Upper Niobrara-White Groundwater Model

Nebraska Department of Natural Resources

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Contents

List of Figures

List of Tables

1 Introduction

Agriculture in the semi-arid northwest corner of Nebraska has come to rely heavily on irrigation water, where available. Originally limited to a narrow swath of irrigated lands following the path of the Niobrara River where streamflows could be diverted and channeled to nearby fields, the advent of groundwater irrigation technology during the mid-20th century greatly expanded the reach of irrigated agriculture in the region. This increase in water use has affected the underlying aquifer and hydrologically connected waterways, causing water level declines in Box Butte County and prompting the designation of the Niobrara River down to the Dunlap diversion gage as fully appropriated in 2004.

The Upper Niobrara-White Natural Resources District (UNWNRD) and the Nebraska Department of Natural Resources (Department) undertook a plan to develop and implement an integrated management plan (IMP) for areas within the district following the fully appropriated determination. The planning process is an adaptive one, always seeking to evaluate and incorporate the best available science into management decisions. The groundwater model documented here is part of that process: an incremental step in improving the tools available for analysis of water supplies and uses in the upper portion of the Niobrara River Basin.

The model described in the following sections was developed to build upon previous groundwater models and studies in order to create a tool for both the Department and the UNWNRD to use in the evaluation of management scenarios. Previous studies include the Box Butte Model (Ayers, 2007), Niobrara Basin hydrostratigraphic analysis (Ayers, 2010), and the 2004 assessment of water supply and uses in the region (DNR, 2004). This project utilized the data and findings from these studies to guide the construction of the Upper Niobrara-White (UNW) numerical groundwater model to meet four purposes:

1. To quantify, at yearly and seasonal (irrigation/non-irrigation) scales, the water supply in the basin above Gordon in a manner that is consistent with the Department's basin water supply concepts.
2. To quantify depletions to the baseflow component of gaged flow in the Niobrara River due to groundwater and surface water irrigation development.
3. To evaluate the impact of management scenarios, employing varying degrees of groundwater and surface water use, on Niobrara River baseflows.
4. To quantify and assess the effect of groundwater development in Box Butte County on the contribution of groundwater to surface water, including but not limited to the Niobrara River and Snake Creek.

The UNW groundwater model achieves these purposes and, in so doing, provides a suitable tool for the evaluation of management scenarios and the estimation of the basin water supply (BWS) and hydrologically connected area for the Department's annual basin evaluation process.

1.1 Report Organization

This report covers the construction and calibration of a MODFLOW-2000 finite difference groundwater model for the UNWNRD area and is organized into five sections. Section 2 describes the model setting and the conceptual model for the groundwater system in the area. Section 3 describes datasets that were developed for or used to support the construction and calibration of the groundwater model. Details of model file construction are provided in Section 4. Section 5 describes the results of the calibration process. Lastly, a discussion of results is provided in Section 6.

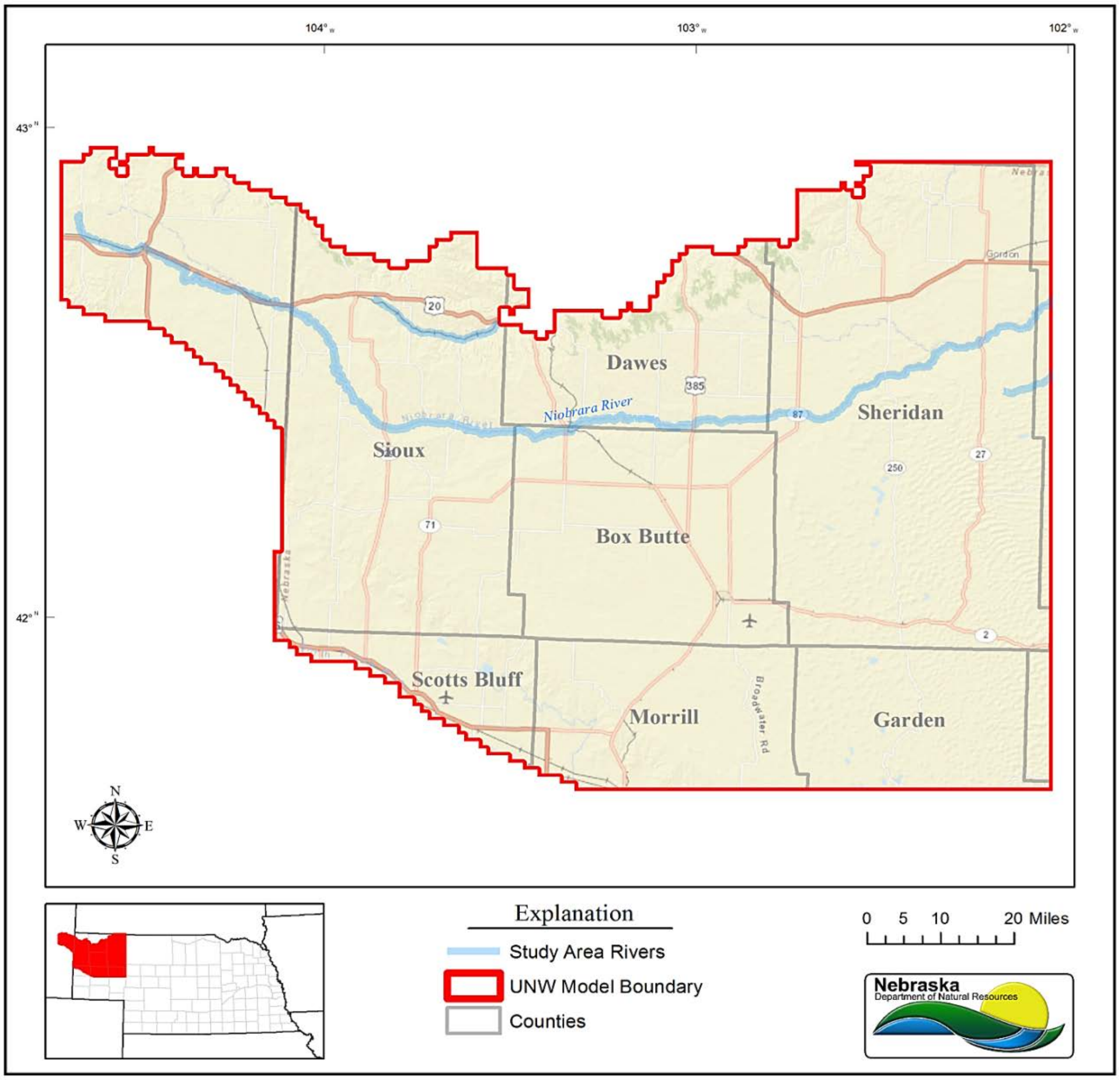


Figure 1. Study Area.

2 Model Setting and Conceptual Model

2.1 Physical Setting

The Niobrara River Basin extends across diverse landscapes from its origin on the high plains of eastern Wyoming to its termination at the Missouri River along Nebraska's northeastern border. The UNW basin considered in this report falls primarily in the Great Plains physiographic province and encompasses topographic regions including plains, sand hills, valleys, bluffs, rolling hills, and dissected plains. The UNW area climate is considered to be semi-arid, characterized by large annual variations in temperature and an annual mean precipitation of approximately 15 inches (HPRCC, 2012).

The UNW groundwater model area covers the portion of the Niobrara River Basin beginning at the headwaters of the Niobrara River near the town of Manville, Wyoming, east to a line roughly coincident with the boundary of Sheridan and Cherry Counties in Nebraska. The point at which the Niobrara River exits this model area on the eastern boundary is about 10 miles downstream of the USGS stream gaging station near Gordon, Nebraska. Figure 1 shows the area represented in the UNW groundwater model in relation to the Niobrara River and counties located within Nebraska and Wyoming.

2.1.1 Topography and Elevation

The UNW model area, in general, is characterized by areas of rolling plains and table lands dissected by narrow valleys or canyons that accommodate intermittent and perennial streams. The Pine Ridge Escarpment forms a distinct topographic break between the Niobrara River drainage and those of the White River and Hat Creek drainages to the north (Bradley and Rainwater, 1956; Gwillim et al., 1940). To the south, the Box Butte Table serves as the boundary, albeit less distinct, between the Niobrara and North Platte drainages (Cady and Scherer, 1946; Souders et al., 1980). The Box Butte Table is dissected by small ephemeral streams oriented in a predominantly southeasterly direction (Souders et al., 1980). The southeast portion of the model area is marked by the dune formations of the western sand hills region, roughly coincident with the Box Butte-Sheridan County line.

The landscape generally slopes downward to the east through the UNW model area, with land surface elevations ranging from nearly 5,500 feet in the western portions near Wyoming, to 3,000 feet in the east and south along the North Platte River. Elevations in the Box Butte County area, dominated by the Box Butte Table, range from 4620 feet on the uplands to approximately 3800 feet near the Niobrara valley in the north. The Niobrara drainage area begins west of the Rawhide fault near Manville, Wyoming with the channel at the headwaters sitting at an altitude of roughly 5,300 feet (Bradley and Rainwater, 1956). The channel slope varies in steepness as it crosses more roughly rolling topography in Wyoming and western Sioux County, Nebraska, into more gently rolling lands in the central and eastern part of the model area. Overall, the channel drops at an average rate of 10 feet per mile from west to east, with the elevation at the Sheridan-Cherry County line at 3,400 feet (Bradley and Rainwater, 1956).

For the most part, the Niobrara River channel and valley floor sit well below the surrounding landscape. In the western portion of the model area where terrain is more variable, Sioux County, for example, the valley floor is 200-500 feet below the surrounding land surface (Bradley and Rainwater, 1956; Souders et al., 1980). The difference in elevation is less extreme farther east, with valley floor elevations estimated at 90 feet below the surrounding land surface, although this can be higher where sand hills are present (Bradley and Rainwater, 1956; Souders et al., 1980).

2.1.2 Geology

The UNW model area near-surface geology (i.e. in the zone reaching roughly 1000 feet below land surface in most areas) is dominated by units of unconsolidated sand, silt, and clay deposited between and including Cretaceous and Quaternary periods. In Wyoming, Precambrian metasedimentary/metavolcanic rock outcrop or subcrop in areas near the Rawhide fault (Hinckley et al., 2009). At the top of Cretaceous-age units, the Pierre shale underlies the majority of the model area at general depths around or exceeding 1000 feet, except north of the Pine Ridge Escarpment where it forms the base of the White River-Hat Creek valley floor (Burchett, 1986; Cady and Scherer, 1946; Souders et al., 1980).

Oligocene age White River Group sediments rest on the Pierre shale and vary in composition from clay, silt, sand, ash, and some clastic and precipitated material (Souders et al., 1980; Bradley and Rainwater, 1956; Cady and Scherer, 1946). The White River Group is defined by Souders et al. (1980) as including two main formations across portions of the model area: the Chadron and the Brule, each containing one or more distinct hydrogeologic units. The hydrogeologic units are distinguished by sediment types and composition. The uppermost Brown Siltsone unit of the Brule Formation is the most relevant to the model area due to its proximity to the surface near the Niobrara River in northern Box Butte County, and its potential for locally significant groundwater yield (Souders et al., 1980; Burchett et al., 1986).

The Miocene age Arikaree unit (variably referred to as a group or unit, depending on location, geologist, and convention) in turn, overlies the White River Group formations. The Arikaree that exists throughout most of UNW model area is composed of sand, sandstone, and silty sand deposited by a mix of fluvial and eolian processes (Souders et al., 1980; Ayers, 2007). The Arikaree exists at the land surface in the area extending from the Rawhide Fault in Wyoming to areas north and south of the Niobrara River valley in Box Butte, Dawes, and Sheridan Counties (Burchett et al., 1986). The Arikaree thickness varies from minimal in areas where it pinches out, to more than 500 feet in southwestern Box Butte County (Ayers, 2007). The base of the Arikaree in the model area slopes generally eastward and southward while, in those same directions, the total thickness of Arikaree sediment increases (Cady and Scherer, 1946).

The Ogallala Group is another primary aquifer unit that consists of gravelly sand, sand, siltstones, and clay. This formation outcrops in the western portion of the study area and then thickens to the east. In Sheridan County, the unit can exceed 800 feet in thickness. Overlaying this formation in eastern portions of the study area are Quaternary sands which constitute the “sand hills” of the region. These sands are very permeable and allow precipitation to contribute to the aquifer as recharge. On average, the Ogallala formation is more transmissive than the Arikaree. Its water levels vary greatly, from near surface in many wetland areas, to more than 300 feet below the surface in others (DNR, 2004).

2.2 Flow System

2.2.1 Niobrara River

The Niobrara River is a highly aquifer-supplied river whose headwaters originate in eastern Wyoming. It is a perennial stream from approximately the Nebraska-Wyoming stateline, downstream through the remaining portion of the UNW study area, with flow generally present year-round. Since the late 1800’s, the Niobrara has been a significant source of water for water rights holders along the river. In 1948, the Box Butte Reservoir and canal distribution system, completed by the Bureau of Reclamation, began to provide irrigation for the Mirage Flats irrigation district.

The flows in the Niobrara River are due in part to precipitation runoff, but the predominant source is groundwater. The river begins in south eastern Wyoming, cutting through the water bearing Arikaree formation. As the river bends though Sioux, Dawes, and Sheridan Counties, it gradually begins to run over the more prolific Ogallala formation. These formations play a key role in both the quantity of water in the river, and the quantity of water that can be relied upon for irrigation.

Typical flows in the river are around five cubic feet per second near the stateline, around 15 cubic feet per second at the gage at Agate, and between 20 to 40 cubic feet per second at the gage above Box Butte Reservoir. The records from the streamgages upstream of Box Butte Reservoir, however, show indications that the streamflow has been decreasing over time (Figures 2-4). According to Department analysis in a 2004 report, the amount of surface water available for diversion from the Niobrara River upstream of the Mirage Flats canal diversion has continued to decrease since the project was completed (DNR, 2004). At the stateline, the five-year annual average flow decreased by 567 acre-feet from the 1956-1960 time period to the 1996-2000 time period. For the same time periods, the average flow above Box Butte Reservoir decreased by 4,332 acre-feet. Records also show that diversions to the Mirage Flats canal averaged 19 percent less per year during the 1976-2003 time period than during the 1948-1975 time period.

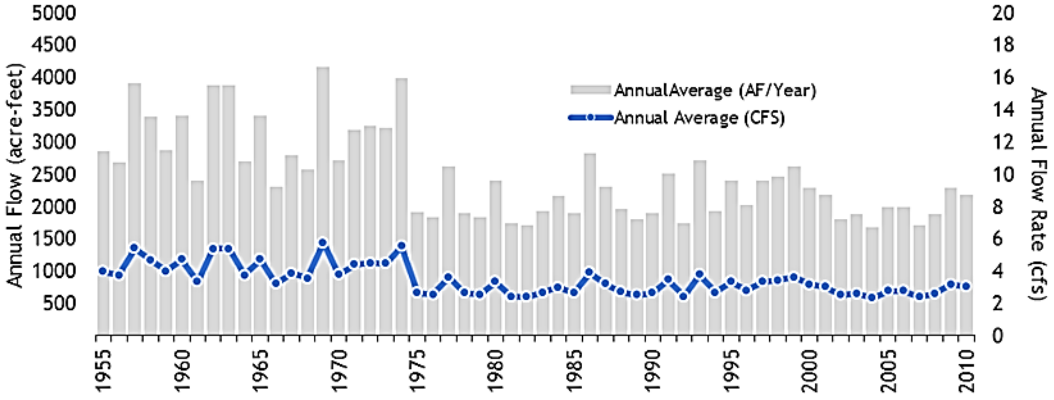


Figure 2. Average annual flow of the Niobrara River at the stateline gage.

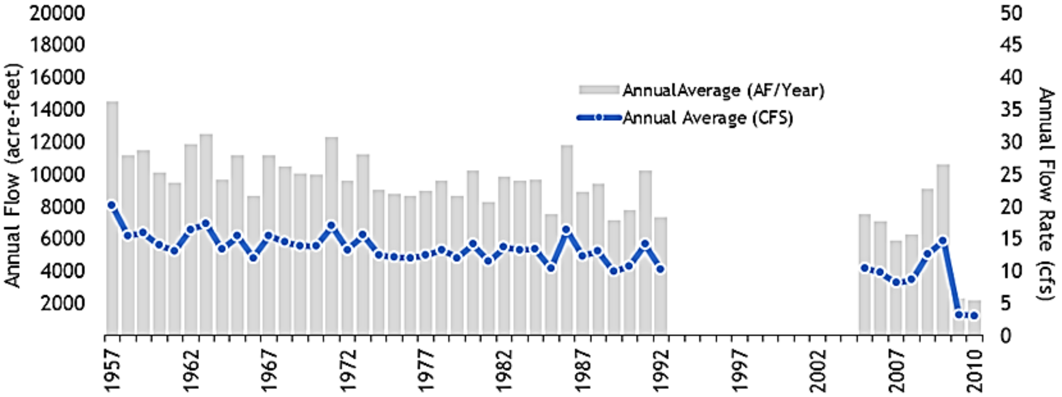


Figure 3. Average annual flow of the Niobrara River at Agate.

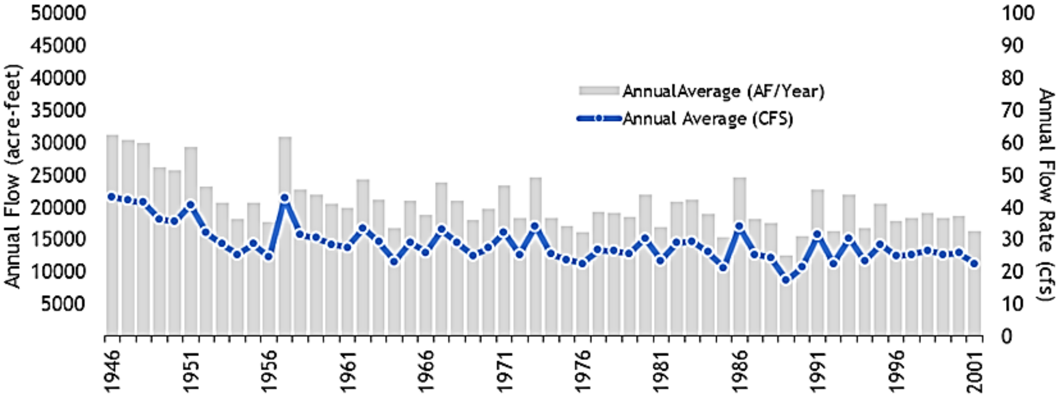


Figure 4. Average annual flow of the Niobrara River above Box Butte.

