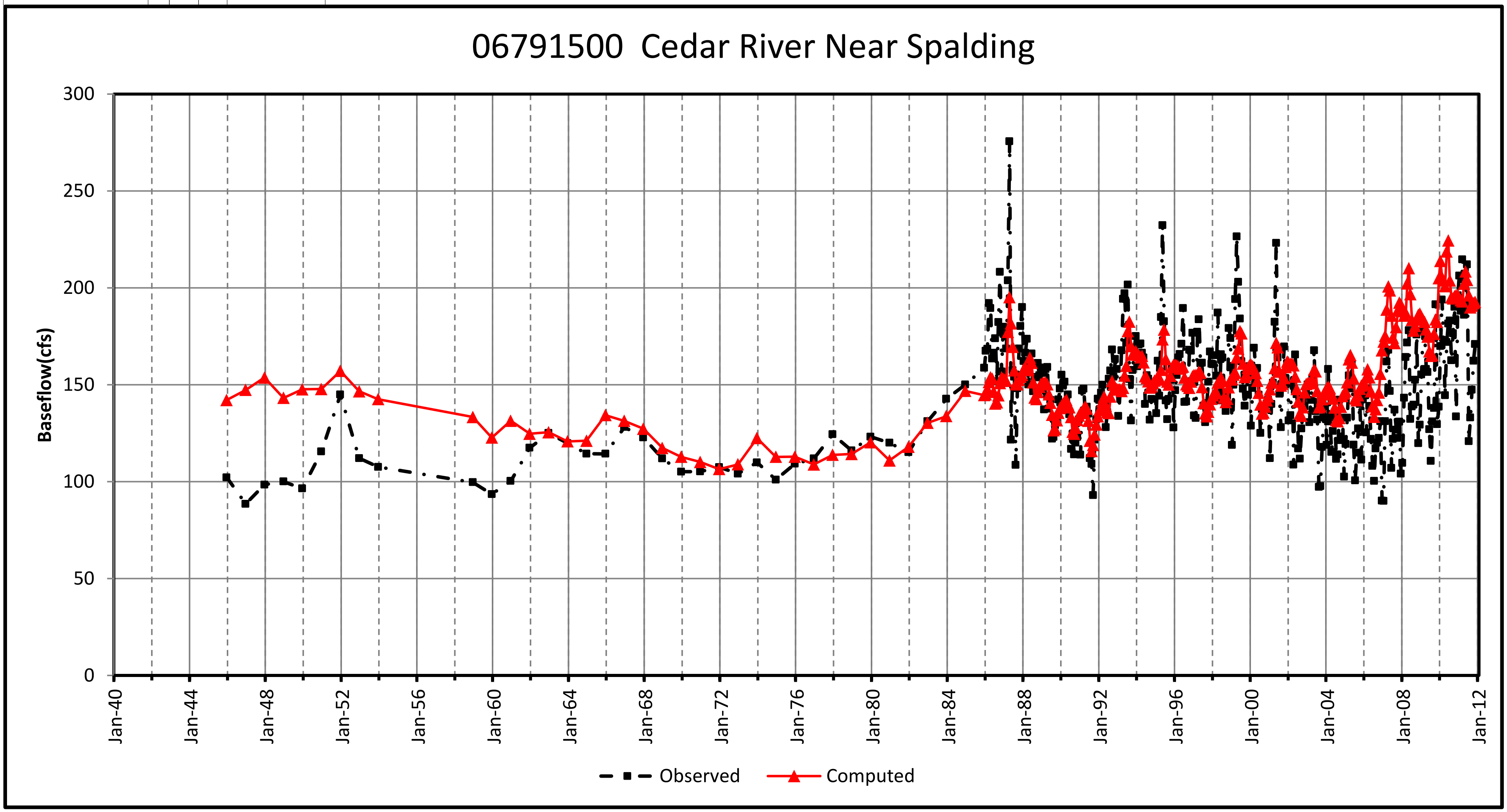
06790500 North Loup River Near Saint Paul
Baseflow(cfs)
0
200
400
600
800
1000
1200
1400
1600
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



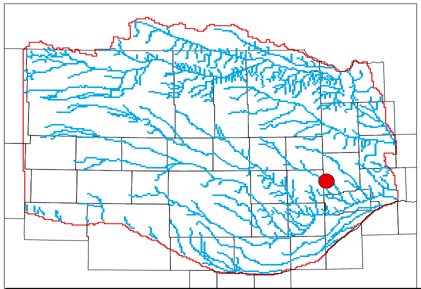


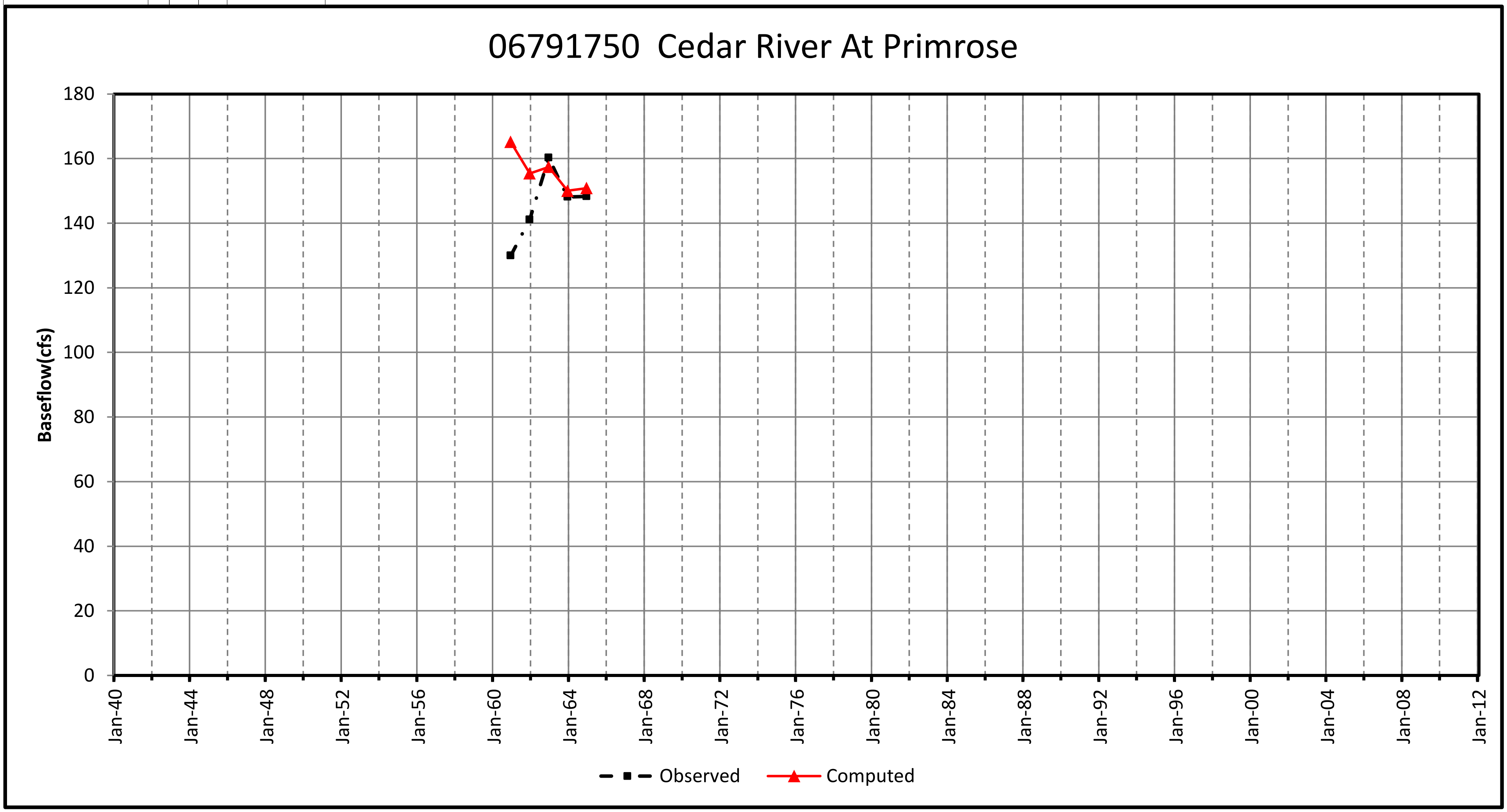
06791000 Spring Creek At Cushing
Baseflow(cfs)
0
2
4
6
8
10
12
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

