Project Completion Report

Box Butte County – Niobrara River Numerical Groundwater Flow Model

Nebraska Department of Natural Resources Task Orders #5 and #6

Submitted by:

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Executive Summary

Results obtained from the studies conducted under Nebraska Department of Natural Resources' Task Order numbers 5 and 6 are presented in this report and in electronic files contained in the attached CD. The main objective of these studies was to determine the effect, if any, of large-scale regional pumping on the base flow of the Niobrara River. Task Order #5 involved the construction and implementation of a groundwater-flow model to simulate hydrogeologic and hydraulic conditions, including groundwater extraction by large-capacity wells, for Box Butte County and the surrounding region. Task Order #6 was a study of the upper reaches of the Niobrara River to obtain estimates of stream-bed hydraulic conductivity to be used as input to the modeling effort.

The groundwater-flow model was calibrated to predevelopment by primarily adjusting recharge flux through a trial-and-error process until a reasonable fit was obtained to the observed water table configuration of 1938. Once calibrated to predevelopment heads, transient simulations were run to model the change in heads due to pumping for the time period between 1938 and 2005. Results from these simulations were compared with observed heads for available years.

After satisfactory results were obtained from the transient simulations with all large-capacity wells in the model domain were pumping, two additional scenarios were tested. These were simulations where all wells were turned off and where only those well in Box Butte County and its proximity were active. The computer program ZONEBUDGET, which computes the water budget for user-defined zones, was run coincident with all simulations. Both head and water budget computation results were then used to determine the effect of pumping on the base flow the Niobrara River.

Based on model results, reductions in the base flow of the Niobrara River is due primarily to localized pumping effects, rather than from groundwater extraction on a regional scale. A comparison of simulated outflow values for selected reaches of the Niobrara River indicates that 1) flow characteristics in the uppermost part of the basin did not change greatly over the period of pumping indicating that base flow is not significantly reduced by large-scale pumping, 2) significant changes in base flow appear to have occurred after about 1960 in the middle and lower reaches, 3) the maximum change in flow for the middle reach due to all wells pumping is 19.6% and only 4.4% for Box Butte wells , both maximum reductions occur at the end of the 2005 pumping season, 4) the maximum change in flow for the lower reach is about 24.4% for all wells and only 2.5% for Box Butte wells, again, both occur at the end of the 2005 pumping season. Overall, the Niobrara River appears to be a gaining stream along most of its flow path, with the exception of the uppermost part of the basin.

The conclusion is that the affects of large-scale regional pumping appears to not impact base flow in the Niobrara River to any significant degree. Rather, localized pumping, especially where irrigation wells are situated near the river, reduces base flow on the order of 20% to 25%. For the most part, the Niobrara River valley is somewhat isolated from the extensive pumping taking place in Box Butte County. The upper reach is sufficiently distance from the pumping center that the cone of depression has little effect on the water table. Much of the middle reach transects units of the White River group that are considered to be nearly impermeable, and thus, provide a hydrogeologic barrier, preventing the northward expansion of the cone of depression. Pumping along the lower reach of the Niobrara River has a much greater influence on base flow reduction simply due to the proximity of the extraction wells to the river.

Introduction

Box Butte County and the surrounding area have a relatively long history of groundwater pumping for agricultural purposes. Irrigation utilizing groundwater began about 1938 with the installation of a handful of wells. By 1950 the number of irrigation wells had grown to around 90 and by 1970 the number of wells exceeded 500. During the following decades the number of irrigation wells increased dramatically to nearly 2000 wells currently in operation. As a consequence, the continual use of groundwater over the past 68 years has resulted in a significant drawdown cone beneath a large portion of Box Butte County.

Concern has been raised regarding the potential affect of pumping in the region on the flow within a part of the upper Niobrara River basin. To address this concern, field work was conducted to determine river bed hydraulic conductivity (DNR Task Order #5) in conjunction with numerical groundwater flow model studies (DNR Task Order #6) in an effort to quantify the relationship between the large-scale groundwater withdrawal occurring in the area and base flow within the upper reaches of the Niobrara River. Results of this study are presented in this report and accompanying appendices and electronic files.

Physical Description of the Niobrara River

Stream Flow Characteristics

A number of U.S. Geological Survey (USGS) stream gauging stations have been established along the upper reaches of the Niobrara River. Those of interest to this study are listed in Table 1, along with the years of data available from the USGS national stream-flow database and the Nebraska Department of Natural Resources. Appendix A contains hydrographs

of monthly stream flow in cubic feet per second (cfs) for the stations listed in Table 1. The time axis for all hydrographs is of the same length (in months beginning in 1931) so that comparisons of stream-flow rates between stations over time can be made.

USGS Gauging Station Name	**USGS Station Number**	**Longitude West**	**Latitude North**	**Years of Record**
Wyoming-Nebraska Border	06454000	104.0592	42.65667	1955 to Present
Agate Fossil Beds	06454100	103.7911	42.42278	1957 to 1992
Above Box Butte Reservoir	06454500	103.1708	42.45972	1946 to Present
Below Box Butte Reservoir	06455500	103.0681	42.45694	1946 to Present
Near Dunlap	06455900	102.9236	42.46250	1931 to 1971
Near Hay Springs	06456500	102.6944	42.48333	1950 to 1964
Near Gordon	06457500	102.2111	42.63333	1945 to 1994

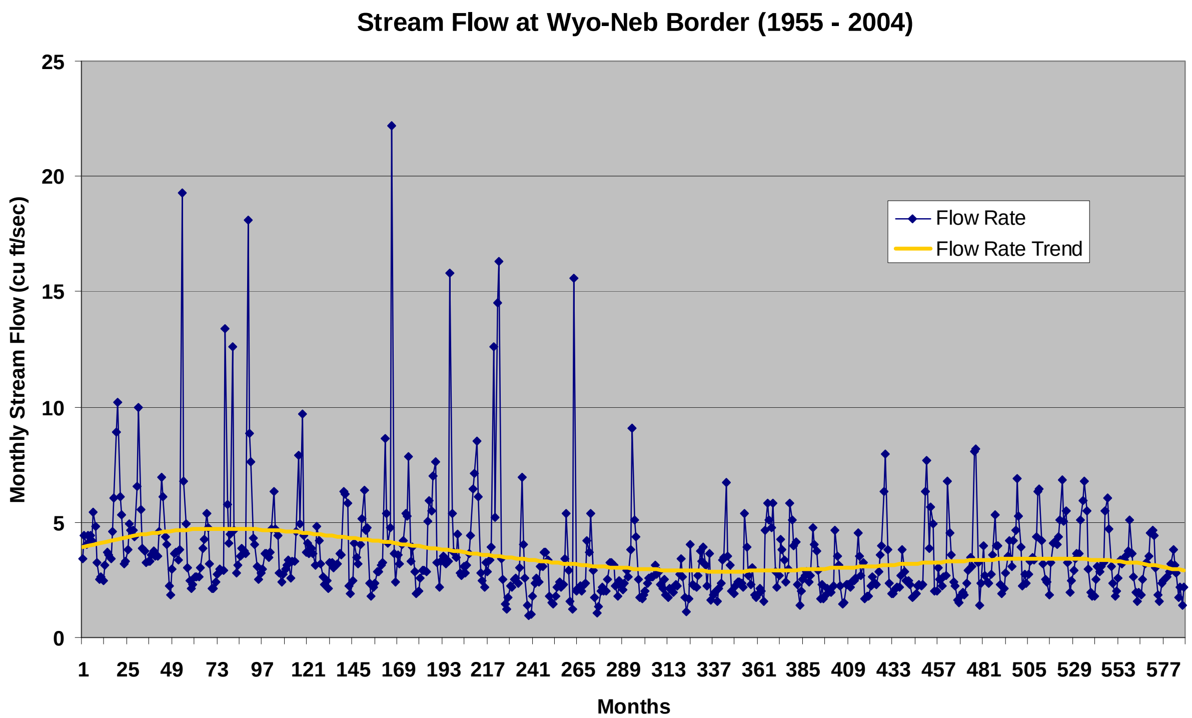
Table 1. Years of record for USGS stream gauging stations within the upper Niobrara River basin.

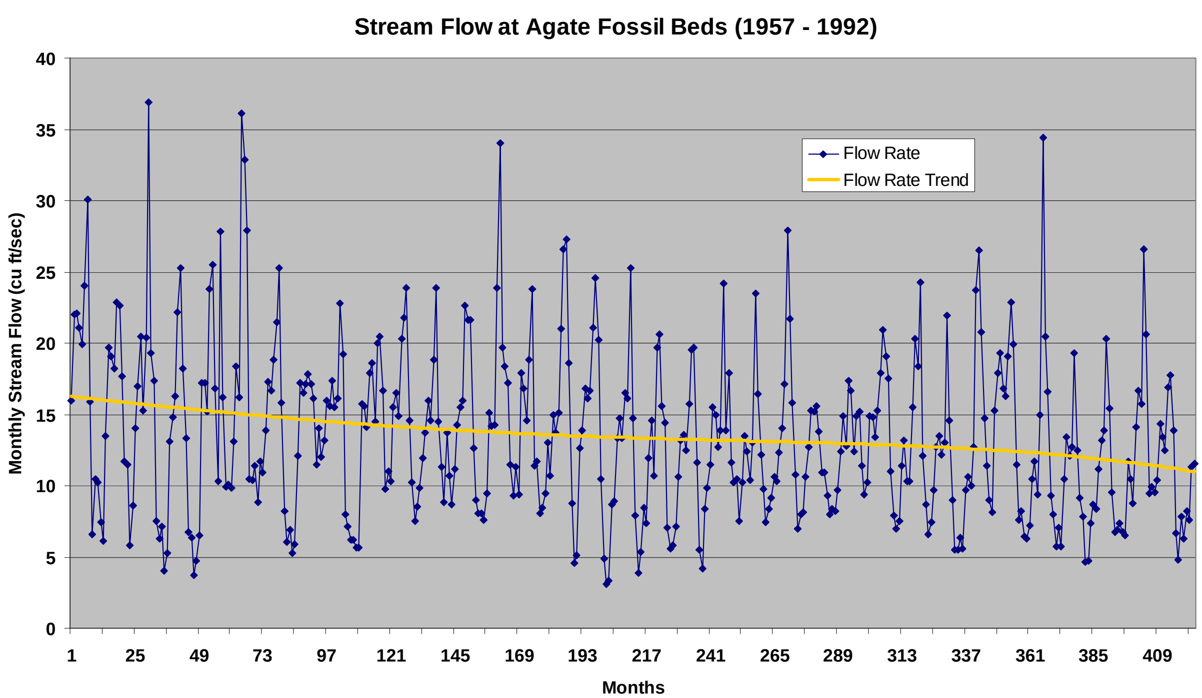
Although no hydrograph separation techniques were used to determine base-flow values, a rough estimate can be made from examining the low-flow characteristics of the monthly hydrographs exhibited in Appendix A. For example, the gauging station located at the Wyoming and Nebraska border has an estimated base-flow range between 2 and 3 cfs. Further downstream, near the Agate Fossil Beds, base flow appears to be in the range of 4 to 7 cfs, a net gain of only 2 or 3 cfs to the stream over a flow distance of about 25 miles. An estimate of base flow in the Niobrara above Box Butte Reservoir is in the range of 5 to 15 cfs. The flow distance between gauging stations is approximately 23 miles. Again, the net gain from groundwater inflow is only a few cfs. The hydrograph for the gauging station below Box Butte Reservoir shows the influence of intentional releases of water from the reservoir during part of the crop growing season beginning about 1947. Further downstream, these releases are diverted into the irrigation canal system that was constructed for the Mirage Flats Irrigation District. Comparing

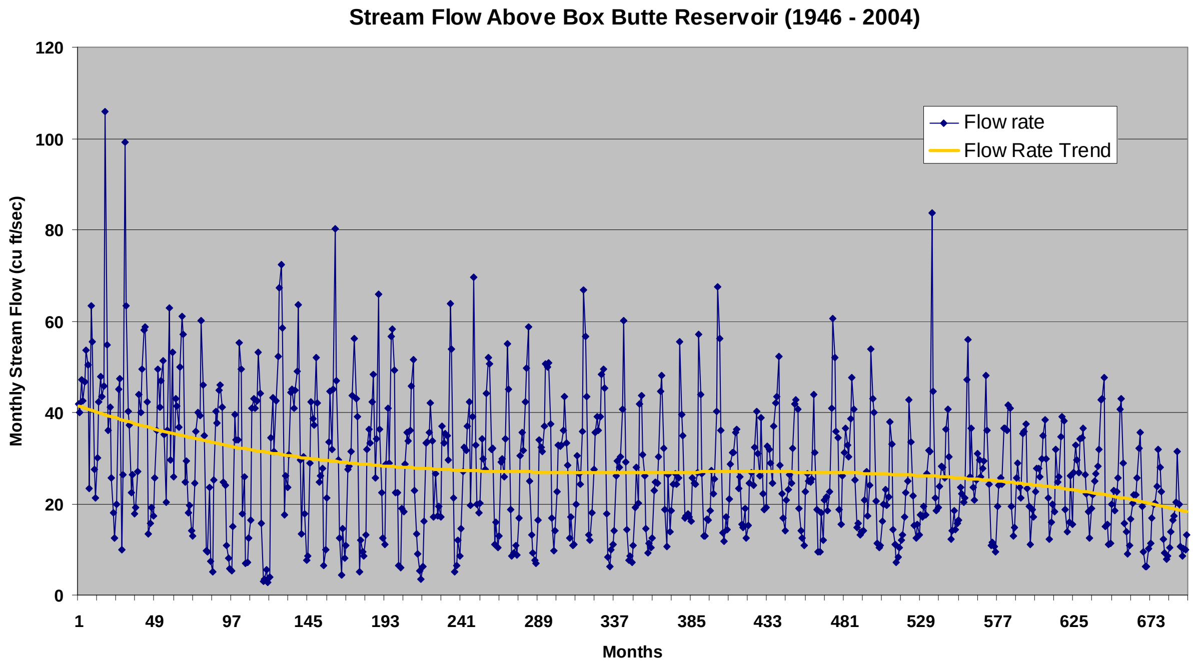
the hydrographs for the station below the reservoir and the station at the Dunlap diversion dam indicates a net gain in base flow from essentially zero at the Box Butte Reservoir Dam to about 10 to 15 cfs at the Dunlap gauging station; a distance of only about 7 or 8 miles. Unfortunately, the stream-flow record for the Hay Springs gauging station, located just south of Mirage Flats, is relatively short, making comparisons with other station data tenuous at best. At least for the period of record, base flow appears to average about 20 cfs over a reach of 9 or 10 miles. Approximately 30 miles downstream is the Gordon gauging station. An estimate of base flow from the hydrograph of this station ranges between 60 and 90 cfs. Considering stream flow gain per mile of flow distance for the other stations, the Gordon records indicate a significantly greater inflow of groundwater per mile of stream channel. Just to the southeast of Mirage Flats, the Niobrara River crosses the contact between units of the Arikaree Group to the west and units of the Ogallala Group to the east. This change in geologic terrain or, more specifically, a change in groundwater flow regimes, probably accounts for a greater groundwater contribution to stream flow due to a more efficient connection between the stream bed of the Niobrara River and the underlying aquifer.

Hydrographs derived from stream flow records for four selected gauging stations are shown in Figure 1. Fourth-order polynomial curves have been fit to the stream-flow values to show the general trend of the transient data. For each station, stream flow appears to decrease in the early part of the record and also in the latter part of the record. A comparison of records that coincide in time (Wyoming-Nebraska and above Box Butte Reservoir) indicates that peak flows have been significantly less in magnitude in the latter years than in earlier years. In addition, the groundwater contribution to in-stream flow appears to be less. It is interesting to note that, for

all four of the stations, the recent decreasing trend in stream flow appears to have begun prior to the most recent drought conditions that have persisted over the region for several years.







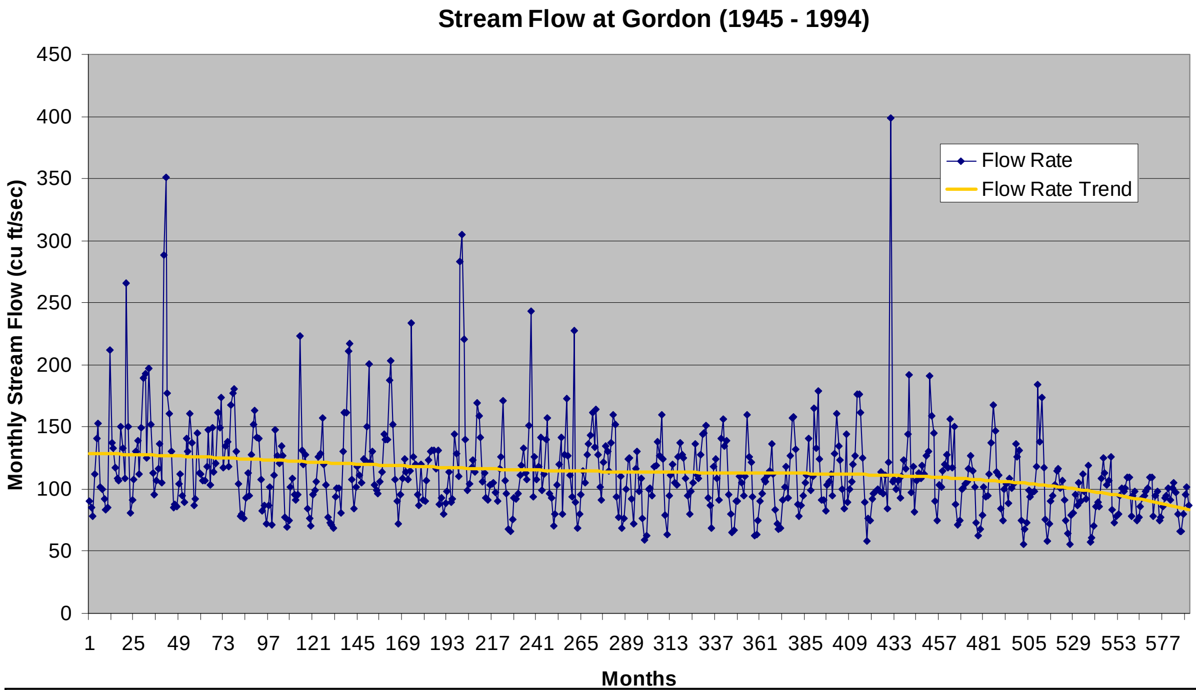


Figure 1. Hydrographs derived from stream-flow data collected at four selected gauging stations located along the upper reaches of the Niobrara River. Fourth-order polynomial trend curves have been drawn to show period-of-record transient behavior of in-stream flow.

Stream Channel Characteristics

Stream channel characteristics, at least by visual observation, appear not to change dramatically along the reach between Agate Fossil Beds and Box Butte Reservoir. The photograph of Figure 2 illustrates the general character of the Niobrara River channel and associated river valley. Note the terraces adjacent to the stream and the lack of bushes or trees. The photograph was taken in July and shows a channel width of approximately 15 to 20 feet with a water depth of only a few inches; stream flow is probably approaching base-flow conditions. Deposits within the channel are composed generally of fine-grained sand and silt with occasional gravel-sized or larger clasts, the latter are probably reworked terrace deposits.

Figure 2. Photograph of the Niobrara River channel near the Agate Fossil Beds.

Below Box Butte Reservoir, the character of the stream channel appears to change little; however, vegetation along the stream banks includes a larger population of trees. The photograph in Figure 3 also was taken in July, but along the Niobrara River near Mirage Flats.

Figure 3. Photograph of the Niobrara River near Mirage Flats.

Sediment comprising the stream bed and the width of the stream channel appear not to be much different than locations further upstream; however, there is an obvious increase in in-stream flow (water depth is about 1 to 1.5 feet), there is an abundance of vegetation other than grass adjacent to the stream channel, and there exists a marshy area between the stream channel and the stream bank.

Stream-bed Hydraulic Conductivity

Nine sites were selected along the Niobrara River between Agate Fossil Beds National Monument and Mirage Flats (Figure 4) for purposes of measuring the stream-bed hydraulic

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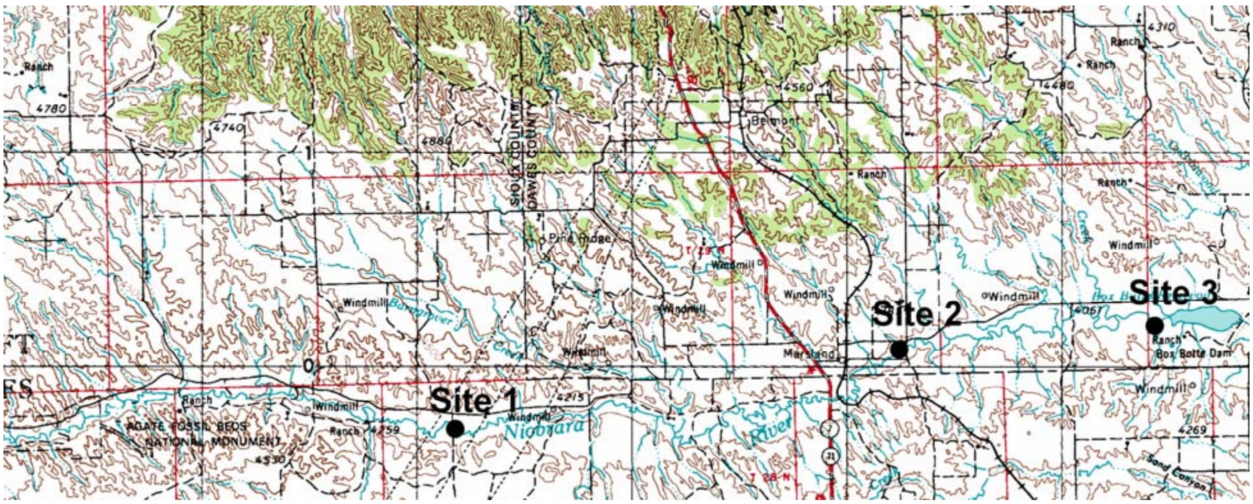

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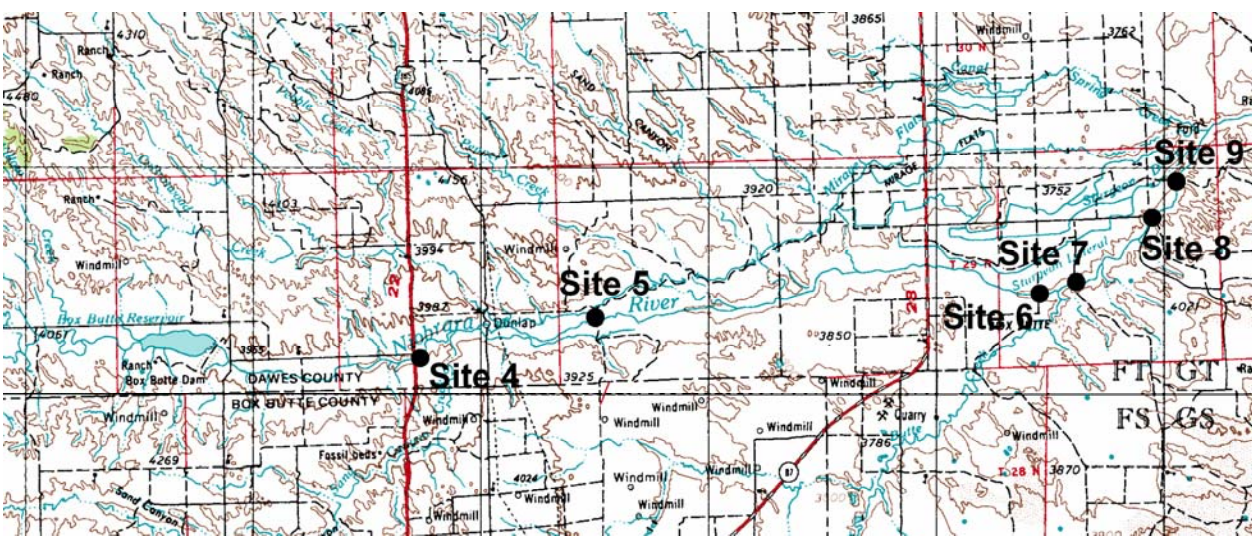

Figure 4. Excepts from the USGS 1:250000 scale Alliance quadrangle showing the locations where stream sediment cores and electrical conductance logs were obtained using the Geoprobe along the western (a) and eastern (b) parts of the upper Niobrara River Basin.

conductivity to be used as input to the groundwater flow model. At each site, a track-mounted model 6610DT GeoProbe was used to collect small-diameter (1.88 inch) streambed sediment cores and to run continuous electrical conductivity logs. Photographs of the sites showing the GeoProbe at work are presented in Appendix B and photographs of the split cores with descriptions are given in Appendix C. In the laboratory, permeameter measurements were taken on the core samples (collected in plastic tubes) to determine hydraulic conductivity of the sediments. Results of the permeability measurements are listed in Table 2.