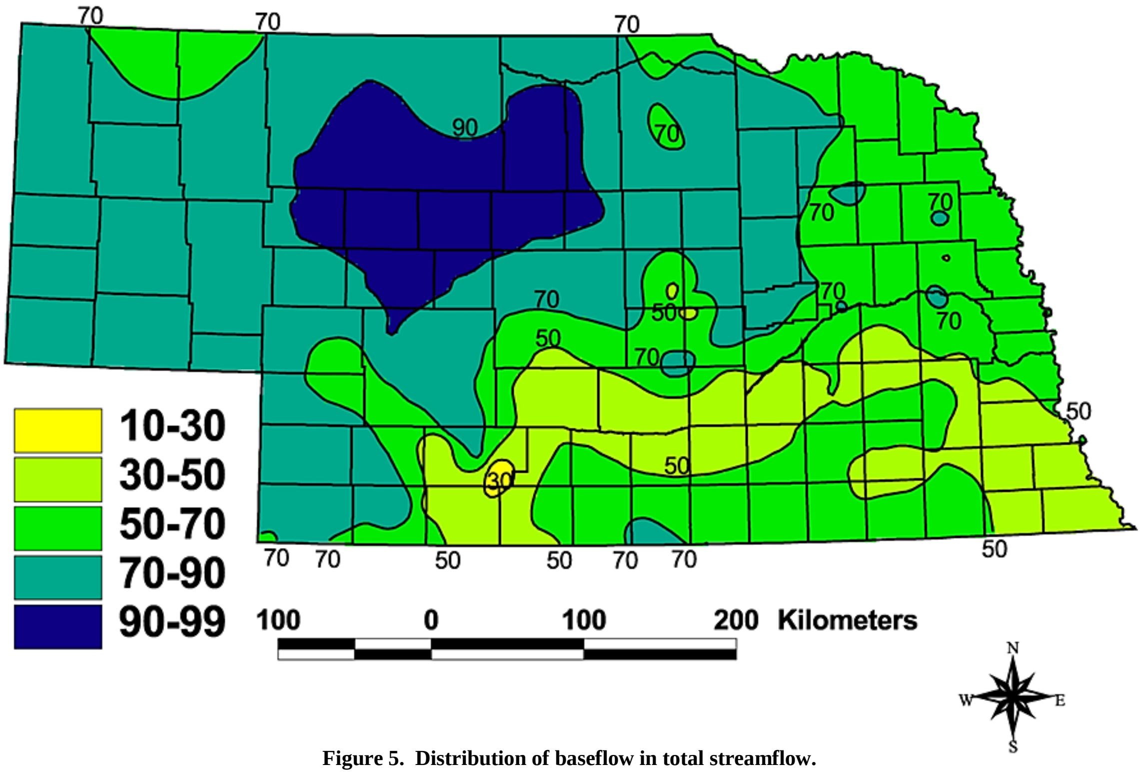


Figure 5. Distribution of baseflow in total streamflow.

Map showing the baseflow index for Nebraska (Szilagyi et al. 2002). In the UNW area, 70-90 percent of river flow originates from groundwater (far northwest portion of Nebraska).

2.2.2 River-Aquifer Connection

The primary indication of a significant connection between the Niobrara River and the underlying formations beneath it is the relatively high volume of flow during times of low precipitation. The amount of water flowing in the river which is contributed by the aquifer is known as baseflow, or groundwater discharge. Baseflow is relatively insensitive to weather conditions. Therefore, rivers with a high degree of connection typically have sustained flows, even during drought periods. Baseflow is, however, sensitive to changes to head in the aquifer. When the head in an aquifer decreases, the flow of water to the river decreases. Quantifying the degree of connection to and the changes in head of the aquifer through time, are the fundamental objectives of this study.

Studies performed in Nebraska to quantify the degree of connection between river systems and aquifers have produced estimates of the proportion of flow in a river that is due to groundwater contribution. A study by Jozsef Szilagyi et al. (2002) suggests that, in the region of the study area, 70-90 percent of river flow can be attributed to seepage from groundwater. This approximation is derived from the baseflow index: an estimate of the ratio of baseflow to total flow volume (Figure 5).

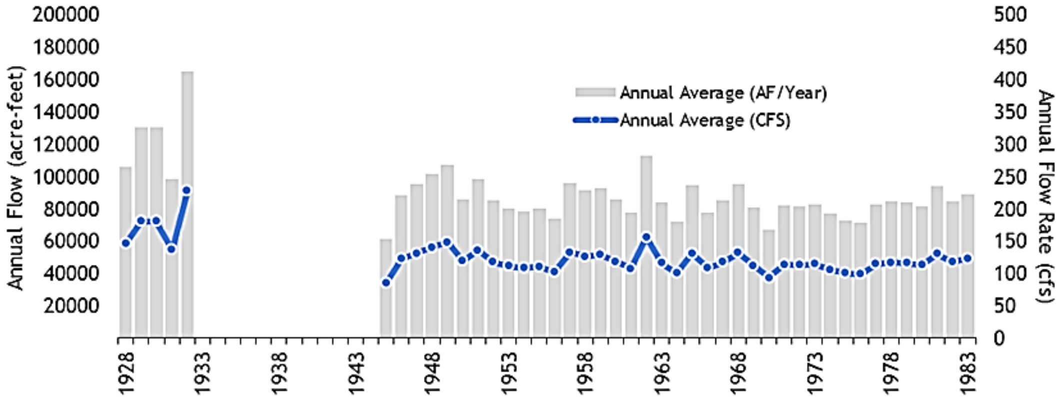


Figure 6. Average annual flow of the Niobrara River below Box Butte.

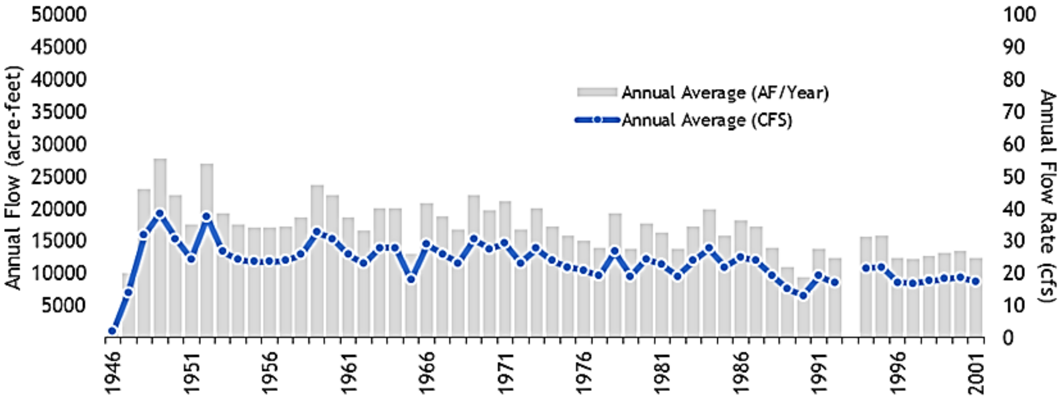


Figure 7. Average annual flow of the Niobrara River at Gordon.

2.2.3 Analysis of Niobrara River Flows

In the past half century, the UNW basin has changed rapidly. The increase in irrigated agriculture after the building of Box Butte Reservoir and the development of many groundwater wells has caused long-term shifts in the water balance. Figures 2-4 and 6-7 show the annual average flow of the Niobrara River for several key gages along its length within the study area. Although the trends are subtle, most gages show a decreasing trend through time.

When regular regression lines are charted for the annual flow and monthly average flow at these gages they show decreasing trends. The R-squared values, however, are low, indicating that the lines do not fit the data well and that the lines are not good predictors of the data. This is likely due to the high amount of variability and dissymmetry in the data.

The Mann-Kendall test can be easily applied to this data. The test is nonparametric, which is still effective when data are not evenly distributed. It is also robust against outliers and large gaps in data (http://www.bae.ncsu.edu/programs/extension/wqg/319monitoring/TechNotes/technote6_trend_analysis.pdf). The Mann-Kendall test compares each value in a time series to successive values in order to determine if there is a trend. Essentially, it allows one to determine if the values increase or decrease over time.

According to Wen and Chen (2006), a Mann-Kendall analysis of streamflow records indicated significant decreasing trends at three gaging stations in the Niobrara River Basin: (1) above Box Butte Reservoir (USGS 06454500); (2) below Box Butte Reservoir (USGS 06455500); and (3) at Gordon, Nebraska (USGS 06457500). Wen and Chen (2006) hypothesize that the decline in streamflow is associated with the use of groundwater in Box Butte County. The same Mann-Kendal trend test was performed on data from gages at the Nebraska-Wyoming stateline (USGS 06454000) and near Agate, Nebraska (USGS 06454100). The analysis indicated a significant decreasing trend at both gages, with the null hypothesis of no trend rejected at greater than a 95 percent confidence level.

Therefore it is apparent that the Niobrara River is experiencing a reduction of flows. There are three ways that flows can be reduced in the river: (1) a reduction of direct runoff as a result of precipitation; (2) an increase in upstream surface water diversions; or (3) a reduction in baseflow.

2.3 Hydrogeologic Framework

The Tertiary-age Ogallala and Arikaree formations are the primary water bearing sediments in the study area, and together form what is known as the High Plains Aquifer. Both of these formations are readily found in the study area, though the water well development gradually shifts from the Arikaree group sediments in the west to the Ogallala in the east. For this study the two formations are modeled as one primary aquifer. This is consistent with UNL’s Conservation and Survey Division (CSD) interpretations of heads in the area because both groups are in connection with each other and do not exhibit separate hydraulic characteristics in the study area (as in different head regimes), and no distinct confining layer exists between the two groups in the study area. The primary aquifer (the High Plains Aquifer) acts as one continuous and hydraulically connected unit. At a regional scale it exhibits properties similar to an unconfined water table aquifer and is connected to many of the surface water features in the study area. The connection between the aquifer and surface water features in this area is a key feature of the region.

2.4 Conceptual Flow Model

The conceptual flow model is a description of a hydrological system that can relate how and where flow occurs in an area. The overall concept of the water cycle in the study area is broken down into two systems: (1) the watershed, where precipitation is the source of recharge and irrigation usage, but is also lost through evapotranspiration; and (2) the groundwater system, where the High Plains Aquifer absorbs precipitation as recharge, stores water, and contributes water to the streams and rivers of the area, while also contributing to irrigation through the pumping of wells. These two systems are connected – changes in land use affect the amount of water recharged into the aquifer, and pumping from the aquifer affects the amount of water in streams and rivers. Human activities over the past century have played a role in shifting this balance through the construction of irrigation systems. The flood application of water to cropland has increased recharge in areas, while increased groundwater pumping has reduced the water levels in the aquifer, and thus decreased flows in nearby streams.

When a groundwater flow model is being developed, much consideration goes into two key components: (1) the boundaries of the model, or the limits or extents of the system’s flows that one intends to explore; and (2) the water budget, or the estimated quantity of flows in the system.

Boundaries can be as simple as the geological extent of an aquifer or a river. Streams can also serve as boundaries, but since they are highly interactive with aquifers, much care is needed to define this relationship. Boundaries can also be established in the model that show no changes in flows through time, thus limiting the transient effects to the model domain. Defining the water budget is an exercise in trying to estimate the inflows and outflows that occur within the model domain. The components of the water budget typically consist of recharge from precipitation, groundwater contribution to the streams and rivers in the area, seepage from canals or drains, evapotranspiration, and pumping for irrigation or municipal use.

2.4.1 Boundaries

The boundaries of the model were designed with the purpose of the model in mind. The purpose of the model was to analyze potential management actions in the UNWNRD. More specifically, to analyze conjunctive management scenarios along the river and explore the effects of changes in groundwater pumping within Box Butte County and in areas along the Niobrara upstream of Box Butte Reservoir. The key to boundary design is to define them in a way that is consistent with hydrogeology. When that is not possible or when an arbitrary boundary must be created, the goal is to ensure that the boundary design does not affect the key areas of the simulation.

The western boundary of the UNW model, located predominantly in Wyoming, is a general head boundary that traces the extent of the Arikaree portion of the High Plains Aquifer. There is a small no-flow portion on the southern edge of the Wyoming area where the aquifer was deemed not to exist. Most of this boundary was described in the UNW model as a general head boundary (GHB). The GHB was implemented in the UNW model to control simulated ambient groundwater levels on the edges of the active model in areas where flow in and out of the model is assumed to occur.

The northern boundary is dominated by the White River Group. This was assumed to be the northernmost extent of groundwater connected with High Plains Aquifer sediments. A GHB was assigned to the north side of the model.

The boundary to the east was arbitrarily located outside of the UNWNRD border so that the model simulation captured the extent of changes within the district’s borders. The area was also far enough away from the main groundwater region and exhibited no significant head change in observation wells. It was modeled as a GHB, which presumes that the groundwater levels there do not change with time. While that is unlikely, the changes over time in that area have been small and have not been significantly affected by groundwater development in the Box Butte or Mirage Flats areas.

The southern boundary is a combination of the North Platte River, modeled as a constant head river boundary, and to the east, a GHB due to the lack of overall change in head in that area.

The Niobrara River and its tributaries were modeled as head-dependent stream boundaries. The description of streams in the model was derived from the National Hydrologic Dataset (NHD). Only the reaches that flowed perennially were chosen for the model.

Four cells in the middle of the active model array were also assigned the GHB condition to approximate the effect of impounded water in Box Butte Reservoir on the underlying aquifer. Figure 8 shows how GHB cells were assigned within the model area. Beyond location assignments, a GHB condition requires a water level elevation and a conductance value.

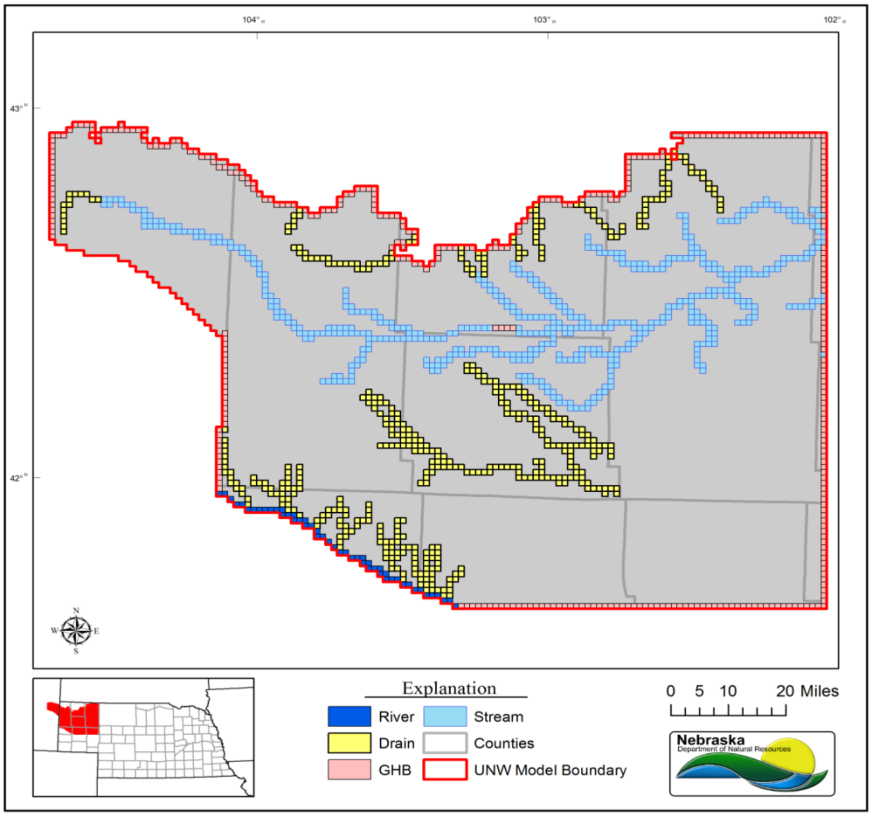


Figure 8. Map of modeled boundaries in the study area.

2.4.2 Water Budget

In order to develop a water budget, various estimates from previous studies were incorporated into this study. Previous studies typically focused on a subset of the area of interest, such as the area around Lusk, Wyoming and Box Butte County in Nebraska. Thus, generalizing water budget estimates from those sources to the larger area of interest in this study is impossible. The parameters for the steady-state model, therefore, were informed at first by these estimates, and then improved upon when more detailed information was collected from field studies. The water budget can be broken down into two main sections: (1) sources (inflows); and (2) sinks (outflows). Key water budget data used for this study are summarized below and represented in Figures 9 and 10.

2.4.3 Sources (Inflows)

2.4.3.1 *Precipitation*

Data from weather stations in the study area at Alliance, Chadron, and Harrison, Nebraska, suggest no significant decrease in precipitation over the past 50 to 75 years of record. (DNR, 2004). Wen and Chen (2006) also observed no significant trends in precipitation in the UNW area, or across the entire state of Nebraska, over the past 50 years. Annual precipitation measured at the Alliance, Nebraska, weather station averaged 16.18 inches per year for the period of 1896-2003, with a minimum of 8.67 inches and a maximum of 25.57 inches (DNR, 2004). Figure 11 shows the long term historical precipitation trend.

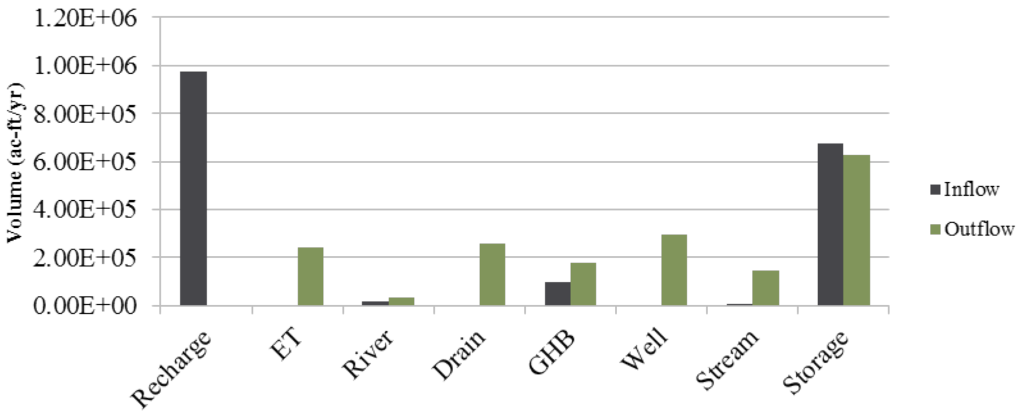


Figure 9. Water budget components and simulated volumes (Transient Simulation).

Budget Component	**Inflow ac-ft/yr**	**Outflow ac-ft/yr**
Recharge	974,116.00	0.00
ET	0.00	242,988.00
River	16,254.00	35,366.00
Drain	0.00	255,346.00
GHB	97,656.00	175,974.00
Well	0.00	293,301.00
Stream	8,451.00	145,158.00
Storage	676,853.00	625,629.00
Total	**1,773,330.00**	**1,773,762.00**

Table 1. Water budget components and simulated volumes (Transient Simulation).