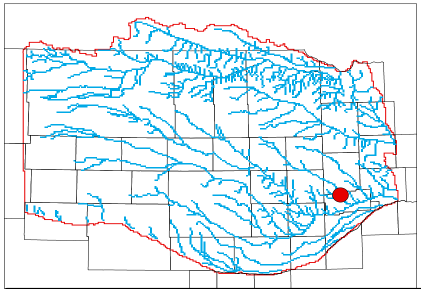


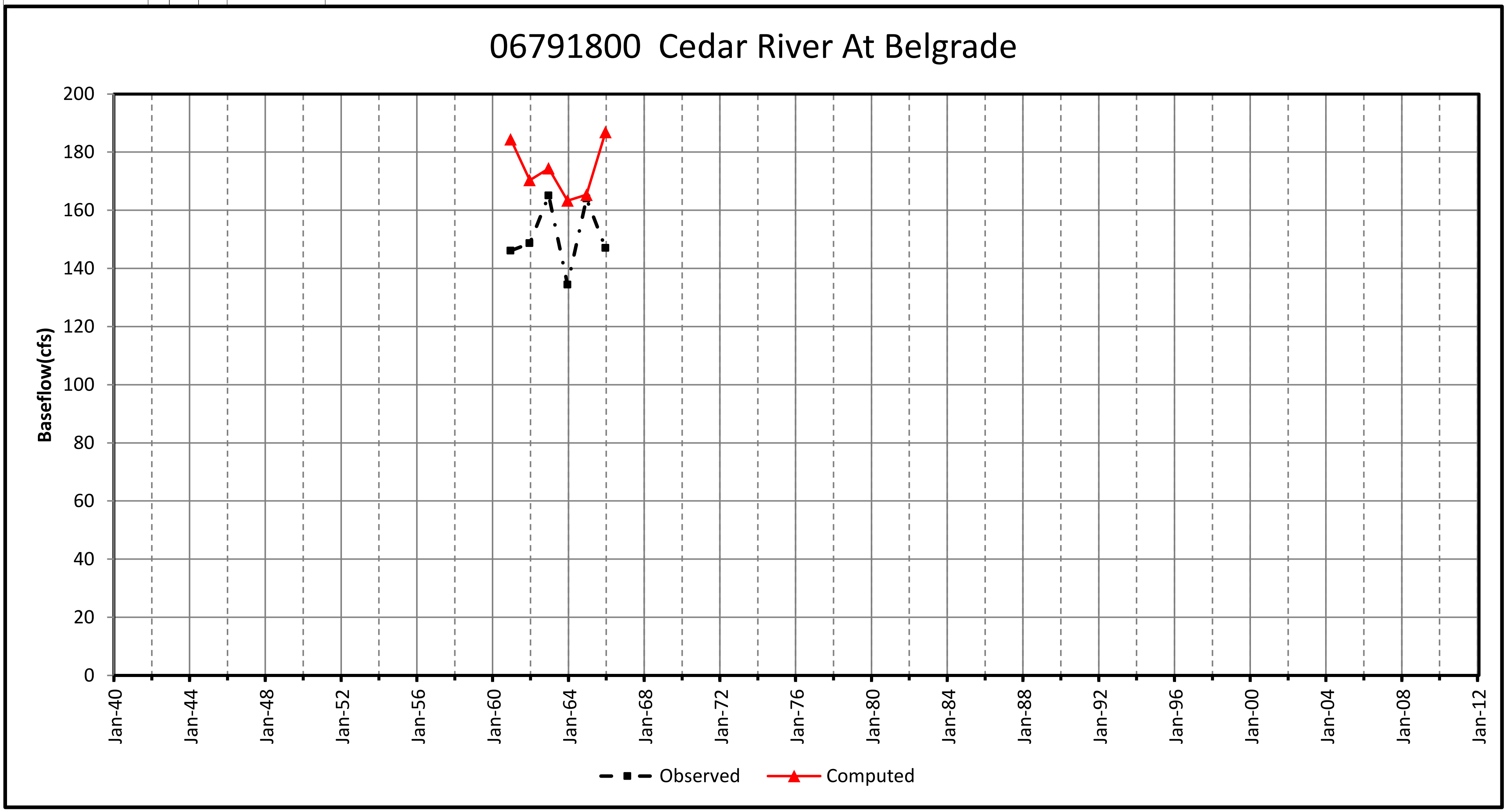


06791500 Cedar River Near Spalding
Baseflow(cfs)
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

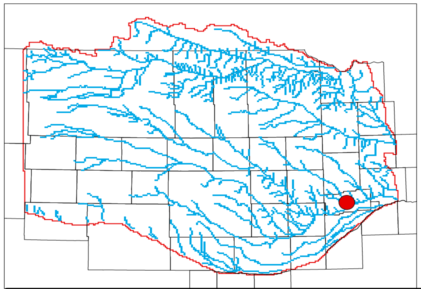


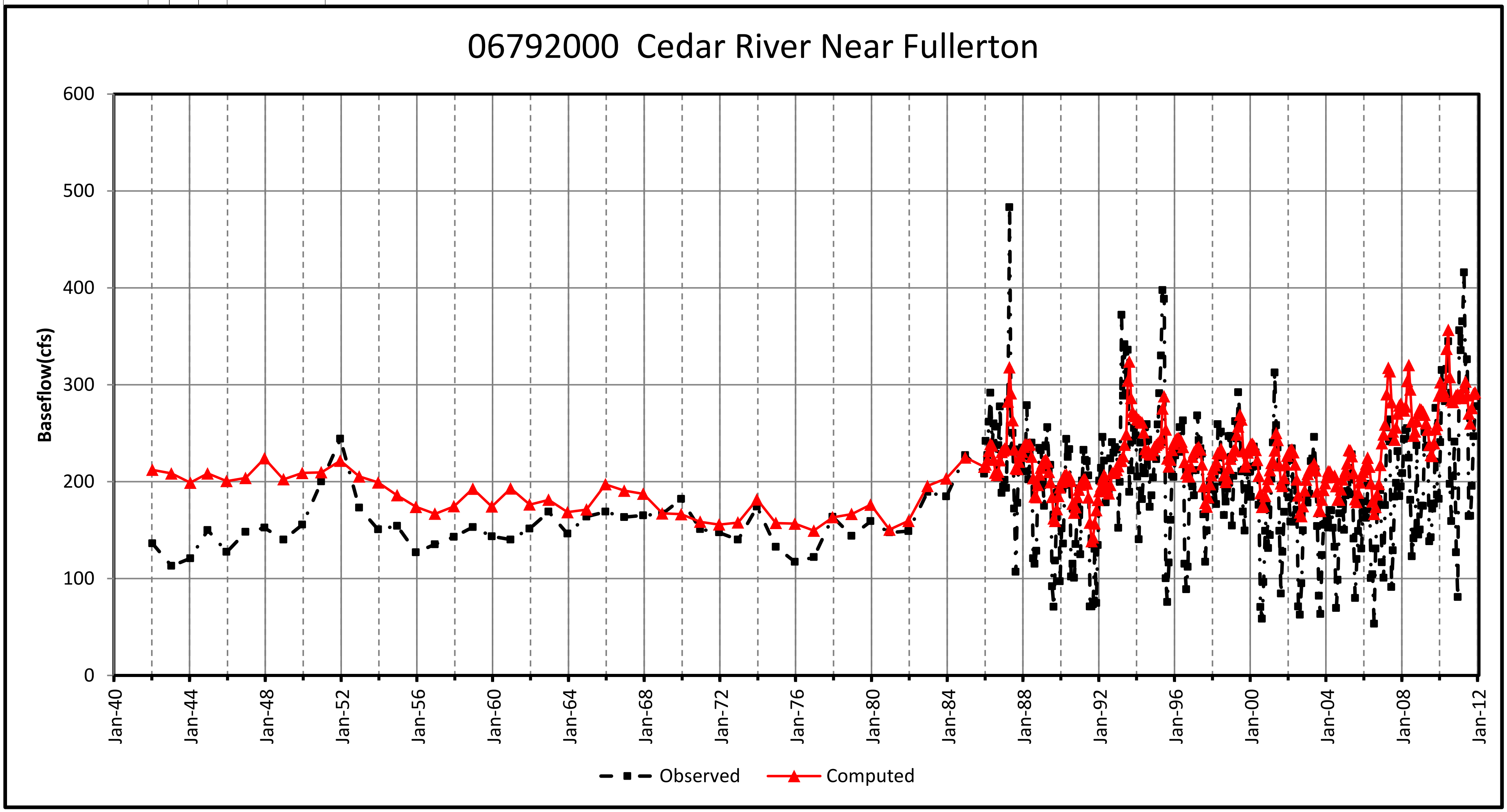

06791750 Cedar River At Primrose
Baseflow(cfs)
0
20
40
60
80
100
120
140
160
180
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

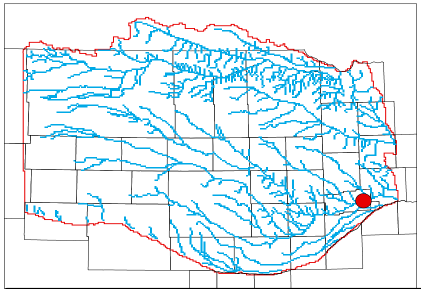


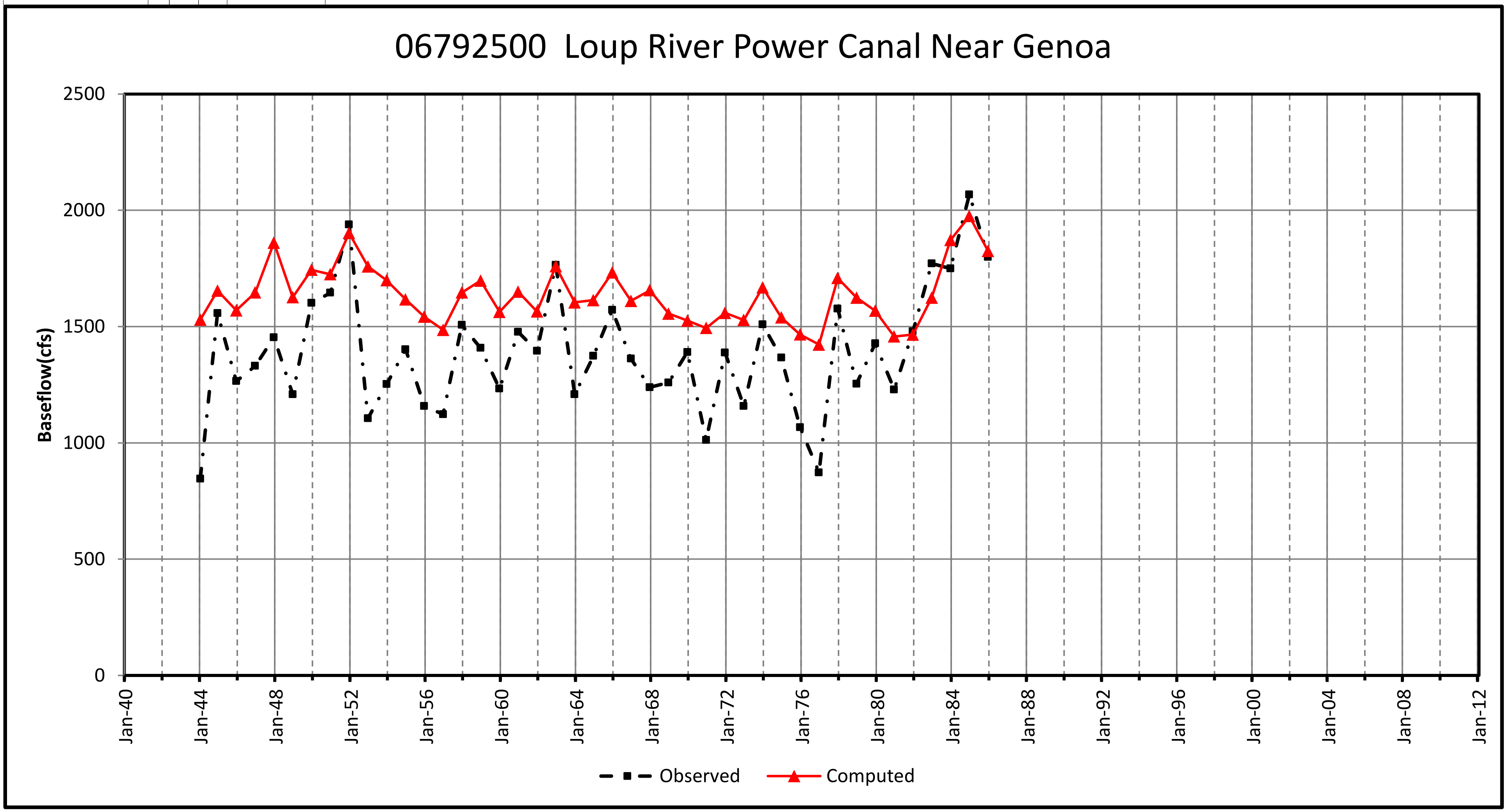


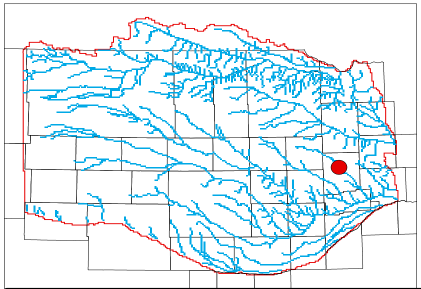
06791800 Cedar River At Belgrade
Baseflow(cfs)
0
20
40
60
80
100
120
140
160
180
200
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