Site ID	**Longitude West**	**Latitude North**	**Length of Core (ft)**	**Vertical Hydraulic Conductivity (ft/d)**
Site 1	103.514694	42.417794	2.8	0.46
Site 2	103.259442	42.448894	4.1	0.39
Site 3	103.168583	42.460847	3.4	3.80
Site 4	102.964869	42.450306	3.7	1.02
Site 5	102.860842	42.463903	1.6	6.17
Site 6	102.629447	42.452772	2.7	0.10
Site 7	102.606381	42.474736	4.6	1.15
Site 8	102.564453	42.495569	4.2	17.32
Site 9	102.554572	42.512514	3.4	30.04

Table 2. Results from permeameter measurements on core samples collected at nine sites along the upper reaches of the Niobrara River.

In general, streambed hydraulic conductivity is relatively low between sites 1 and 7 and increases significantly for sites 8 and 9 (located near Mirage Flats). Sediments deposited by the Niobrara River in the upper part of the basin were derived from a source area underlain primarily by units of the Arikaree Group, mostly the Upper Harrison beds (Bradley, 1956). As indicated by test holes drilled in the region (source: Conservation and Survey Division, statewide test-hole database), these units are composed of silts, siltstones, very fine- to fine-grained sands and sandstones. It follows that the composition of streambed deposits derived from such a source area would be mostly fine-grained particles. Examination of the cores for sites 1 through 7

indicates that streambed sediments in the upper reaches are composed of material derived from units of the Arikaree Group in addition to coarse-grained gravels. The latter are probably the result of reworking of terrace sediments that contain gravel deposited in the past when the Niobrara River was a more competent stream. These cores contain an abundance of silt interbedded with sand layers or mixed with sand. The presence of silt within a sand body significantly reduces the vertical hydraulic conductivity of the streambed material as a whole. The range of hydraulic conductivity measured for Sites 1 through 7 fall within the range of values obtained for silty sands and fine-grained sands (Fetter, 1980, p. 75). Sites 8 and 9 are located along a reach of the Niobrara that transects units of the Ogallala Group that are composed of coarser sediment. The higher hydraulic conductivity values listed for these sites are probably related to streambed sediments derived from a source area comprised primarily of fine- to coarse-grained sandstone and gravel units. Measured hydraulic conductivity for Sites 8 and 9 are in the range of values obtained for well-sorted sands (Fetter, 1980, p. 75).

In addition to the collection of core samples, electrical conductance (EC) logs were run to a depth of 10 feet at each site. The results of the EC logging are shown in the form of graphs in Appendix D. In general, EC depends on the electrical properties of both the pore water and the sediment particles comprising a given subsurface environment. If the pore water is considered fresh (low specific conductance and, conversely, high resistivity), then an EC log measures mostly the electrical properties of sediment grains surrounding the probe and, overall, represents changes in electrical properties with depth. Usually, low conductance values indicate the presence of clay-free, coarse-grained sediments (sand and/or gravel) while higher conductance values suggest a matrix composed of silty sand, silt and possibly clay

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Numerical Groundwater Flow Model

A numerical groundwater-flow model was used to determine the affects on Niobrara River base flow due to the long-term large-scale pumping that has taken place within Box Butte County and the surrounding region. Specifically, the program used was Visual MODFLOW© (professional edition, version 4.1) by Waterloo Hydrogeologic, Inc., Ontario, Canada. This software program is a pre- and post-processor that incorporates MODFLOW-2000 (Harbaugh, et al., 2000), an updated version of the USGS modular, three-dimensional, finite-difference groundwater flow model MODFLOW (McDonald and Harbaugh, 1988). The program provides a groundwater flow modeling environment in which required data are entered into files using various graphical-interface windows. Data such as constant head boundary conditions, stream channel characteristics and stream stage elevations, hydraulic conductivity and storage coefficients, well locations and pumping schedules, transient recharge rates, initial head conditions, and other relevant information are entered into the program using a methodology similar to that used in geographical information systems (GIS) mapping. Input data are then translated into the coordinate system of the flow model and property and boundary values are assigned to each cell within the model domain.

In general, MODFLOW-2000 simulates steady state and transient (non-steady state) flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (restricted to having the principal directions aligned with the grid axes), and the storage coefficient may be heterogeneous. Specified head and specified flux boundaries can be

simulated, as can a head-dependent flux across the outer model boundary that allows water to be supplied to a boundary block or cell within the model domain at a rate proportional to the current head difference between a "source" of water outside the modeled area and the boundary cell.

The groundwater-flow equation is solved using the finite-difference approximation. The flow region is subdivided into blocks or cells in which the medium properties are assumed to be uniform. In plan view, the cells are created from a grid of mutually perpendicular lines that may be variably spaced. Model layers can have varying thickness. A flow equation is written for each cell. Several solvers are provided for solving the resulting matrix problem; the user can choose the best solver for the particular problem. Flow-rate and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

The modular structure of MODFLOW-2000 allows the user to select only those modules or packages that are suitable to the particular problem under consideration. In the construction of the Box Butte-Niobrara model, the following packages were used:

- <u>Basic package</u>; handles a number of administrative tasks for the model such as reading data on the number of rows, columns, layers and stress periods, on major options to be used, and on the file location of input data for those options. Other tasks include the allocation of space in computer memory for model arrays, the reading of data specifying initial and boundary conditions, the reading and implementation of data establishing the discretization of time, the setting up of the starting head arrays for each time step and the calculation of an overall water budget. The package also controls model output according to user specifications.

- <u>Block-centered flow package</u>; computes the conductance components of the finite-difference equation that determine flow between adjacent cells. The package also computes the terms that determine the rate of movement of water to and from storage. To make the required calculations, it is assumed that a node is located at the center of each model cell.

- <u>Recharge package</u>; simulates areally distributed recharge to the groundwater-flow system. This package applies the user-defined recharge rate to the model by multiplying that rate by the horizontal area of each cell in the uppermost layer where recharge occurs.

- River package; simulates the effects of flow between surface-water bodies and the groundwater-flow system. In the package, terms representing seepage to or from the surface features are added to the groundwater-flow equation for each cell affected by the seepage.

- Well package; simulates features such as wells which withdraw water from the aquifer (or add water to it) at a specified rate during a given stress period, where the rate is independent of both the cell area and the head within the cell.

As an aid in the development of model input files, a Microsoft™ ACCESS database was created to contain relevant information such as test-hole locations and lithologic descriptions, observation well locations and water-level measurements, stream-flow records, registered well data and driller's logs, precipitation records and other data. The database is included with this report as an electronic appendix. In addition to the database, a Windows-based application (*TransSchedule*, written in Visual Basic Net) was developed to assist in the preparation of time-dependent schedules such as those associated with pumping, recharge, stream flow, boundary conditions and others relevant to running transient simulations. This application specifically creates input files in the format utilized by Visual MODFLOW.

Simulation Time Frame

Both steady-state and transient simulations were run during the course of the study. Steady-state simulation results were used to calibrate the model, by trial-and-error and parameter adjustment, to pre-development conditions; that is, to the configuration of the water table prior to wide-spreading pumping of groundwater for purposes of irrigation. According to Souders, et al. (1980), pre-development conditions existed up to about 1938, after which, the rate of irrigation well installation increased rapidly. Transient simulations were run to model changes in the water table configuration between 1938 and 2005 (the most complete input dataset). Each year in this period of some 67 years was divided into two time segments according to a general pumping

schedule of 154 days when pumps were on (about mid April to mid September) and 211 days when pumps were off (non-growing season), producing a total of 135 stress periods in the transient model. During a transient model run, each stress period is divided into 10 time steps by the model program. All input data to the model related to time are in units of length (ft) or volume (ft^3) per day (i.e., the basic time increment for the model is a day).

Model Domain and Components

Model construction proceeds through a number of steps from conceptualization of the flow regime to the actual running of the finite-difference code. The first of these steps involves defining the model boundaries, visualizing the various hydrologic and geologic components within those boundaries and establishing the types and magnitude of hydraulic stresses on the flow system. Figure 5 shows portions of the USGS Alliance and Scottsbluff 1:250000 scale quadrangle maps with the model boundary drawn in red; the Box Butte county line is drawn in black as a location reference. The model regime incorporates a number of hydrologic and physiographic features. Most prominent of the hydrologic features is the Niobrara River running sub parallel to the northern model boundary, the Mirage Flats irrigation canals, the Snake Creek in the southern part of Box Butte County, and the Sand Hills lakes area located in the eastern portion of the modeled region. The Niobrara River enters the model domain at the Nebraska-Wyoming border, flows eastward in a well-developed channel, and exits the model domain east of the Mirage Flats. Three tributaries to the Niobrara River have been included in the model; Whistle Creek, Box Butte Creek and Pine Creek. Blue Creek, which drains the Crescent Lakes area, was also included. A network of unlined irrigation canals was constructed to transport water from the Niobrara River to the Mirage Flats area. Water, released from Box Butte Reservoir, is channeled into the canal system at the Duncan diversion dam, usually during the

summer months, as a supplement to groundwater extraction by irrigation wells within the district. Snake Creek forms a closed drainage system that originates in the upland area west of Box Butte County and flows southeastward to mostly eastward to sink near the western margin of the Sand Hills lakes region. The latter is an area with a high population of small lakes that are situated between longitudinal sand dunes (Swinehart et al., 1988). Studies have shown that these lakes are in direct connection with groundwater (Winter, 1986) and, in some cases, act as evaporative sinks within the groundwater-flow system (Gosselin et al.,1994)

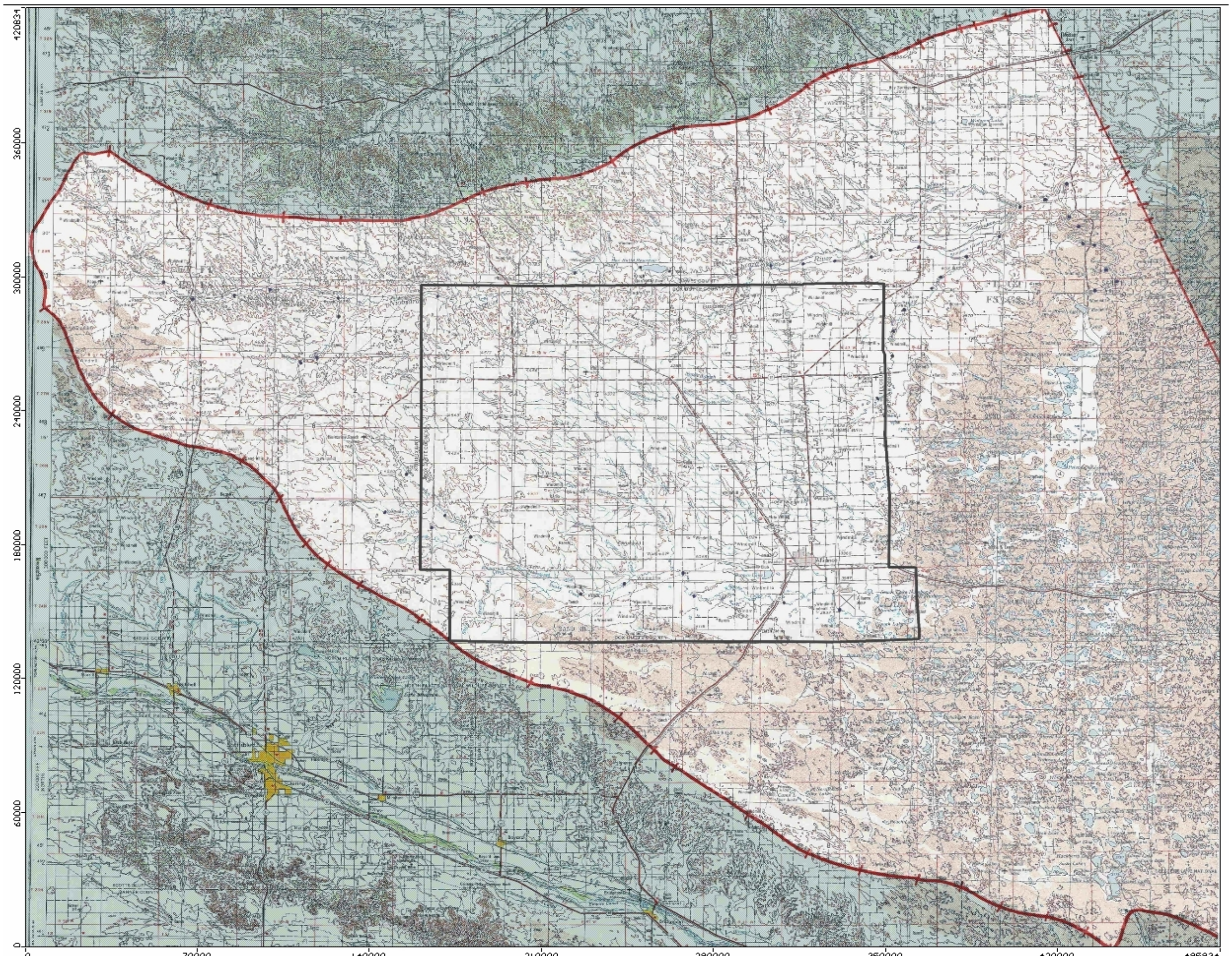

Figure 5. Portions of the Alliance and Scottsbluff USGS quadrangle maps (1:250000 scale) showing outline (red color) of the model area. For reference, Box Butte County is outline in black.

Main physiographic features within the model domain are the prominent uplands and dissected uplands that cover about two thirds of the area and the Sand Hills that occupy the east-central and southeastern portion of the domain. The uplands are characterized by table lands and buttes, in some places dissected by head-ward eroding intermittent streams. Along the northernmost boundary, the topography is relatively rough, while the topography of a large part of Box Butte County is gentle to rolling. The Sand Hills region is composed of stabilized Quaternary-age sand dunes. Because of the inherent sandy soils, recharge from precipitation is very high.

Model Grid and Boundary Conditions

The model domain outlined on the map of Figure 5 is encompassed by a rectangle with the dimensions of 485,834 feet (approximately 92 miles) in the eastward direction and 420,834 feet (approximately 80 miles) in the northward direction. Coordinates of the lower left corner of the rectangle are -104.025738 degrees longitude and 41.626292 degrees north latitude and coordinates of the upper right corner are -102.244133 degrees longitude and 42.769231 degrees north latitude. A 200-by-200 node horizontal grid oriented parallel with true north was constructed over the rectangular area producing cell blocks with the dimensions of about 2,104 feet by 2,429 feet. To form the three-dimensional finite-difference grid, the model domain was further subdivided into 3 layers, each representing a hydrostratigraphic unit with unique hydraulic properties.

Groundwater flow boundary conditions for the model domain were determined by observing the water table configuration for 1995 drawn on the Alliance and Scottsbluff 1:250000 scale quadrangle maps (Dreeszen, 2001a, Dreeszen, 2001b). Constant head no-flow boundaries along the north and south model domain borders coincide with groundwater divides. These

divides separate the flow system beneath Box Butte County and the surrounding region from the North Platte River valley located to the south and the White River drainage system located to the north. Head values were assigned to various points on the boundary according to the magnitude of the potential gradient along the divide, the slope between points was considered to be linear. The westernmost border of the model domain is coincident with an equipotential contour segment (4600 ft) that roughly parallels part of the Nebraska-Wyoming line. This boundary represents constant head conditions that allow groundwater to flow into the model domain. Similar boundary conditions were assigned to a section of the extreme southeastern-most border coincident with a segment of the 3700-foot equipotential contour (located a short distance south of the Crescent Lakes National Wildlife Refuge). Constant head, no flow conditions were established along a part of the eastern model border to represent a prominent groundwater mound that has persisted through the years in this region. Assigned head values for all of the boundary segments were held constant throughout transient simulations.

Representation of surface water bodies (i.e., River Package), such as rivers, streams and lakes, within the model domain was accomplished by assigning various physical and hydrological characteristics to grid cells in which those water bodies occur. MODFLOW simulates the surface water/groundwater interaction via a seepage layer separating the water body from the groundwater-flow system. The required input data include the free water surface elevation, the elevation of the bottom of the seepage layer and the conductance (numerical value representing the resistance to flow) of the seepage layer. The conductance value may be calculated using:

$$C = \frac{K \times L \times W}{M},$$

where L is the length of the stream reach through a grid cell, W is the width of the stream in the grid cell, M is the thickness of the seepage layer (stream or lake bed) and K is the vertical hydraulic conductivity of the seepage bed material. For simulations that include lakes (or wetlands), the L and W variables would correspond to the X and Y dimensions of the grid cell. River or lake conditions are assigned using the graphical capabilities of Visual MODFLOW by digitizing the location of the lake or the route of the stream, then entering the required dimensional parameters (derived from USGS 7.5 minute topographic maps). Values of hydraulic conductivity (Table 2) obtained from the field work were used to calculate stream-bed conductance. The program translates the input data and assigns the appropriate values to each grid cell that contains a surface water body.

Areal recharge is considered an inflow boundary condition for purposes of groundwater-flow modeling. Recharge flux was defined by establishing zones that represent areas with different rates at which water, introduced at the ground surface, enters the ground-water body. The recharge rate is a parameter that is not often determined over a given area, but rather, it is assumed to be a percentage of the precipitation. This percentage typically ranges from 5% to 20% depending on many different factors including:

- The predominant land use and vegetation type**,**
- The surface topography (slope), and
- The soil-cover material.

An initial estimate of recharge for the model was made by assuming that the amount of water reaching the water table over the entire model domain was 5% of the long-term average rainfall for the region (about 15 in/yr). Steady-state simulation results using this initial recharge rate were compared to pre-development water table maps for Box Butte County (Souders, et al.,

1980; Pettijohn and Chen, 1984). Additional recharge zones were then defined for portions of the model domain where simulated heads grossly overestimated or underestimated observed heads. Rates of recharge for these additional zones were derived by multiplying the initial rate by either a value less than one or a value greater than one depending on the outcome of the trial-and-error simulation. The process was repeated until a reasonable fit between simulated heads and observed heads was obtained. Figure 6 shows the distribution of recharge zones over the modeled area and Table 3 lists the steady-state recharge rate (the values used for calibration) for each zone.

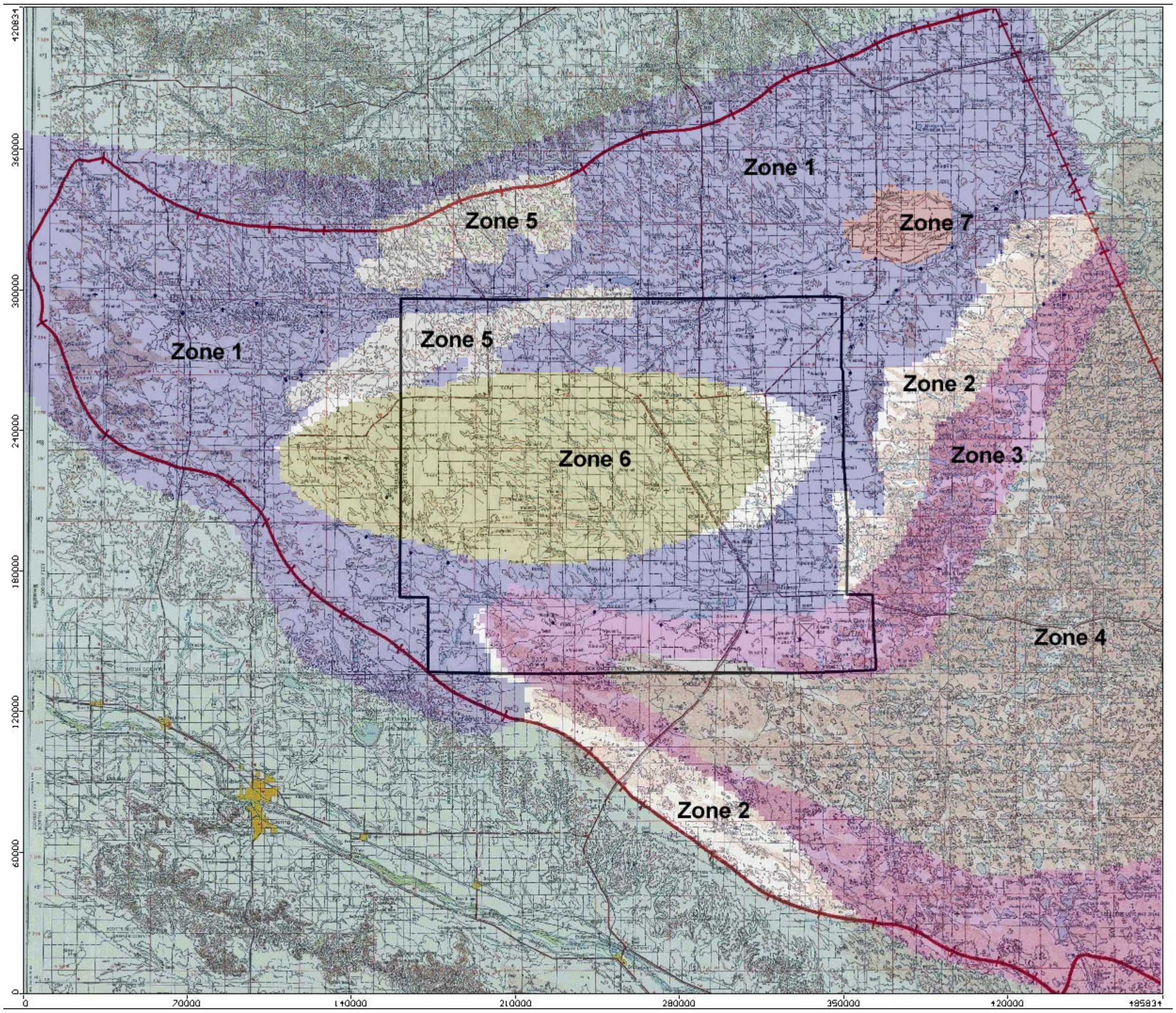

Figure 6. Map of the model domain showing the areal distribution of recharge zones.

Recharge Zone Number	Steady-State Recharge (ft/d)	Percent of Precipitation
1	0.000171	5
2	0.000240	7
3	0.000510	15
4	0.000689	20
5	0.0	0
6	0.000290	8
7	0.000171	5 + Canal Seepage

Table 3. Steady-state recharge rates per zone.

The recharge zones shown in Figure 6 represent a variety of surface conditions that contribute to the rate at which water is transferred to the subsurface. For example, Zones 1 and 2 represent soil and infiltration conditions that have developed on surface exposures of stratigraphic units of the Arikaree and Ogallala groups. Zone 5 covers some of the same geologic units as those in Zones 1 and 2, but the area is deeply dissected by tributary streams of the Niobrara River. Souders et al. (1980) have suggested that these areas of the region contribute little to no recharge to the subsurface. Zones 3 and 4 are within the Sand Hills region and represent much higher rates of recharge then for the remaining model domain. Comparisons of simulated steady-state head and observed head for 1938 indicate that the region represented by Zone 6 apparently receives a slightly greater amount of recharge than the surrounding zones. This may be due to the concentration of irrigation wells where return flow may contribute a significantly greater amount to the overall recharge flux. Zone 7 represents a special case where recharge over a portion of the model somain has been augmented by a system of unlined irrigation canals. Beginning in the late 1940s, during the growing season water has been diverted from the Niobrara River into the canal network constructed for the Mirage Flats Irrigation District (US Bureau of Reclamation, 1965). As a result, years groundwater levels beneath Mirage Flats rose by several feet over time. Because of this phenomenon, the recharge schedule was modified to account for the excess flux due to canal seepage.

Transient recharge rates (recharge schedules) were derived by distributing precipitation over the two primary time divisions; that is, when pumps were on and when pumps were off. Using the application *TransSchedule*, recharge schedules for each zone were constructed by extracting the daily rainfall values for the period between mid April and mid September and summing those amounts then dividing by the total number of days in the time period to obtain a

daily precipitation rate. The same procedure was performed for the period between mid September and mid April. This process was repeated for each stress period in the simulation. The multiplication factor for each recharge zone was applied to the daily precipitation rates to obtain a schedule of recharge flux to the model.

Hydraulic Properties

The model grid was further divided into three layers, each representing a separate hydrostratigraphic unit. Layer 1, the uppermost layer in the model, is composed primarily of Quaternary- and Ogallala-age stratigraphic units that make up the surficial geology of the eastern half of the model domain. A hydraulic conductivity value of 70 ft/day was assigned to K_x and K_y (hydraulic conductivity in the x and y directions of the grid, respectfully) and a value of 10 ft/day was assign to the vertical hydraulic conductivity (K_z); a specific yield value of 0.20 was assigned to the entire first layer. The second layer represents units comprising the Arikaree Group, the primary aquifer that underlies most of the region. Hydraulic conductivity in the horizontal directions was assigned a value of 25 ft/day and K_z was assigned a value of 5 ft/day. The specific yield of layer 2 was assigned a value of 0.15. Layer 3 is composed of stratigraphic units of the White River Group. These units are considered to be essentially impermeable; therefore, very low hydraulic conductivity and specific yield values were assigned to the third layer; 0.5 ft/day for K_x and K_y, 0.1 ft/day for K_z, and 0.01 for specific yield.