The lack of a significant trend in precipitation suggests that the gradual reduction of flows in the Niobrara River may be due to a reduction in baseflow. Since the main factor that affects quantity of baseflow is head in the aquifer beneath the river, this study will explore the groundwater dynamics of the study area and how changes in head through time have affected the Niobrara River. The most prominent change in the basin that can significantly affect head is well development and the pumping of groundwater for irrigation. It is important, therefore, to understand the history of irrigation development in the UNW basin, and how surface water and groundwater development is managed.

2.4.3.2 *Recharge*

Recharge estimates have traditionally been determined to be less than 1 inch per year for the UNW basin, and it is understood that the percentage of precipitation that infiltrates the aquifer is greatest in the sand hills region of the study area. (Bradley and Rainwater, 1956). In the Box Butte area, groundwater recharge from precipitation was estimated to be from 0.06 of an inch per year, to 4 inches per year, with the highest number attributed to the exposed Arikaree formation in the center of Box Butte County (Pettijohn and Chen, 1984).

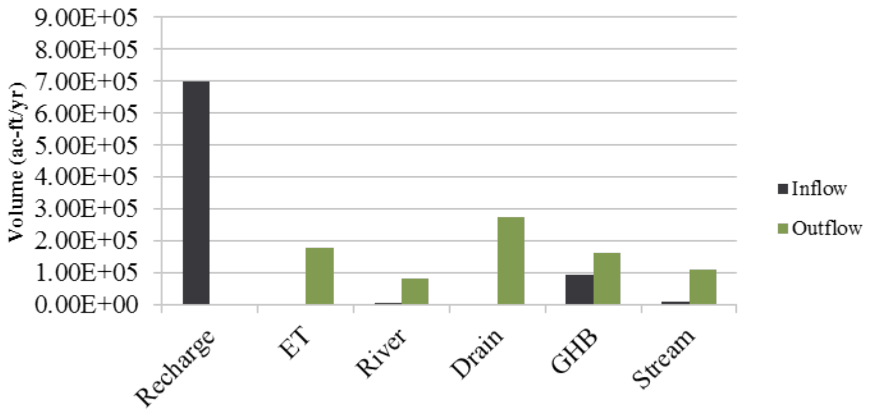


Figure 10. Water budget components and simulated volumes (Steady-State Simulation).

Budget Component	Inflow ac-ft/yr	Outflow ac-ft/yr
Recharge	698,386.90	0.00
ET	0.00	178,758.30
River	1,264.80	80,751.40
Drain	0.00	274,389.50
GHB	92,661.40	160,683.10
Stream	10,237.40	107,991.00
Total	**802,550.50**	**802,573.30**

Table 2. Water budget components and simulated volumes (Steady-State Simulation).

Souders et al. estimate that in Box Butte County, less than 10 percent of the water applied to land by wells is returned as recharge. At the time of the Bradley and Rainwater report (1956), the Mirage Flats area had seen a water table rise of 5 to 10 feet due to groundwater recharge of irrigation water. Thus, areas associated with surface irrigation likely experience the greatest rates of additional recharge.

2.4.3.3 *Seepage from canal systems*

In Box Butte County, Souders et al. (1980) estimated that any canal delivery had a negligible effect on groundwater recharge. In the Mirage Flats area and the North Platte Valley, however, canal seepage is deemed significant (Bradley and Rainwater, 1956; COHYST, 2010).

2.4.3.4 *Stream leakage*

Streams in the UNW model area are generally gaining streams, which means that they are taking on water from the underlying aquifer. Because of this, these streams behave as an outflow, which is described below. On the otherhand, streams that were once perennially flowing but are now wetland areas with occasional ephemeral flow were viewed as contributors to the surface water system and were modeled as drains (Figure 8).

2.4.3.5 *Boundary inflows*

Since the UNW model study area is arbitrarily defined on its western border, the natural flow of groundwater from higher elevations to lower causes a gradient that allows groundwater to naturally flow

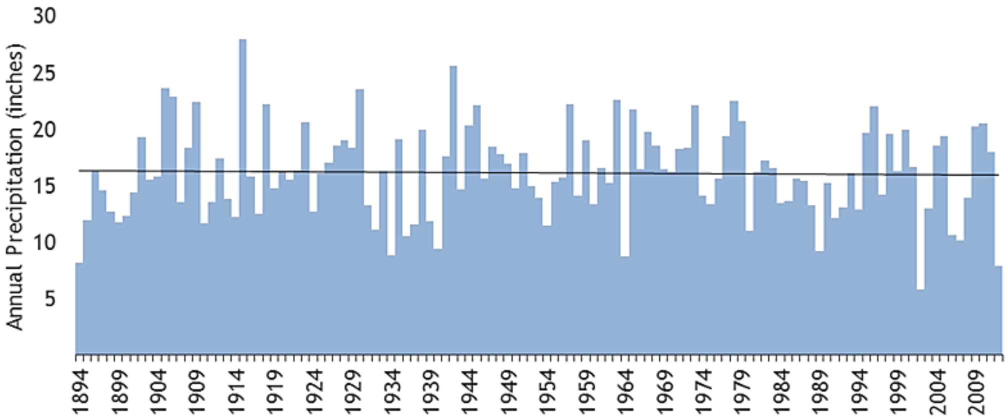


Figure 11. Historical annual precipitation recorded at Alliance, Nebraska.

eastward under the model area. Estimates suggest that this accounts for about 12 percent of the inflow budget (Figure 10).

2.4.4 Sinks (Outflows)

2.4.4.1 *Pumping*

The development of groundwater irrigation in the past century has played a key role in the amount of water that is leaving the aquifer. Prior to much of that development, Bradley and Rainwater (1956) estimated that around 8,400 acre-feet per year was discharged by wells as early as 1952 and the total amount of irrigated acres was around 5,600. That value has increased since then, and the resultant stress on the groundwater system is the key stress modeled in this study.

2.4.4.2 *Groundwater contribution to Niobrara baseflow, tributaries and drains*

The average annual discharge at the USGS gage above Box Butte Reservoir is around 20,000 acre-feet and 95,000 acre-feet at Gordon. Most of this is the result of groundwater discharge. It is thought that nearly half of the outflows in the water budget can be attributed to the baseflow component of the Niobrara River, as well as the various tributaries and drains in the basin.

2.4.4.3 *Evapotranspiration*

Souders et al. (1980) estimated that in the northern area of Box Butte County, there was a negligible loss of groundwater to evapotranspiration. In the southern portion, however, the amount lost can be more significant: up to 150,000 acre-feet per year. In the overall water budget, the estimated outflow due to evapotranspiration is approximately 25 percent.

2.4.4.4 *Boundary outflows*

Since the UNW model study area is arbitrarily defined on its eastern border, the natural flow of groundwater from higher elevations to lower causes a gradient that allows groundwater to naturally flow eastward under the model area. Estimates suggest that this accounts for about 20% of the outflow budget (Figure 10).

3 Data and Inputs

3.1 Land Use

The most significant change in the basin over the past 50 years has been the development of irrigated agriculture. This development has created a major change in the water balance and is the impetus for this modeling effort. Simulating how the aquifer has responded through time to development by humans involves a careful study of land use changes and the resulting water balance changes that have occurred over the past half century.

Changes in land use were estimated and pumping and recharge were calculated through the transient time period and calibrated with the observed changes in heads during this period. This process began through an effort by the UNWNRD to record all acreage being irrigated, and the creation of a database that captures changes to the landscape through time.

The National Agricultural Statistics Service (NASS) provided a historical distribution of crop type and the percentage of irrigated versus non-irrigated acres (NASS, 2013). This information was combined with the certified acres database created by the UNWNRD. Acres were designated to be irrigated or non-irrigated with distinctions made for whether the crop was irrigated from surface water, groundwater, or both. This dataset was compared and adjusted with satellite data from the 2005 land-use map developed by the Center for Advanced Land Management Information Technologies (CALMIT, 2005). An average of the two estimates was used to attribute crop type and land use parameters used in the CROPSIM process. The CROPSIM process, a soil-water balance model developed by Derrell Martin at the University of Nebraska, was the tool used to develop the hydrologic response of the system as a result of the changes in the basin (Martin et al., 1984; Martin, 2000). The key outputs of the CROPSIM process in regard to the groundwater model are the estimate of recharge, which is the amount of precipitation that infiltrates into the aquifer, and the estimate of pumping from the aquifer, which is the amount of water that the irrigators in the basin needed to make up for the lack of precipitation. Both of these components of the groundwater model will be described in more detail below.

3.2 Evapotranspiration Rates

Groundwater leaves the system through the many sand hill lakes and wetland areas in the Niobrara River Basin. To determine the extent of this wetland coverage, the US Fish and Wildlife Service's "National Wetlands Inventory" was used to determine where evaporation was occurring in the basin (USFWS, 2011). The rate was determined by adopting research conducted by Joseph Szilagyi (Szilagyi, 2010; Szilagyi and Kovacs, 2010). Because of the lack of data in the Niobrara region, this estimate was used simply to get a general value that could represent long-term, predevelopment water loses in the system.

3.3 Aquifer Properties

Source data guiding the assignment of hydraulic conductivity values came primarily from the Ayers study and previous COHYST work (Ayers, 2007; COHYST, 2010). Constant values taken from the Lusk study (Hinckley et al., 2009) in Wyoming were used to fill-in the western portions of the model for which no other data was available. The Ayers data, comprised of points having estimated hydraulic properties associated with a particular stratigraphic unit, were queried to yield only points having K data for the corresponding model layer (Ayers, 2007). For each layer, this data was combined with the points taken from the other sources and interpolated using the inverse-distance weighting method. The interpolated

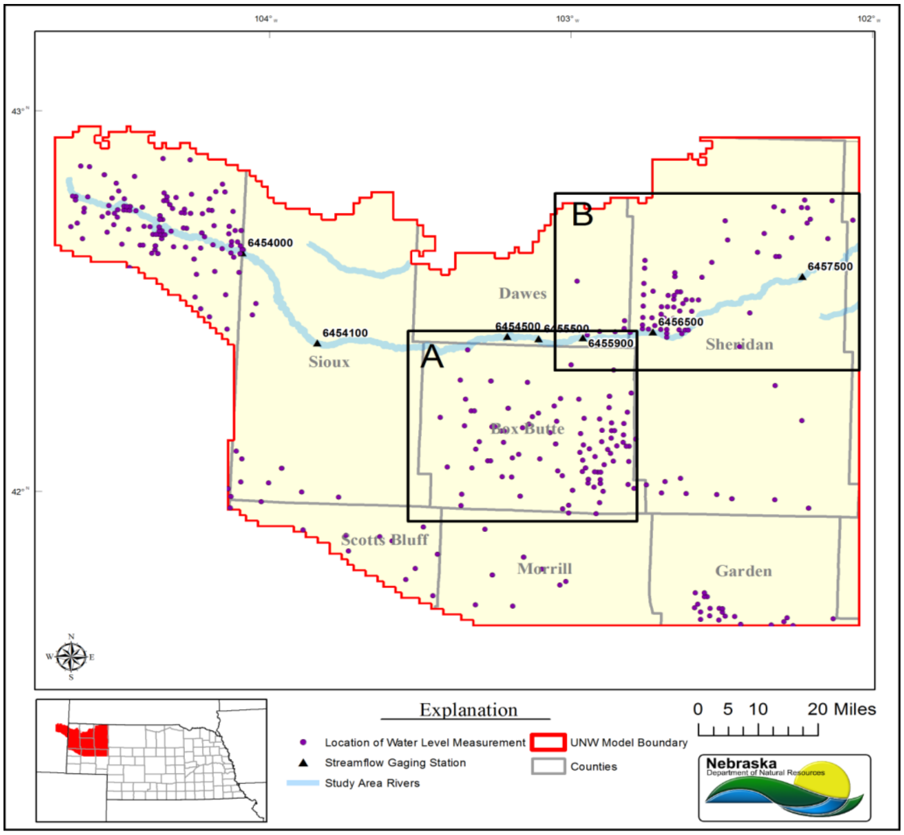


Figure 12. Map of calibration targets in the study area.

data was then aggregated to the model grid array so that each cell had a hydraulic conductivity value. When available, the starting aquifer storage properties were assigned from the Ayers study (Ayers, 2007) in the model domain and average textbook values for storage properties were used elsewhere. These properties were zoned and adjusted during the calibration process. Horizontal anisotropy hydraulic conductivity was assumed to be negligible throughout the domain; however, vertical hydraulic conductivity anisotropy was set to a value of 0.1, suggesting that vertical hydraulic conductivity is one-tenth the magnitude of horizontal hydraulic conductivity (a standard assumption for bedded sedimentary aquifers). The anisotropy for vertical hydraulic conductivity was set as a calibration parameter and adjusted where warranted during the calibration process.

3.4 Calibration Targets

3.4.1 Steady-State Heads

Head targets were compiled from the US Geological Service’s (USGS) National Water Information System (USGS, 2012). A database was created with all possible measurements in the area and was filtered for measurements prior to the year 1960, when much of the groundwater irrigation began in the area. In order to capture the effects of pumping in more recent time periods, the static water level around 1960 was approximated. Trendlines were plotted for each of the wells and most of the trends ranged less than 10 feet over the entire time period, so an average was used for the head calibration target. For the Wyoming portion of the study area, data from the Lusk Study was used (Hinckley et al., 2009). In that study, predevelopment to current depth to water for 13 wells were included. In total, only about 60 wells provided data useful enough to assist with calibrating a steady-state model. Nonetheless, the data satisfied the intention of developing a predevelopment simulation.

3.4.2 Transient Heads

The head targets used for the transient simulation were compiled from the USGS National Water Information System (USGS, 2012) in a similar process as was outlined for the steady-state head targets described above.

A database was created with all possible measurements in the area, and was filtered for measurements after the year 1960. In many cases, the recording of water levels in the basin’s wells occurred in the fall and spring for each year. Some wells had records spanning the entire time period, while others only had a few data points. There were more than 400 wells in the Nebraska and Wyoming area that provided data useful enough to assist with calibrating the transient model, the distribution of which is shown in Figure 12.

3.4.3 Baseflows

In order to estimate baseflow in the Niobrara River, the streamflow data at 13 USGS streamflow-gaging stations (Figure 12) were analyzed to determine approximate baseflow conditions through each station’s entire period of record. The index to baseflow program (BFI) developed by the US Bureau of Reclamation (USBR, 2012) was used to generate the time series. For the purposes of the steady-state simulation, with the understanding that most of the period of record has been under the influence of man –made changes to the basin, the approach taken was to compare the simulated values with an average of the baseflow time series at an early range of time created by the BFI program.

4 MODFLOW Groundwater Flow Model

The USGS MODFLOW-2000 (MF2K) (Harbaugh et al., 2000) code was selected for use in simulating the groundwater flow system because of functionality and flexibility of model packages (particularly in regard to representation of the aquifer framework), the ability of the code to robustly solve for groundwater heads and flow over large and complex model domains, compatibility of the code and most packages with industry standard graphical user interfaces like Groundwater Vistas, and general familiarity of technical staff with MODFLOW conventions and operations.

- Assumptions are critical to understanding the results of the simulation. The key assumptions made in this model are: The High Plains Aquifer in the study area is unconfined.
- The grid cell size of 1 mile by 1 mile, square is sufficient to understand the general hydraulics of the region, and is supported by the amount of observational data recorded through the past century. While some areas in the study area have little data, such as areas of the sand hill region and areas just east of the stateline, many of the key regions for analysis (Box Butte County and the Mirage Flats area) have sufficient data to support this choice.
- The time frame chosen to represent the "pre-development" time frame was assumed to be pre-1960. Although development in the basin occurred prior to then, the data to support more complex modeling does not exist prior to 1960. After 1960, the majority of groundwater development occurred in the basin, and the assumption was made that most of the human effect could be seen by modeling the change from 1960 to present.
- Since this study uses a steady-state model to approximate the heads in the aquifer prior to the increase of well development, an assumption is made that such a steady-state model represents a stable, static aquifer system residing in a long-term equilibrium.
- The relatively un-transmissive White River Group was assumed to have little interaction with the overlying High Plains Aquifer in the study area and was included to provide a base to the aquifer, especially in areas where the aquifer was at its minimal thickness. A constant thickness of 100 feet was assumed in order to simulate this layer.

4.1 Discretization

4.1.1 Steady-State Simulation (Pre-development to 1960)

The purpose of a steady-state simulation is to simulate the hydrological system at a time prior to any man-made changes. The results (head values) of the steady-state simulation were then used as the starting conditions for the transient model. One of the main assumptions is that prior to human changes in the area (by irrigation, developing wells, etc.), the hydrological system was in equilibrium, or a "steady-state" condition. This assumption is generally false, as there are climate forces and geomorphological forces that change through time, as well as changes in the amount and timing of flows. Since it is extremely difficult to model those changes, a steady-state model is an approximation of the hydrological system in a pre-human development state. The inputs of the model are derived from field studies, geological mappings, and the earliest available hydrologic data. The primary output of the model is the water table elevation of the aquifer before man-made changes in the basin. A summary of these inputs and outputs are described below.

4.1.2 Transient Simulation periods

A driving purpose of the UNW groundwater model is to simulate the effect of groundwater withdrawals (overwhelmingly to support irrigation) on baseflows to the Niobrara River and water levels in the High Plains Aquifer. While human activities have been impacting the hydrology of the region since Europeans settled the area in the 1800s, the historical scope of the groundwater model was limited to a more recent period, one that captured the bulk of the changes in water use in the 20th century.

The UNW groundwater model simulates the time period spanning the approximate onset of groundwater irrigation development in the region, through the year 2010. This time period was separated into two sequential parts – one period to simulate pre-groundwater development conditions, and one period to simulate the more recent 50 years (1960-2010) of groundwater development in the region. For purposes of this model, the predevelopment period was not defined to correspond to a specific year, but rather the model was constructed to simulate the average condition of the groundwater system in the region prior to widespread development of irrigation pumping wells. This generally corresponds to the 1940s and early 1950s, as the first substantial increase of irrigation well development began in the 1960s (Souders et al., 1980).

The decision to split the predevelopment and development periods in the groundwater model at 1960 was also influenced by the quality and extent of available model input data. The reliability and spatial coverage of climate and land-use datasets, both critical components of the CROPSIM process that defines inputs to the groundwater model, decrease considerably as one considers periods in the more distant past. A significant breakpoint in the data reliability and coverage for the UNW model area was determined to occur at 1960.

The predevelopment condition was simulated in the model using a single steady-state stress period. Simulation in this manner assumes the system is in an approximate state of dynamic equilibrium, i.e. no net change in the volume of water stored in the aquifer. An inherent requirement of this simulation approach is a balance of water sources (recharge, boundary condition leakage into the aquifer) with water sinks (evapotranspiration, pumping, boundary condition leakage out of the aquifer), the result of which is a hydraulic head distribution reflecting that balance. This head distribution satisfies a system of equations within the limits of user-prescribed allowable error, and may not necessarily be a unique solution. The goal of the steady-state simulation period in the UNW groundwater model was to produce a head distribution consistent with the general understanding of the groundwater system in the area prior to significant development pressures, that in turn serves as a robust starting point for the development period simulation.