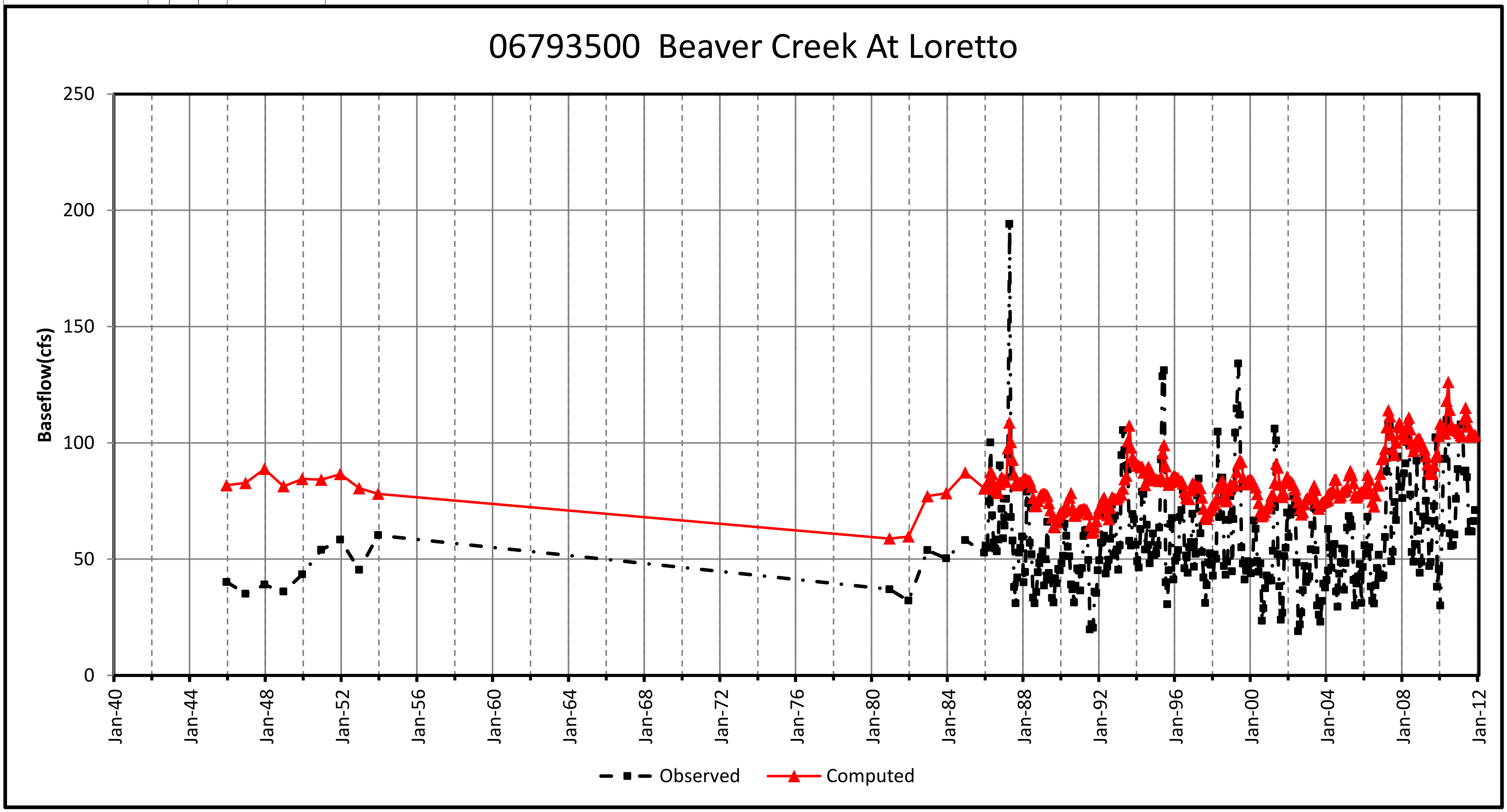



06792000 Cedar River Near Fullerton
Baseflow(cfs)
600
500
400
300
200
100
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

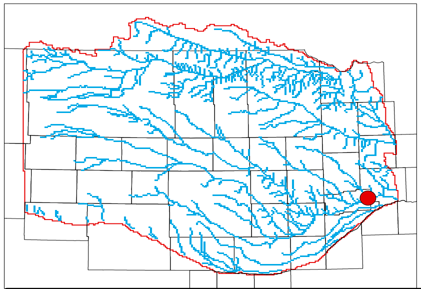


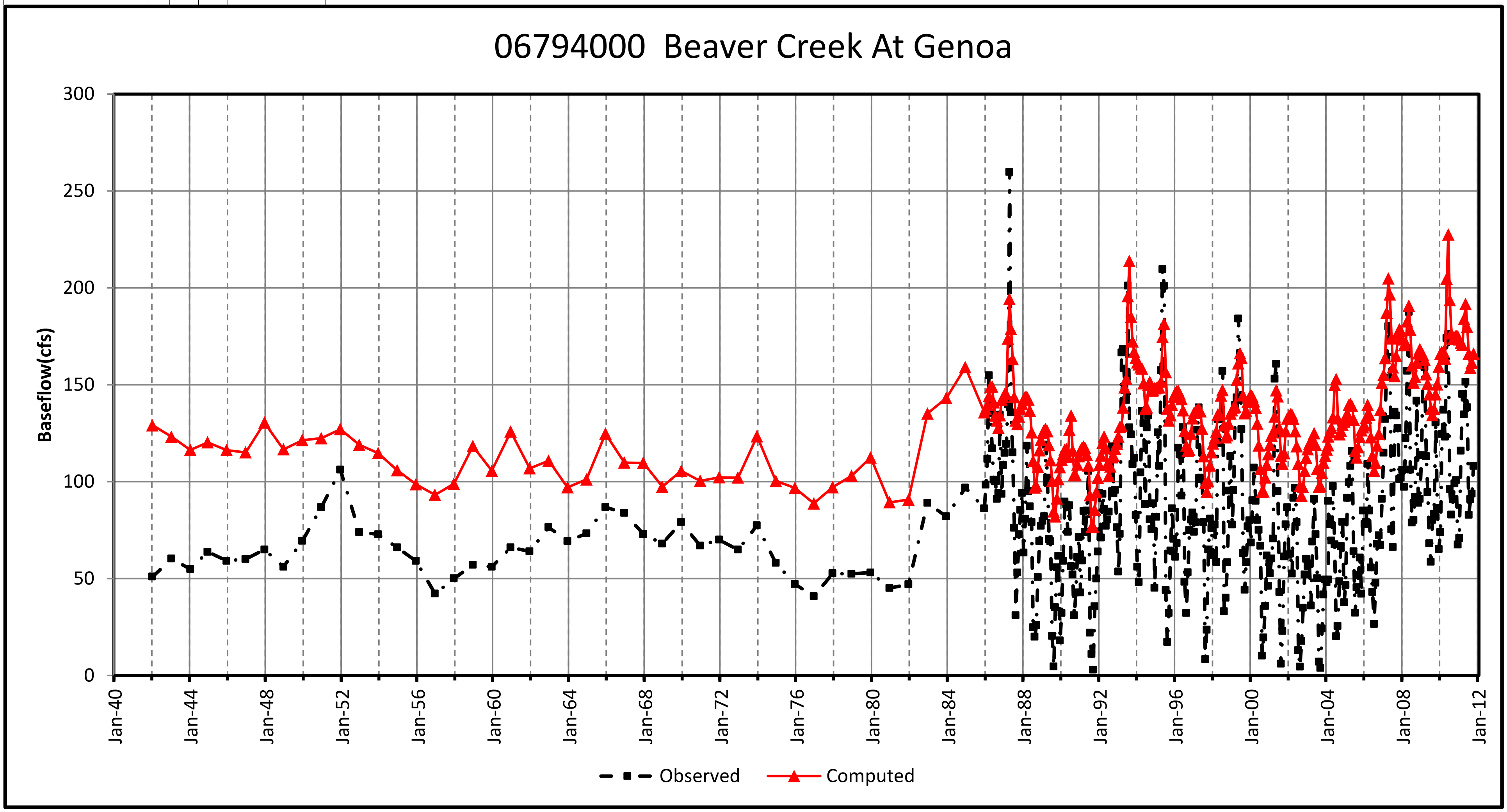

06792500 Loup River Power Canal Near Genoa
Baseflow(cfs)
2500
2000
1500
1000
500
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