Hydraulic property values listed above are based on data published in various reports. In an early study of the region, Cady and Scherer (1946) determined that the hydraulic conductivity of the Harrison-Monroe Creek formation in the west-central part of Box Butte County was about 30 ft/day and the storage coefficient was 0.15. Bradley (1956) reported a value for the storage coefficient of the Harrison sandstone near Agate of 0.157 determined from laboratory

measurements. As part of a study of the Mirage Flats area, the US Bureau of Reclamation determined values of hydraulic conductivity for the underlying units (mainly the Upper Harrison beds) to be in the range of 27 to 40 ft/day and a general storage coefficient of 0.15. Pettyjohn and Chen (1984), in an early groundwater flow modeling study, estimated from specific capacity data on irrigation wells a range of less than 10 ft/day to about 40 ft/day for a combined hydraulic conductivity for the aquifer beneath Box Butte County. Souders et al. (1980) computed hydraulic conductivity values from analysis of test-hole logs to be in the range of near zero for well cemented sandstones and some clayey silt units to more than 132 ft/day for some sand and gravel beds in the Ogallala Group.

In Visual MODFLOW, ground surface and layer-top elevations are entered using a variety of methods. The program will then contour the elevation data and assign the results to each of the cells within the model. Elevation information was obtained from USGS digital elevation model data for ground surface topography and from published maps augmented with test-hole log data for elevations of the contacts between various hydrostratigraphic units. The maps illustrated in Figures 7 and 8 show the configuration of the tops of layers 2 and 3, respectively.

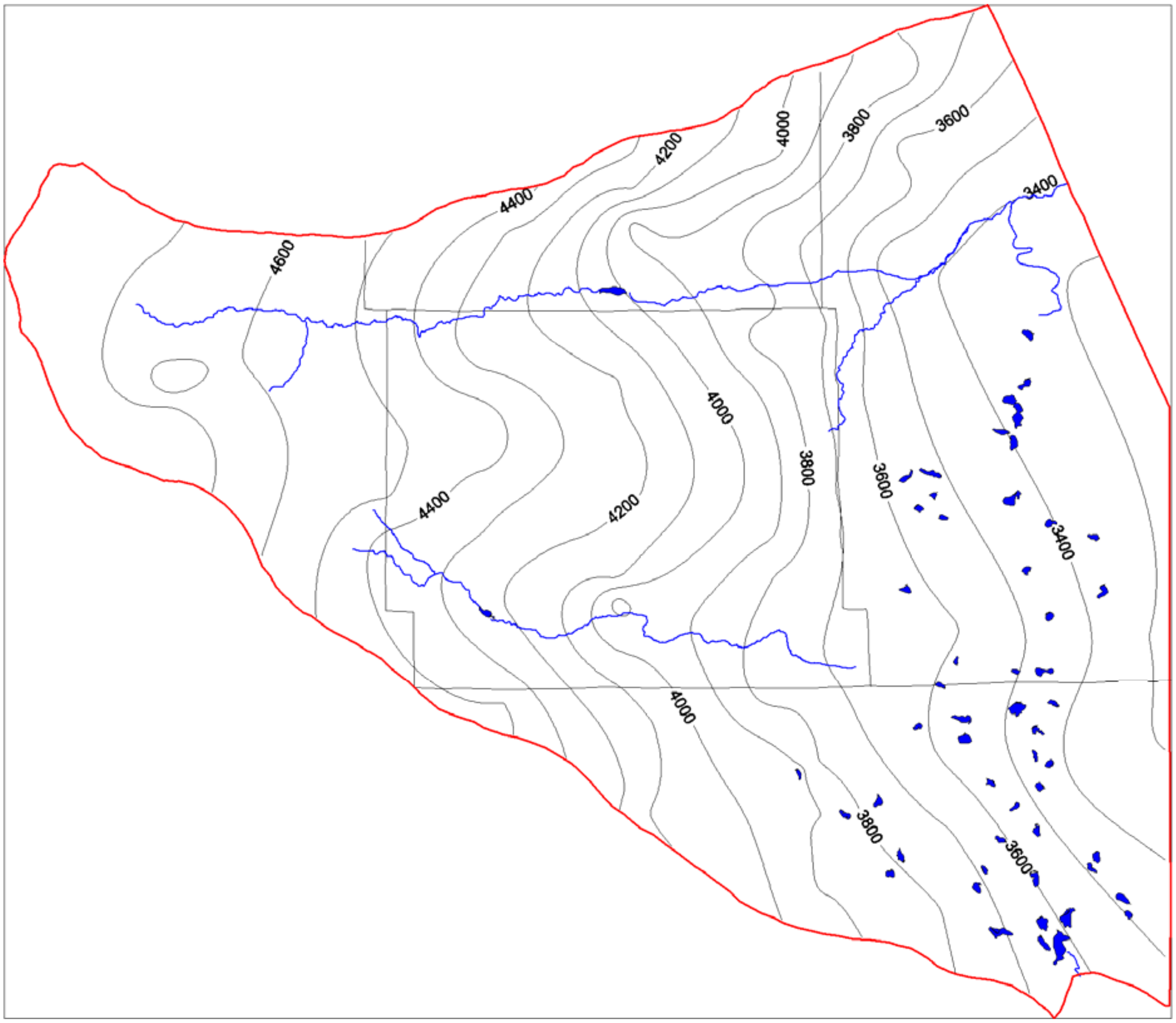

Figure 7. Schematic of the model domain showing the configuration of the top of layer 2; the primary aquifer composed of units of the Arikaree Group. Elevation contour interval is 100 feet.

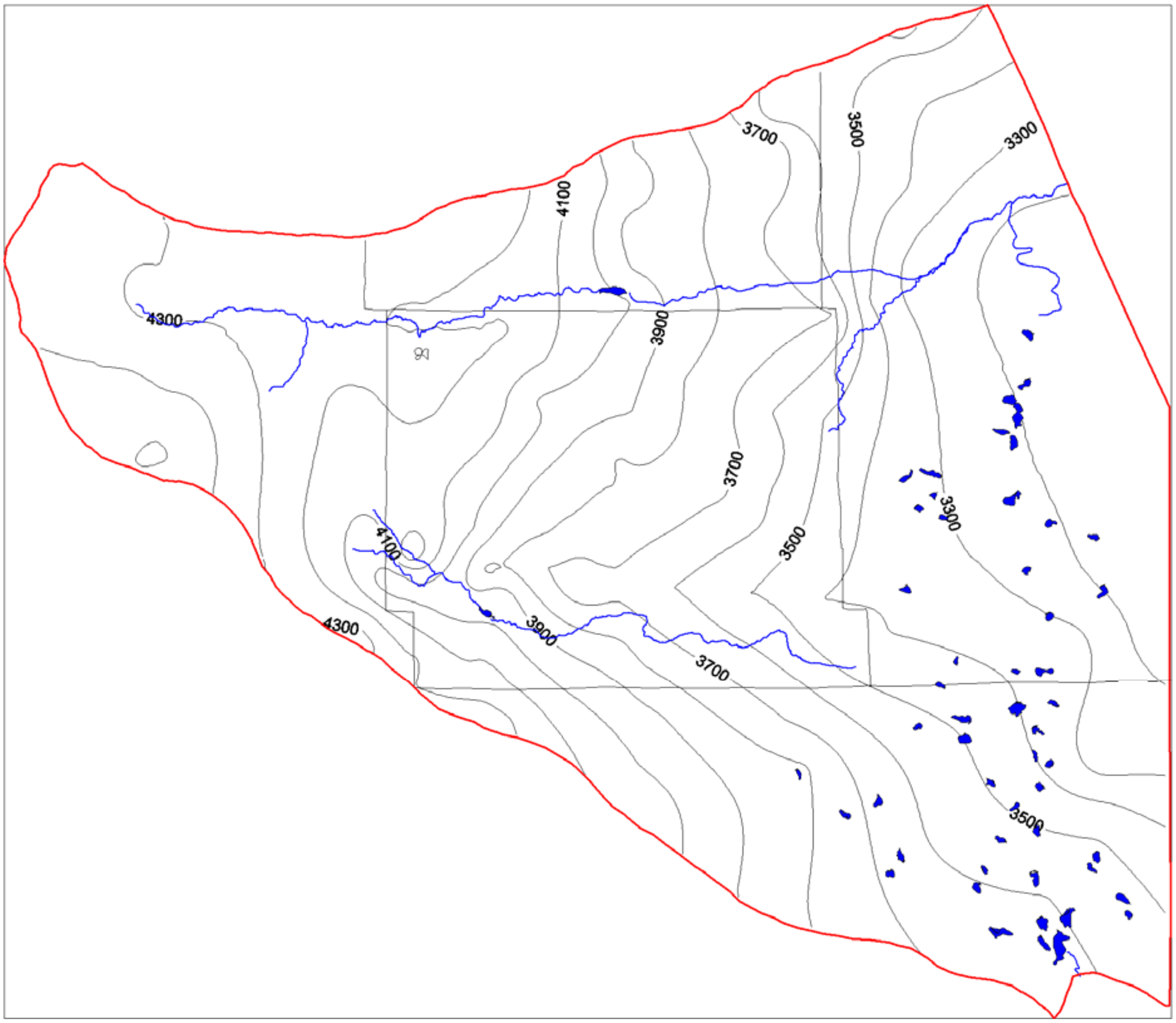

Figure 8. Schematic of the model domain showing the configuration of the top of layer 3; composed of units of the White River Group. Elevation contour interval is 100 feet.

Development of Pumping Well Schedules

The model contains 1,817 pumping wells (Figure 9). Location information and general characteristics for each well are contained in tables comprising the database (attached as electronic Appendix G), as well as the pumping schedule that was constructed utilizing the application *TransSchedule*.

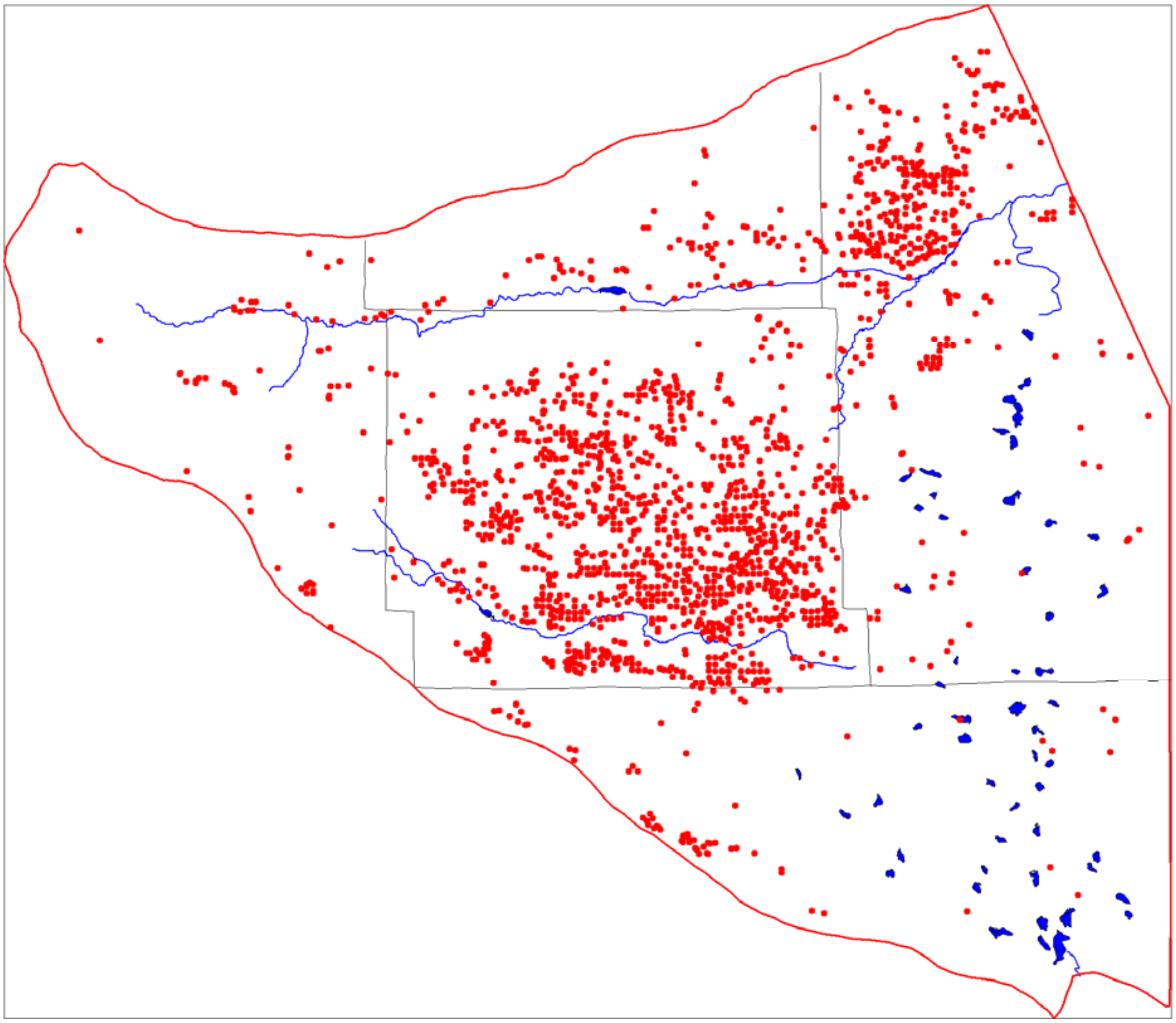

Figure 9. Map of the model domain showing the distribution of pumping wells.

The process developed to generate pumping schedules for the model wells involved several steps. First, registered well data for Box Butte County and parts of the surrounding counties, including driller's logs, were downloaded from the Nebraska Department of Natural Resources databank website. Next, a computer program was written to identify only those registered wells that were located within the model boundaries. The next step in the process was the most problematic; determination of pumping rates. Downloaded data included the date of completion, the pumping rate and the number of acres to be irrigated for each registered well. Dates of

completion were used to identify the startup times of pumping wells within the simulation. However, it was found that pumping rates could not be used directly. An initial plot of pumping rate versus number of acres irrigated (Figure 10) showed no correlation between the two

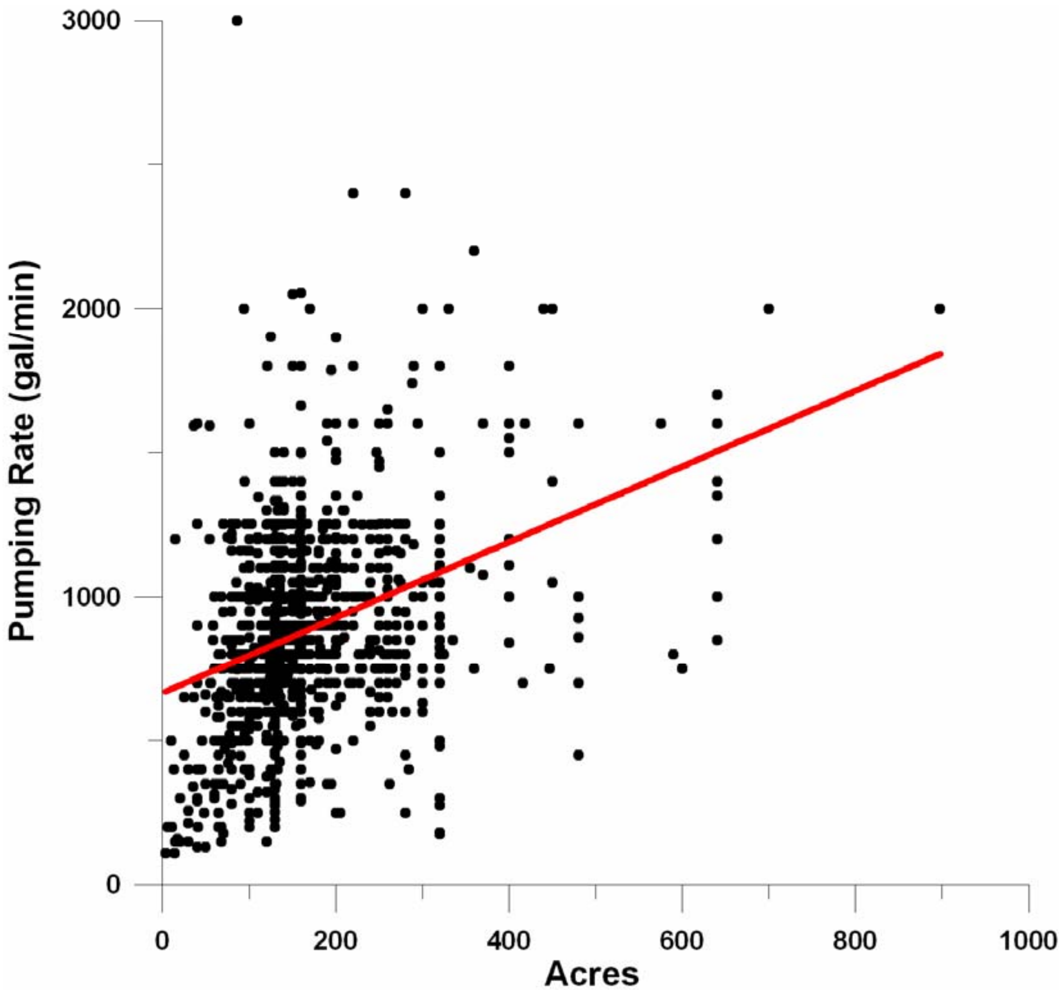

Figure 10. Plot of registered well pumping rates and number of acres irrigated. Data from the Nebraska Department of Natural Resources databank.

variables. Some wells were pumping at a rate of 800 to 900 gal/min to irrigate 10 acres while others were pumping the same amount to irrigate 160 acres or more. A different approach was needed. It was assumed then, that the number of acres irrigated would provide a better estimate of the amount of water required during a given growing season (i.e., simulation stress period).

Most crops grown in the region require between 12 inches and 18 inches of water per acre (University of Nebraska Extension) between the months of April and September (in the model, a stress period of 154 days). Taking a conservative estimate of 16 inches of water per acre and applying this amount to the area of irrigated land per well and converting to gallons per minute, provides an initial estimate of pumping rates for all of the wells within the model domain. To complete the determination of simulation pumping rates, it was assumed that some of the pumped water would return to the water table as recharge. Souders et al. (1980) suggested that return flow to the aquifer was probably less then 10% of the irrigation water pumped from the groundwater flow system. The modeling study by Pettyjohn and Chen (1984) estimated that recharge from seepage of irrigation water was between 10% and 15%. A value of 10% was selected as a reasonable factor to reduce pumping rates over a given stress period to account for seepage losses from irrigated fields. The final pumping schedule was constructed using the application *TransSchedule* that produced the required input file to the modeling program.

Simulation Results

In the run phase, Visual MODFLOW allows the first time step to be set to steady-state mode to establish initial conditions for the remaining simulation. For the Box Butte-Niobrara model, the steady-state results represent the 1938 predevelopment condition and, thus, can be compared to the observed water table configuration for that year. Souders et al. (1980, p. 87) presented a water-table map for Box Butte County that was derived from early water-level measurements and other data. Their map and the results of the steady-state run are shown in Figures 10 and 11, respectively. Simulated heads in the primary aquifer (layer 2) match fairly closely to those observed in 1938. There are some discrepancies between observed and simulated heads in some areas of the model domain where the model does not fully account for

real-world geological or hydrological factors or the comparison of head values in layer 2 with

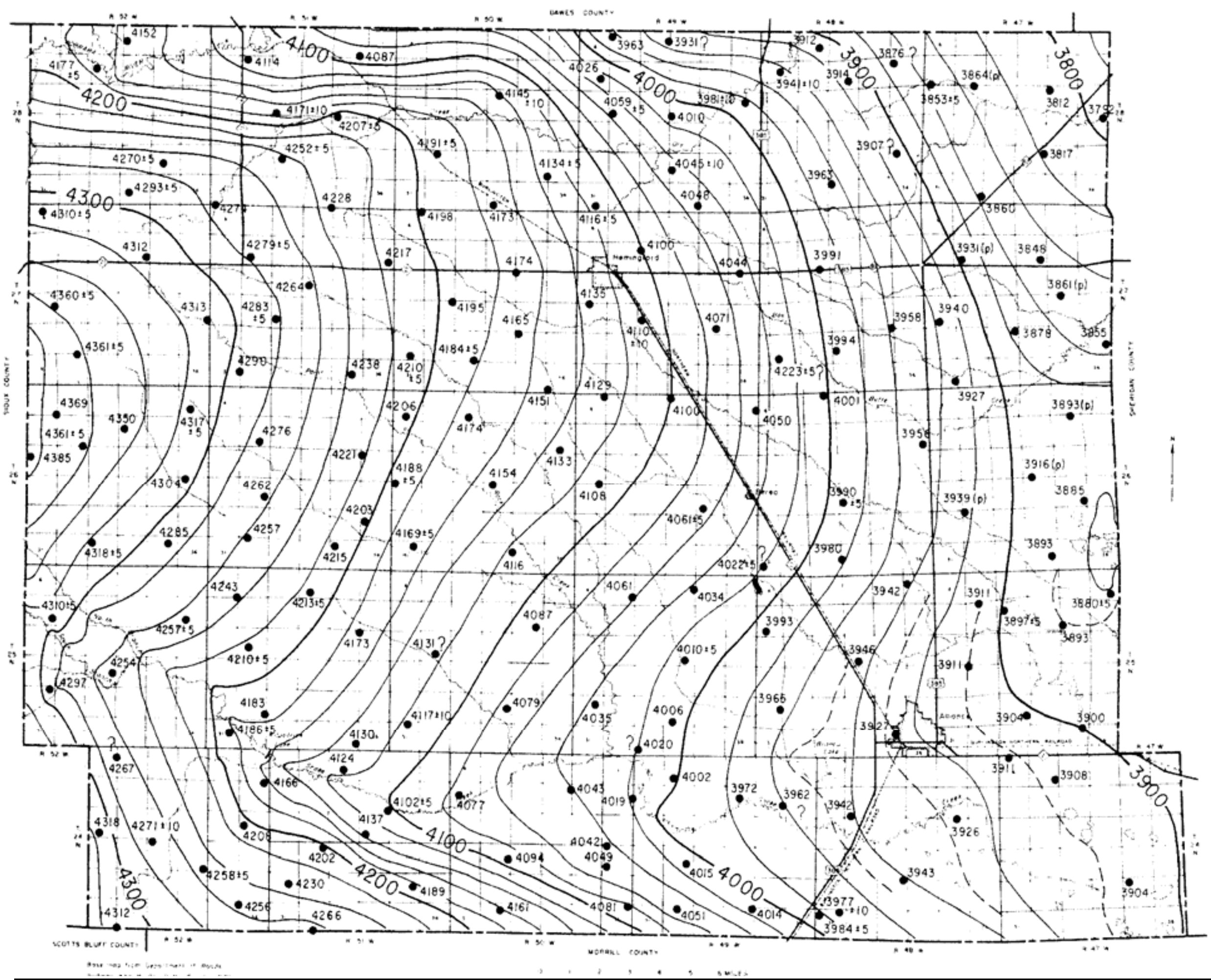

Figure 11. Map showing the water table configuration for Box Butte County in 1938 (Souders et al., 1980, p. 87). Contour interval is 20 feet.

observed heads is not necessarily valid (measured water levels may not represent heads in deeper parts of the aquifer); however, the general shape of the predevelopment head configuration is well represented by the simulation results.