Groundwater development in the UNW basin was simulated using transient stress periods over the period starting in January 1960 and ending in December 2010. Stress periods were defined for each of the intervening 612 months in the simulation period. Stress period lengths were assigned, consistent with the calendar year, such that stress periods varied from 28 to 31 days in length with the inclusion of a leap day every fourth year in February. The use of transient stress periods in the MODFLOW groundwater model allows storage volumes to vary (storage change is non-zero) and is meant to accommodate varying seasonal stresses through a given year, as well as changes in the form of those stresses over multi-year and decadal scales.

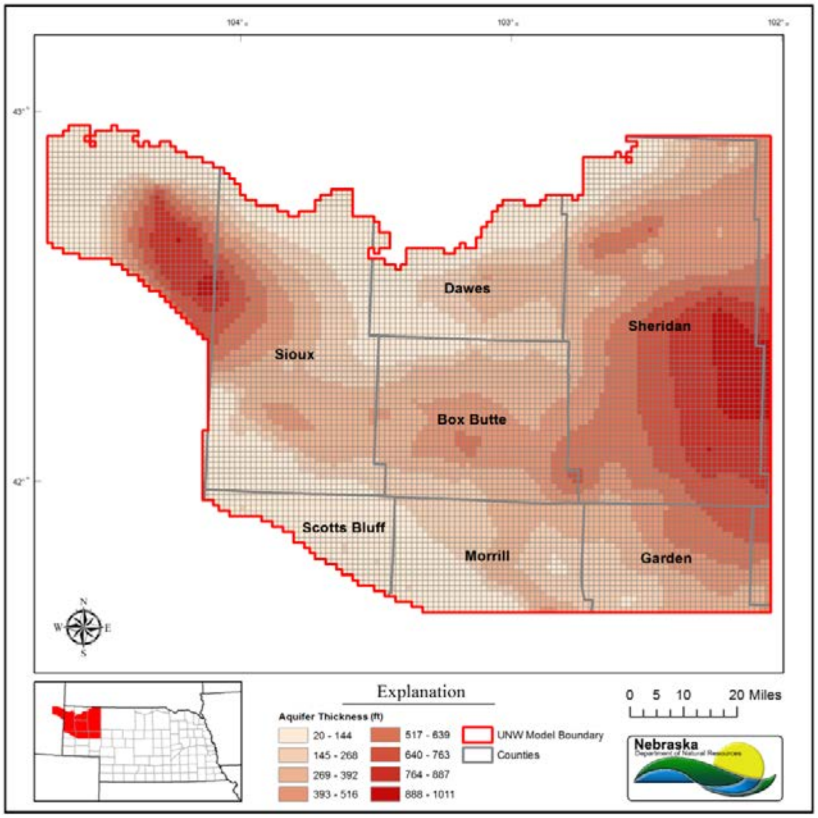


Figure 13. Map of High Plains Aquifer (layer1) thickness in the study area.

4.1.3 Layers

Although there are two primary geologic formations in the region that are prolific sources of supply, they are hydraulically connected and exhibit characteristics that suggest that they exhibit consistent hydraulic behavior. Also, in much of the model area where well development is occurring, wells are completed in either formation or both, especially in Box Butte County, where both formations are present. Thus, the mapped heads in the area are hydraulically consistent and are mapped as one unit, the High Plains Aquifer (CSD, 2012). The top of the aquifer was determined to be the top of the surface elevation, for which a 10 meter DEM (USGS, 2012) was used. The base of the aquifer was determined to be the top of the White River Group, which was part of a study by Ayers (2007). Therefore, there are two layers in the resultant model: one layer describing the High Plains Aquifer (a combination of the Arikaree and Ogallala formations) and the top part of an underlying layer describing the much less permeable White River Group formation. A minimum thickness of 20 feet was used for the top layer and a constant thickness of 100 feet was used for the bottom layer (Figure 13).

4.2 Boundary Conditions

4.2.1 Streams (STR)

The Niobrara River and its key perennial tributaries were modeled as head dependent streams using the STR package in MODFLOW. The major reaches were modeled as reaches (Figure 8) and the streams' parameters were zones on these reaches. The elevations of the stream and drain boundaries were determined by the 10 meter DEM. The width of the streams was set to 10 feet. The thickness of streambed deposits was set to 1 foot. The elevation of the stream bottom was set to 1 foot below the stream stage. Conductance values for the stream reaches ranged from 1.00 x 10^{-8} to 9.78 x 10^{4} with an

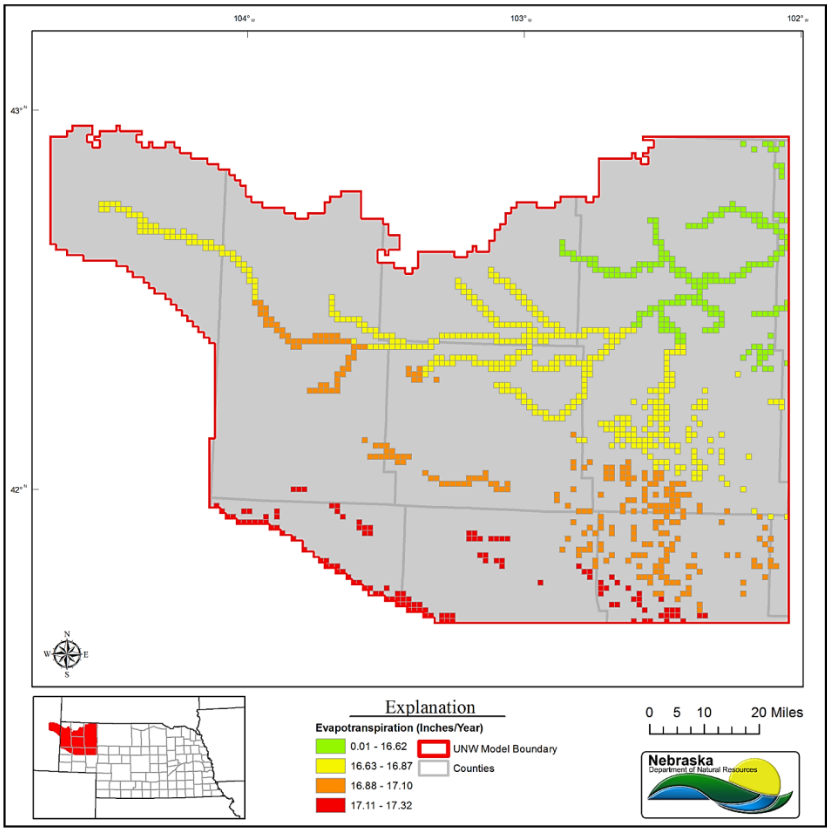


Figure 14. Map of High Plains Aquifer (layer1) evapotranspiration in the study area.

average of 3.00 x 10^4. The conductance was calculated by multiplying the length of each stream segment by a hydraulic conductivity of 1.87 feet per day and a width of 10 feet and dividing by a thickness of 3.39 feet. The hydraulic conductivity was estimated by averaging the vertical hydraulic conductivities of core samples from the Niobrara River as reported by Ayers (2007). Only the average of the first seven samples was used and the last two were excluded. This was done because after examining well logs, photos, and electrical conductance logs, there was no explanation as to why the conductivities reported for these samples were so high. It is likely that the samples were disturbed in the tubes before permeability tests were conducted in the lab. The length of the cores as reported by Ayers were averaged to estimate the thickness of the river bed sediments. These same values of K and thickness were used in the drain file as well (Ayers, 2007).

4.2.2 Drains (DRN)

Several drain boundaries were established where the heads in the area suggested that a drain may describe groundwater discharge that does not contribute to the overall baseflow, leakage from the stream to the aquifer, and streamflow in the Niobrara system. The NHD dataset helped determine some of these areas as streams that did not flow consistently. Local knowledge was also used to define these reaches.

4.2.3 Rivers (RIV)

The southern boundary of the model was modeled as the North Platte River. The NHD data set was used to determine the general position and length of the river segments, and the elevations were derived from

the DEM provided by the USGS. Conductance values for the river cells ranged from 1.05 x 10^3 and 8.81 x 10^5 with an average of 1.35 x 10^5 square feet per day.

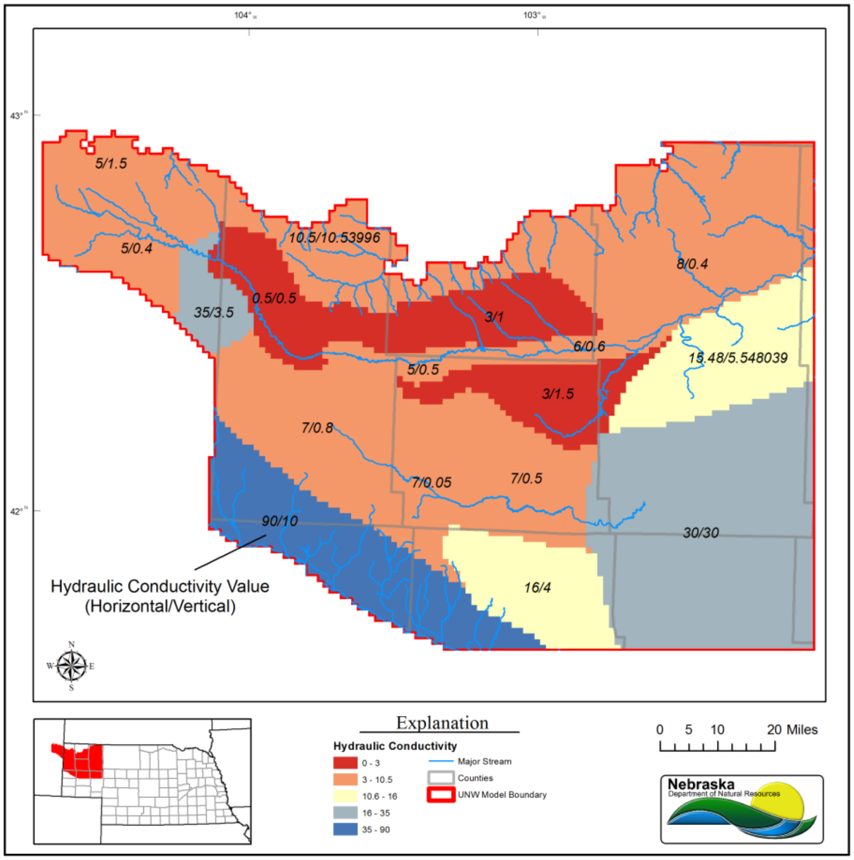


Figure 15. Map of High Plains Aquifer (layer 1) hydraulic conductivity in the study area.

4.2.4 General Head Boundary (GHB)

For the steady-state simulation, the CSD's 1979 statewide water table contour map was used to guide water level assignment of the model border GHB cells (CSD, 2012). It was assumed that this 1979 map adequately approximated, at least on a regional scale, the configuration of the water table under pre-development conditions.

4.2.5 Evapotranspiration (EVT)

The evaporation package in MODFLOW was used to describe water that may leave the groundwater system through the many sand hill lakes and wetland areas in the Niobrara basin. To determine the extent of this wetland coverage, the Fish and Wildlife Service's "National Wetlands Inventory" was used to attribute an evapotranspiration rate to each affected grid cell (USFWS, 2011). The rate was determined by adopting research conducted by Szilagyi (Szilagyi, 2010; Szilagyi and Kovacs, 2010). The rates used in the model can be seen in Figure 14.

Because EVT occurs primarily in narrow riparian zones along the incised valleys of this region, a one mile resolution was not sufficient to resolve the boundary between where EVT should be simulated and where it should not, such as on the valley sidewalls and uplands. Therefore, the maximum EVT surface was assigned as the streamtop plus 15 feet in the cells of the stream, and the surface top in all other cells. An extended extinction depth of 15 feet was used to account for the portion of the cell that goes beyond the valley floor.

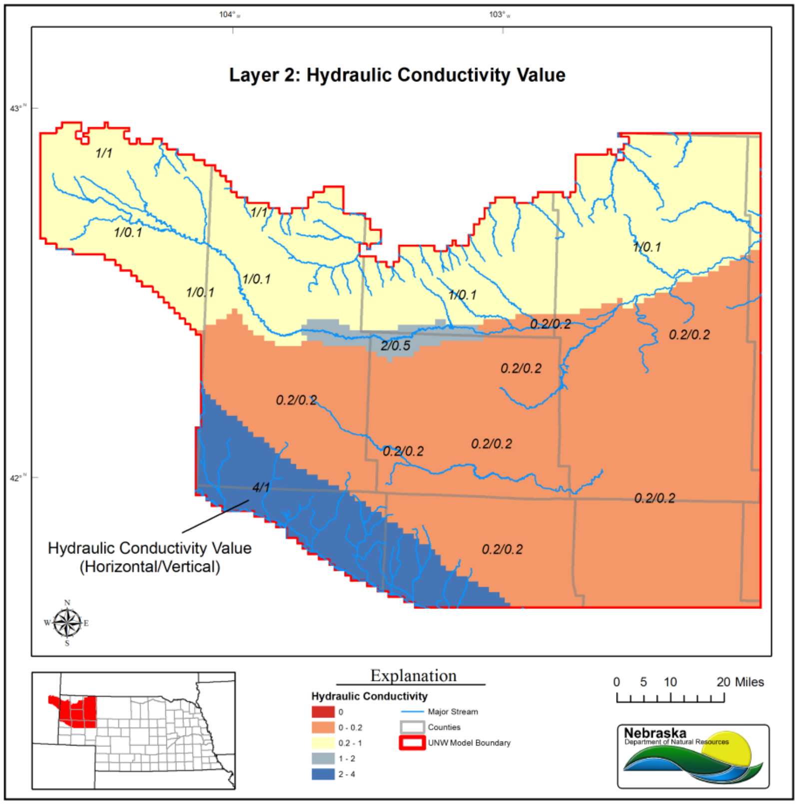


Figure 16. Map of High Plains Aquifer (layer 2) hydraulic conductivity in the study area.

4.2.6 Steady-State Water Levels

The most spatially complete water level dataset currently available for the model area was determined to be a digitized water table elevation map representing conditions in 1979. This map was produced by geologists at the CSD and was available as a GIS dataset via UNL's School of Natural Resources' website (CSD, 2012). It was assumed that the 1979 generalized water table elevations would sufficiently approximate pre-1960's water levels based on the supposition that a regionally insignificant amount of groundwater extraction had occurred in the intervening period.

4.3 Aquifer Properties

4.3.1 Hydraulic conductivity

The basis for a MODFLOW groundwater flow model is the assignment of hydraulic properties to the active model cells that represent the hydrogeologic system being simulated. Steady-state models, by definition, assume zero change in storage, making storage terms (Sy, Ss) superfluous to the head and flow calculations. Therefore, hydraulic conductivity (K) was the only hydraulic property assigned for the steady-state portion of the model. Horizontal hydraulic conductivity was assigned in the model using zones in layers 1 and 2 (Figures 15 and 16). Horizontal hydraulic conductivity values were uniform across each zone but varied between zones. Vertical hydraulic conductivity values are used in MODFLOW in the calculation of flow between two layers. Vertical hydraulic conductivity was implemented in the model (and modified in calibration) through assignment of vertical hydraulic conductivity multipliers. In the case where this multiplier was set to 1, vertical hydraulic conductivity matches horizontal conductivity for that zone. Multipliers less than one reduce vertical hydraulic conductivity relative to horizontal hydraulic conductivity for that zone.

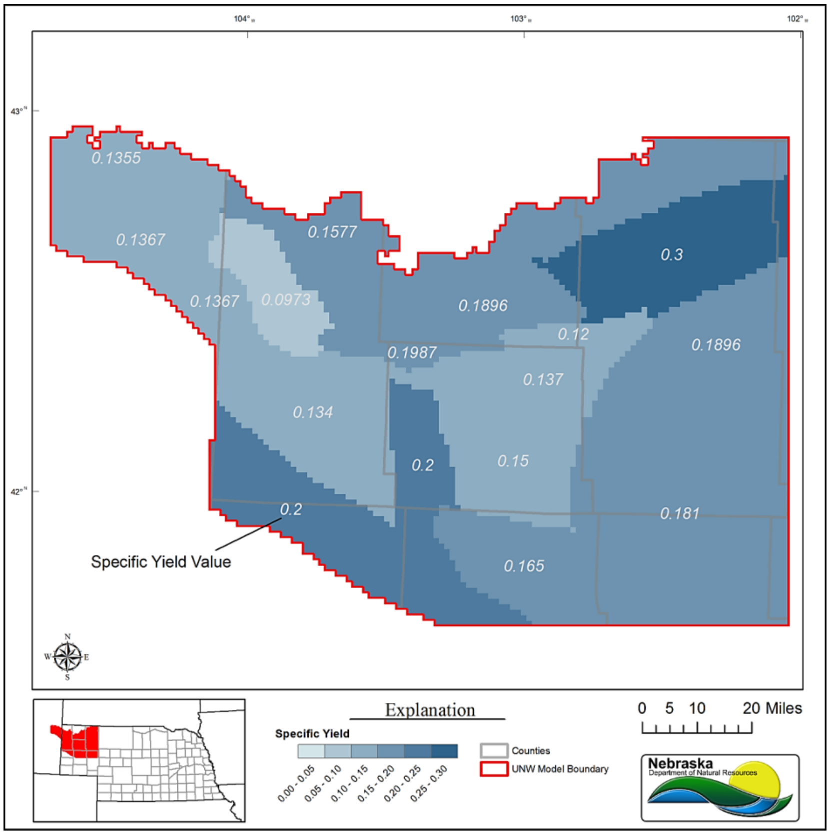


Figure 17. Map of High Plains Aquifer (layer1) specific yield in the study area.

Zones were used to speed up the calibration process while ensuring enough diversity in the parameters to match historical observations. Overall, there were 16 zones with calibrated values for hydraulic conductivity. Calibrated horizontal hydraulic conductivity values ranged from a minimum of 0.5 to a maximum of 90 in the study area with a mean value of 18.6.

Hydraulic properties can be implemented in MODFLOW through various groundwater flow packages, including the block-centered flow (BCF) package, layer-property flow (LPF) package, and hydrogeologic unit flow (HUF) package. The LPF package was used in this model.