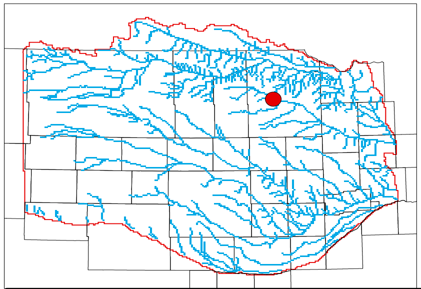


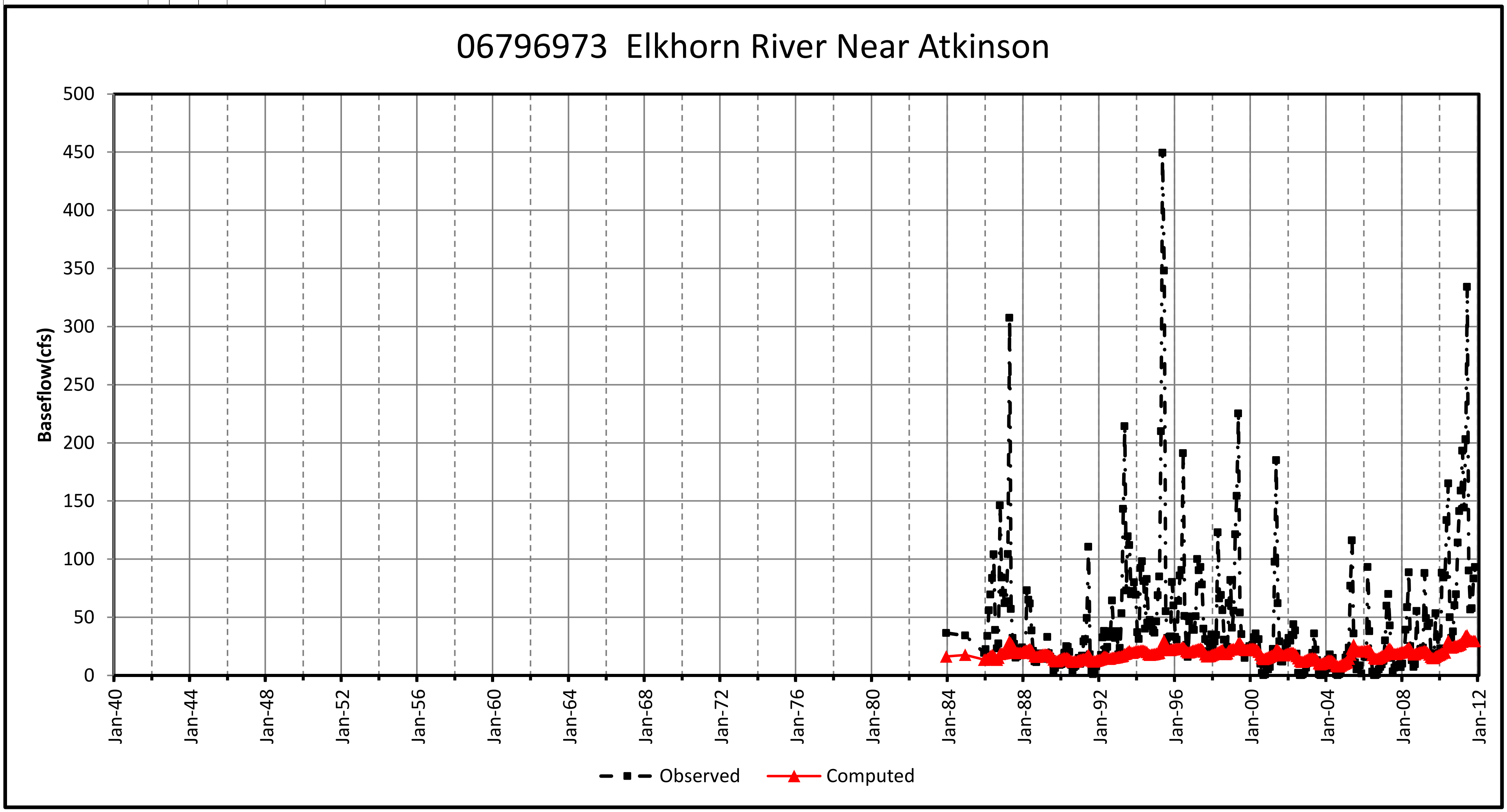
06793500 Beaver Creek At Loretto
Baseflow(cfs)
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



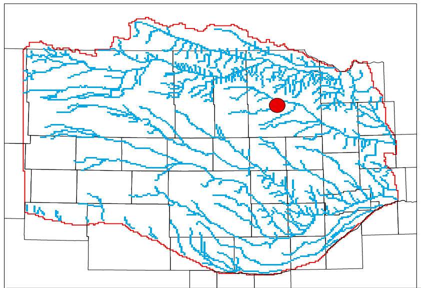


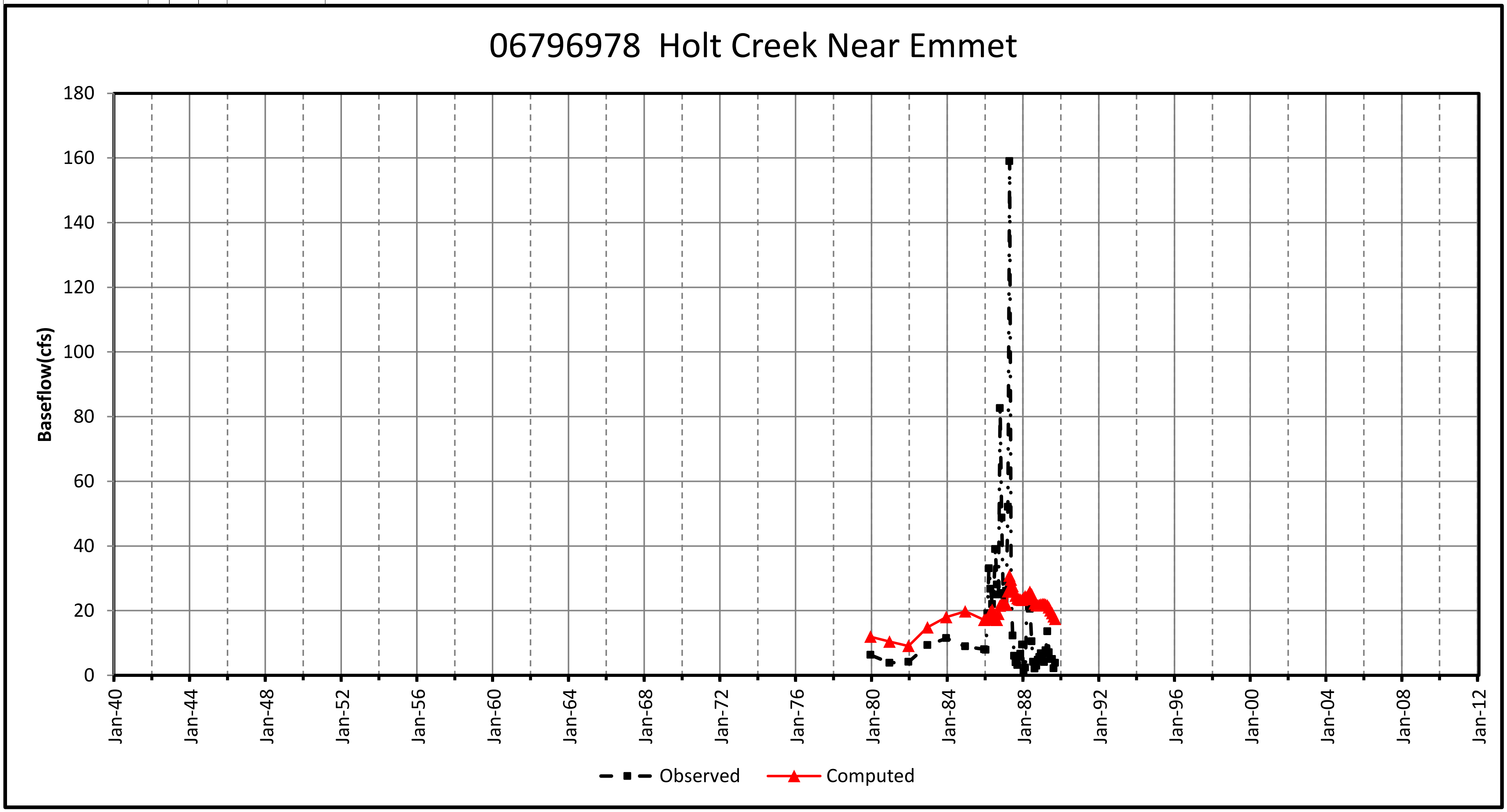
06794000 Beaver Creek At Genoa
Baseflow(cfs)
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



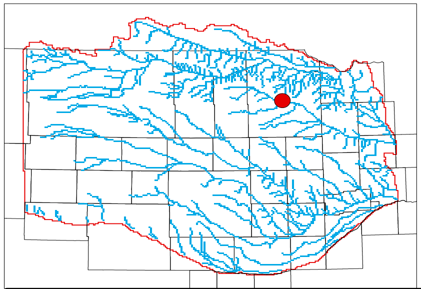


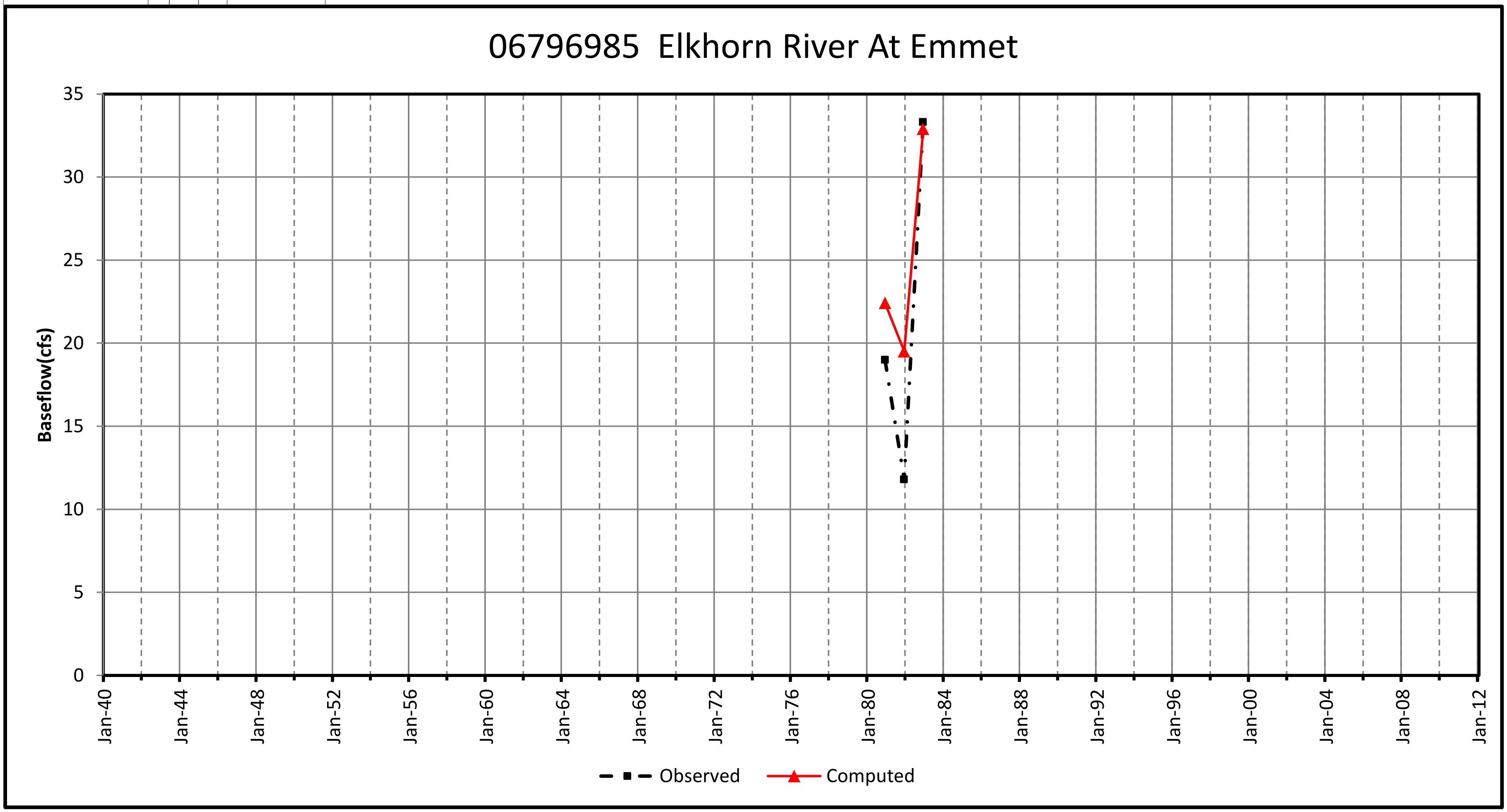
06796973 Elkhorn River Near Atkinson
Baseflow(cfs)
500
450
400
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