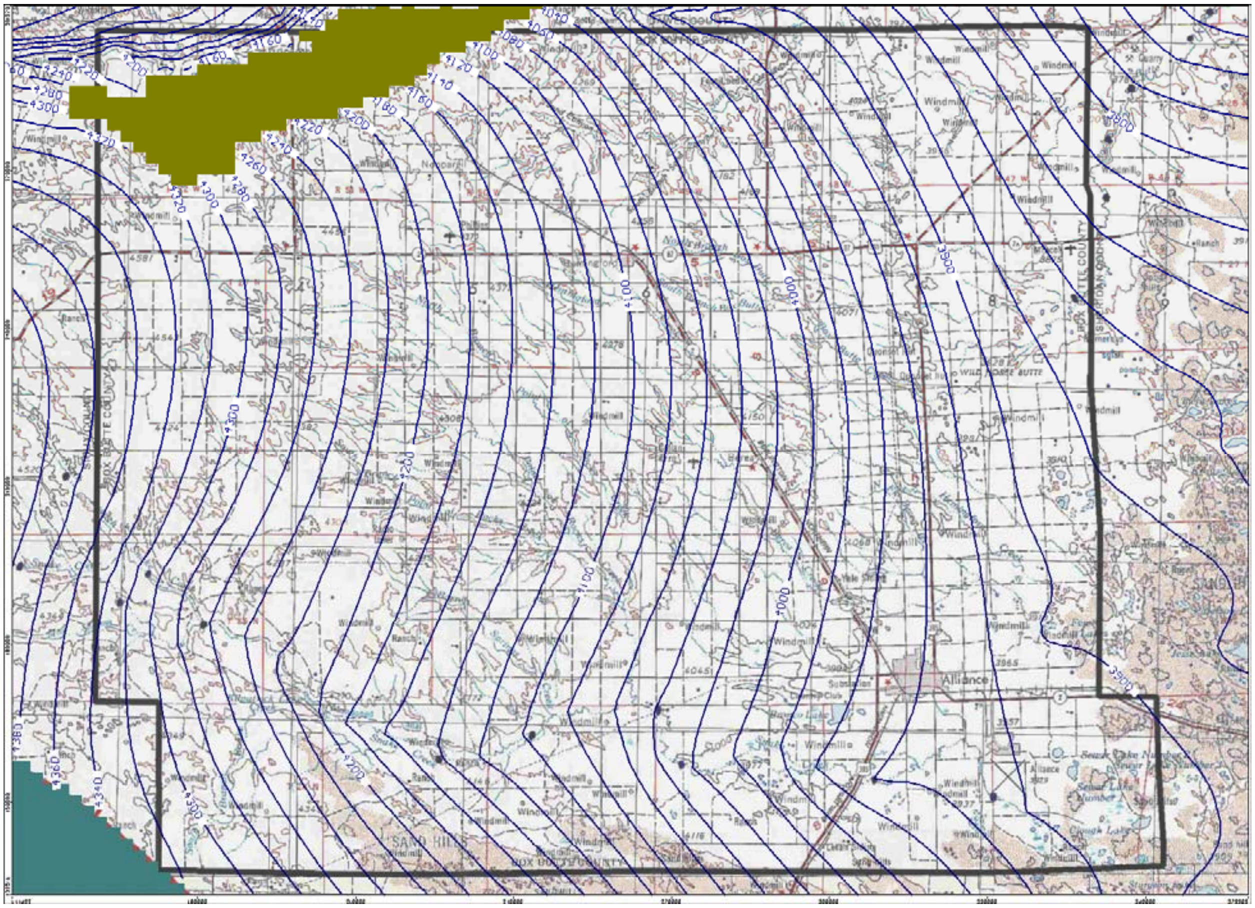

Figure 12. Portion of the model domain showing the simulated hydraulic head configuration in layer 2 for the predevelopment conditions of 1938. The olive color region indicates the absence of layers 1 and 2. Contour interval is 20 feet.

Once the model was calibrated to predevelopment groundwater-flow conditions, two basic simulations were run: 1) post development between 1938 and 2005 with pumping; and, 2) post development between 1938 and 2005 without pumping. The purpose of running these two simulations was to compare the resultant water budgets for selected areas within the model domain and determine the overall affect of pumping on the base flow of the Niobrara River. MODFLOW source files and output listing text files generated by the modeling program are provided in electronic Appendix H.

A measure of how well transient simulation results fit observations can be made by comparing model generated heads for each stress period with measured water-level elevations in observation wells. Of the total number of USGS observation sites within the model domain, 26

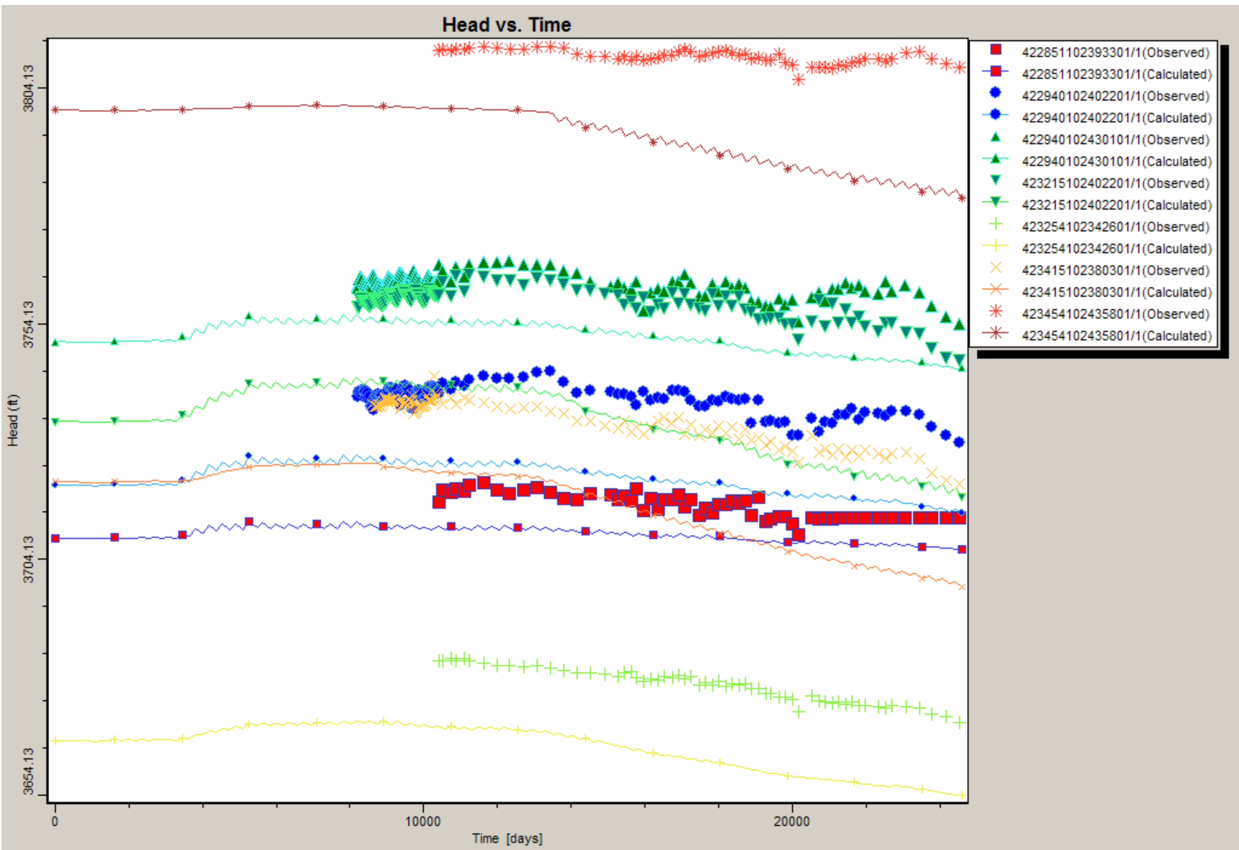

Figure 13. Plot of observed head versus time and simulated head versus time for observation wells located in the Mirage Flats area.

were selected to compare measured heads with simulation results. The hydrographs and other information regarding the selected sites are presented in Appendix F. Figures 13 and 14 show plots of simulated heads and measured heads from observation wells located in the Mirage Flats area and in the central part of Box Butte County, respectively. In some cases the model under estimates the observed water levels and in others the model over estimates observed water levels;

however, the model appears to simulate the general trend in water-level change observed over the period of record for the various observation sites. To obtain an absolute fit to observed data,

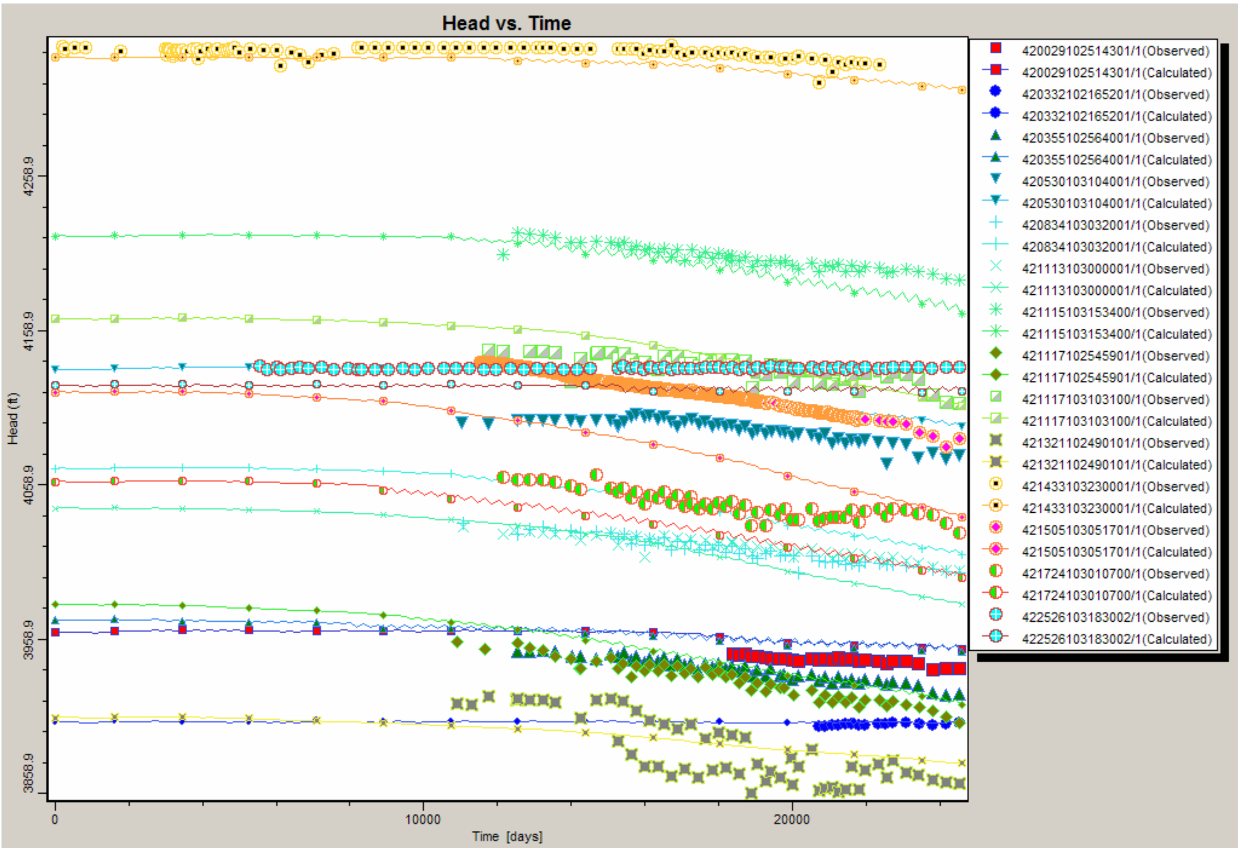

Figure 14. Plot of observed heads versus time and of simulated heads versus time for observation wells located within Box Butte County.

model input parameters could be "tweaked", that is, adjusted until a near perfect fit is obtained; however, the justification for doing so would be unfounded given the amount of field information available.

Water table contours illustrated on the model domain map of Figure 15 show the difference between predevelopment conditions and those conditions simulated for the year 2005. Green contour lines represent the water-table configuration for 1938 and red contours represent the

water-table configuration for 2005 in layer 2. It is apparent that the overall change in head has been significant since the beginning of pumping for irrigation purposes.

Figure 16 shows a map of the simulated drawdown for layer 2 at the end of the 2005 pumping season. The extensive cone of depression caused by irrigation well pumping has affected nearly all of Box Butte County with a maximum drawdown approaching 95 feet. In

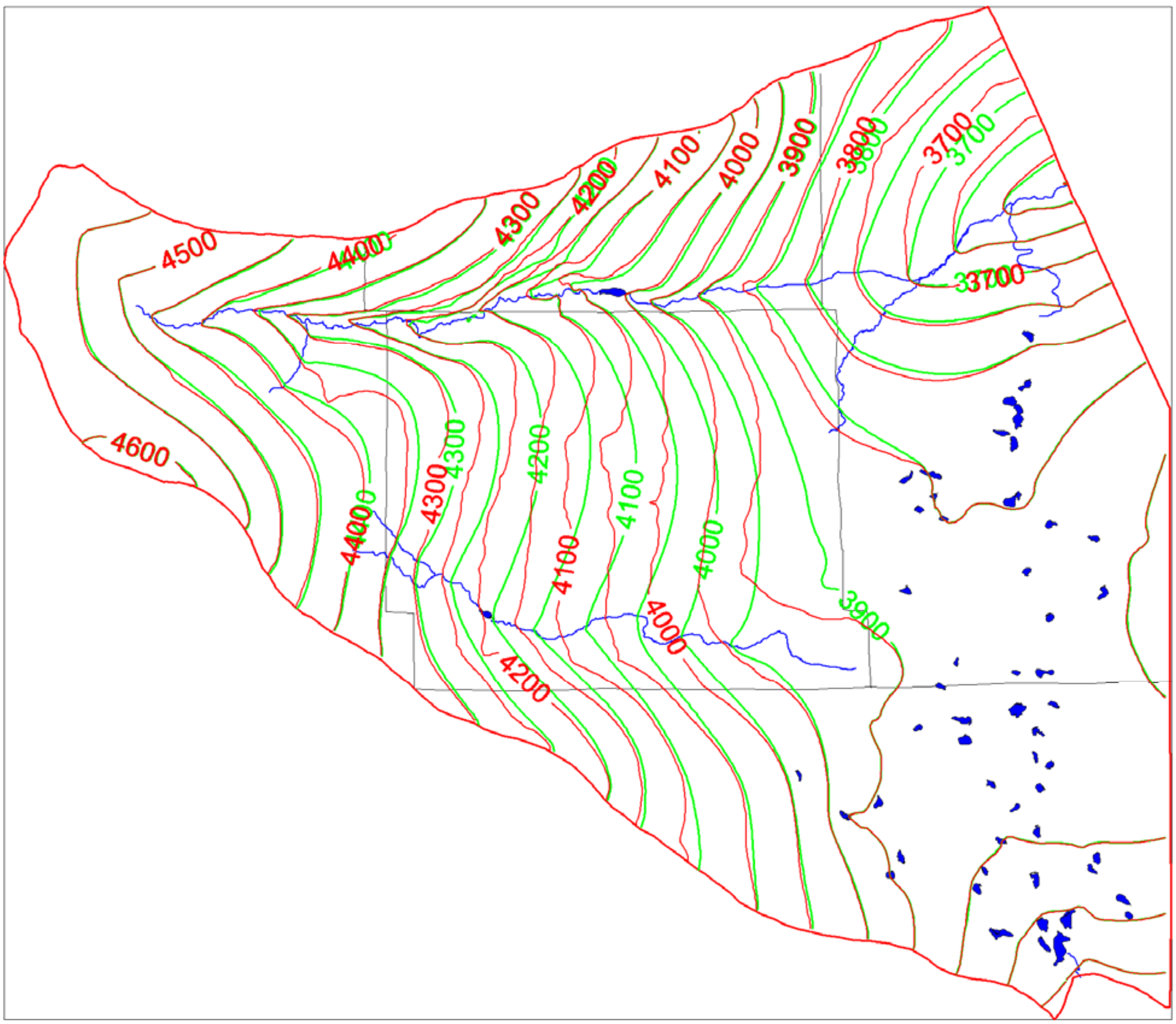

Figure 15. Map of the water-table configuration for predevelopment conditions (green contours) and for simulated 2005 conditions (red contours). Contour interval is 50 feet.

addition, pumping within the Mirage Flats area has caused a lowering of the water table on the order of about 20 feet relative to predevelopment conditions. It appears that nearly the entire model domain has been impacted by pumping to some degree, including the Niobrara River valley as evident by upstream shifts in water table contours indicated on the map of Figure 15.

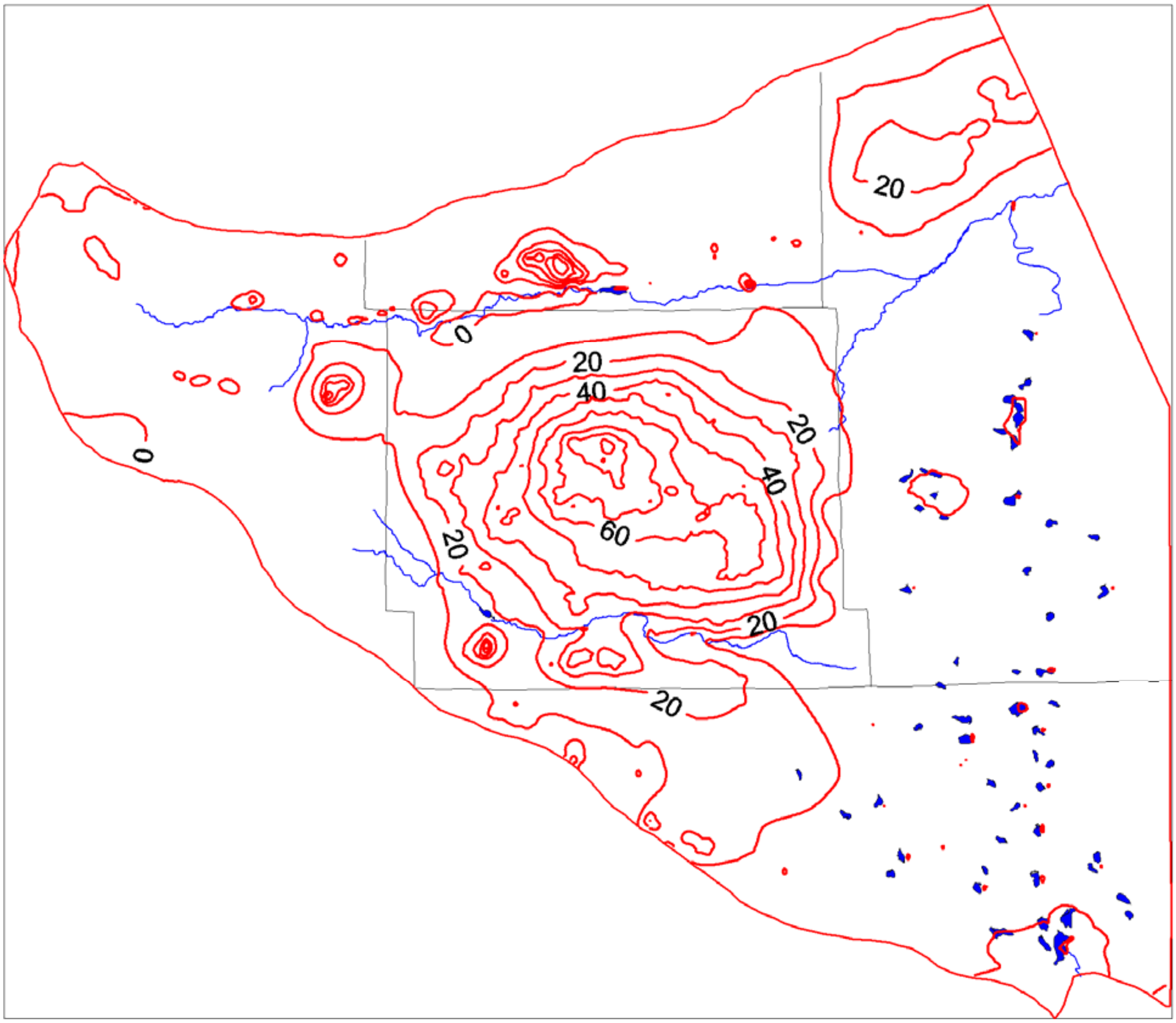

Figure 16. Map showing the configuration of the drawdown cone generated from simulation results. Contour interval is 10 feet.

Affects of Pumping on the Niobrara River

Visual MODFLOW allows the user to define various water-budget zones within the model domain to aid in the interpretation of simulation results. The computations are performed by the computer program ZONEBUDGET (Harbaugh, 1990), which calculates sub-regional water budgets using cell-by-cell flow data saved by MODFLOW. A number of budget zones were defined for reaches of the Niobrara River and Snake Creek. These zones are illustrated on the model domain map of Figure 17. Snake Creek is represented by a single zone, while the Niobrara River is represented by several zones that divide the stream route into an upper reach (from the Nebraska-Wyoming border to Agate), middle reach (from Agate to the Box Butte Reservoir including Whistle Creek) and a lower reach (from Box Butte Reservoir to the eastern model boundary).

Table 3 lists the results of running ZONEBUDGET for the upper, middle and lower reaches of the Niobrara River (output from ZONEBUDGET is provided as text files in electronic Appendix I). The results listed represent the net outflow in cubic feet per second at the end of the stress period for the corresponding times and were derived from the two transient simulations where all wells were allowed to pump (**Pmp** column heading) and where all wells were turned off (**No Pmp** column heading). A comparison of model simulated outflow values for the various reaches of the Niobrara River indicates that 1) flow characteristics in the uppermost reach have not changed greatly over the period of pumping, 2) significant changes in net flow appears to have occurred after about 1960 in the middle and lower reaches, 3) the maximum change in flow for the middle reach due to pumping is about 19.6%, which occurs at the end of the last stress period, 4) the maximum change in flow for the lower reach is about 24.4%, which also occurs at

the end of the last stress period. Overall, the Niobrara River appears to be a gaining stream along most of its flow path.

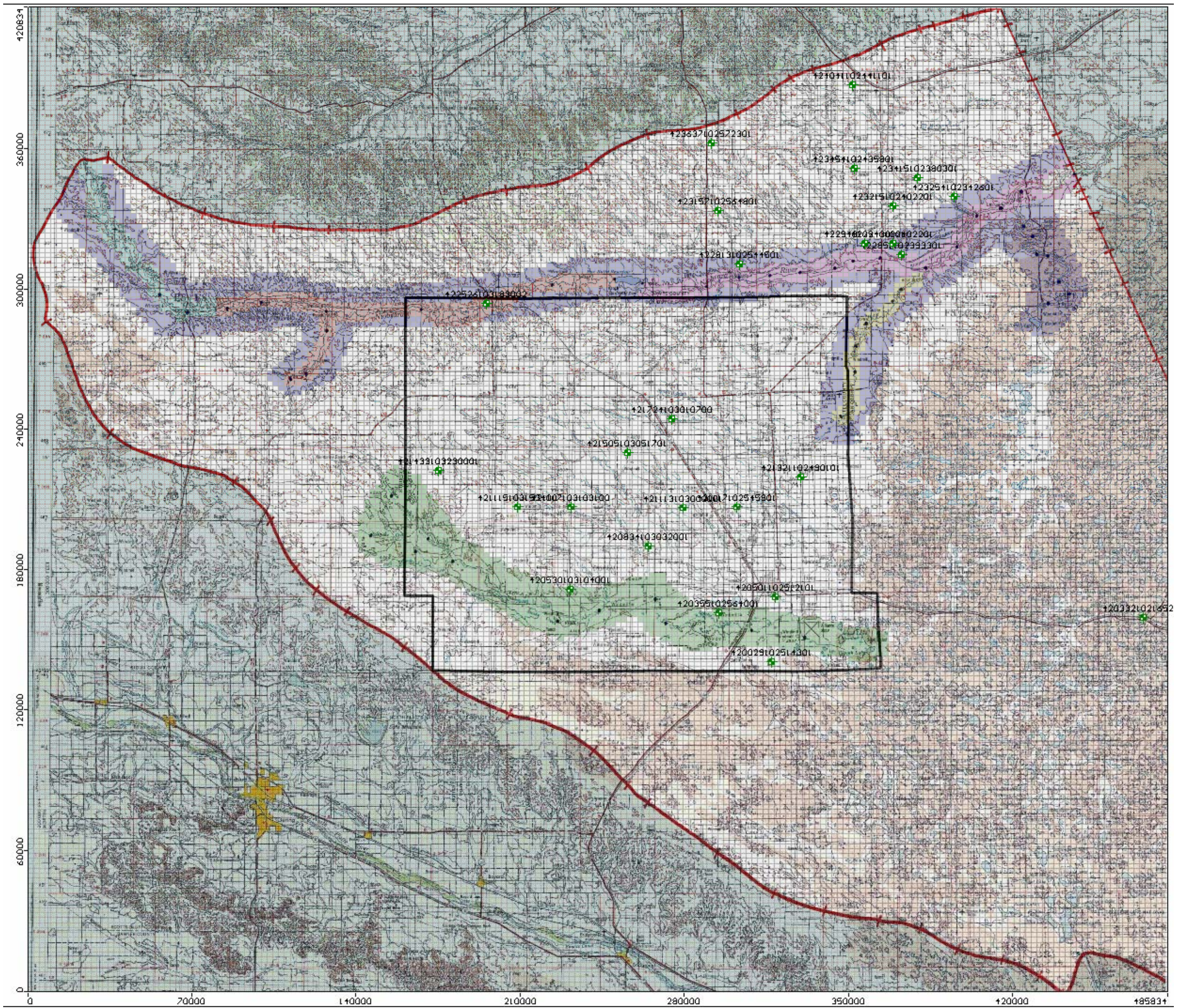

Figure 17. Map of the model domain with water-budget zones outlined in colors.

Year	Simulation Days	Upper Reach (cfs)		Middle Reach (cfs)		Lower Reach (cfs)	
		No Pmp	Pmp	No Pmp	Pmp	No Pmp	Pmp
1938	154	22.93	22.92	51.47	51.74	158.37	158.28
1947	3439	23.44	23.44	52.58	52.78	162.09	161.94
1957	7089	23.49	23.49	53.27	52.54	171.62	170.82
1967	10739	23.56	23.54	52.96	51.20	173.60	166.89
1977	14389	23.62	23.45	52.94	48.50	172.95	160.31
1987	18039	23.27	22.95	51.73	44.82	172.58	148.40
1997	21689	22.97	22.50	51.73	42.52	169.20	136.44
2005	24609	22.87	22.31	51.78	41.63	167.56	126.74

Table 4. Simulated base flow for the upper, middle and lower reaches of the Niobrara River derived from various stress periods of two model simulations; pumping of all wells and all wells turned off. Flow units are in cubic feet per second.