4.3.2 Storage

In the UNW model area, the Ayers study data was used to provide values for specific yield (Ayers, 2007). For the most part, the values for Ogallala were used. Quaternary point data was used where Ogallala point data was unavailable or non-existent. In much of the Wyoming area, data from the Lusk study (Hinckley et al., 2009) and COHYST (COHYST, 2010) were used. The constant value of .15 used in the Lusk study was used in the entire Wyoming portion of the model, except the southern portion of Goshen County where COHYST model values were used; these are the same Sy values used in layer 2 (Arikaree). COHYST Western Model Unit Sy were used where there was no data from the Ayers borehole analyses. Values in the study area for the aquifer (layer 1) ranged from just under 0.1 to 0.3, and the average was 0.17 (Figure 17)

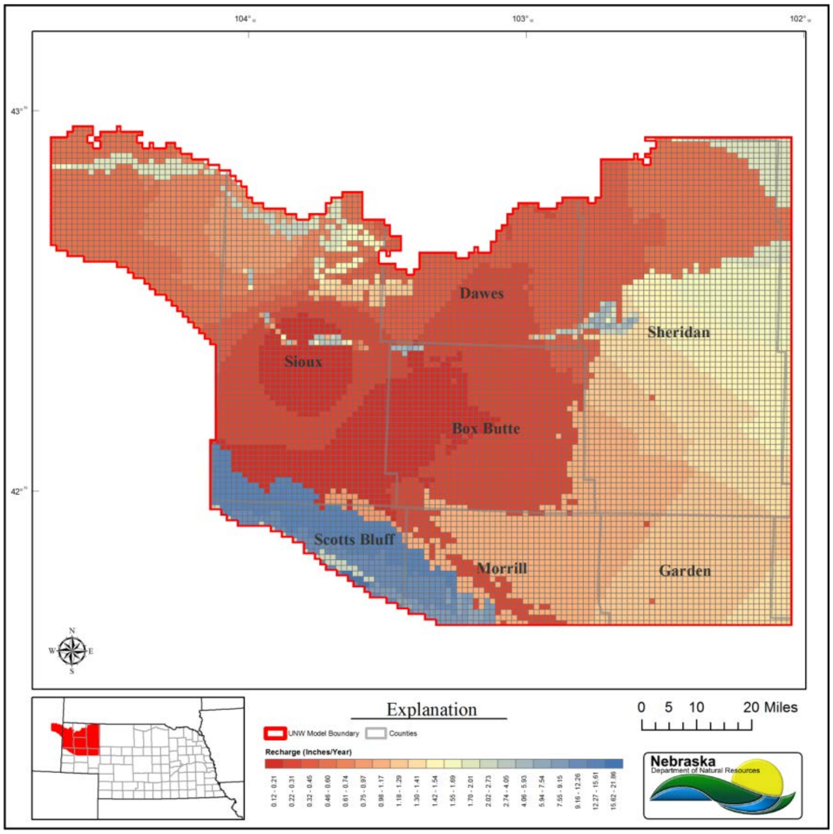


Figure 18. Map of High Plains Aquifer (layer1) recharge in the study area (Steady-State).

4.4 Stresses

4.4.1 Pumping

Since there are no historical pumping records for the irrigators in the basin, the amount of water pumped for irrigation was estimated. The estimation assumed that irrigators are only going to pump what the crops need. What the crops need is dependent on how much naturally occurring precipitation has occurred and the evapotranspiration needs of the crop. In simulating watershed processes, the CROPSIM process incorporates this relationship. Historical precipitation datasets were used and the watershed simulation used the land use data described above to estimate the amount of water that is needed for pumping to meet the amount of water needed for irrigation (or the Net Irrigation Requirement). This requirement is then entered into the groundwater model as pumping and distributed spatially by grid cell in a pattern that mimics the spread of irrigation in the land use datasets. Monthly irrigation requirements were directly caluculated through the assumed irrigation season: May through September.

Much of the pumping data used in the analysis for the Wyoming area of the model was taken from the USGS study done on the Arikaree formation in the area of Lusk County in 1977 (Crist, 1977). Pumping datasets were estimated in the same fashion as for the Nebraska counties, however, due to the lack of a certified acres database or detailed satellite imagery for the area of Wyoming within the study area, the estimates of land use were primarily based on NASS data. Pumping and recharge data created from the CROPSIM process, therefore, should be considered a rough estimate.

4.4.2 Recharge

Recharge for the steady-state model was derived from the CROPSIM process. Estimates were made based on assumptions of land use in the basin prior to human development. For the most part, the assumption was that the area was predominantly grassland and rangeland, although a more considerable amount of agricultural development had occurred along the North Platte River Valley. The use of numerous surface water irrigation canals along the North Platte River resulted in increased recharge values in the southwestern portion of the study area. The runoff and recharge properties that were simulated from the CROPSIM process were a rough characterization of this pre-development period. The values ranged from 0.1 inches per year to nearly 22 inches per year, with an average of 1.5 inches per year (Figure 18).

Transient datasets for recharge were generated using the model CROPSIM. Certified acres datasets, precipitation, land use and soils data, and climate data were used to build a coverage of land use change due to agriculture through the simulation time period. Surface water irrigators diverting portions of the Niobrara River's flows cause induced recharge into the aquifer. Estimates of this recharge were also made through the use of diversion records and an accounting of canal efficiencies through time as measured by Department field staff. Increased recharge due to the application of water from pivot irrigation was also considered. These factors were incorporated into the land use dataset that informs the CROPSIM model. Like pumping data, the recharge information varies month to month based on the variability of precipitation that naturally occurs, as well as human variability related to canal operations and recharge created by canal seepage. Factors like canal recharge were distributed monthly through the assumed irrigation season: May through September.

5 Calibration

5.1 Steady-State

The steady-state model was calibrated with the goal of obtaining aquifer properties that provide stable heads which generally match the water table elevations in the pre-development era. This early water table information is quite rare, so the CSD 1979 water table elevation map and a map created by Souders et al. representing the water table elevation in 1975, were used to compare simulated heads (Souders et al., 1980; CSD, 2012). Stream conductance was adjusted to achieve a rough match for baseflows in the steady-state simulation. Recharge was adjusted as needed through the CROPSIM process. This meant that where heads appear to be significantly off in an area, the parameters in the CROPSIM process were adjusted within limits to achieve a better estimate of recharge in that area. Hydraulic conductivity was adjusted in conjunction with the recharge provided by CROPSIM to achieve a rough steady-state head calibration.

Once the hydraulic conductivity and recharge placed the heads in proximity to the earliest data, the aquifer properties and the initial heads were then imported to the transient model in order to simulate the effects of groundwater development and land use change in the area.

5.1.1 Simulated Water Budget for Steady-State Simulation

The water budget terms for the entire UNW model area are shown in Figure 10. This figure shows the various water budget components represented in the model: Drain, GHB, River, Evapotranspiration; Stream, and Recharge.

For a stable model, the amount of water coming into the model (inflows) should match the amount of water leaving the model (outflows). In this model, inflows are dominated by recharge, and outflows are relatively distributed by drains, GHB, ET, and stream discharge.

5.1.2 Comparison of Measured and Simulated Heads

The simulation of steady-state, or predevelopment, water levels was compared with published water level data from the CSD (CSD, 2012). The steady-state simulation was meant to approximate the water levels before development. The intent was for the steady-state model to provide the starting water level elevation for the transient model, which is intended to simulate change to the predevelopment condition due to human activities such as pumping and land use changes. Since the simulation actually represents water levels that would have been present before any human activities occurred, it is expected that they would not exactly match targets that existed after development in the model area began. Thus, the water levels generated from the steady-state model generally represent the condition in 1960, which is the start of the transient model.

5.2 Transient

Similar to the calibration process for the steady-state model, the simulated head outputs for the transient model were compared with the observed head calibration targets described above. The simulated heads were adjusted by changing the hydraulic conductivity in both the steady-state model and the transient model. Storage parameters were adjusted in the transient simulation to achieve better trend matches.

Recharge and pumping were also viable parameters for adjustment. Since the recharge estimates and input file were created by the CROPSIM process, the CROPSIM model was adjusted to provide better fitting data to the groundwater model. Typically, crop and soil water balance parameters and application efficiencies were adjusted in the CROPSIM process. The calibration of heads in the groundwater model is highly dependent on the data provided by the CROPSIM model. Since the groundwater model and the CROPSIM model are separate, the calibration process between the two was an indirect and iterative process.

When heads achieved a suitable match, the stream package was analyzed to determine the match between the calculated baseflow and the simulated baseflow. If there was too little or too much flow in the streams, pumping and recharge were adjusted (through the CROPSIM process) to better simulate flow.

5.2.1 Simulated Water Budget for Transient Simulation

Figure 9 shows the various water budget components represented in the transient model: Recharge, Evapotranspiration, Constant Head, River, Lake, Drain, GHB, Well, Stream, and Storage.

For a stable model, the amount of water coming into the model (inflows) should match the amount of water leaving the model (outflows). In this model, inflows are dominated by water coming out of storage, and outflows are relatively distributed by ET, drains, GHB, stream discharge, and storage.

5.2.2 Comparison of Measured and Simulated Heads

5.2.2.1 *Box Butte Area*

The Box Butte area has experienced drawdown due to groundwater pumping for over 50 years. This is reflected in the observations that irrigators have taken through time, as well as the maps that the CSD has produced to document water level changes in Nebraska through time.

A selection of hydrographs from the Box Butte region are included to show how the models simulate the head in Box Butte County (Figures 19 and 20). The wells were chosen for the overall length and quality of their record.

5.2.2.2 *Mirage Flats Area*

The Mirage Flats area has also experienced drawdown due to groundwater pumping in recent years. This is reflected in the observations that irrigators have taken through time, as well as the maps that the CSD has produced to document water levels in Nebraska through time. While the amount of drawdown is less than in the Box Butte area, it is still significant.

Figures 21 and 22 include a selection of hydrographs from the Mirage Flats region to show how the model simulates the head in the area. The wells were chosen for the overall length and quality of their record.

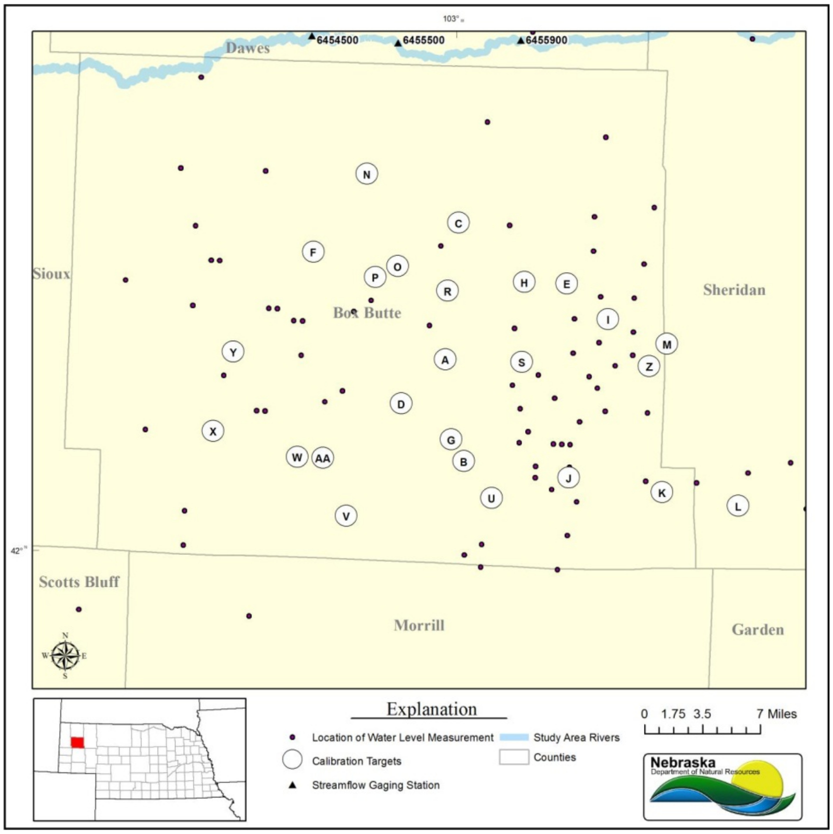


Figure 19 Map showing calibration targets in Box Butte County.

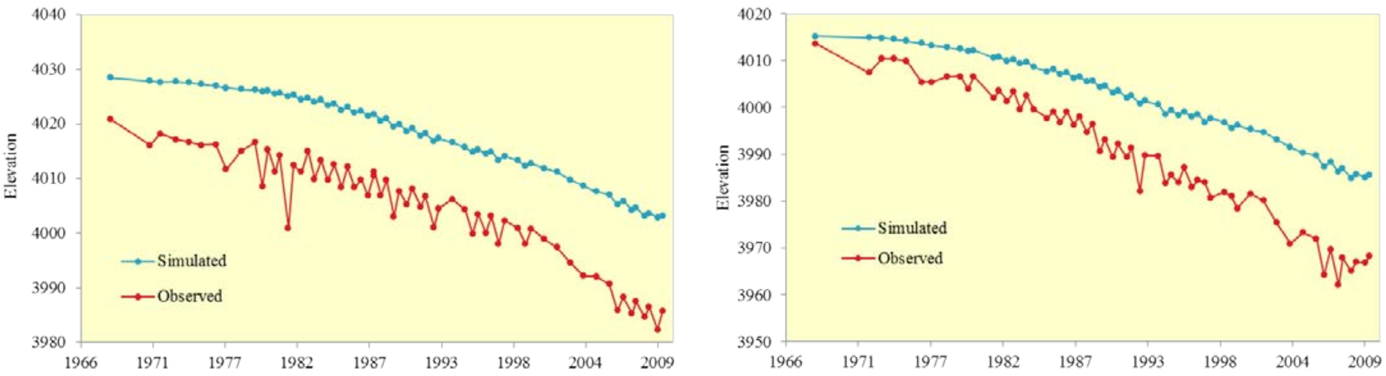
The tarets are labeled with letters, each of which is referred to in Table 3 and in the observed vs. simulated streamflow charts shown in Figure 20.

Calibration Target	USGS Station Number	Calibration Target	USGS Station Number
A	421113103000001	**M**	421235102445701
B	420628103021901	**N**	422052103062500
C	421831102592400	**O**	421554103034501
D	420834103032001	**P**	421505103051701
E	421516102520901	**Q**	421332103070801
F	421627103094500	**R**	421456103000001
G	420703102594901	**S**	421117102545901
H	421514102544401	**T**	421051103000000
I	421321102490101	**U**	420355102564001
J	420524102511301	**V**	420236103065901
K	420419102444902	**W**	420530103104001
L	420409102392101	**X**	420646103163701

Table 3. Box Butte County calibration targets and associated USGS Station Numbers.

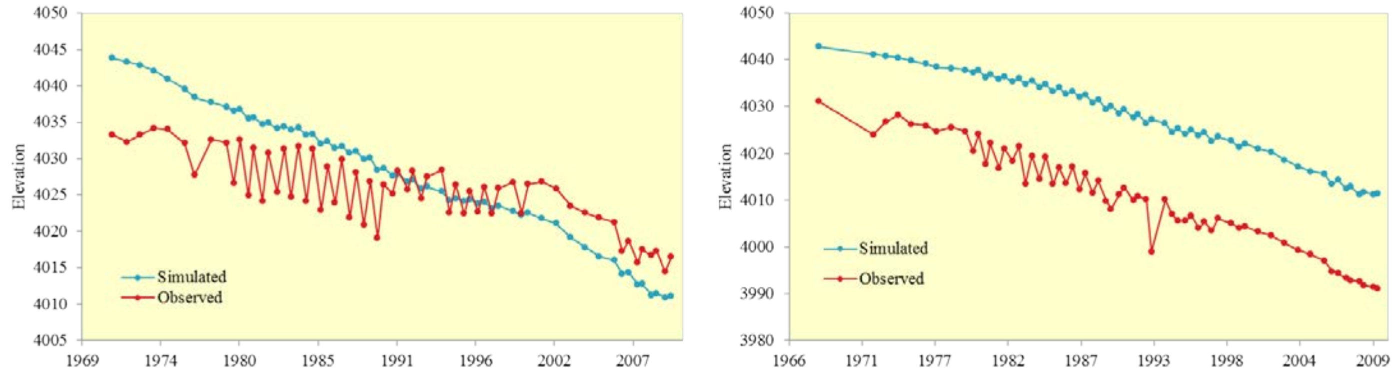
(A) USGS Site 421113103000001

(B) USGS Site 420628103021901



(C) USGS Site 421831102592400

(D) USGS Site 420834103032001



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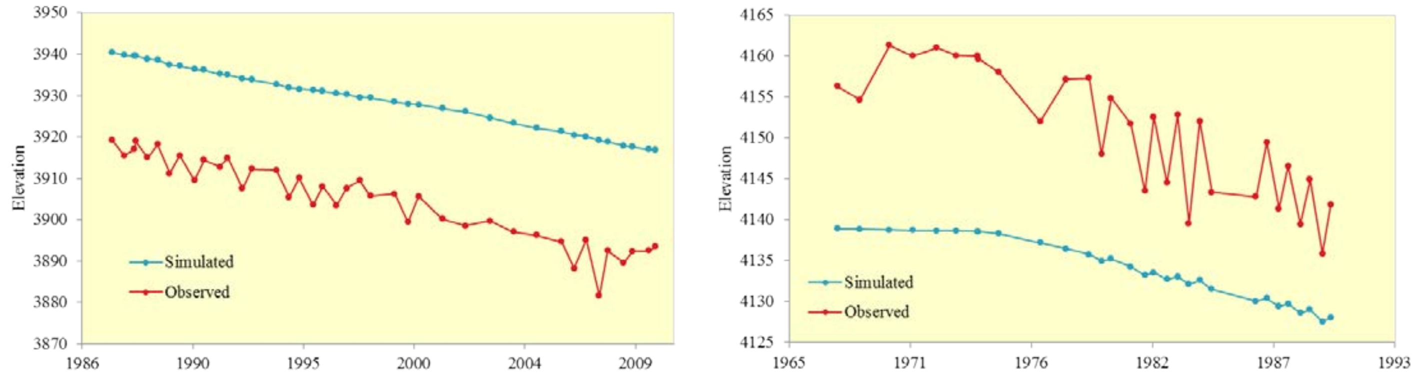