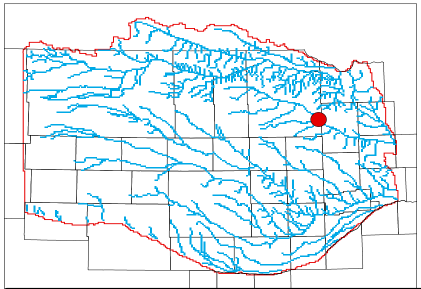


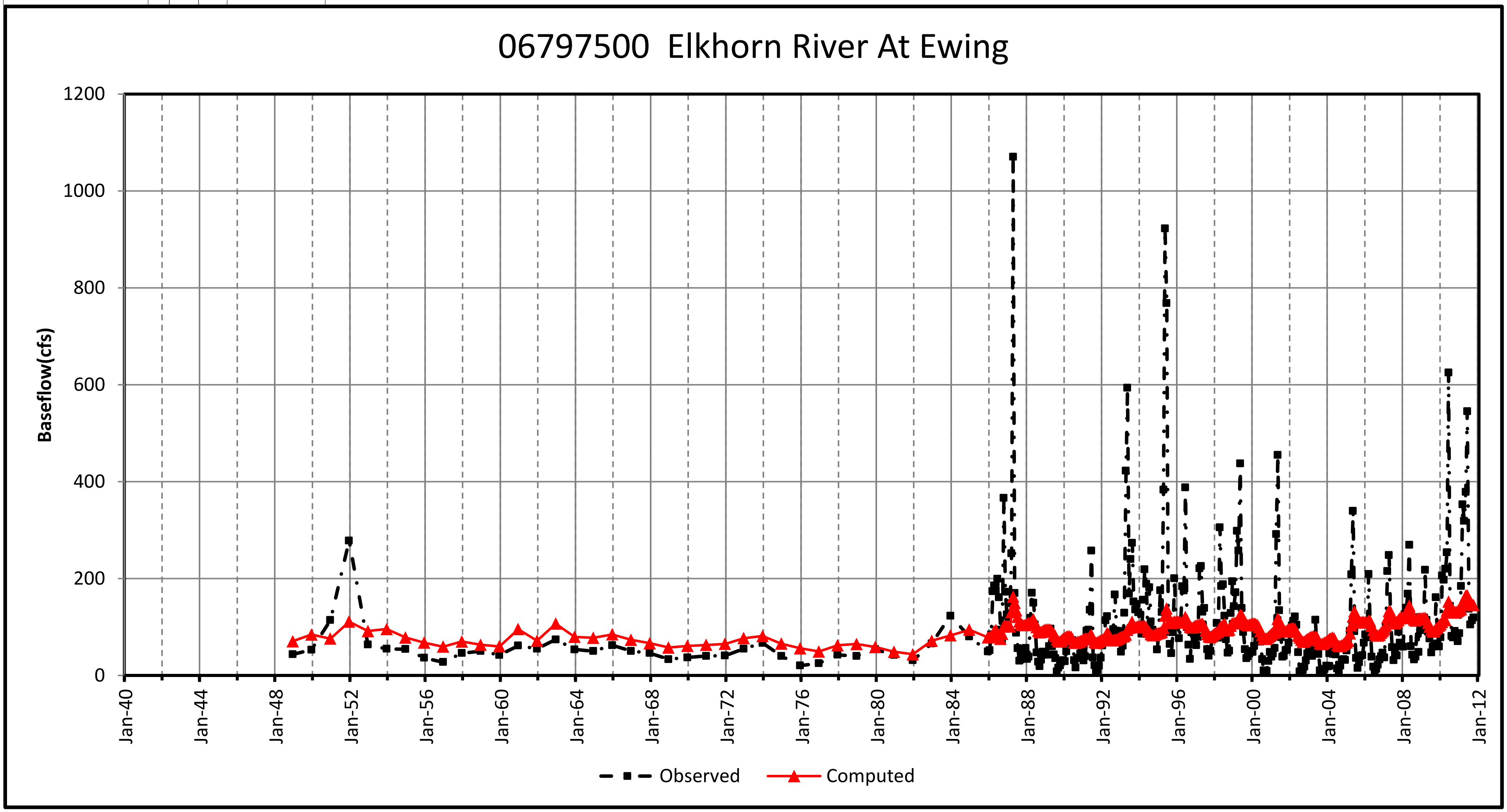
06796978 Holt Creek Near Emmet
Baseflow(cfs)
180
160
140
120
100
80
60
40
20
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



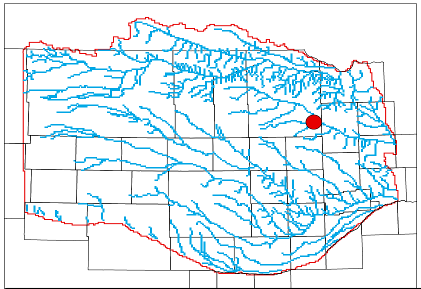


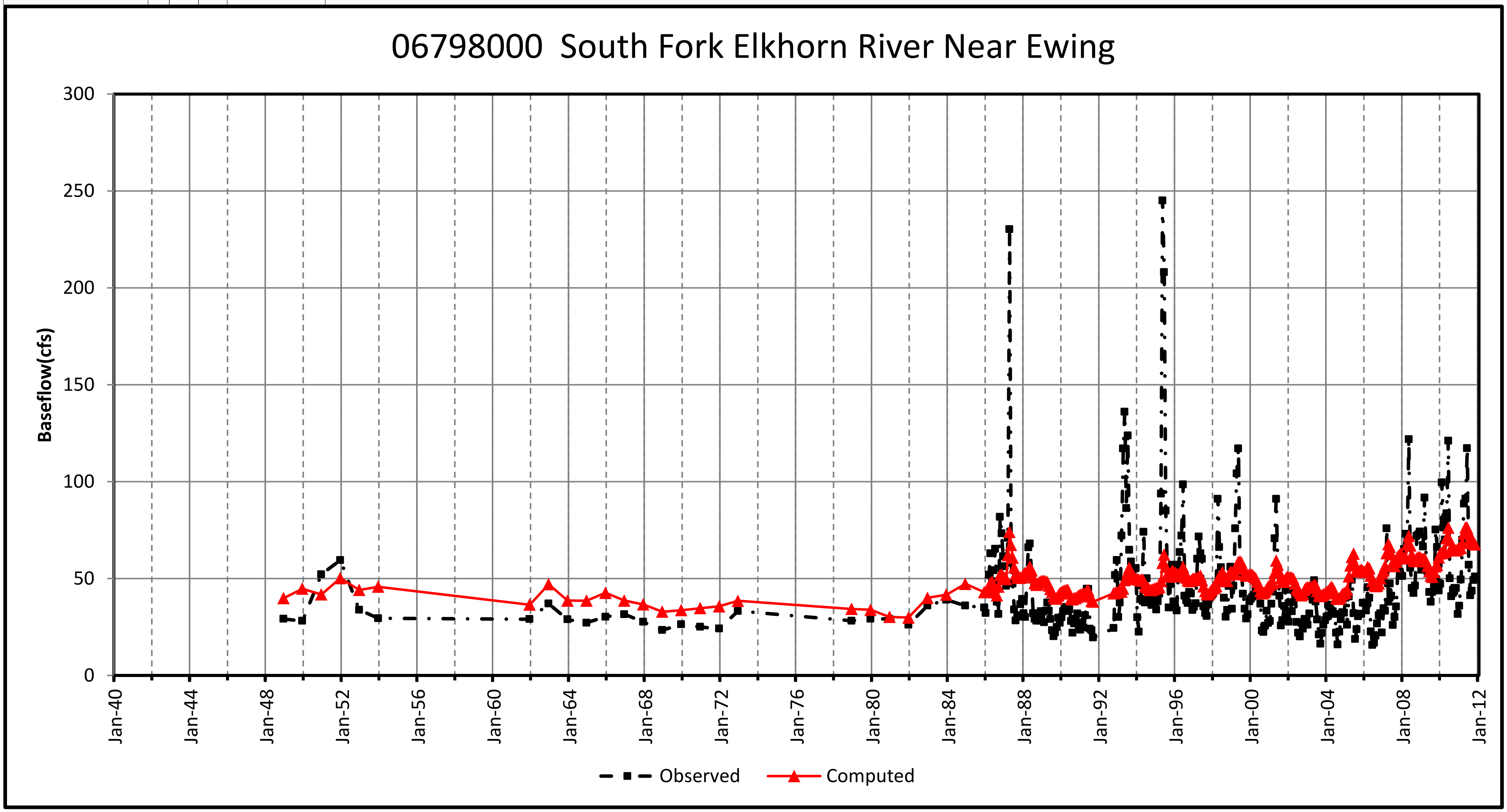
06796985 Elkhorn River At Emmet
Baseflow(cfs)
0
5
10
15
20
25
30
35
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