To evaluate the affect of groundwater extraction in Box Butte County, an additional transient simulation was run where pumping wells in the vicinity of the Niobrara River valley were turned off, leaving those wells in Box Butte County and adjacent area active (MODFLOW source files and output listing file are provided in electronic Appendix H). Table 4 lists the results obtained from this simulation along with the no-pumping simulation. Again, the uppermost reach seems to be slightly influenced by regional pumping. Results for the middle reach indicate that base flow is reduced by only about 4.4% due to pumping in Box Butte County as compared to 19.6% reduction by all wells pumping. For the lower reach, base flow is reduced by only about 2.5% as compared to 24.4% by all wells. These results indicate that the majority of the influence on base flow of the Niobrara River is due to local pumping in the Mirage Flats area and elsewhere rather than to regional pumping.

Year	Simulation Days	Upper Reach (cfs)		Middle Reach (cfs)		Lower Reach (cfs)	
		No Pmp	**BB Pmp**	**No Pmp**	**BB Pmp**	**No Pmp**	**BB Pmp**
1938	154	22.93	22.92	51.47	51.74	158.37	158.28
1947	3439	23.44	23.44	52.58	52.78	162.09	162.00
1957	7089	23.49	23.49	53.27	52.44	171.62	171.50
1967	10739	23.56	23.55	52.96	53.13	173.60	173.44
1977	14389	23.62	23.58	52.94	53.06	172.95	172.14
1987	18039	23.27	23.13	51.73	51.24	172.58	170.53
1997	21689	22.97	22.71	51.73	49.71	169.20	165.88
2005	24609	22.87	22.53	51.78	49.49	167.56	163.31

Table 5. Simulated base flow for the upper, middle and lower reaches of the Niobrara River derived from various stress periods of two model simulations; pumping of only those wells in the vicinity of Box Butte County and all wells turned off. Flow units are in cubic feet per second.

Based on model simulation results, reductions in the base flow of the Niobrara River is due primarily to localized pumping effects, rather than from groundwater extraction on a regional scale. For the most part, the Niobrara River valley is somewhat isolated from the extensive pumping taking place in Box Butte County. The upper reach is sufficiently distance from the pumping center that the cone of depression has little effect on the water table. Much of the middle reach transects units of the White River group that are considered to be nearly impermeable, and thus, provide a hydrogeologic barrier, preventing the northward expansion of the cone of depression. Pumping along the lower reach of the Niobrara River has a much greater influence on base flow reduction simply due to the proximity of the extraction wells to the river.

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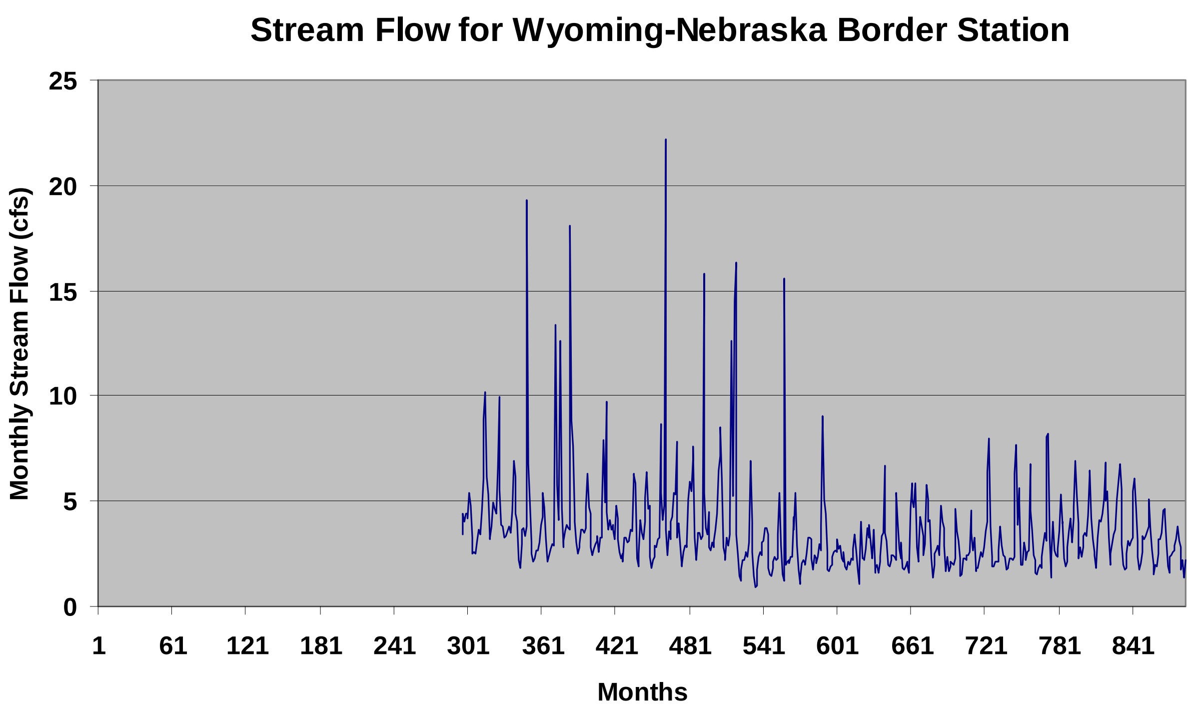
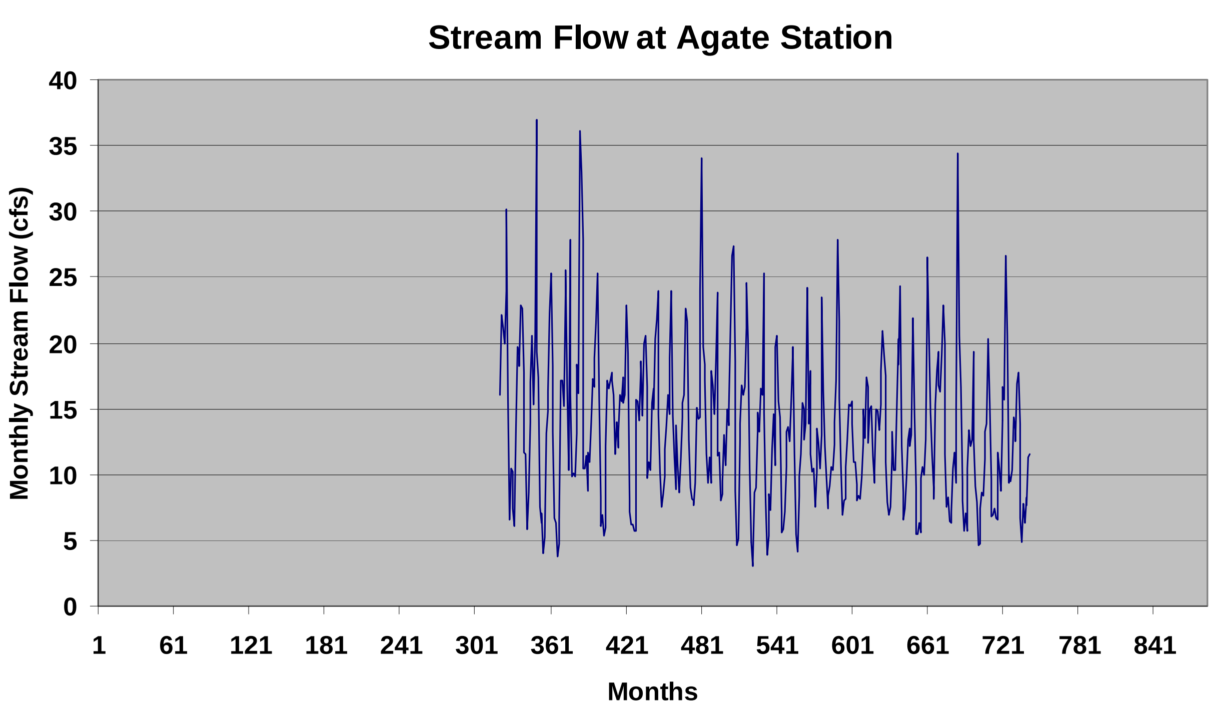
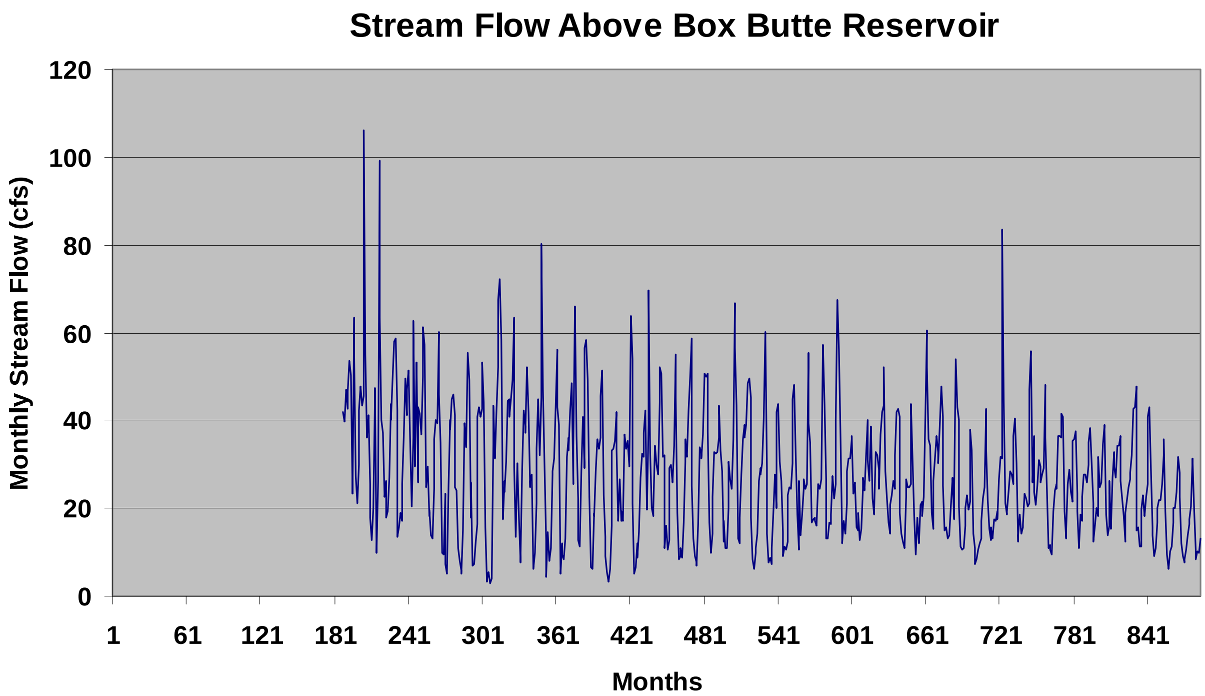
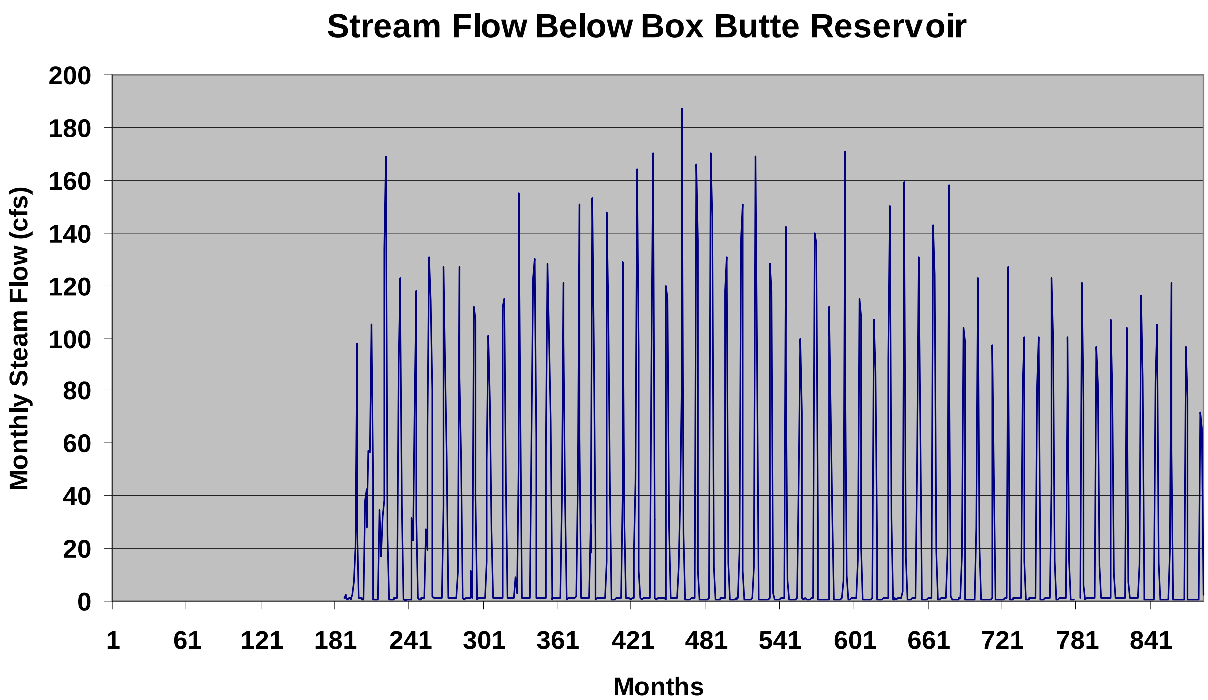
Appendix A: Stream Hydrographs for Selected USGS Gauging Stations



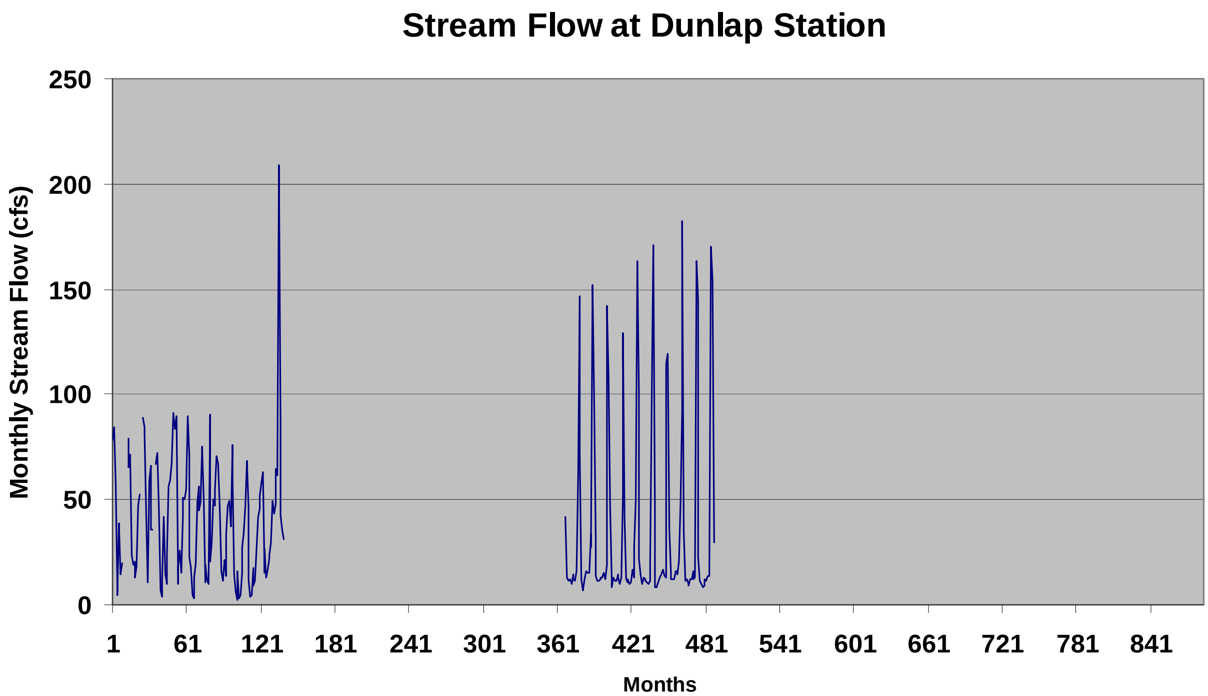


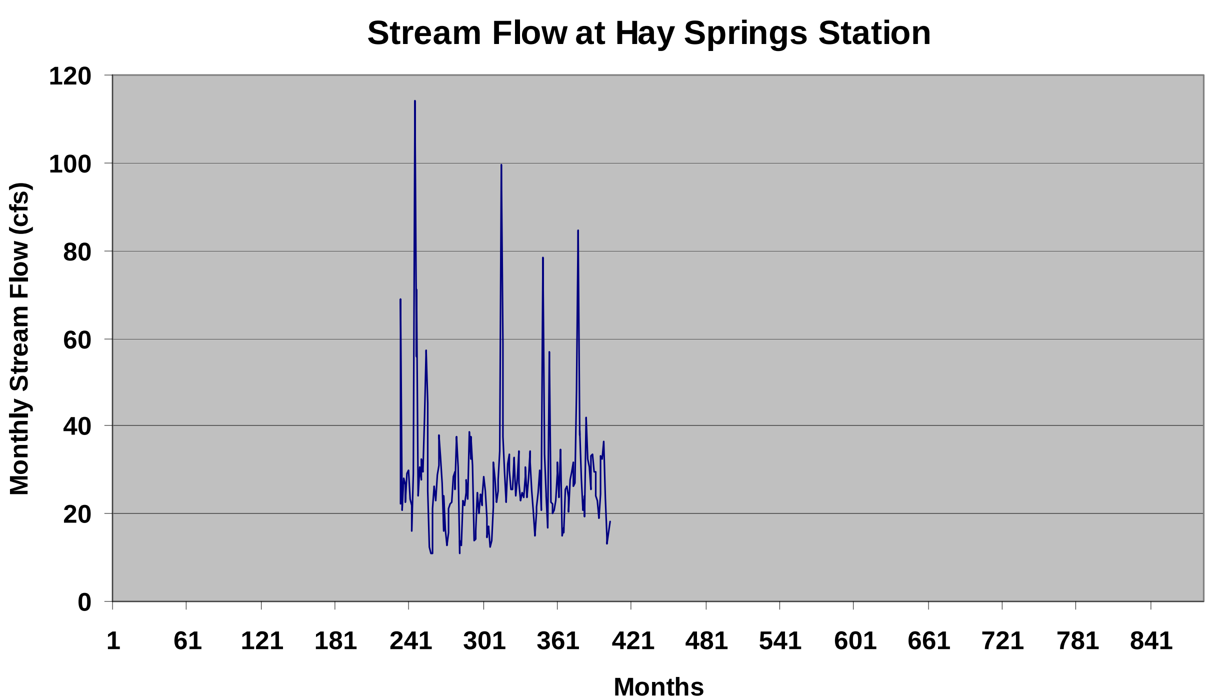


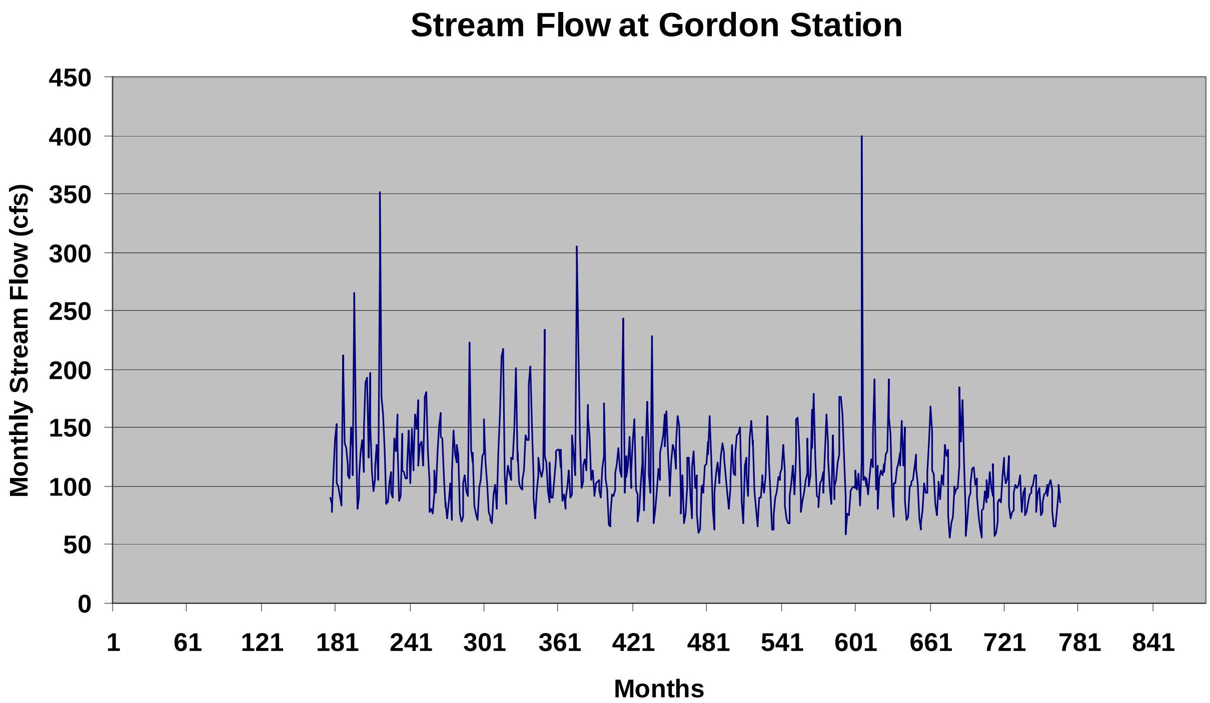
Stream Flow Above Box Butte Reservoir
Monthly Stream Flow (cfs)
0
20
40
60
80
100
120
1
61
121
181
241
301
361
421
481
541
601
661
721
781
841
Months



Stream Flow Below Box Butte Reservoir
Monthly Steam Flow (cfs)
0
20
40
60
80
100
120
140
160
180
200
1
61
121
181
241
301
361
421
481
541
601
661
721
781
841
Months


Stream Flow at Dunlap Station
250
200
150
100
50
0
Monthly Stream Flow (cfs)
1
61
121
181
241
301
361
421
481
541
601
661
721
781
841
Months


Stream Flow at Hay Springs Station
120
100
80
60
40
20
0
Monthly Stream Flow (cfs)
1
61
121
181
241
301
361
421
481
541
601
661
721
781
841
Months


Stream Flow at Gordon Station
450
400
350
300
250
200
150
100
50
0
Monthly Stream Flow (cfs)
1
61
121
181
241
301
361
421
481
541
601
661
721
781
841
Months

Appendix B: Photographs of GeoProbe Sites

Site 1
Loc: T28N, R53W, sec 9, BCCA
Quad: Whistle Creek NE
County: Sioux
Approx. Elev: 4238 ft

Site 2
Loc: T29N, R51W, sec 36, BBBB
Quad: Marsland
County: Dawes
Approx. Elev: 4077 ft

Site 3
Loc: T29N, R50W, sec 27, ADCB
Quad: Box Butte Reservoir West
County: Dawes
Approx. Elev: 4014 ft

Site 4
Loc: T29N, R48W, sec 33, BBBC
Quad: Box Butte NW
County: Dawes
Approx. Elev: 3889 ft

Site 5
Loc: T29N, R47W, sec 30, ADAA
Quad: Box Butte NE
County: Dawes
Approx. Elev: 3837 ft

Site 6
Loc: T29N, R45W, sec 29, BBBB
Quad: Skunk Lake NW
County: Sheridan
Approx. Elev: 3688 ft

Site 7
Loc: T29N, R45W, sec 20, DADA
Quad: Skunk Lake NE
County: Sheridan
Approx. Elev: 3676 ft

Site 8
Loc: T29N, R45W, sec 14, BBAB
Quad: Skunk Lake NE
County: Sheridan
Approx. Elev: 3647 ft

Site 9
Loc: T29N, R45W, sec 11, AABA
Quad: Hay Springs SE
County: Sheridan
Approx. Elev: 3638 ft

Appendix C: Core Descriptions and Photographs

Site 1: Core length 2.80 feet.

Depth (ft)	Description
0.0 – 0.30	Sand, fine grained, very silty; medium brown color
0.30 – 1.65	Sand and silt, interbedded; silt is dark brownish gray to black color, sand is medium brown color
1.65 – 2.80	Sand, fine to medium grained, some very thin silt layers; medium to light brown color


2.8 ft

Site 2: Core length 4.10 feet.

Depth (ft)	Description
0.0 – 0.75	Sand , fine grained, moderately silty; medium brown color.
0.75 – 0.95	Gravel and sand, sand is fine to medium grained, medium brown in color; gravel is fine grained with some medium grained.
0.95 – 4.10	Sand, very fine to medium grained with some sandstone clasts, very silty between 1.40 to 1.60 ft. and 2.20 and 2.30 ft., greater amount of silt below 2.90 ft.; med brown color.