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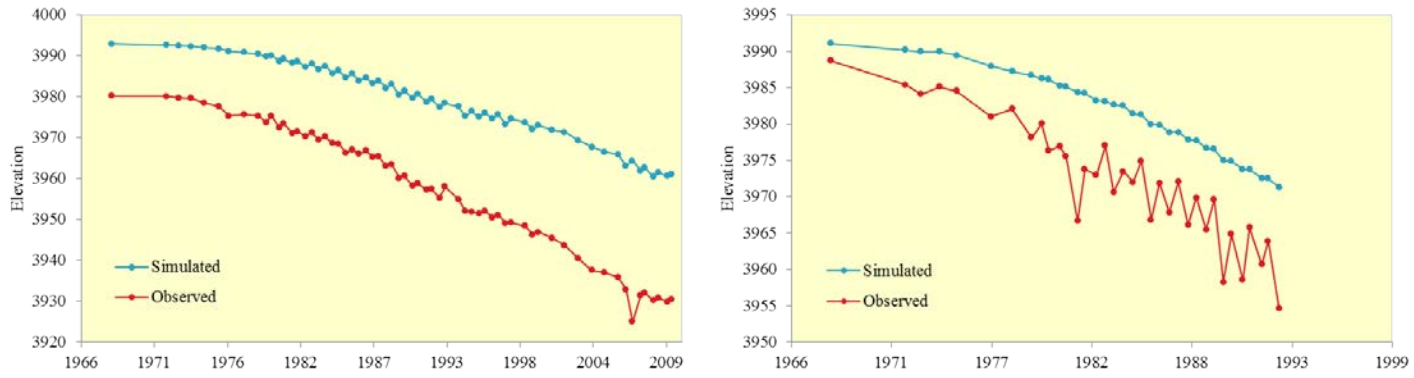
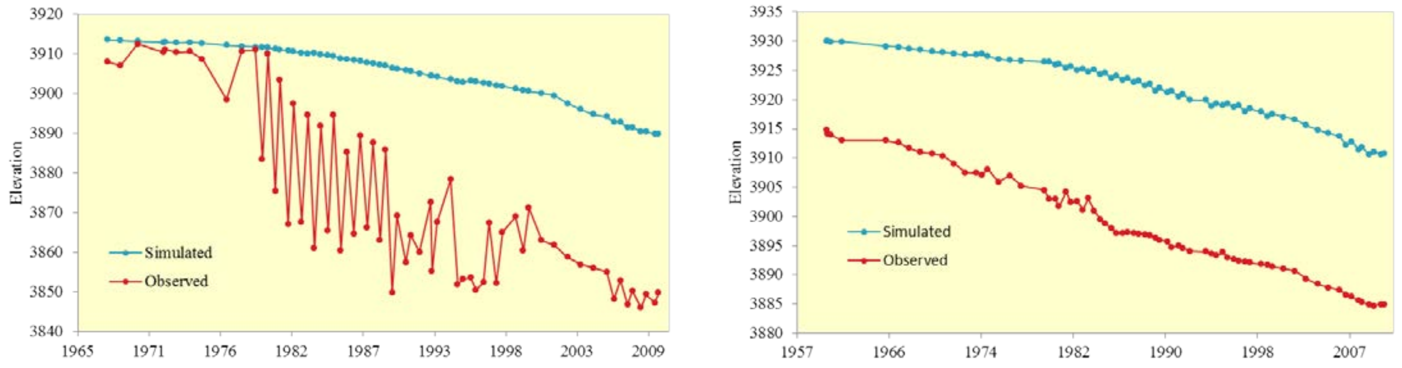


Figure 20 (Page 1 of 3). Panel of charts showing observed vs. simulated streamflow for each of the Box Butte calibration targets shown in Figure 19 and Table 3.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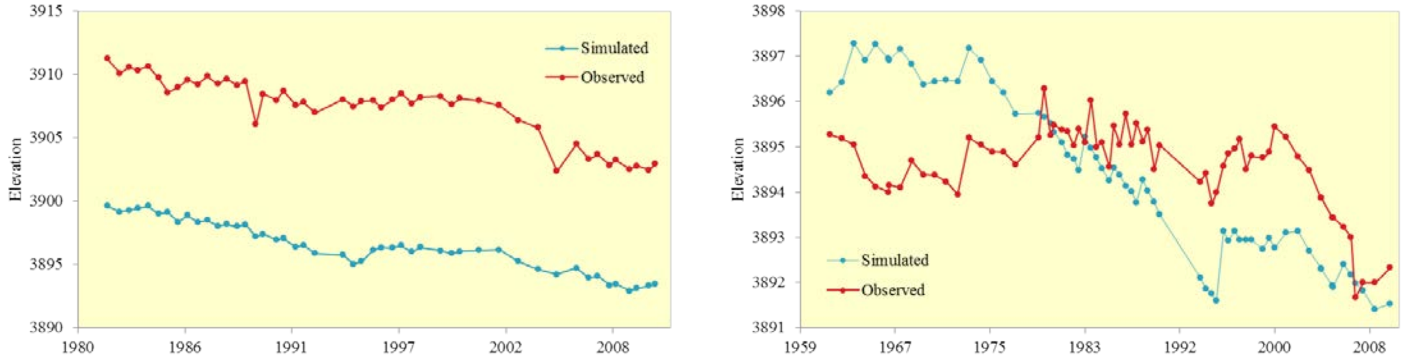
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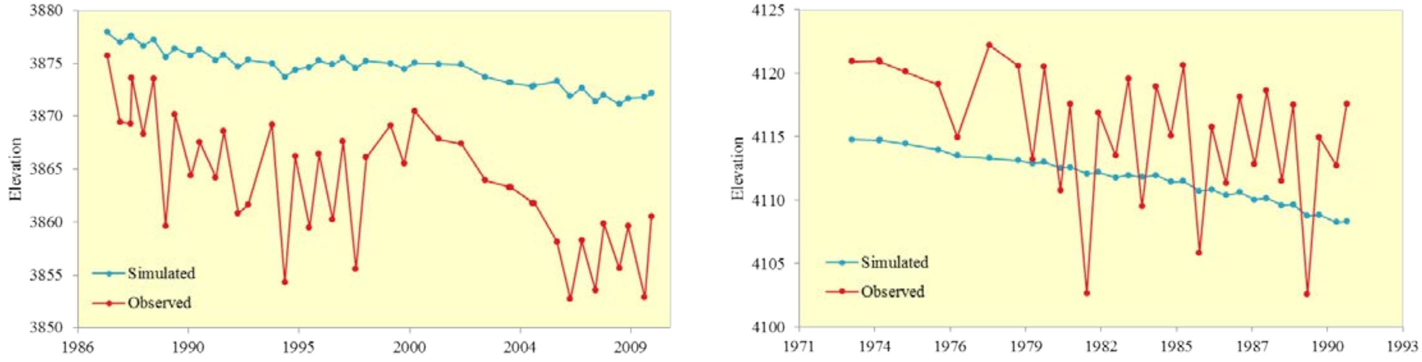
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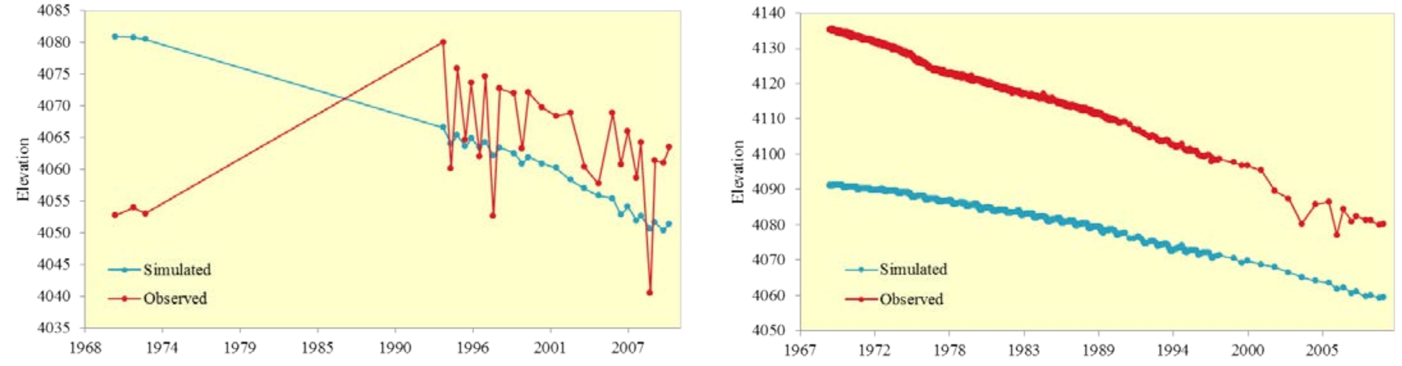
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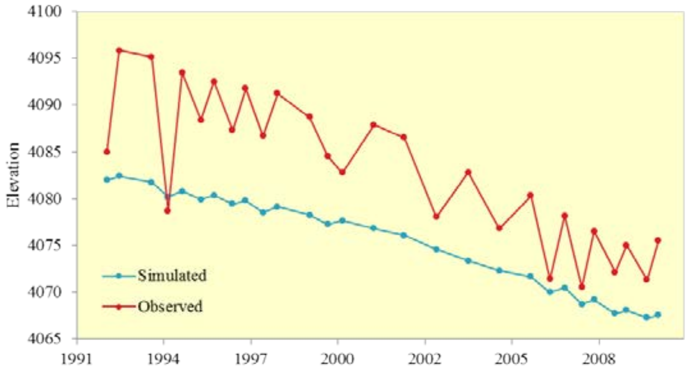
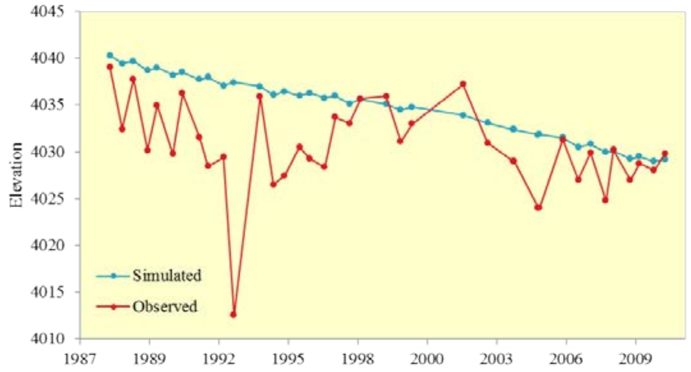
Figure 20 (Page 2 of 3). Panel of charts showing observed vs. simulated streamflow for each of the Box Butte calibration targets shown in Figure 19 and Table 3.



(Q) USGS Site 421332103070801



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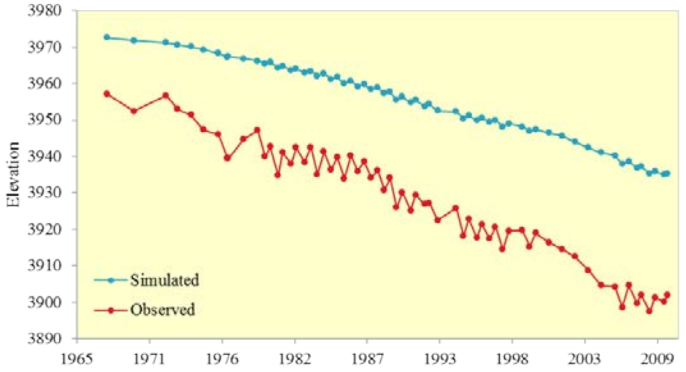

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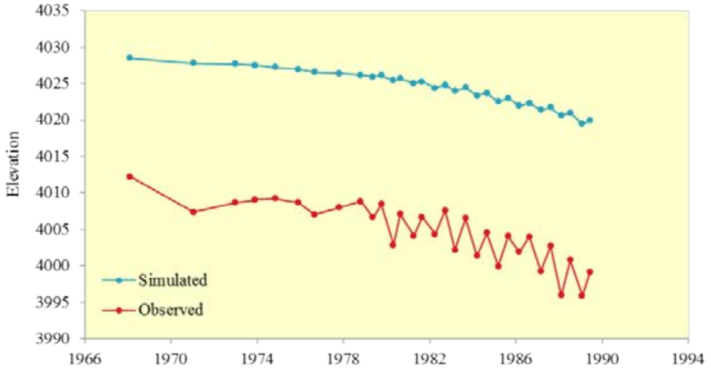

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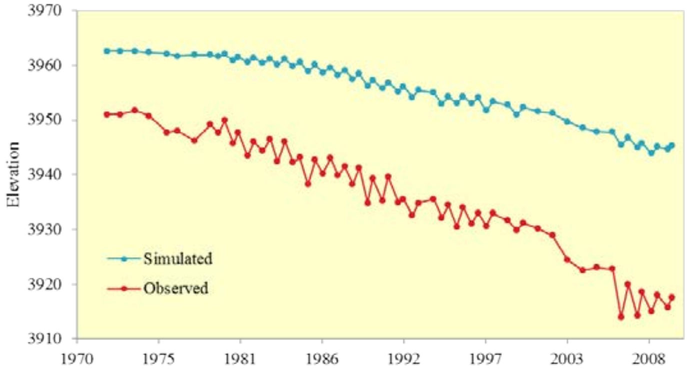

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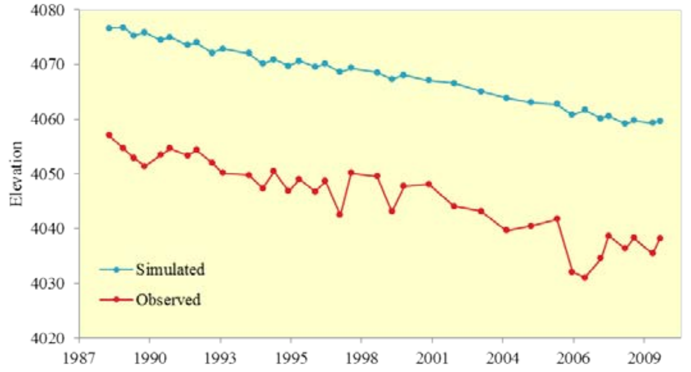

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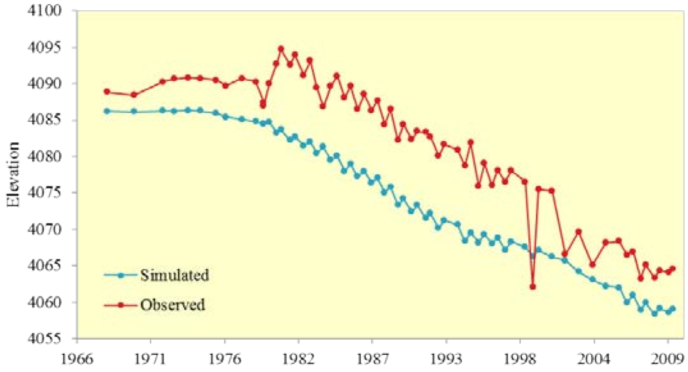

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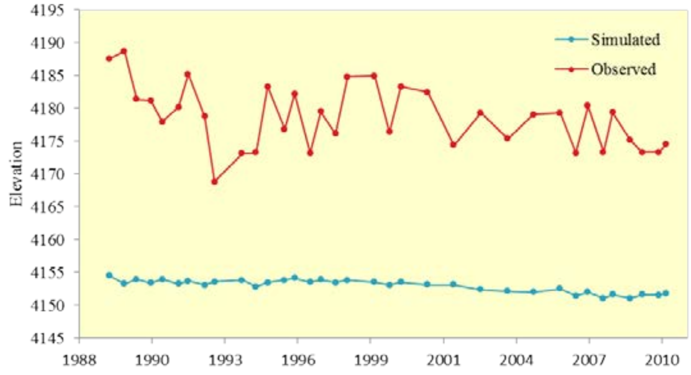


(X) USGS Site 420646103163701

Figure 20 (Page 3 of 3). Panel of charts showing observed vs. simulated streamflow for each of the Box Butte calibration targets shown in Figure 19 and Table 3.

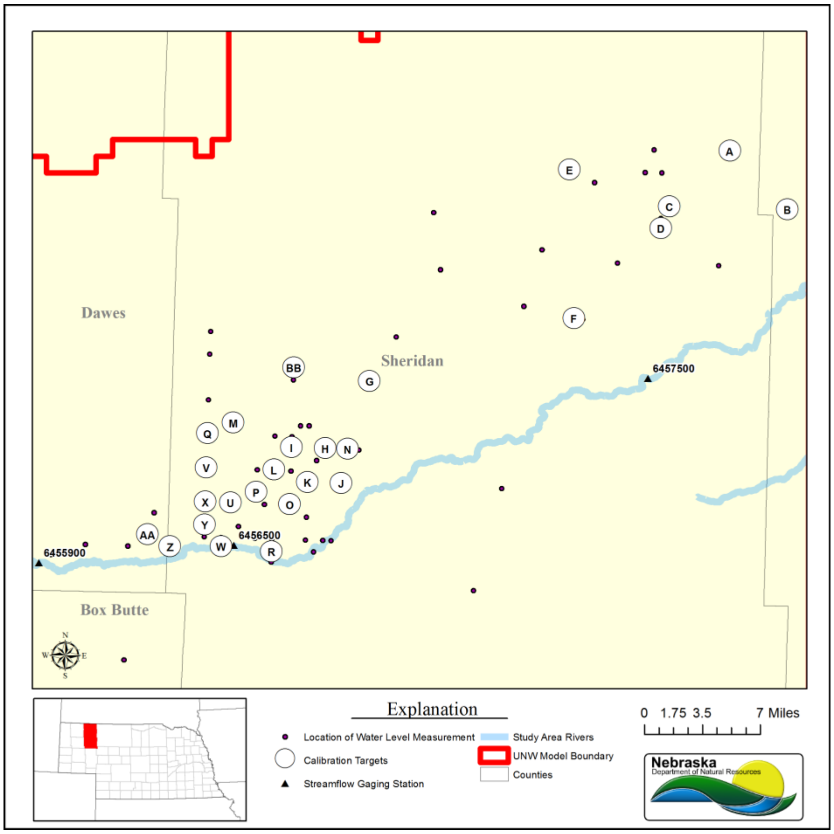


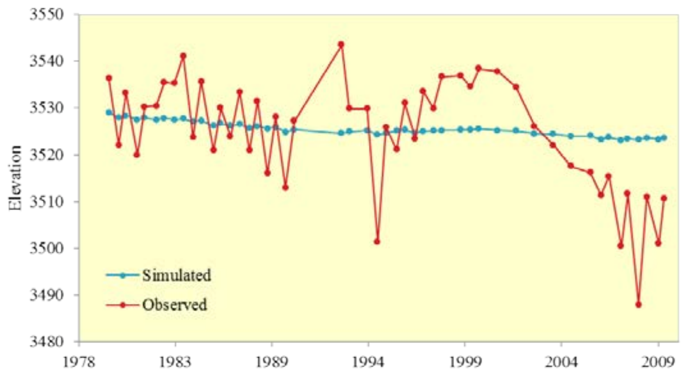
Figure 21. Map showing calibration targets in the Mirage Flats area of Sheridan County.

The tarets are labeled with letters, each of which is referred to in Table 4 and in the observed vs. simulated streamflow charts shown in Figure 22.

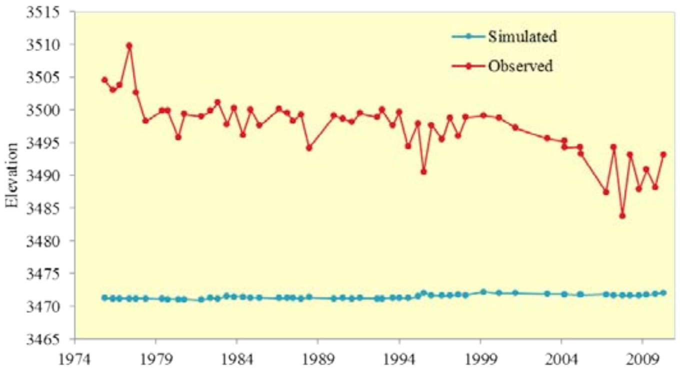
Calibration Target	USGS Station Number	Calibration Target	USGS Station Number
A	425057102071601	**O**	423131102374801
B	424747102030601	**P**	423215102402201
C	424743102114801	**Q**	425046102125901
D	424722102120101	**R**	422851102393301
E	424928102183801	**S**	422940102402201
F	424145102182501	**T**	423034102415001
G	423811102323101	**U**	423124102422501
H	423415102352301	**V**	423317102435801
I	423415102380301	**W**	422940102430101
J	423254102342601	**X**	423127102440701
K	423222102364601	**Y**	423032102435401
L	423320102391501	**Z**	422924102461701
M	423543102421301	**AA**	422942102472801
N	423150102342601	**BB**	422850102522301

Table 4. Mirage Flats calibration targets and associated USGS Station Numbers.