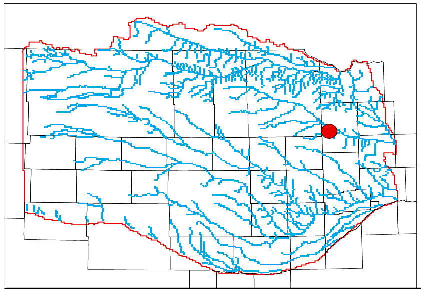


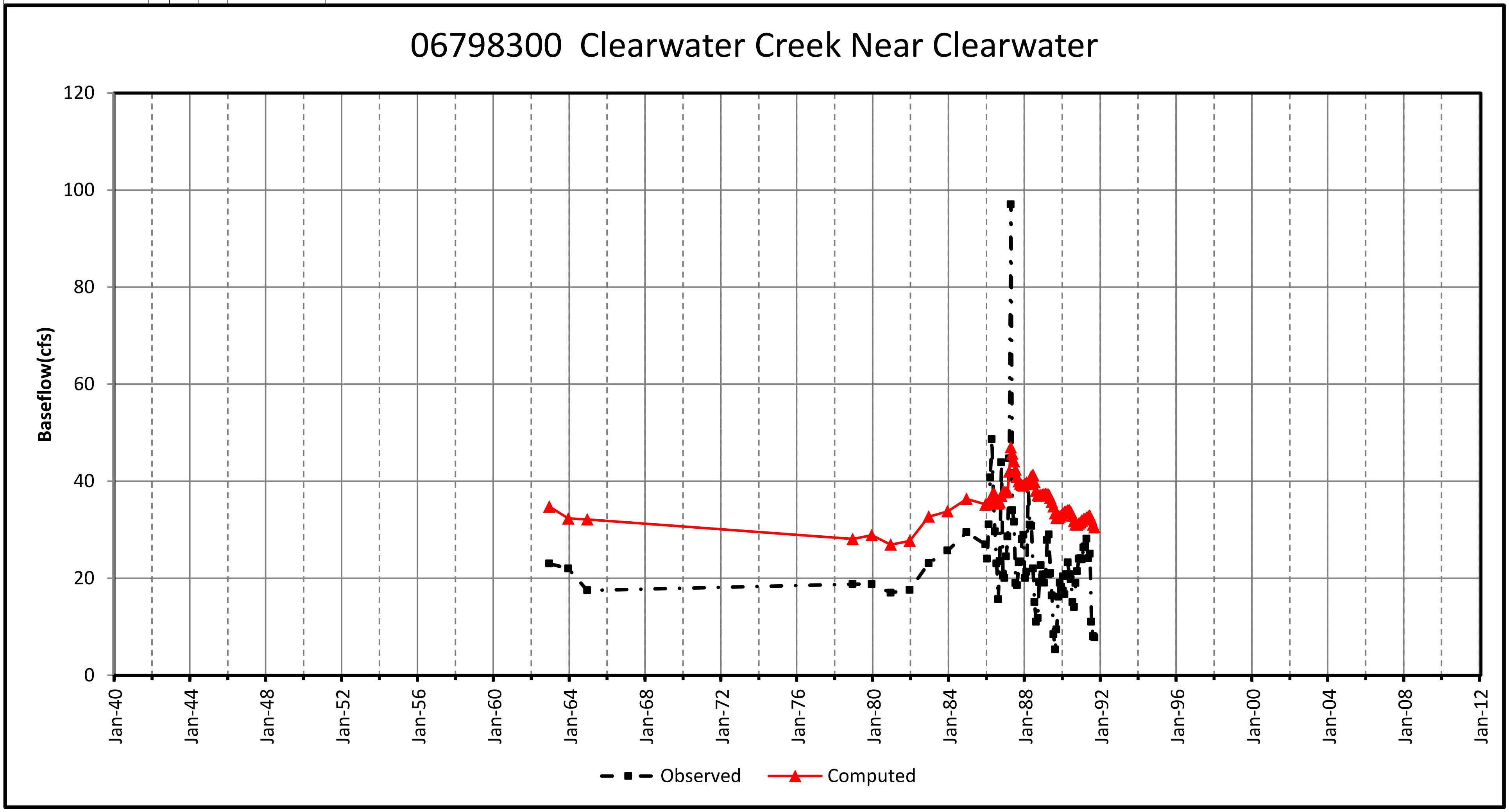
06797500 Elkhorn River At Ewing
Baseflow(cfs)
0
200
400
600
800
1000
1200
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



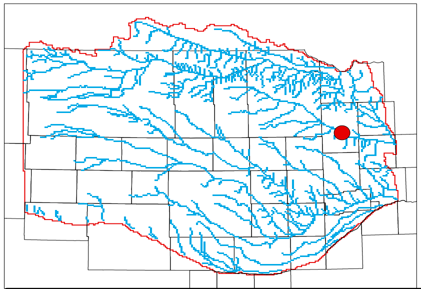


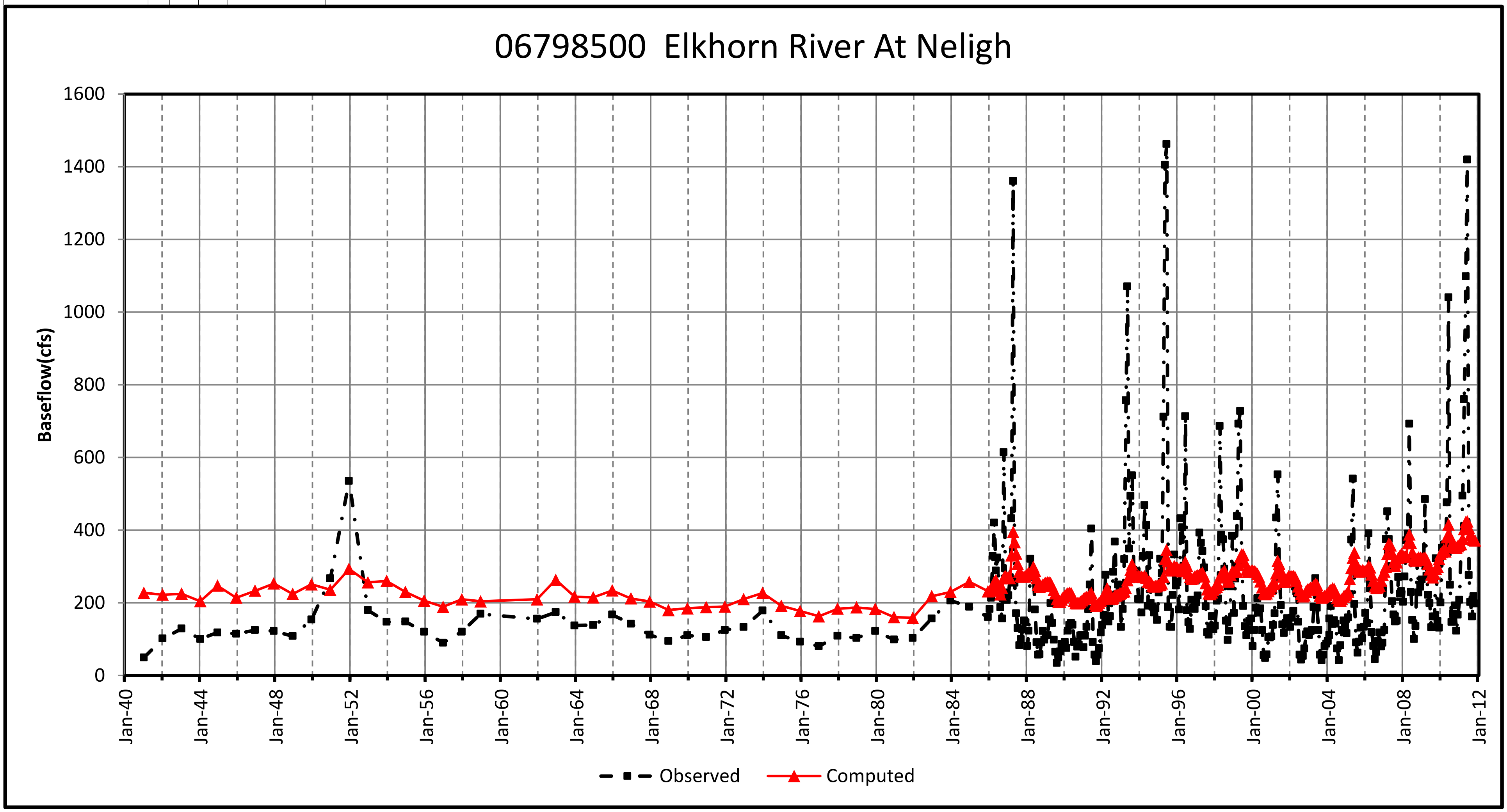
06798000 South Fork Elkhorn River Near Ewing
Baseflow(cfs)
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