4.1ft

Site 3: Core length 3.40 feet.

Depth (ft)	Description
0.0 – 2.10	Sand and gravel, fine to medium grained sand with abundant fine to medium grained gravel; sand is medium brown color.
2.10 – 3.40	Sand, fine grained, silty, some black clay layers near bottom, prominent interbedded silt layers; medium brown color


3.4ft

Site 4: Core length 3.70 feet.

Depth (ft)	Description
0.0 – 0.10	Sand, fine grained; medium brown color
0.10 – 0.45	Silt and sand, sand is very fine to fine grained, brownish gray color
0.45 – 3.70	Sand, fine to medium grained with some fine to medium grained gravel mixed with sand, some silt layers; medium brown color


3.7 ft

Site 5: Core length 1.60 feet.

Depth (ft)	Description
0.0 – 0.20	Sand, fine to medium grained, very silty; dark brown color.
0.20 – 1.60	Sand, fine to medium grained, thin layers of very silty sand; light to medium brownish gray color.


1.6 ft

Site 6: Core length 2.70 feet.

Depth (ft)	Description
0.0 – 0.95	Sand, medium to very coarse grained, with gravel layers, gravel is medium to coarse grained
0.95 – 1.05	Silt, dark brown color
1.05 – 1.80	Sand, fine to very coarse grained with some fine grained gravel
1.80 – 2.70	Silt, dark brown color


2.7 ft

Site 7: Core length 4.60 feet.

Depth (ft)	Description
0.0 – 0.25	Sand and gravel, sand is fine to medium grained with fine to coarse gravel; light brown color
0.25 – 1.15	Sand, medium grained becoming coarser below 0.80 ft.; light to medium brown color
1.15 – 2.40	Sand, fine grained, very silty, some gravel below 2.20 ft., medium brown color
2.40 – 4.60	Silt and sand, sand is fine grained, some gravel at 3.70 ft.; medium brown color


4.6 ft

Site 8: Core length 4.20 feet.

Depth (ft)	Description
0.0 – 0.50	Sand and gravel, sand is fine grained with medium grained gravel; medium to dark brown color
0.50 – 1.90	Sand, fine to medium grained with some medium to coarse grained gravel at 0.80 ft and 1.20 ft; light to medium brown color
1.90 – 4.20	Sand, fine grained with some medium to coarse grained gravel between 2.5 and 2.9 ft; sand becomes very fine grained and silty below 2.9 ft.; medium brown color

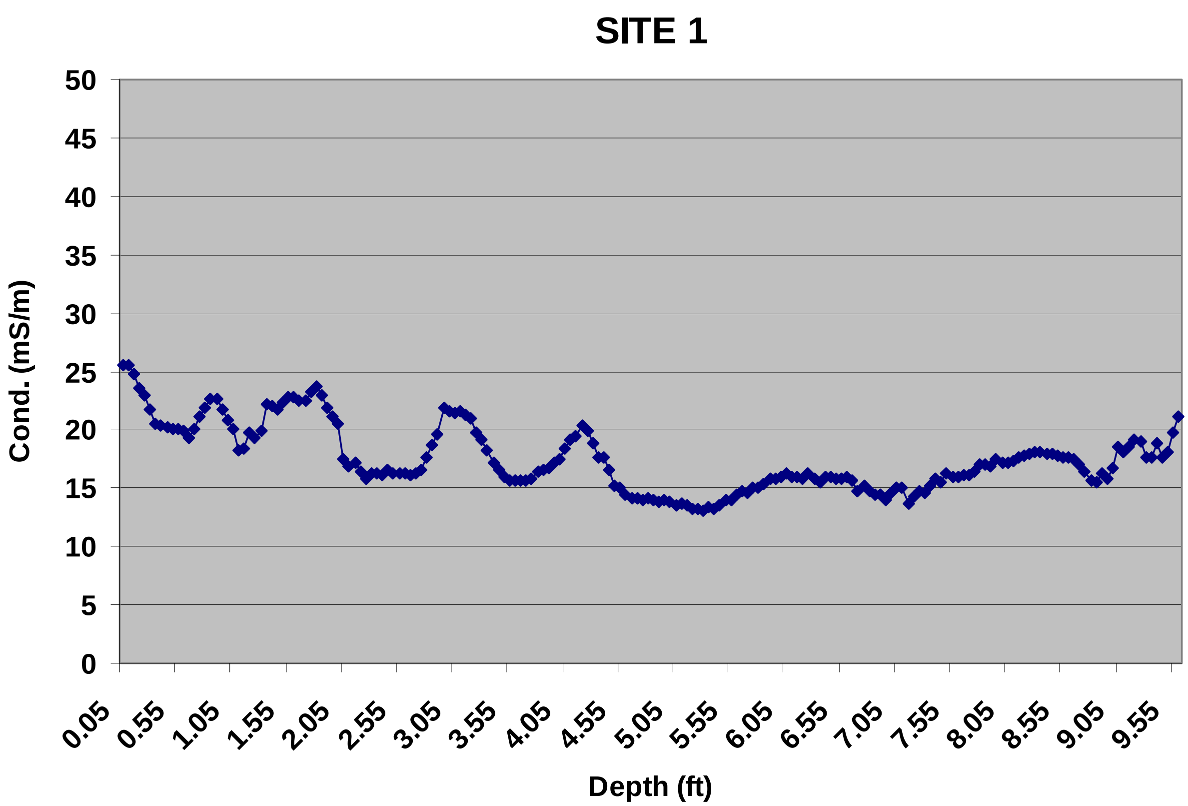

4.2 ft

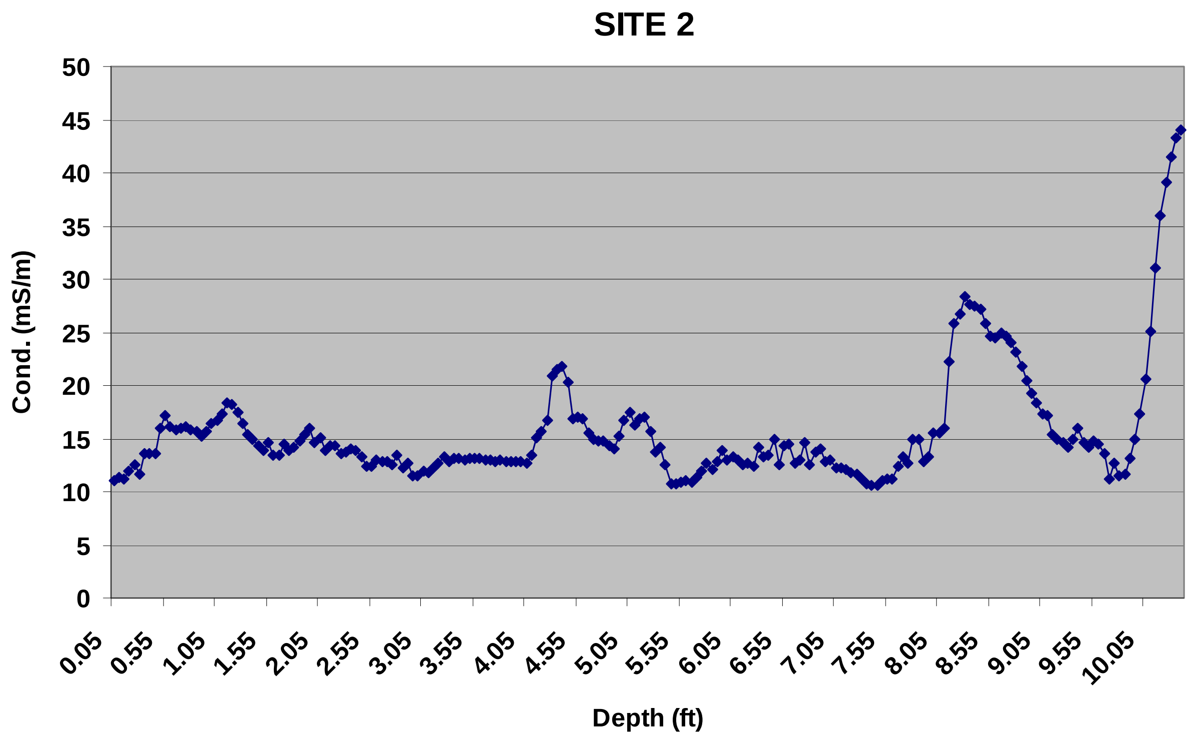
Site 9: Core length 3.40 feet.

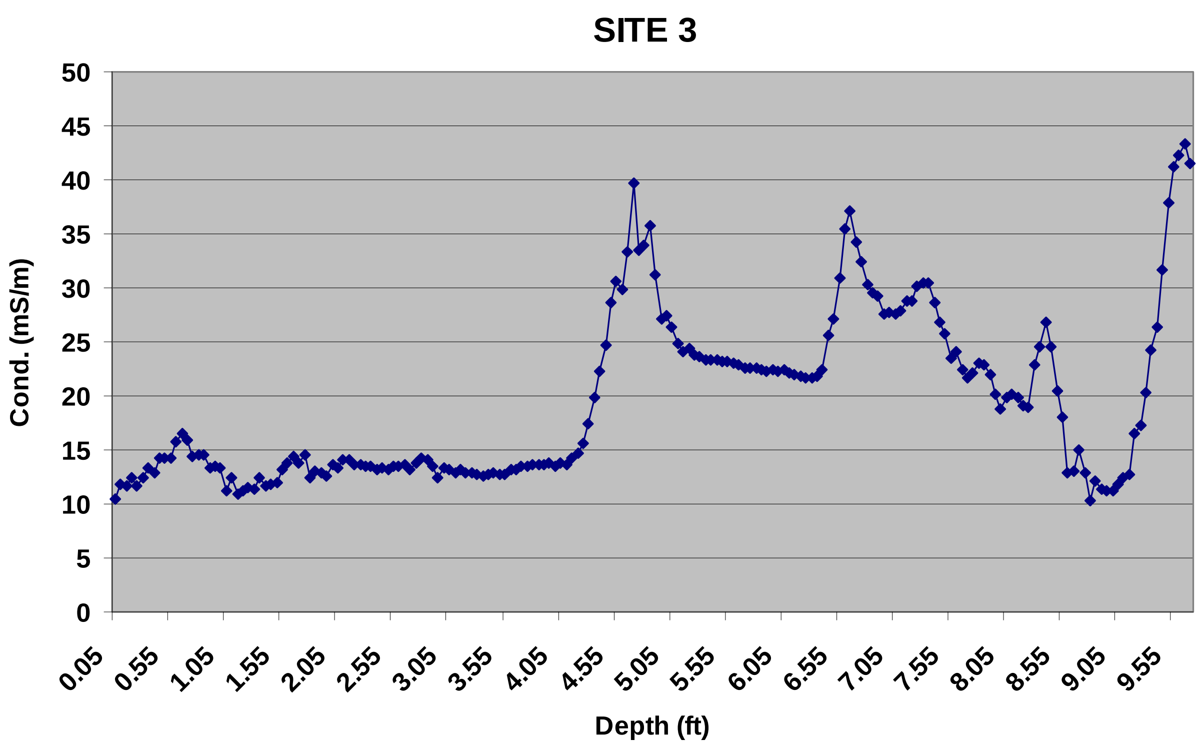
Depth (ft)	Description
0.0 – 0.30	Silt, sandy; dark brown color
0.30 – 1.45	Sand, fine grained with rare gravel; light to medium brown color
1.45 – 2.55	Sand, fine grained, some interbedding with silty sand; light to medium brown color
2.55 – 3.40	Sand and silt, interbedded, sand is fine grained; bedding is well defined, rare gravel; sand is light brown, silt is medium to dark brown color

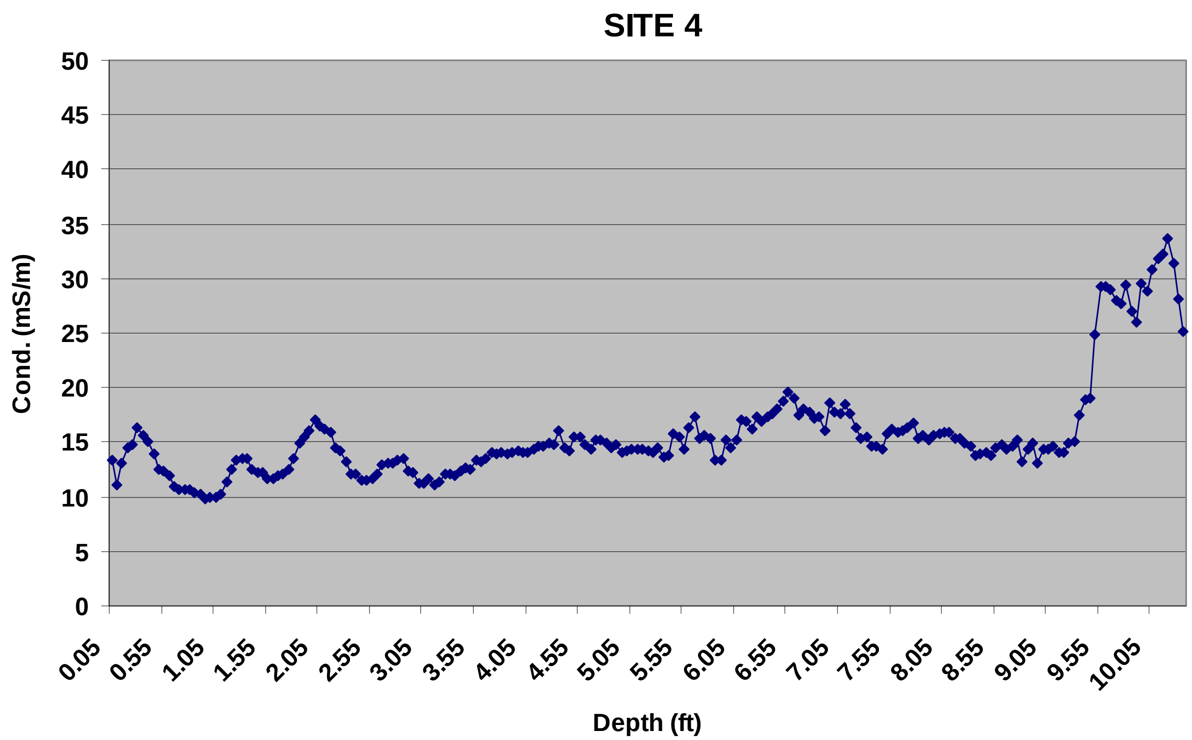

3.4 ft

Appendix D: GeoProbe Site Electrical Conductivity Logs

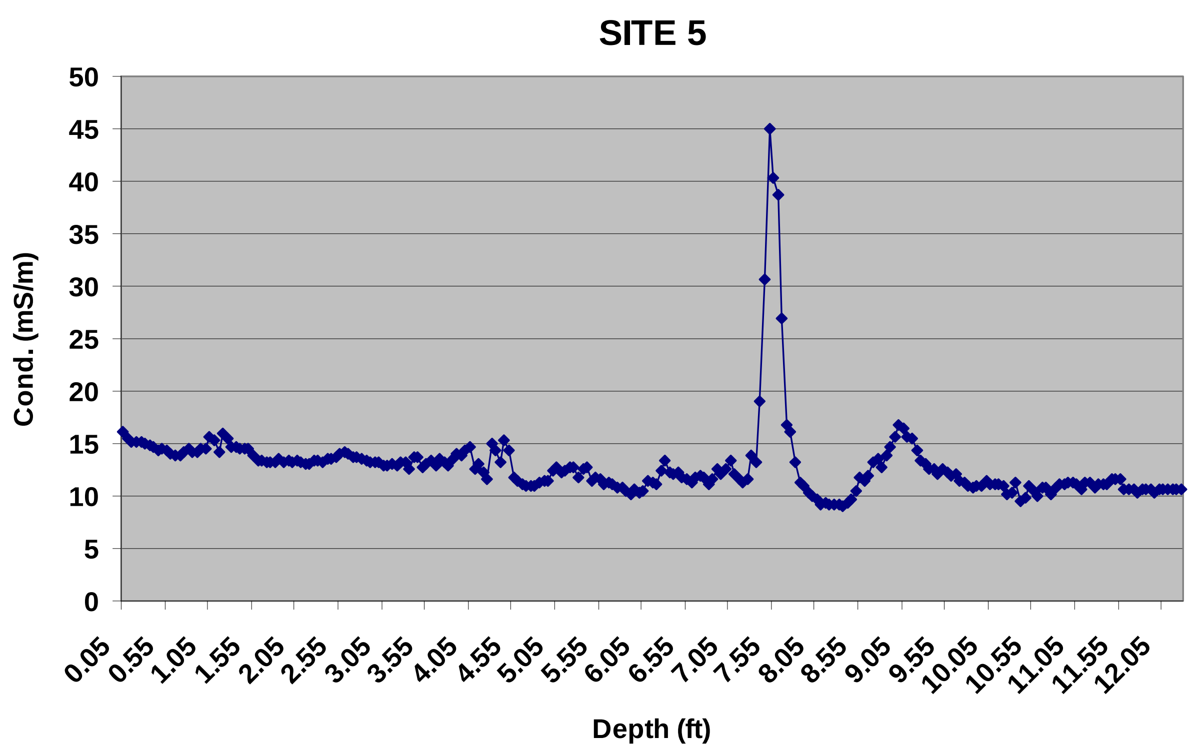



SITE 2
Cond. (mS/m)
0
5
10
15
20
25
30
35
40
45
50
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
10.05
Depth (ft)

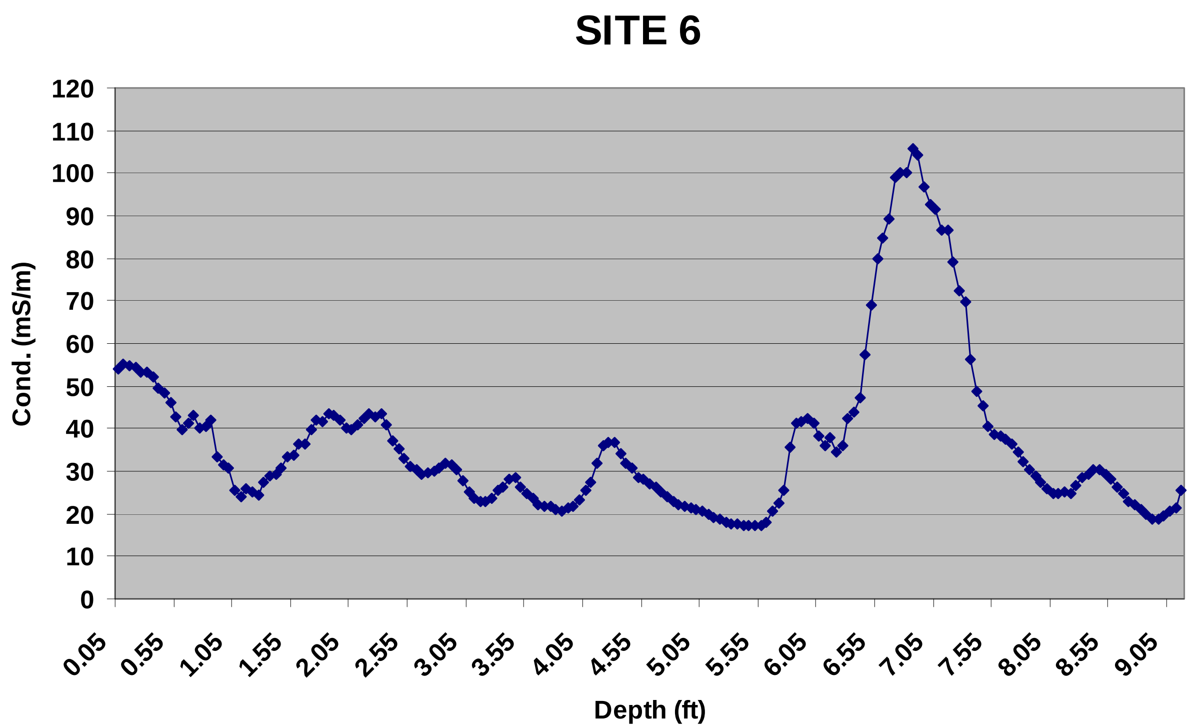

SITE 3
Cond. (mS/m)
0
5
10
15
20
25
30
35
40
45
50
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
Depth (ft)

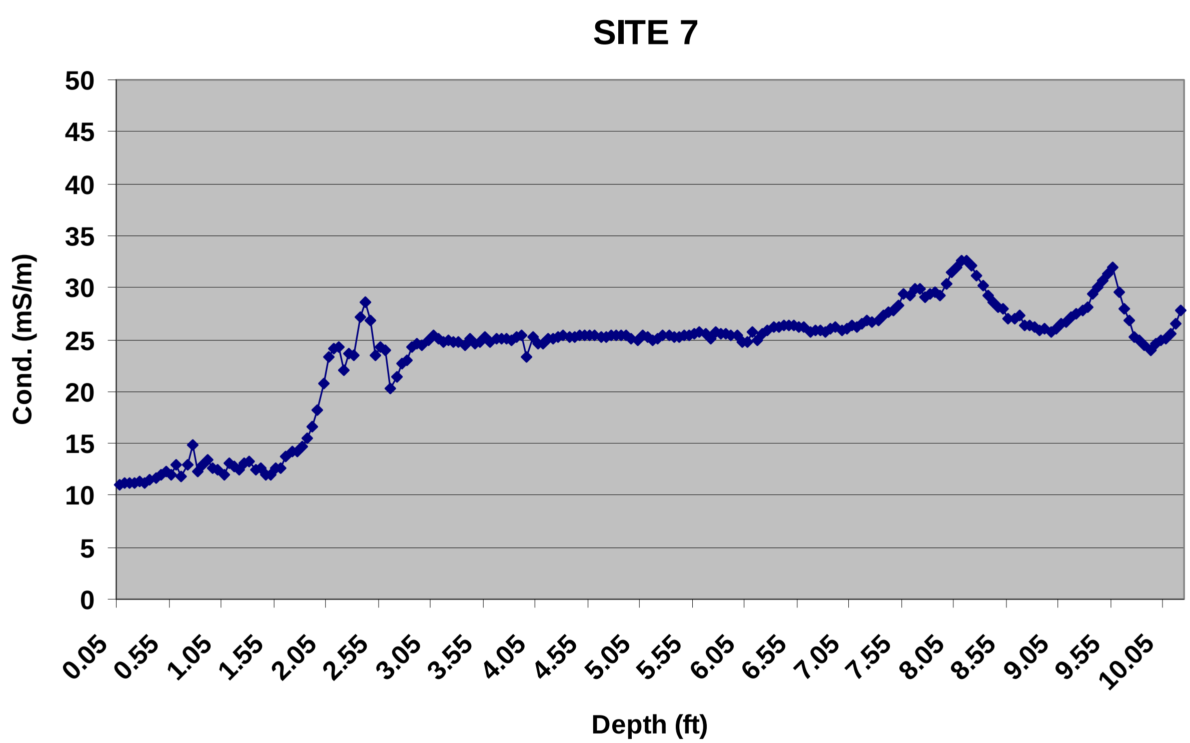


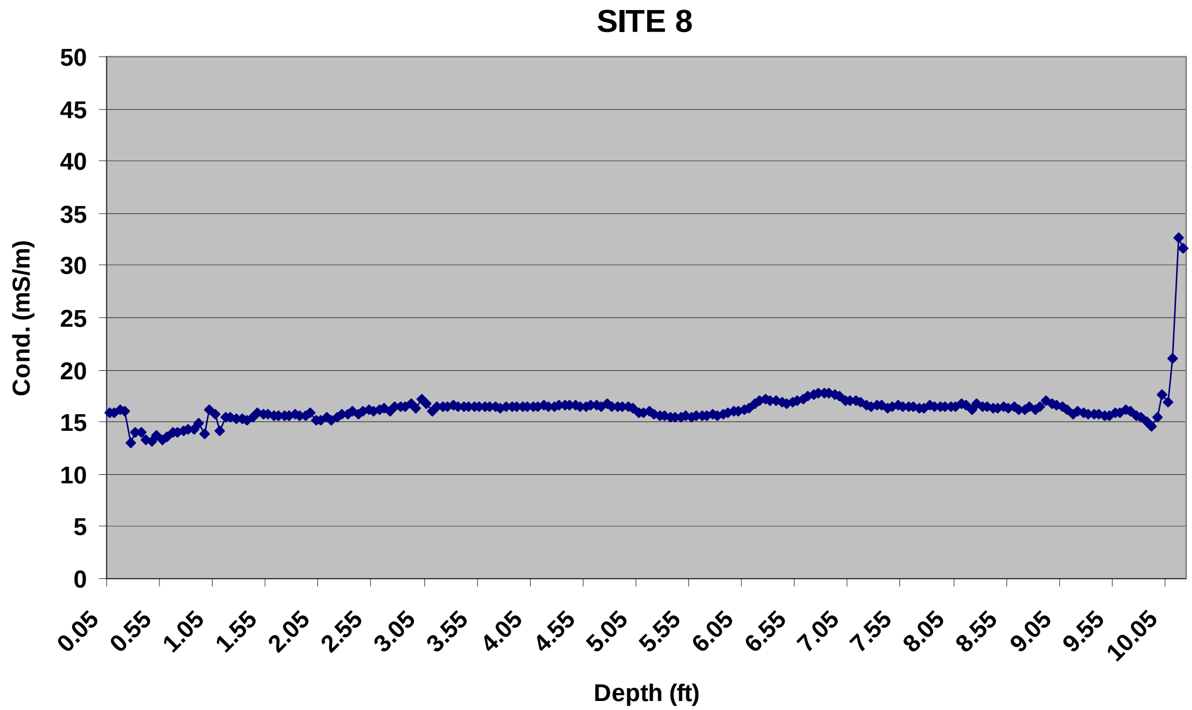
SITE 4
Cond. (mS/m)
0
5
10
15
20
25
30
35
40
45
50
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
10.05
Depth (ft)