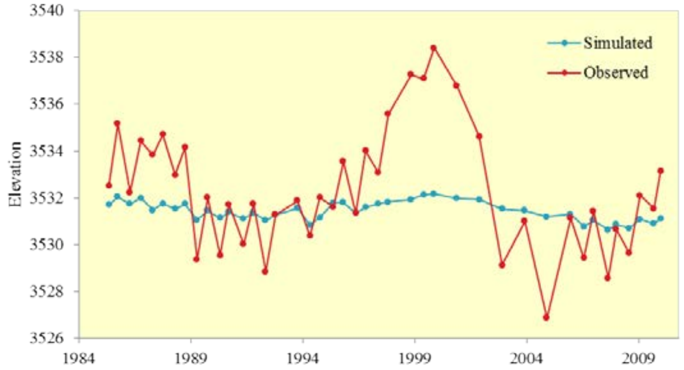
(A) USGS Site 425057102071601



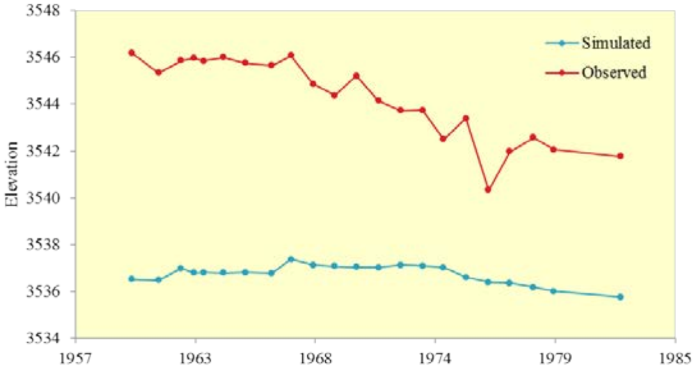
(B) USGS Site 424747102030601



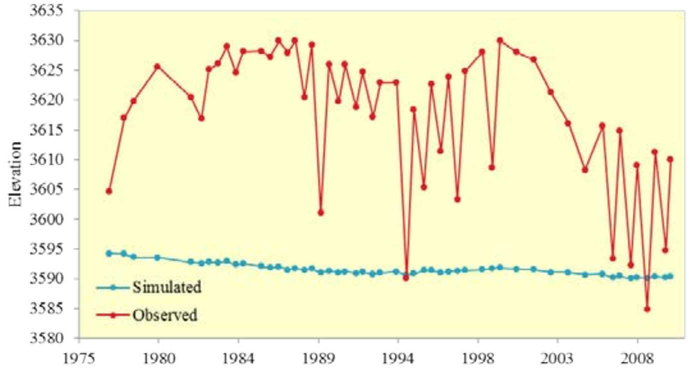
(C) USGS Site 424743102114801



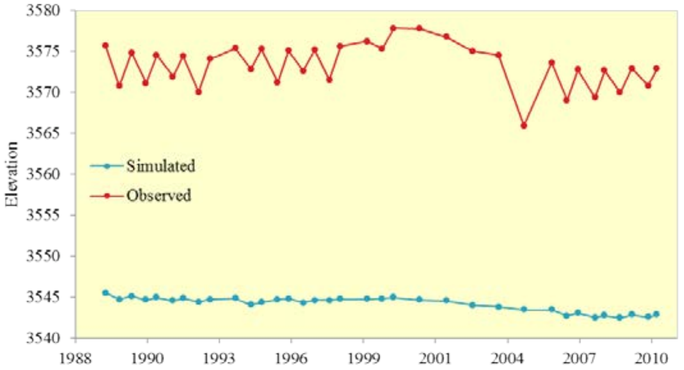
(D) USGS Site 424722102120101



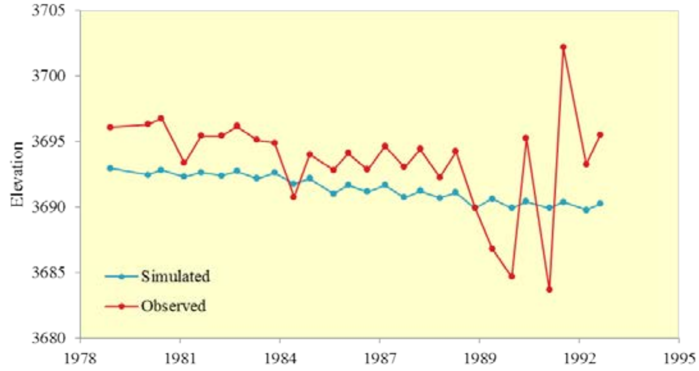
(E) USGS Site 424928102183801



(F) USGS Site 424145102182501



(G) USGS Site 423811102323101



(H) USGS Site 423415102352301

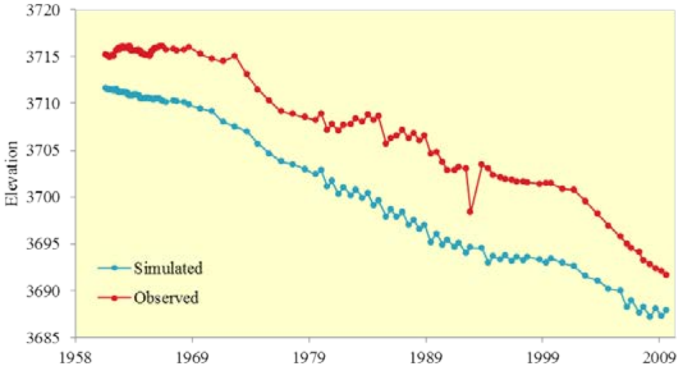
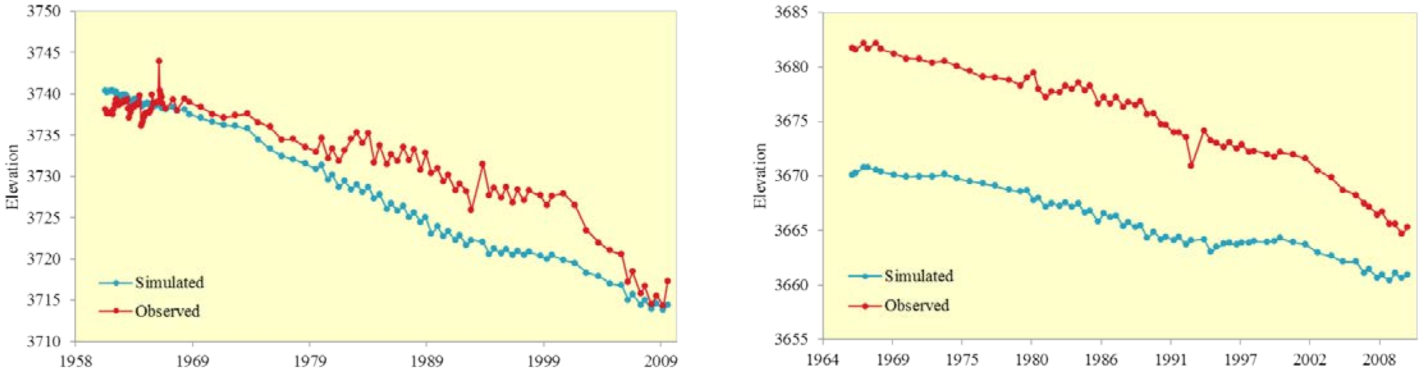


Figure 22 (Page 1 of 4). Panel of charts showing observed vs. simulated streamflow for each of the Mirage Flats calibration targets shown in Figure 21 and Table 4.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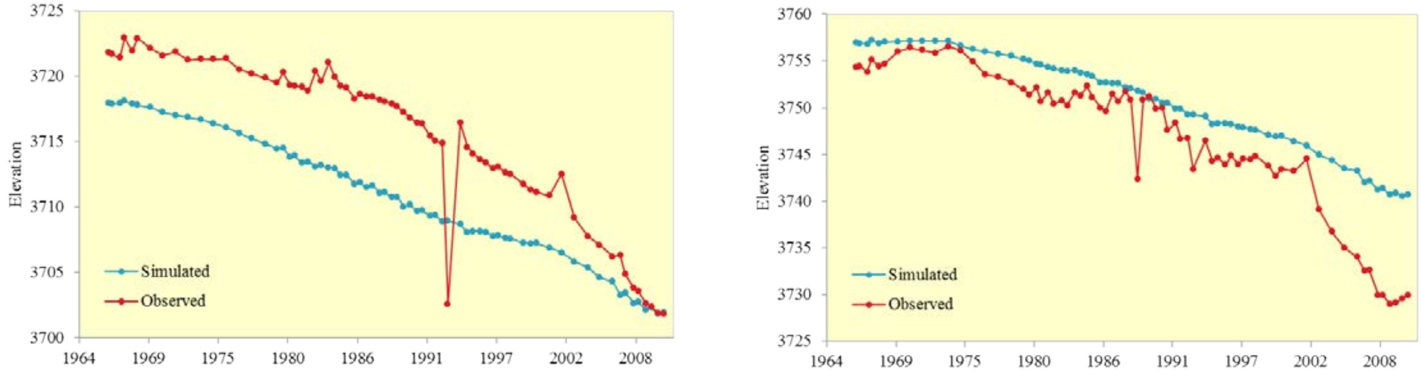
(J) USGS Site 423254102342601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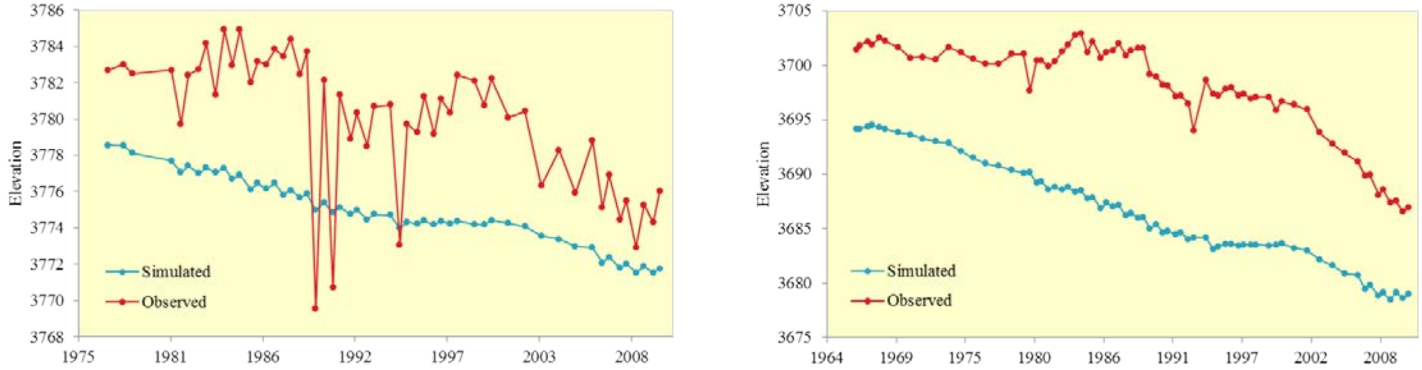
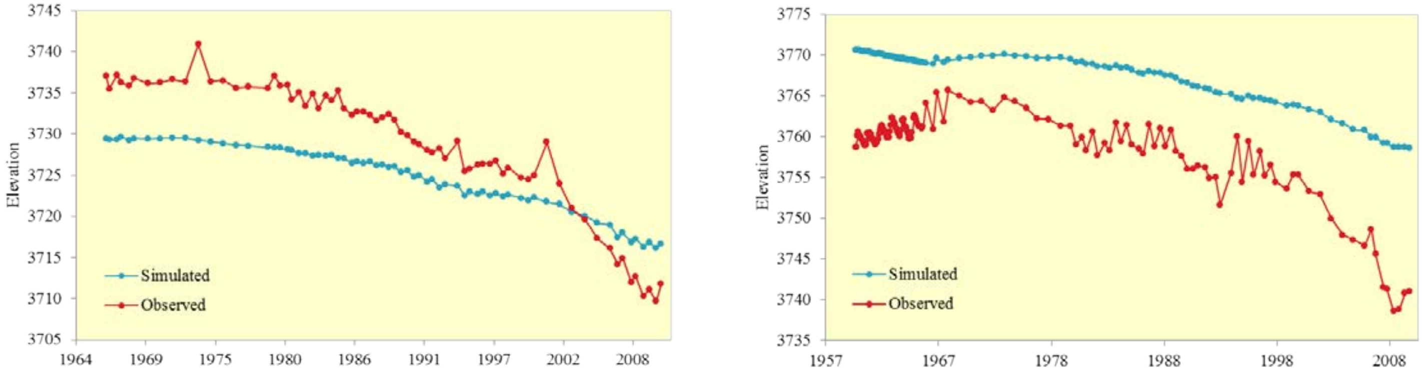
(L) USGS Site 423320102391501

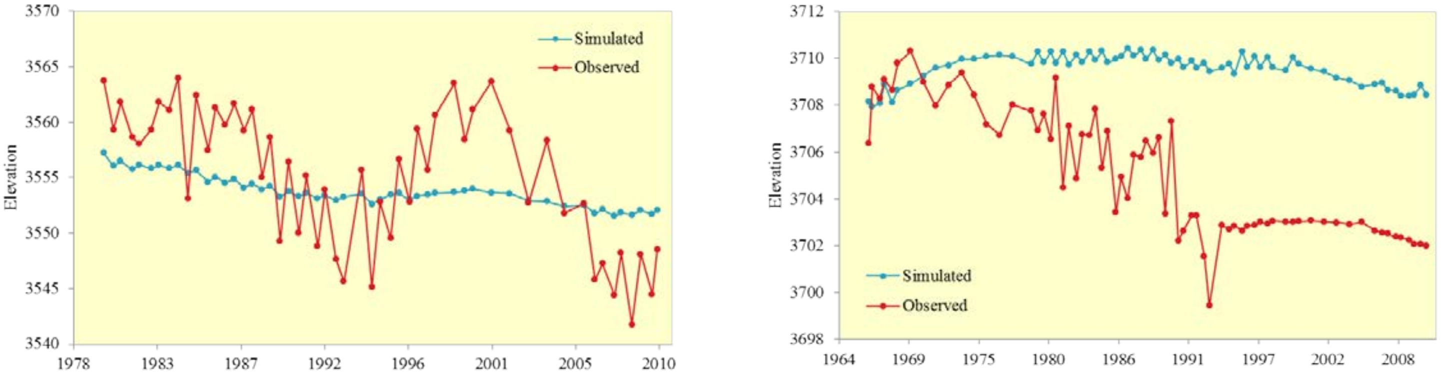

(M) USGS Site 423543102421301

(N) USGS Site 423150102342601


(O) USGS Site 423131102374801

(P) USGS Site 423215102402201

Figure 22 (Page 2 of 4). Panel of charts showing observed vs. simulated streamflow for each of the Mirage Flats calibration targets shown in Figure 21 and Table 4.



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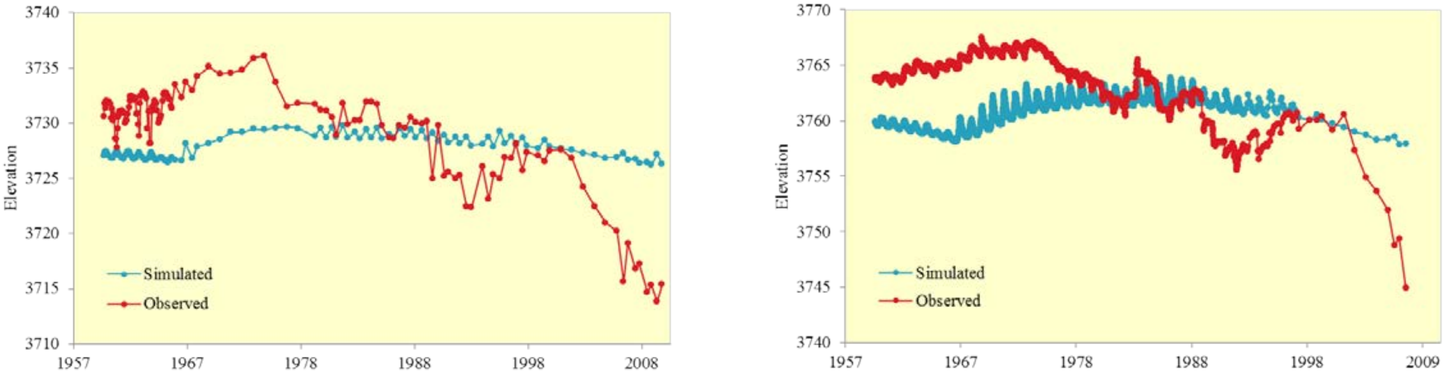
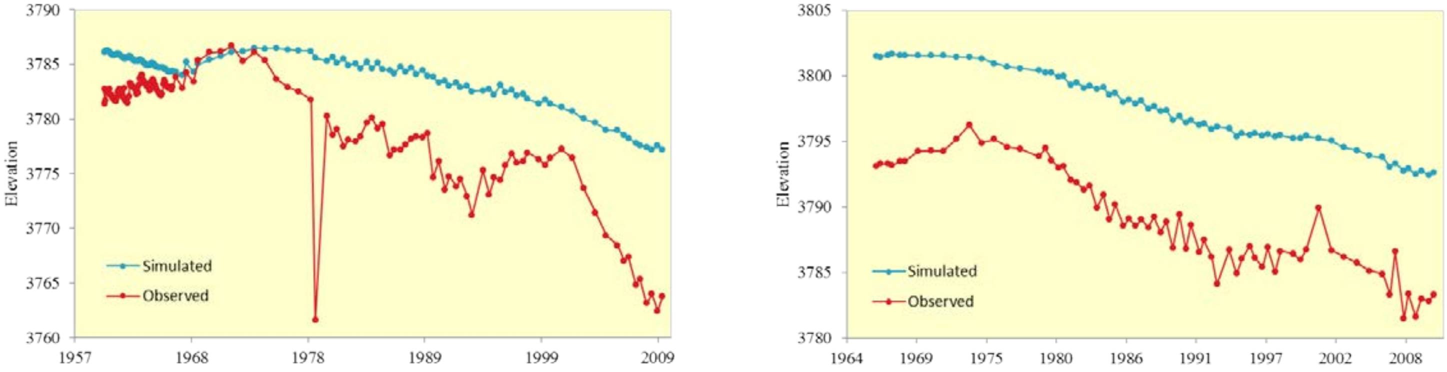
(R) USGS Site 422851102393301