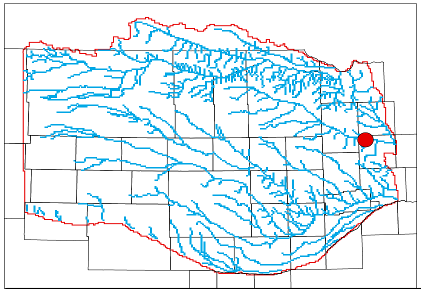


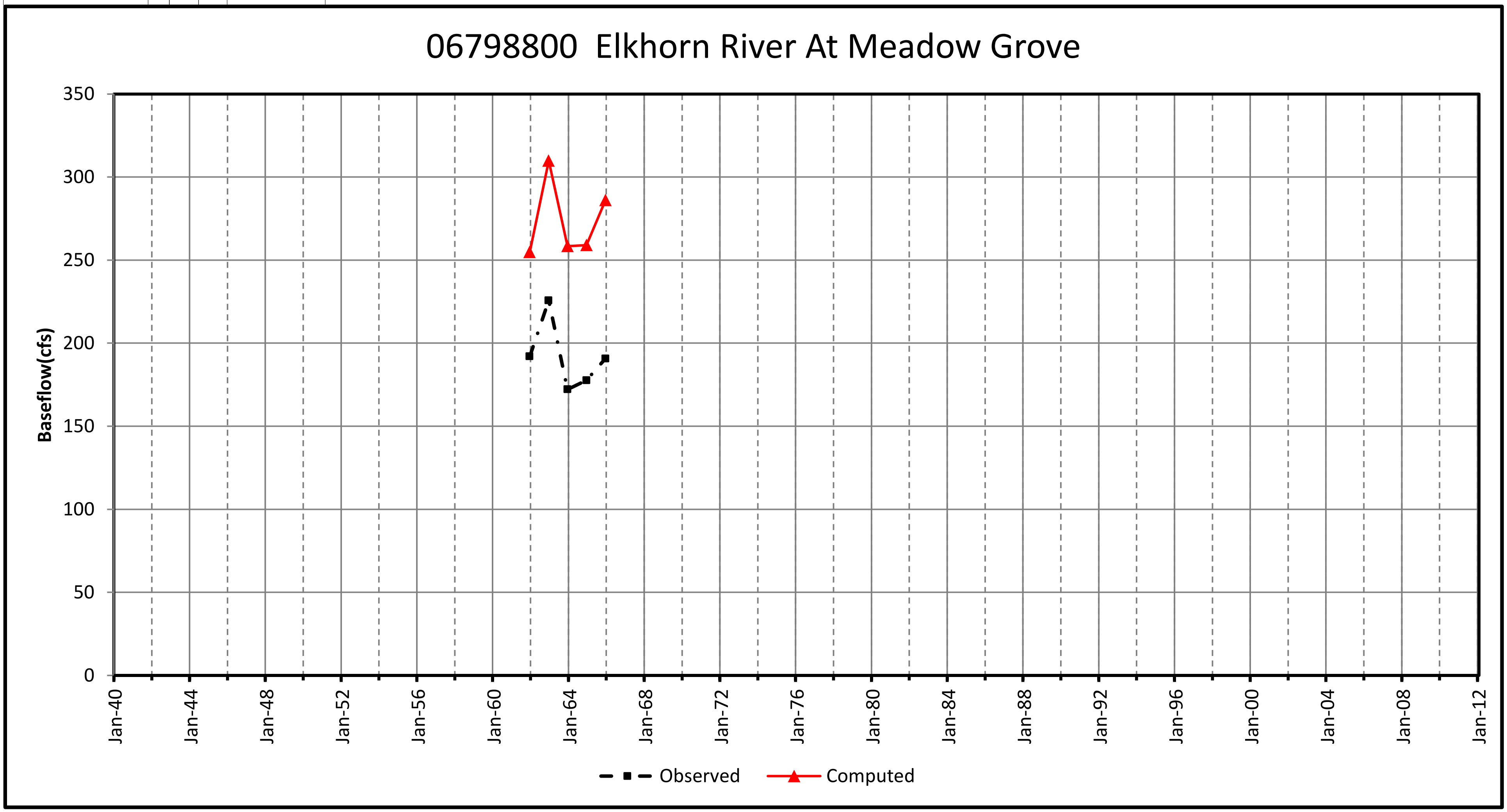


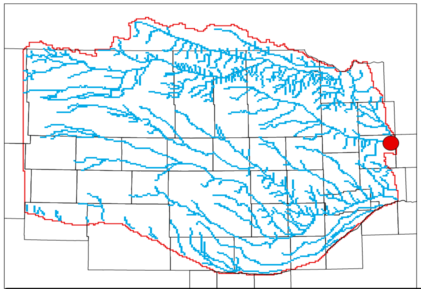
06798300 Clearwater Creek Near Clearwater
Baseflow(cfs)
120
100
80
60
40
20
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

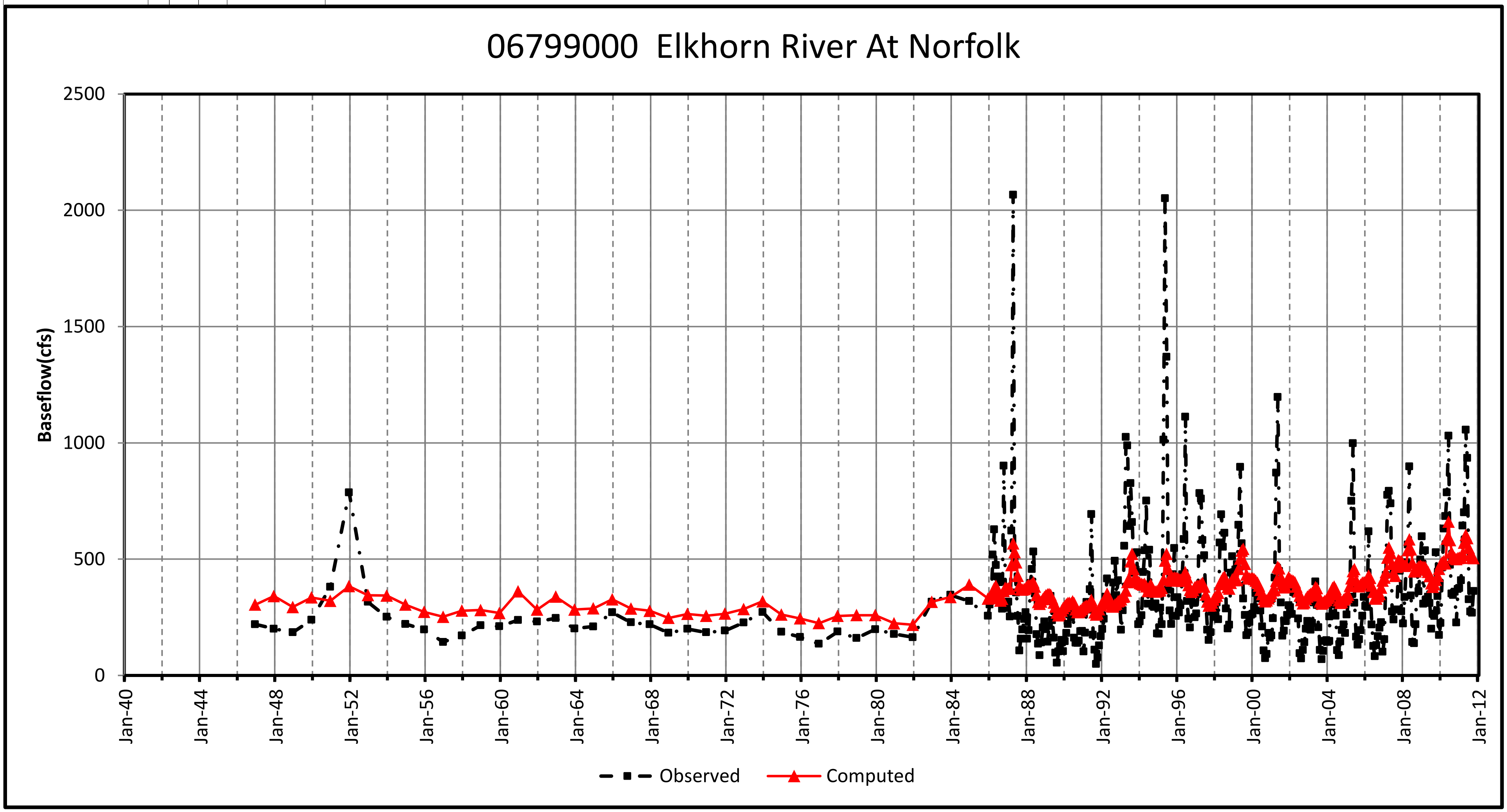



06798500 Elkhorn River At Neligh
Baseflow(cfs)
0
200
400
600
800
1000
1200
1400
1600
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