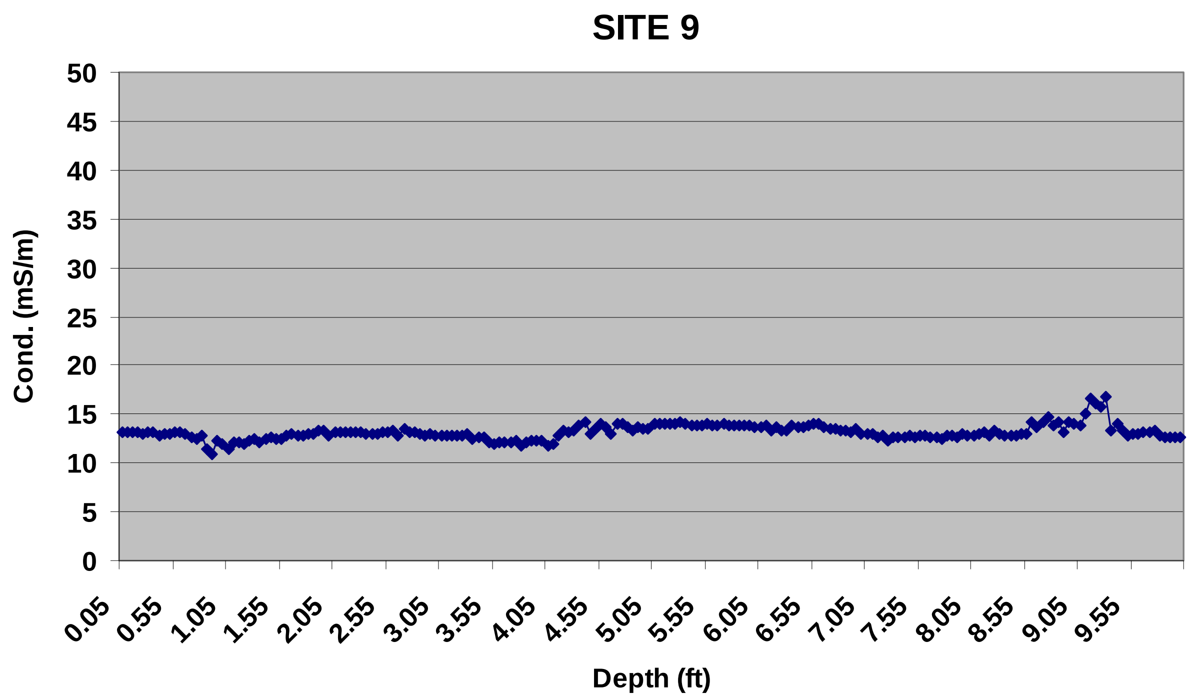


SITE 5
Cond. (mS/m)
0
5
10
15
20
25
30
35
40
45
50
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
10.05
10.55
11.05
11.55
12.05
Depth (ft)

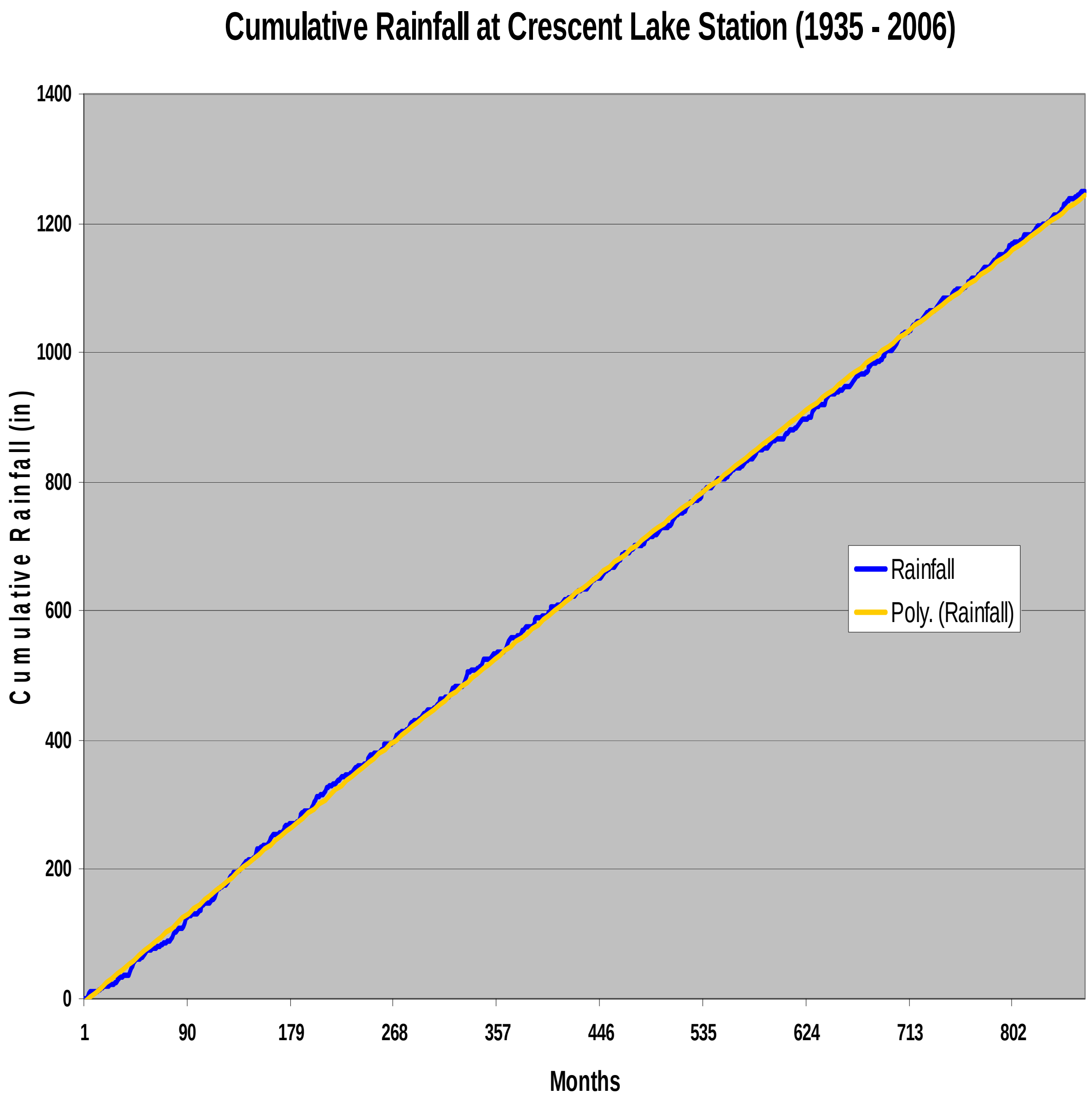

SITE 6
Cond. (mS/m)
0
10
20
30
40
50
60
70
80
90
100
110
120
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
Depth (ft)

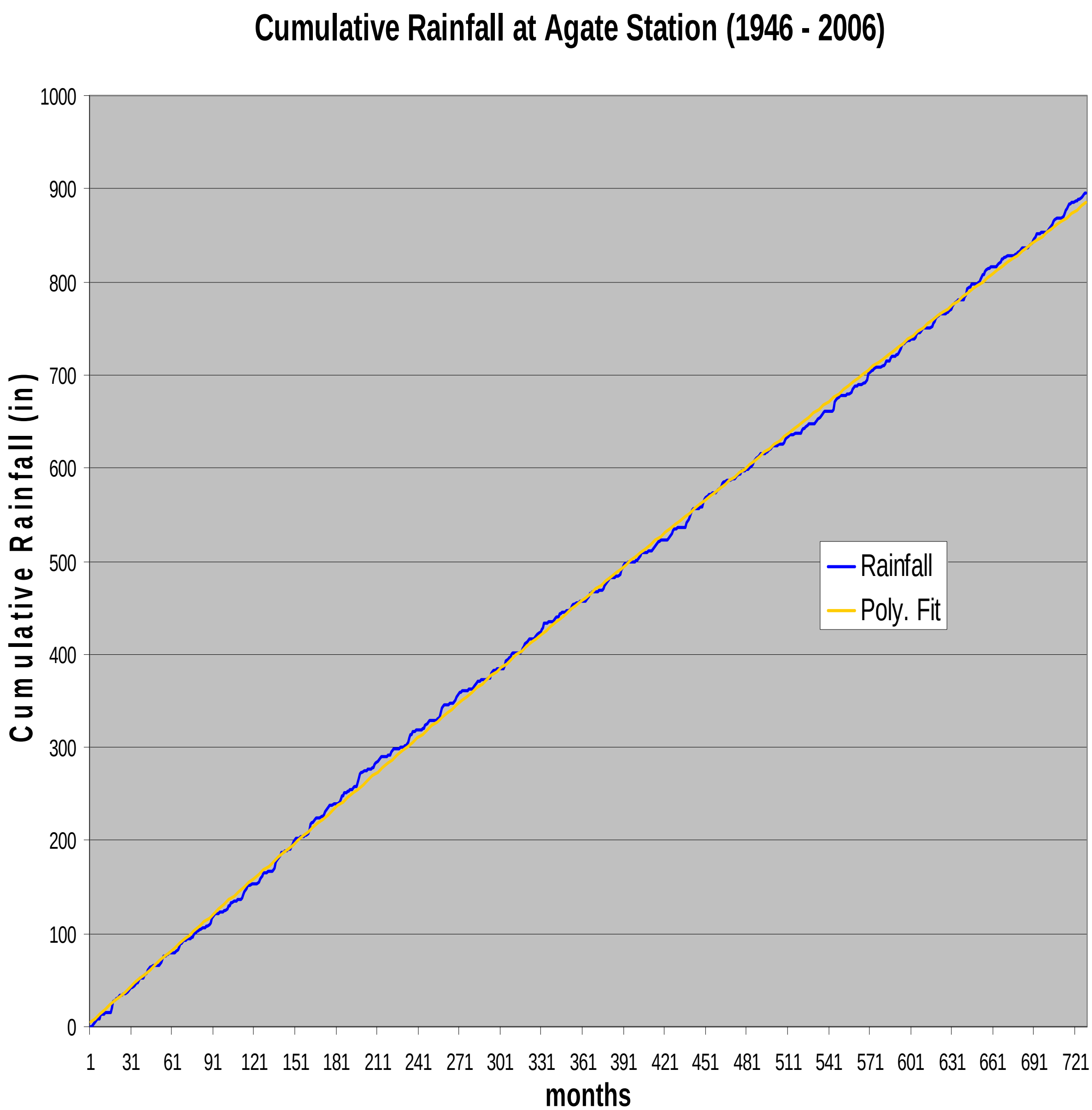

SITE 7
Cond. (mS/m)
0
5
10
15
20
25
30
35
40
45
50
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
10.05
Depth (ft)


SITE 8
Cond. (mS/m)
50
45
40
35
30
25
20
15
10
5
0
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
10.05
Depth (ft)

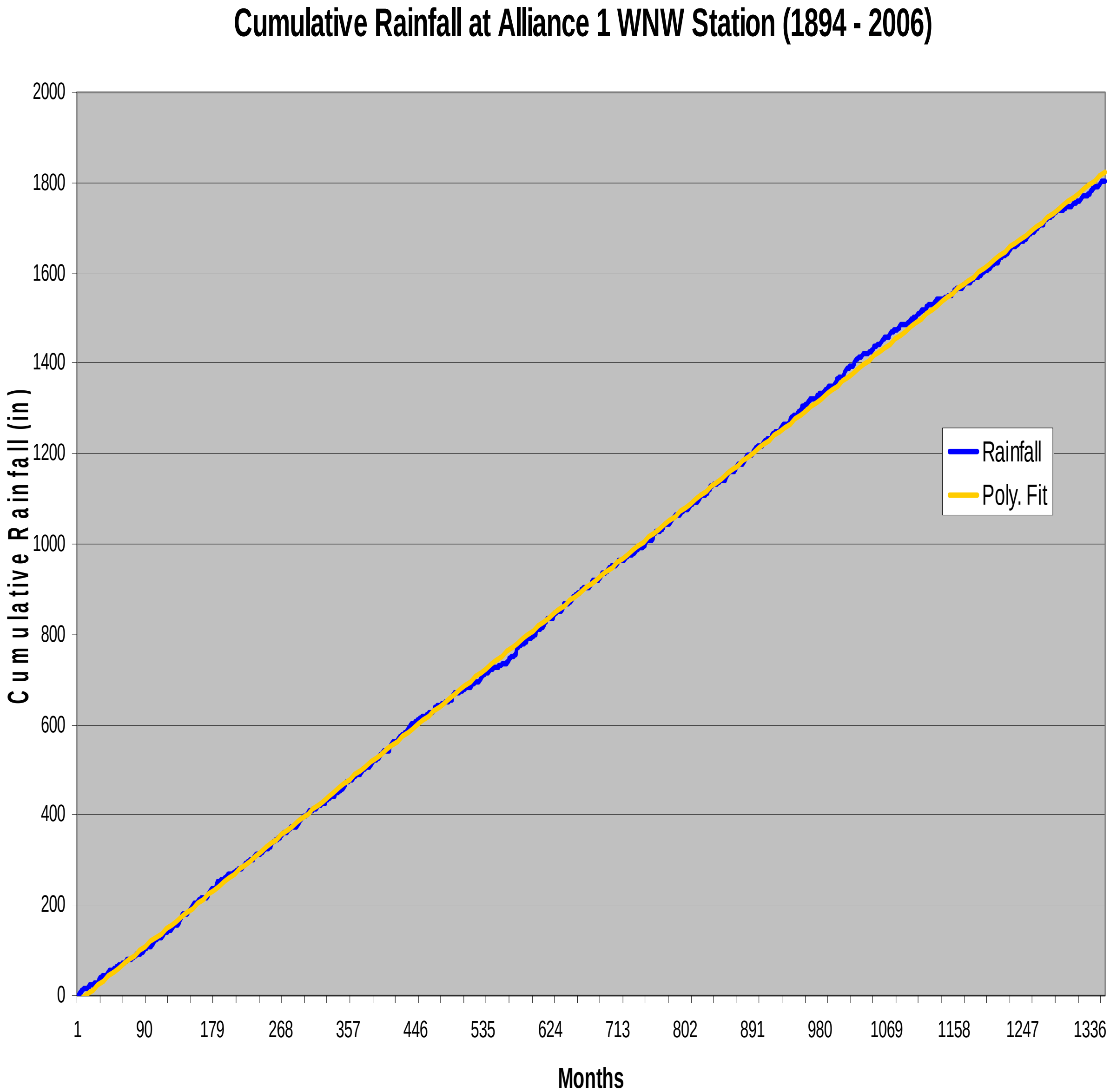

SITE 9
Cond. (mS/m)
50
45
40
35
30
25
20
15
10
5
0
0.05
0.55
1.05
1.55
2.05
2.55
3.05
3.55
4.05
4.55
5.05
5.55
6.05
6.55
7.05
7.55
8.05
8.55
9.05
9.55
Depth (ft)

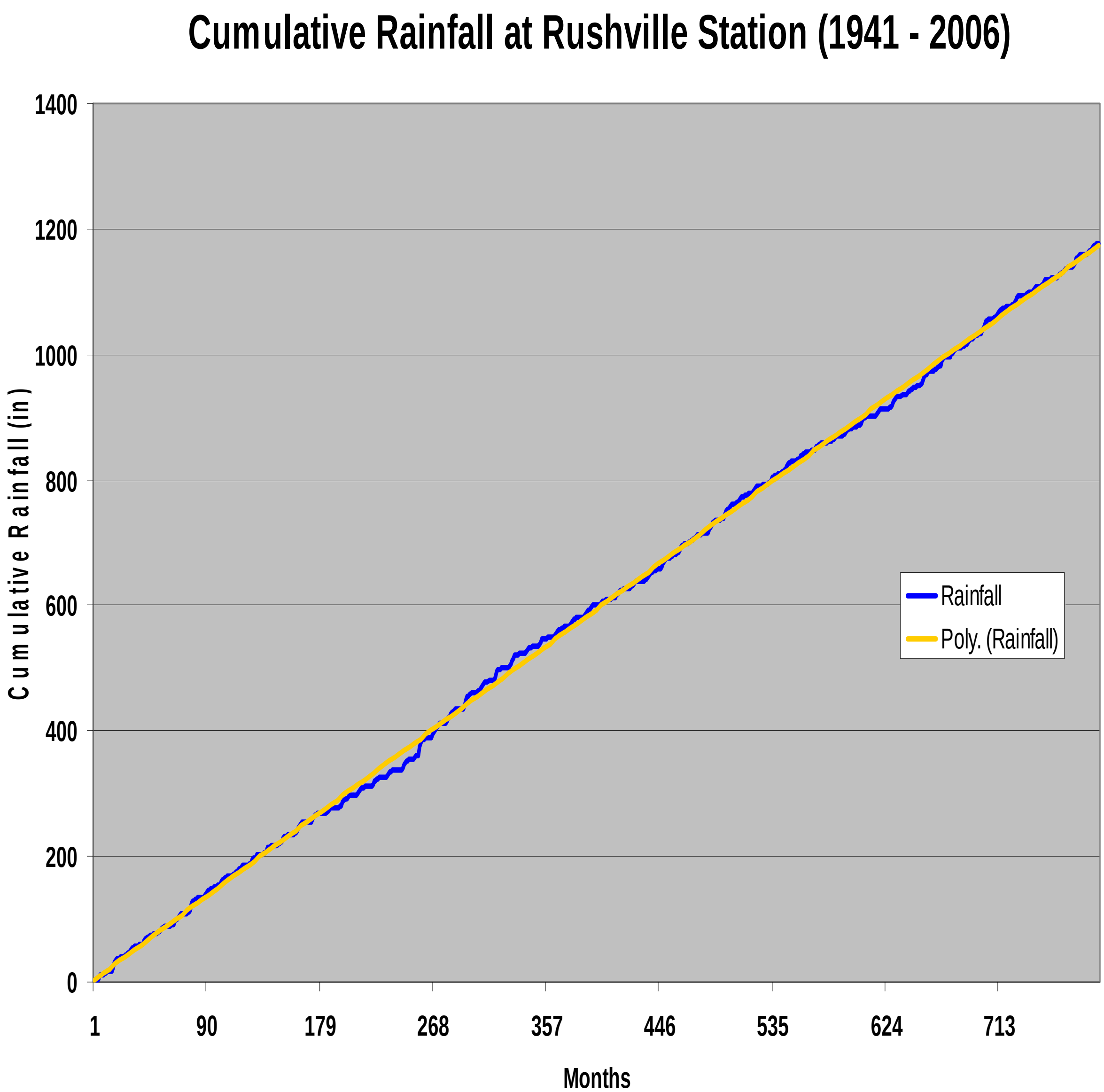
Appendix E: Cumulative Rainfall Graphs for Selected Weather Stations



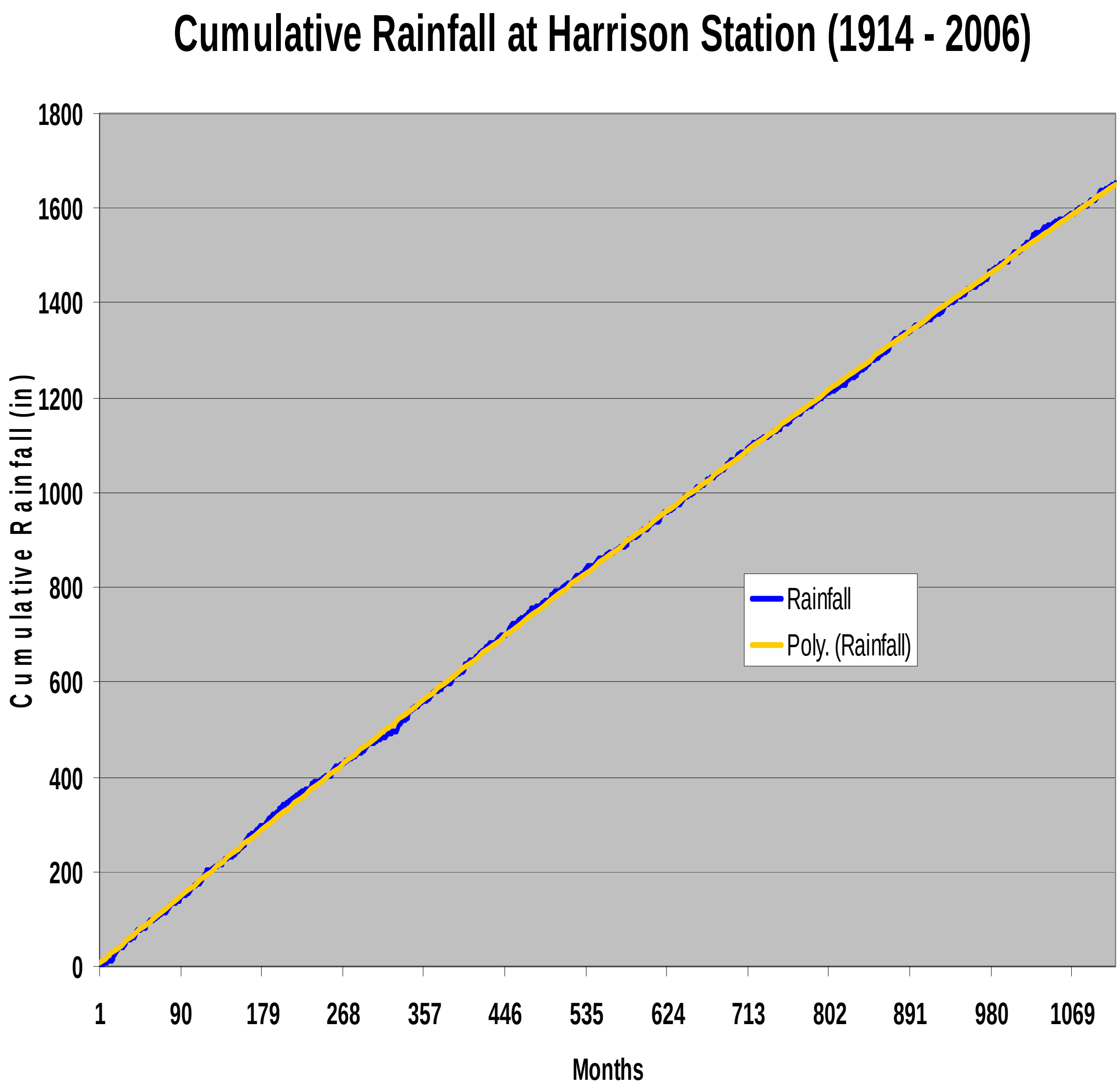


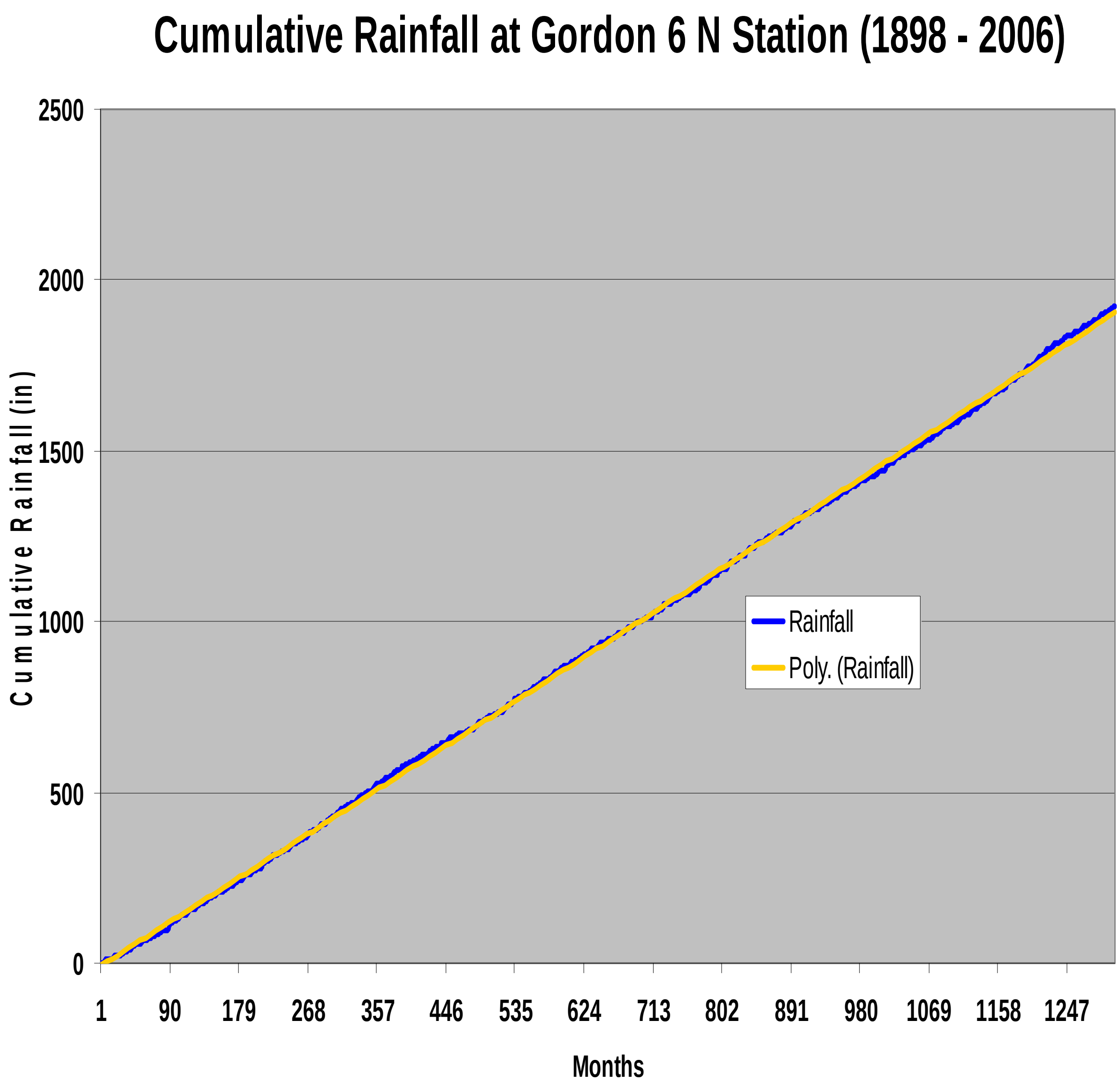
Cumulative Rainfall at Agate Station (1946 - 2006)
Cumulative Rainfall (in)
1000
900
800
700
600
500
400
300
200
100
0
Rainfall
Poly. Fit
1 31 61 91 121 151 181 211 241 271 301 331 361 391 421 451 481 511 541 571 601 631 661 691 721
months