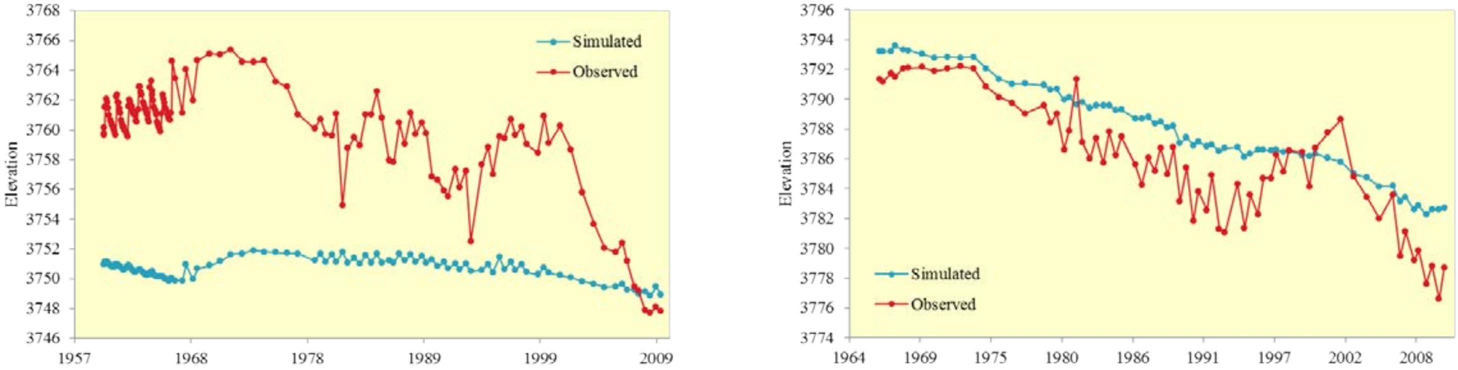
(S) USGS Site 422940102402201

(T) USGS Site 423034102415001



(U) USGS Site 423124102422501

(V) USGS Site 423317102435801



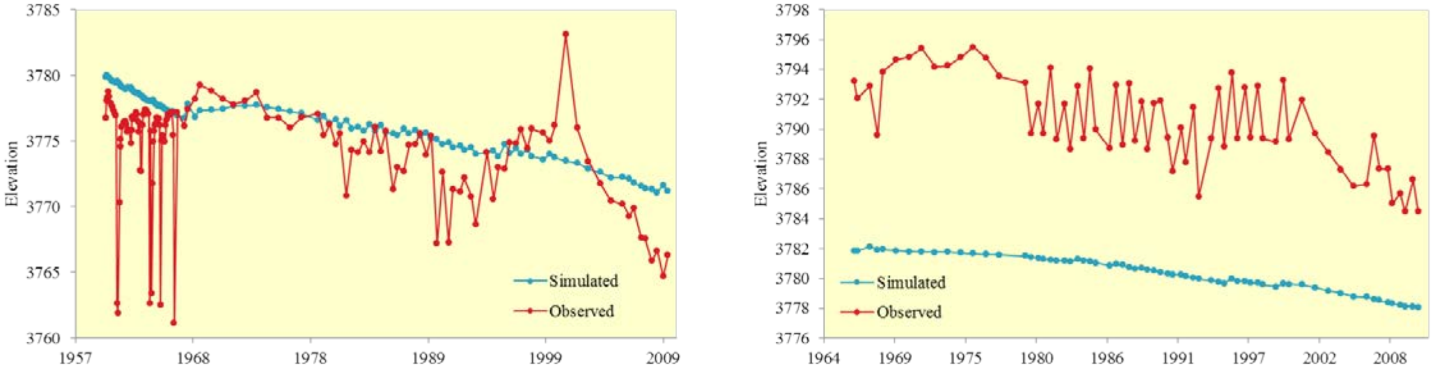
(W) USGS Site 422940102430101

(X) USGS Site 423127102440701

Figure 22 (Page 3 of 4). Panel of charts showing observed vs. simulated streamflow for each of the Mirage Flats calibration targets shown in Figure 21 and Table 4.

(Y) USGS Site 423032102435401

(Z) USGS Site 422924102461701



(AA) USGS Site 422942102472801

(BB) USGS Site 422850102522301

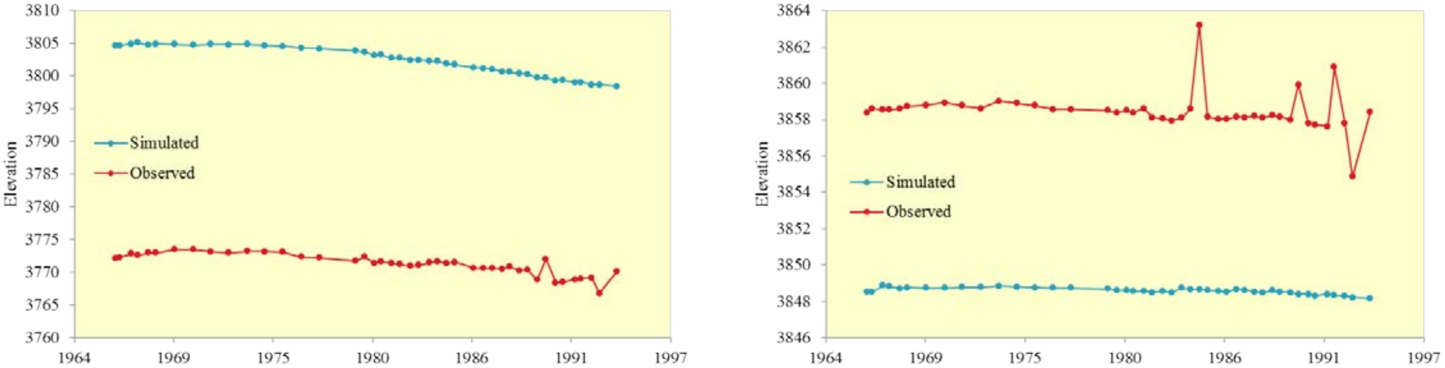


Figure 22 (Page 4 of 4). Panel of charts showing observed vs. simulated streamflow for each of the Mirage Flats calibration targets shown in Figure 21 and Table 4.

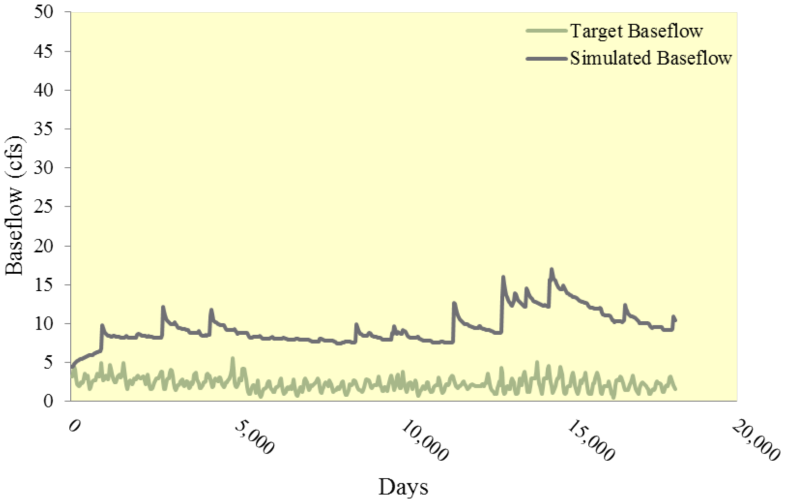


Figure 23. Simulated baseflow versus target baseflow at the stateline gage.

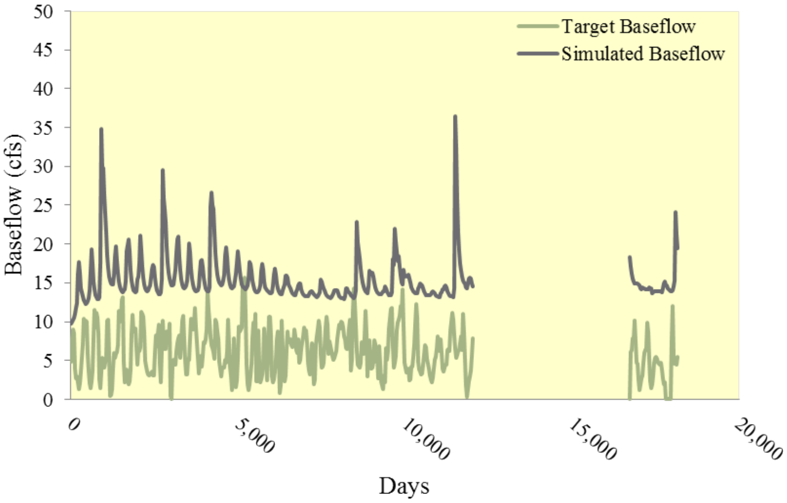


Figure 24. Simulated baseflow versus target baseflow gain in the stateline to Agate reach.

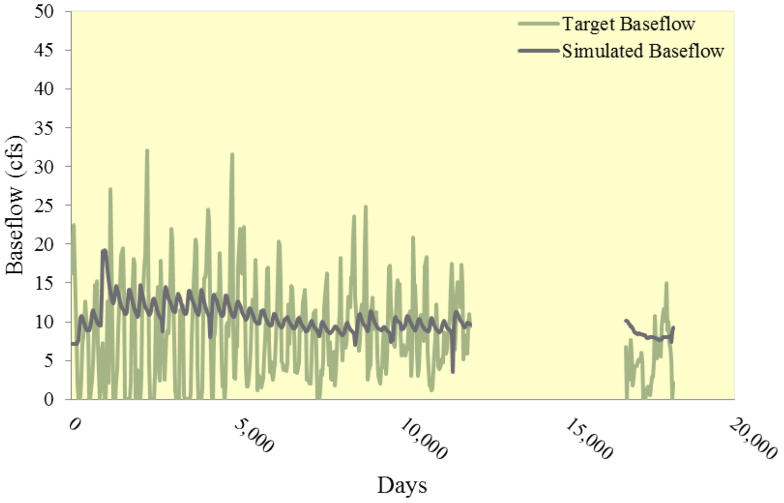


Figure 25. Simulated baseflow versus target baseflow gain in the Agate to above Box Butte reach.

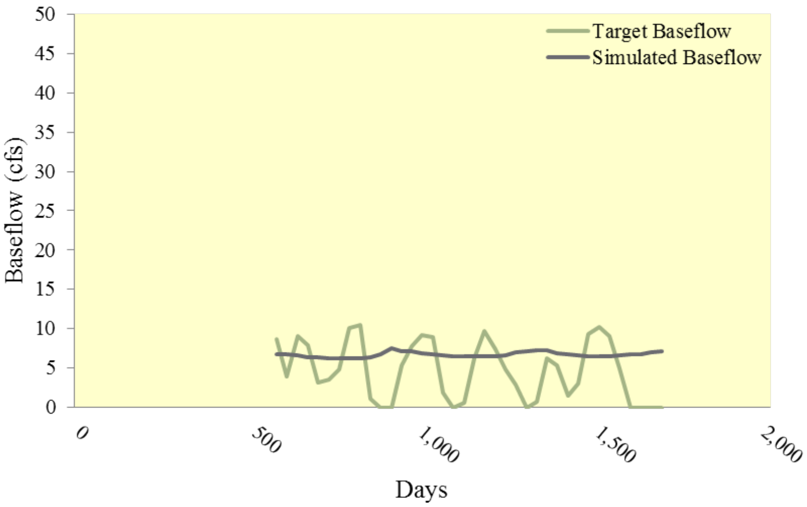


Figure 26. Simulated baseflow versus target baseflow gain in the Duncan to Hay Springs reach.

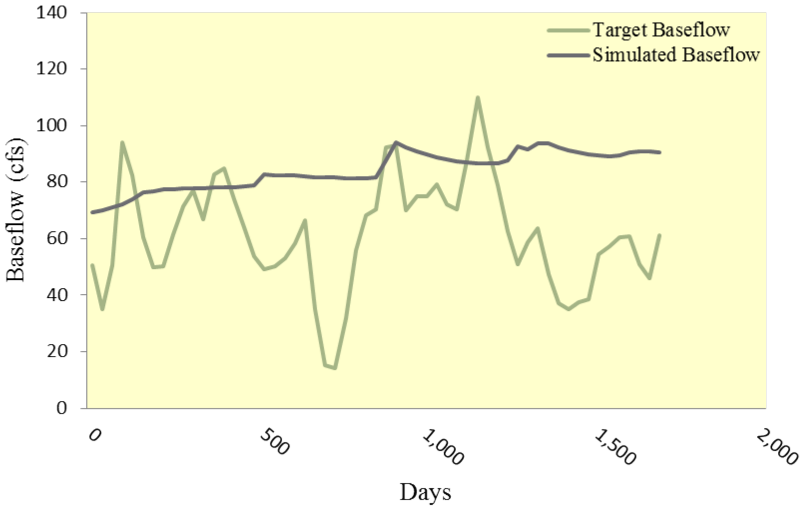


Figure 27. Simulated baseflow versus target baseflow gain in the Hay Springs to Gordon reach.

5.2.3 Comparison of Measured and Simulated Baseflows

The simulation of baseflow, which resulted from the model runs, is compared with the target baseflow, which is the calculated estimate for baseflow separation derived from the BFI program. This comparison was made for baseflow at the stateline gage (Figure 23). At all other gages, comparisons were made using the gain between two gages (Figures 24-27).

Generally, the main reaches of interest were the reach upstream of Box Butte Reservoir (from the stateline gage to the gage above Box Butte), and the reach downstream of Box Butte Reservoir (from the below Box Butte gage to the Gordon gage). Comparisons of these main reaches can be seen in Figures 28 and 29.

While the fit at the stateline is a little high, the actual amount of water is small, so it does not affect much of the calibration downstream. Figure 24 shows the simulated gain from the stateline to Agate to be slightly higher than the target values. Possible reasons for this include: too much recharge in that area of the model, not enough groundwater ET, or heads that are too high. Since recharge is an output of the CROPSIM process, the land use characteristics in this reach may need to be revisited. The area may exhibit more ET than was modeled due to the fact that the river valley in that reach is an area where visible seeps and wetlands occur frequently. Heads in the area are difficult to estimate due to the very limited amount of data.

Inversely, the Agate to above Box Butte reach is slightly low. There could be several reasons for this (same as those outlined above), but also including the fact that the aquifer may be slightly more connected to the stream than modeled.

The upstream reach as a whole looks to be a representative match (Figure 28). Simulated baseflow downstream of the Box Butte Reservoir also shows a reasonable match to observations. While the overlapping records at the Duncan to Hay Springs reach, and the Hay Springs to Gordon reach, were shorter than those observed in other reaches, the simulated baseflows appeared to match well (Figures 26 and 27). The simulated baseflows matched the observations well in the whole downstream reach (Figure 29). The simulation does show a gradual decline in gain through time, suggesting that the modeled groundwater development is causing a shift.

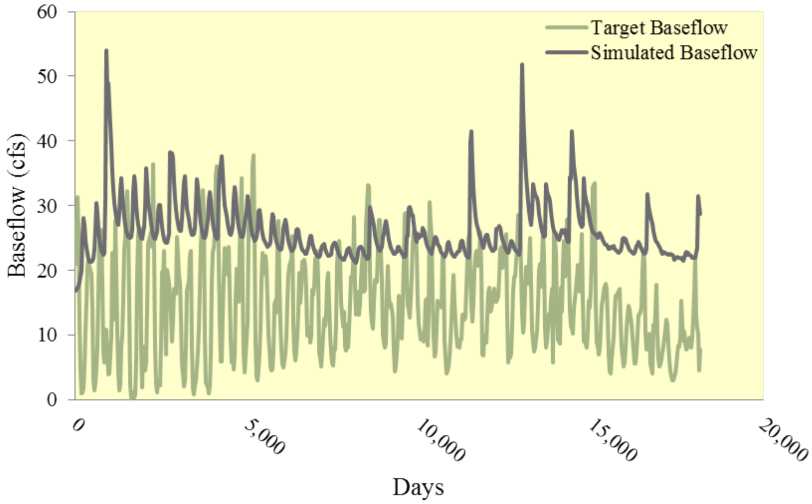


Figure 28. Simulated baseflow versus target baseflow gain in the stateline to above Box Butte reach.

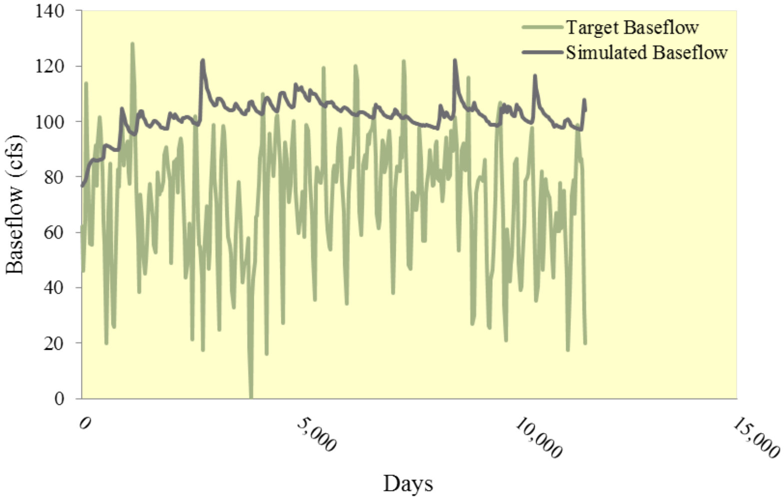


Figure 29. Simulated baseflow versus target baseflow gain in the above Box Butte to above Gordon reach.

6 Discussion and Conclusion

In order to study the hydrology of the UNW region, a numerical groundwater model was constructed using MODFLOW in conjunction with the best available datasets for topology, hydrogeology, and surface water. Land use modeling was also included in this effort in order to investigate changes over time in the High Plains Aquifer as a result of recharge and pumping related to human activities. These changes through time were the main stresses to the aquifer that this model sought to explore.

The effects of recharge and pumping associated with human activity were compared to historical measurements in order to assess surface and groundwater interactions. The model was calibrated through the adjustment of CROPSIM results and aquifer properties in order to create simulated flows in the model that captured the magnitude and dynamics of actual flows which have been measured through history. As shown in the head calibration graphs (Figures 20 and 22), and the baseflow calibration graphs (Figures 23 through 29), this model does have the ability to simulate historic conditions and is a good representation of the regional flow system.

Future applications of the model include: quantification of the water supply in the basin, quantification of the depletions to the baseflow component of Niobrara River flow due to increased pumping over the past 50 years, and an evaluation of the impact of proposed management scenarios to the river’s flow.

Improvements to the model calibration may be achieved in the future through additional constraints on pumping rates applied to the CROPSIM model. This will be more easily achieved through the use of metered pumping volume records, which are now being collected over much of the study area.

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