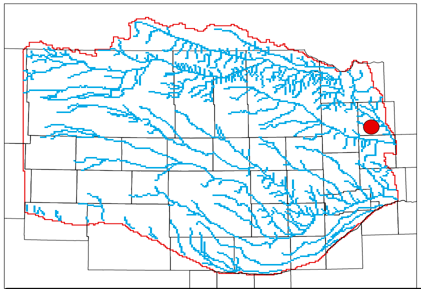


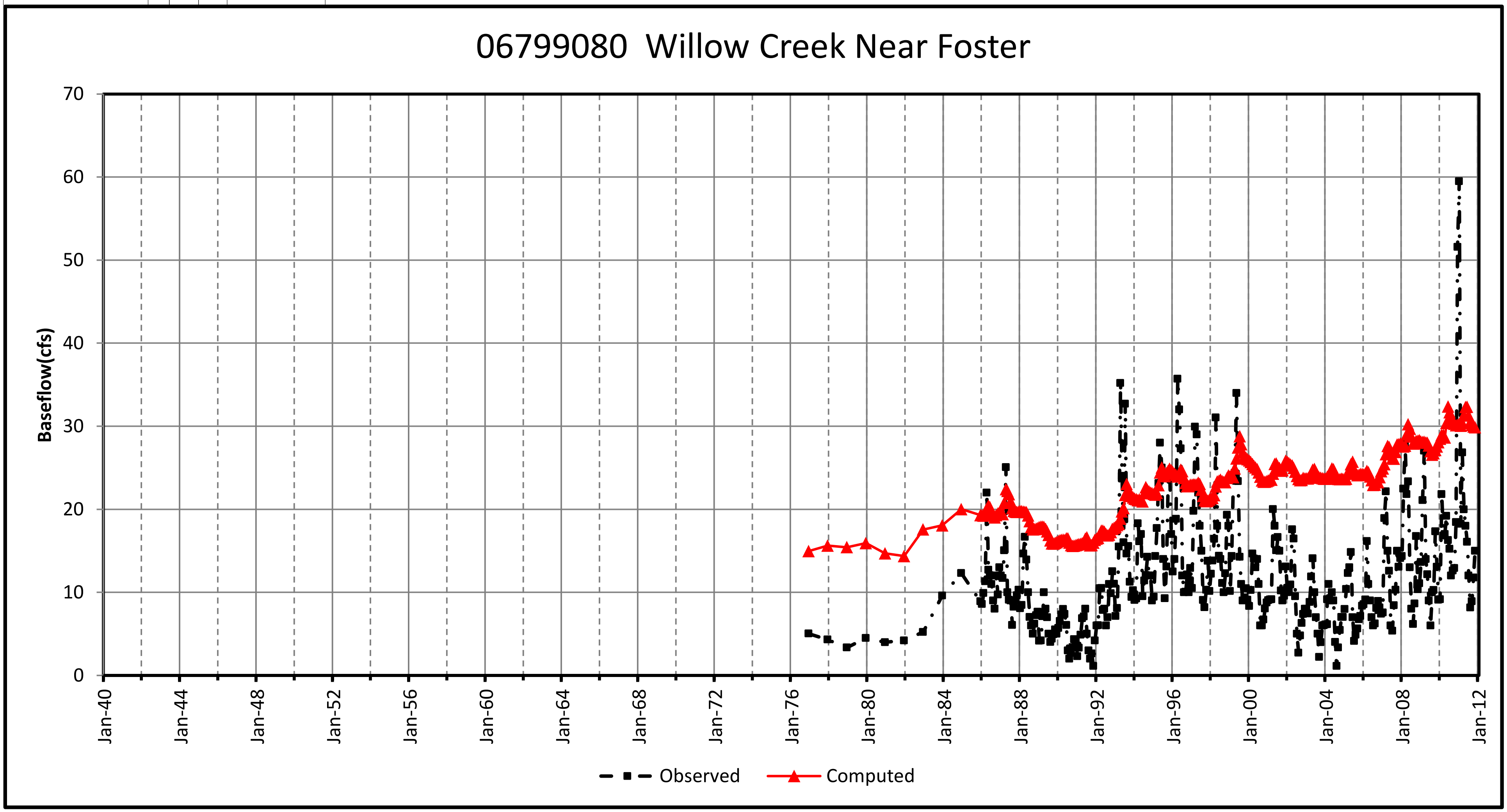

06798800 Elkhorn River At Meadow Grove
Baseflow(cfs)
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed



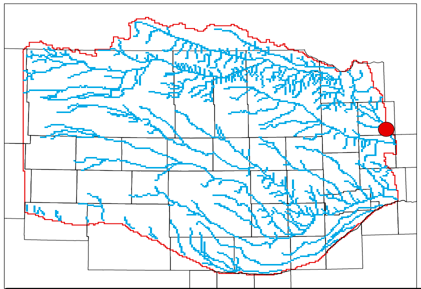


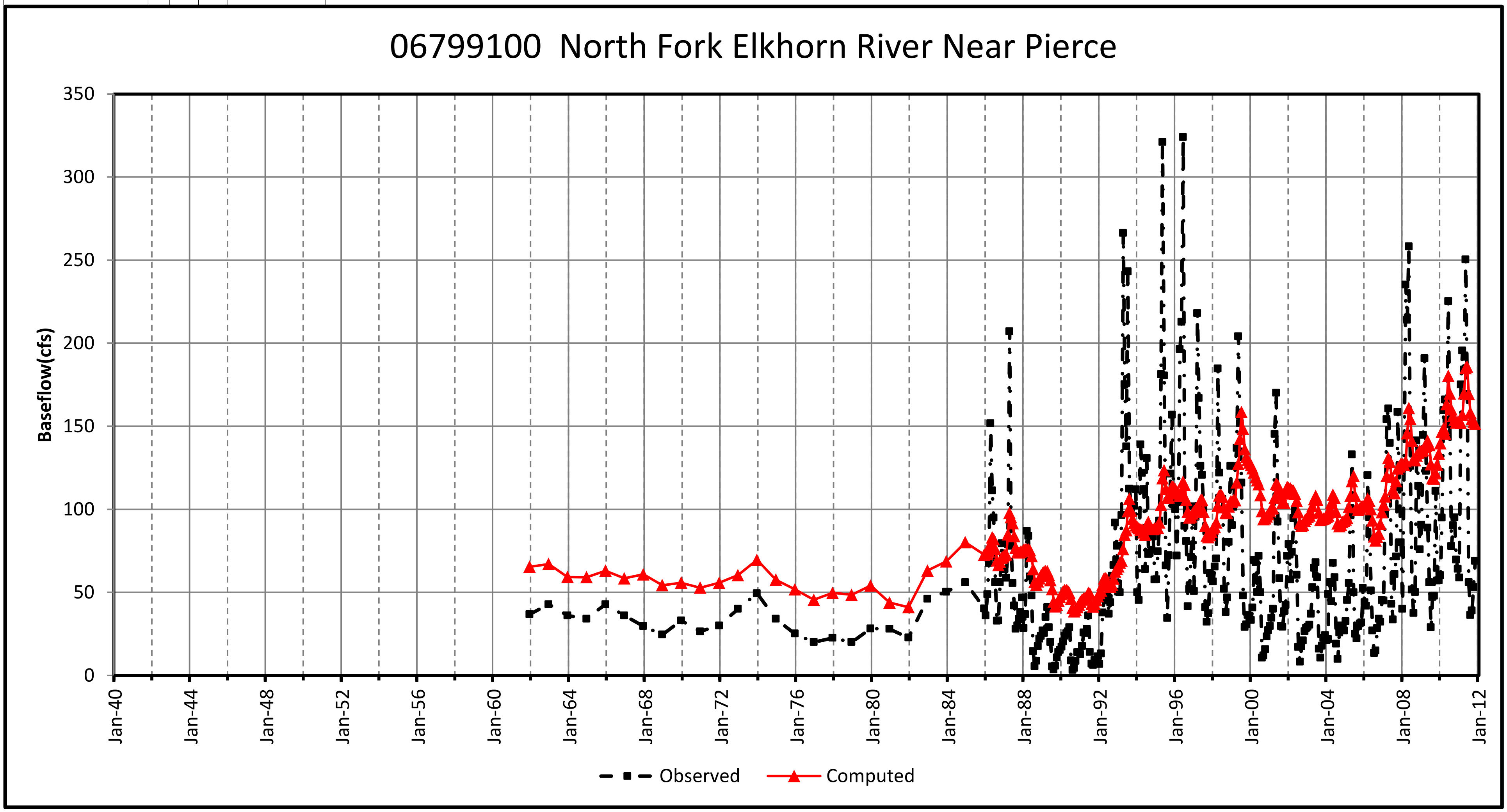
06799000 Elkhorn River At Norfolk
Baseflow(cfs)
2500
2000
1500
1000
500
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

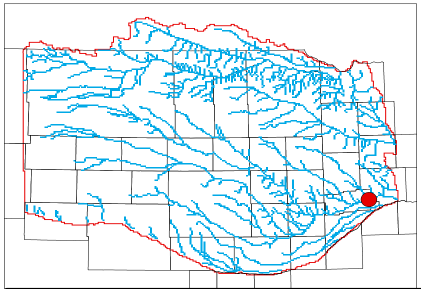


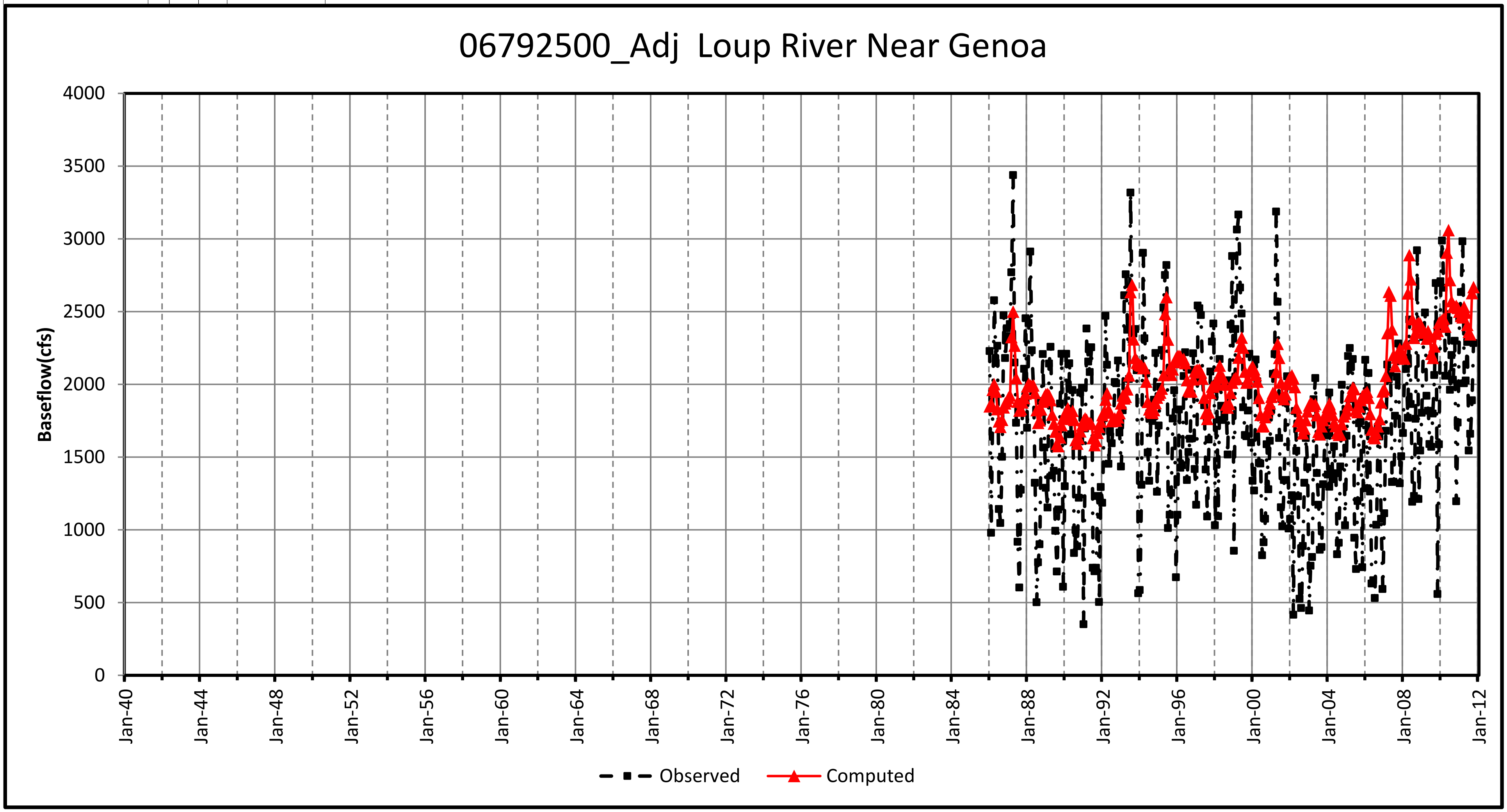


06799080 Willow Creek Near Foster
Baseflow(cfs)
0
10
20
30
40
50
60
70
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed




06799100 North Fork Elkhorn River Near Pierce
Baseflow(cfs)
350
300
250
200
150
100
50
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed





06792500_Adj Loup River Near Genoa
Baseflow(cfs)
4000
3500
3000
2500
2000
1500
1000
500
0
Jan-40
Jan-44
Jan-48
Jan-52
Jan-56
Jan-60
Jan-64
Jan-68
Jan-72
Jan-76
Jan-80
Jan-84
Jan-88
Jan-92
Jan-96
Jan-00
Jan-04
Jan-08
Jan-12
Observed
Computed

# Appendix Z: Electronic Files on DVD