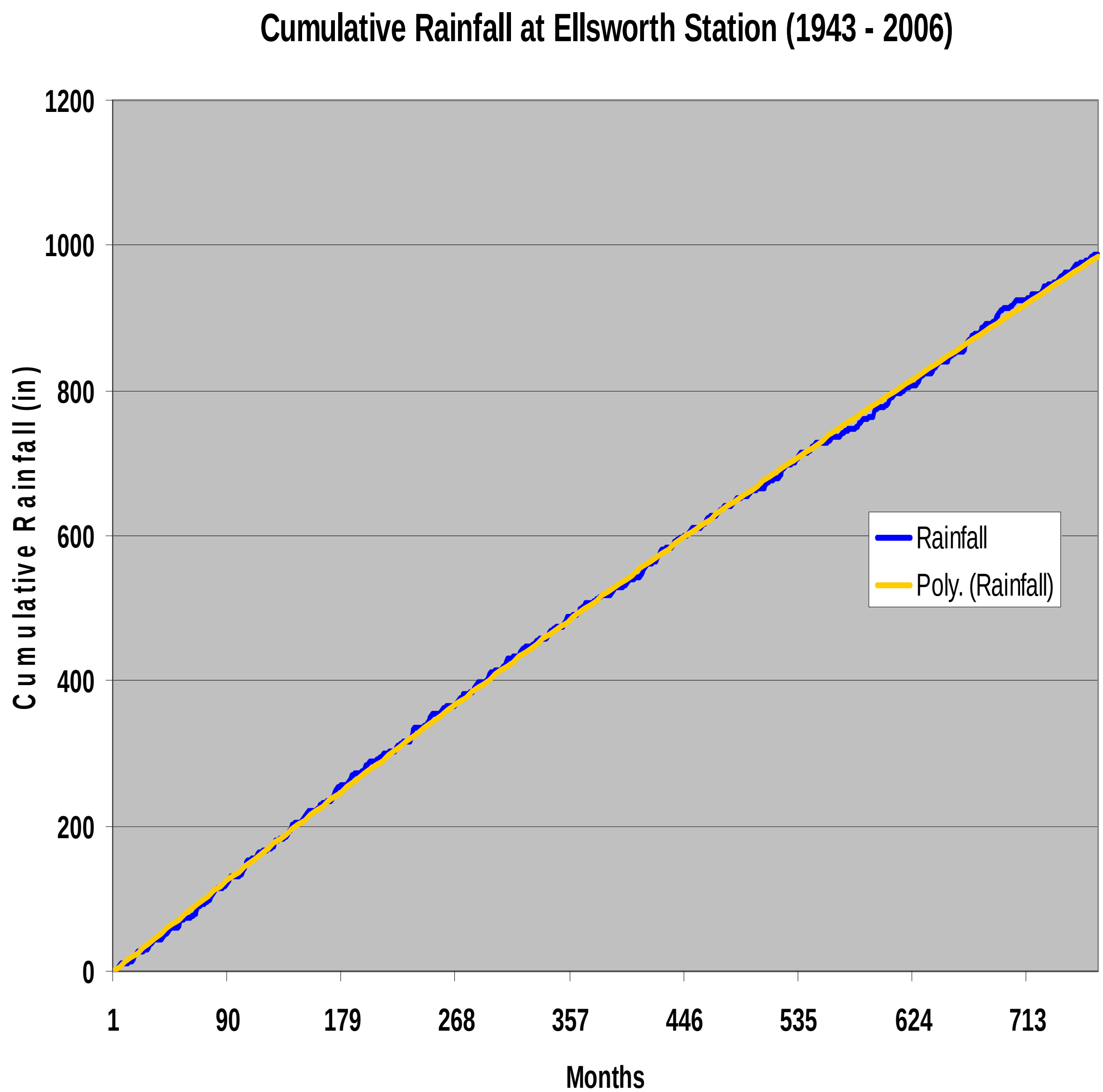

Cumulative Rainfall at Alliance 1 WNW Station (1894 - 2006)
Cumulative Rainfall (in)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1
90
179
268
357
446
535
624
713
802
891
980
1069
1158
1247
1336
Months
Rainfall
Poly. Fit



Cumulative Rainfall at Rushville Station (1941 - 2006)
1400
1200
1000
800
600
400
200
0
Cumulative Rainfall (in)
1
90
179
268
357
446
535
624
713
Months
Rainfall
Poly. (Rainfall)


Cumulative Rainfall at Harrison Station (1914 - 2006)
Cumulative Rainfall (in)
1800
1600
1400
1200
1000
800
600
400
200
0
1
90
179
268
357
446
535
624
713
802
891
980
1069
Months
Rainfall
Poly. (Rainfall)

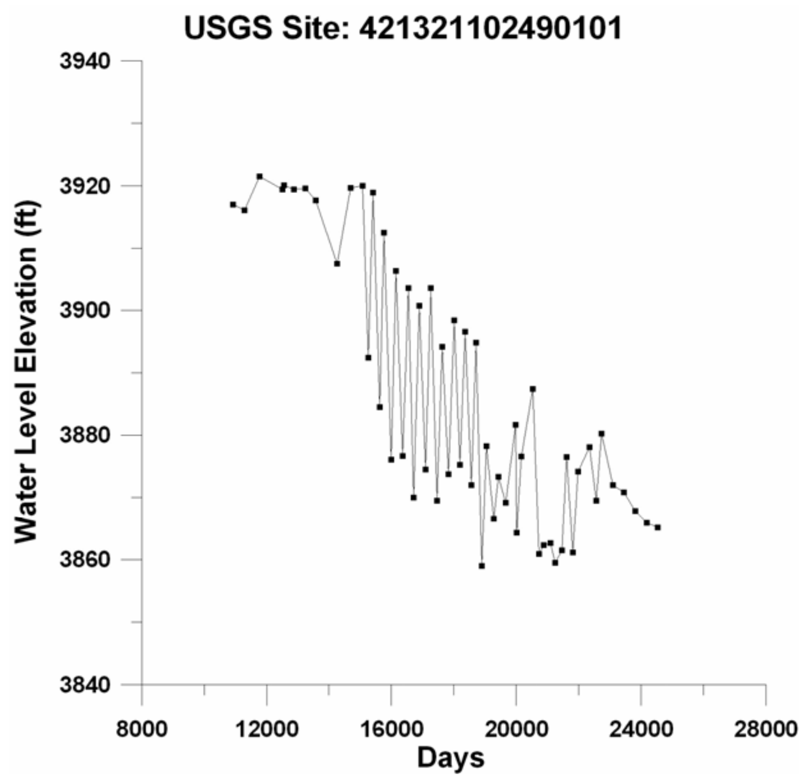

Cumulative Rainfall at Gordon 6 N Station (1898 - 2006)
2500
2000
1500
1000
500
0
Cumulative Rainfall (in)
1
90
179
268
357
446
535
624
713
802
891
980
1069
1158
1247
Months
Rainfall
Poly. (Rainfall)

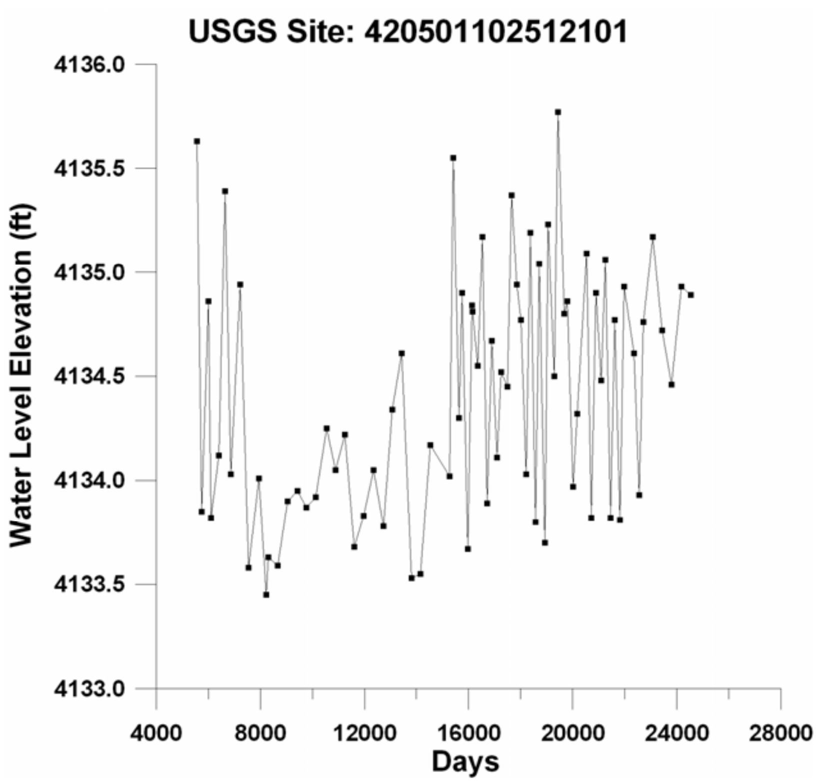

Cumulative Rainfall at Ellsworth Station (1943 - 2006)
Cumulative Rainfall (in)
1200
1000
800
600
400
200
0
1
90
179
268
357
446
535
624
713
Months
Rainfall
Poly. (Rainfall)

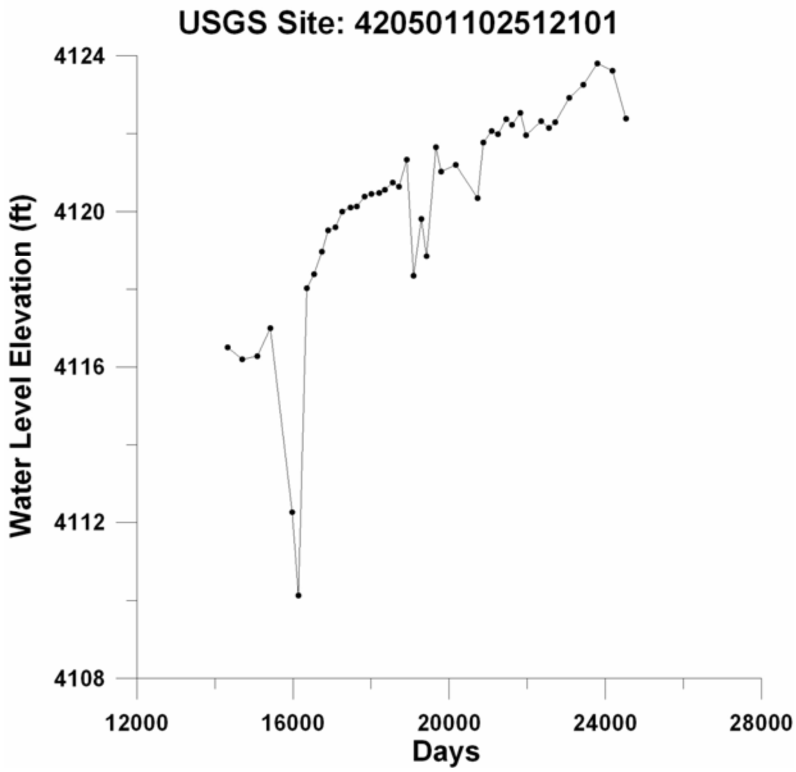
Appendix F: Selected Observation Well Hydrographs

USGS Site ID	Long W	Lat N	X Coord	Y Coord	Elev	Begin Date	End Date	Cnt
423637102572301	102.95	42.61	291480.4	362293.3	4265	4/1/77	3/29/06	44
422526103183002	103.30	42.42	195498.9	293663.9	4138	3/21/53	3/29/06	76
420501102512101	102.85	42.08	318897.2	168374.9	3938	4/27/76	3/25/06	46
420029102514301	102.86	42.00	317230.7	140557.1	3970	5/13/88	3/16/06	29
421433103230001	103.38	42.24	175112.1	222452.8	4436	7/22/38	4/1/99	103
421117102545901	102.91	42.18	302382.2	206829.7	4072	12/4/67	3/30/06	56
421113103000001	103.00	42.18	279582.0	206420.9	4141	4/25/68	3/16/06	56
420834103032001	103.05	42.14	264431.9	190157.2	4110	4/24/68	3/16/06	55
423157102564801	102.94	42.53	294131.0	333653.8	4010	4/1/77	4/5/06	42
422813102544501	102.91	42.47	303445.3	310745.0	3941	7/29/66	4/5/06	62
424041102441101	102.73	42.67	351473.5	387252.7	3830	11/22/36	3/24/06	105
422940102402201	102.67	42.49	368816.5	319644.5	3776	6/21/60	3/24/06	137
422851102393301	102.65	42.48	372528.1	314632.9	3782	7/29/66	3/30/06	62
422940102430101	102.71	42.49	356770.5	319644.5	3813	6/17/60	3/24/06	139
421724103010700	103.01	42.28	274507.7	244364.4	4205	4/29/71	3/16/06	57
421505103051701	103.08	42.25	255571.1	230148.6	4275	8/10/69	3/29/06	1534
420530103104001	103.17	42.09	231102.4	171338.6	4191	5/9/90	3/16/06	57
421115103153400	103.25	42.18	208830.7	206624.6	4312	4/30/71	3/16/06	57
423254102342601	102.57	42.54	395101.5	339796.0	3750	7/28/66	3/24/06	62
423454102435801	102.73	42.58	352457.6	351758.9	3866	7/28/66	3/24/06	62
423415102380301	102.63	42.57	379194.0	347771.3	3756	7/26/61	3/24/06	123
421117103103100	103.17	42.18	231784.8	206829.7	4265	4/6/70	3/16/06	56
420332102165201	102.28	42.05	475622.9	159276.0	3917	10/18/94	3/16/06	17
420355102564001	102.94	42.06	294732.2	161621.7	3969	5/25/72	3/29/06	54
423215102402201	102.67	42.53	368816.5	335499.4	3781	6/21/60	3/24/06	137
421321102490101	102.81	42.22	329501.4	219514.5	3970	12/4/67	4/5/06	57

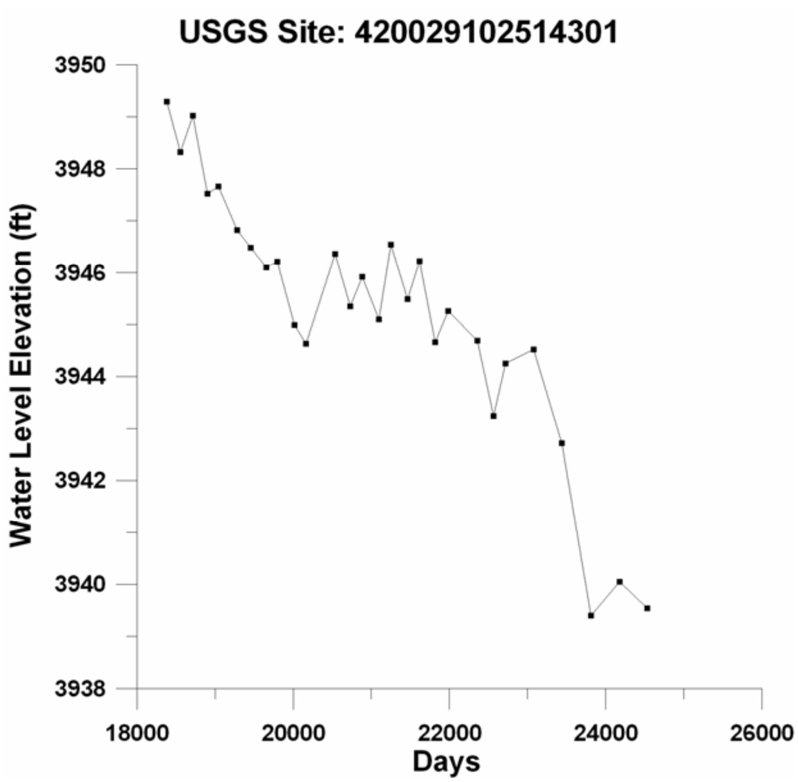
Table F1. Characteristic of USGS observation well used to compare simulation results.


USGS Site: 421321102490101
Water Level Elevation (ft)
3940
3920
3900
3880
3860
3840
8000
12000
16000
20000
24000
28000
Days

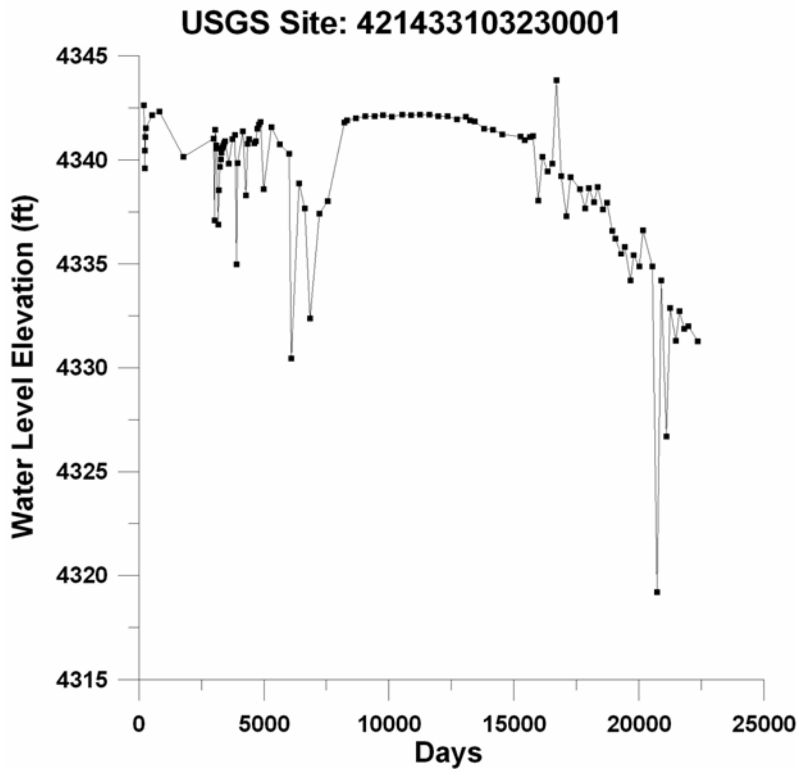

USGS Site: 420501102512101
Water Level Elevation (ft)
4136.0
4135.5
4135.0
4134.5
4134.0
4133.5
4133.0
4000
8000
12000
16000
20000
24000
28000
Days

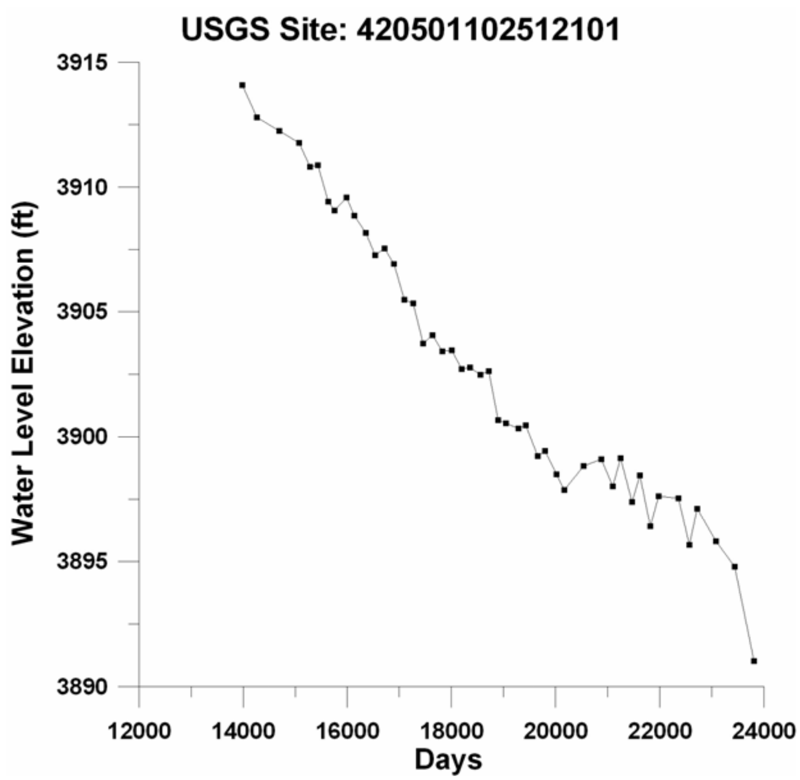


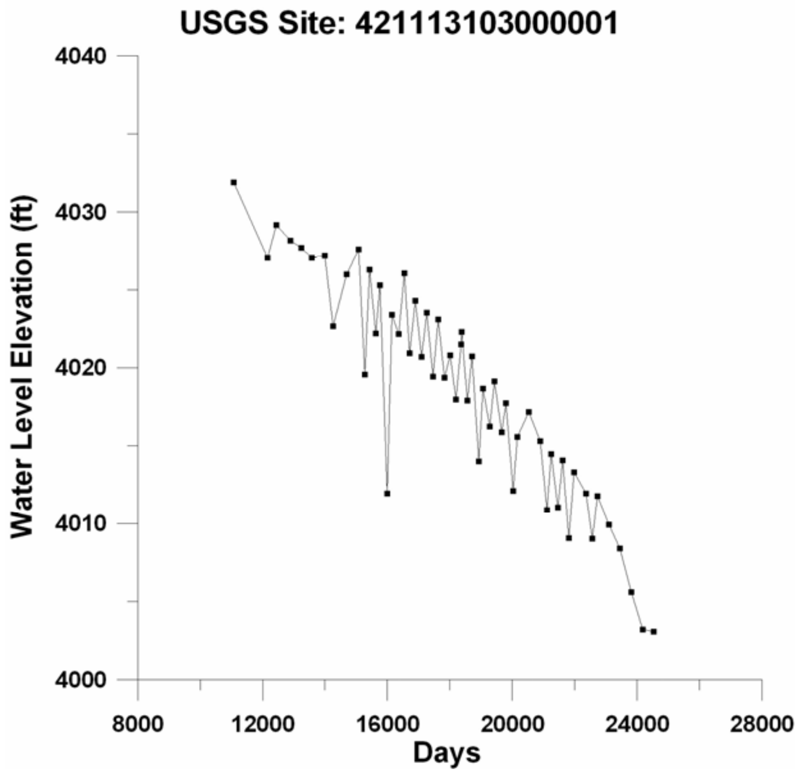
USGS Site: 420501102512101
Water Level Elevation (ft)
4124
4120
4116
4112
4108
12000
16000
20000
24000
28000
Days

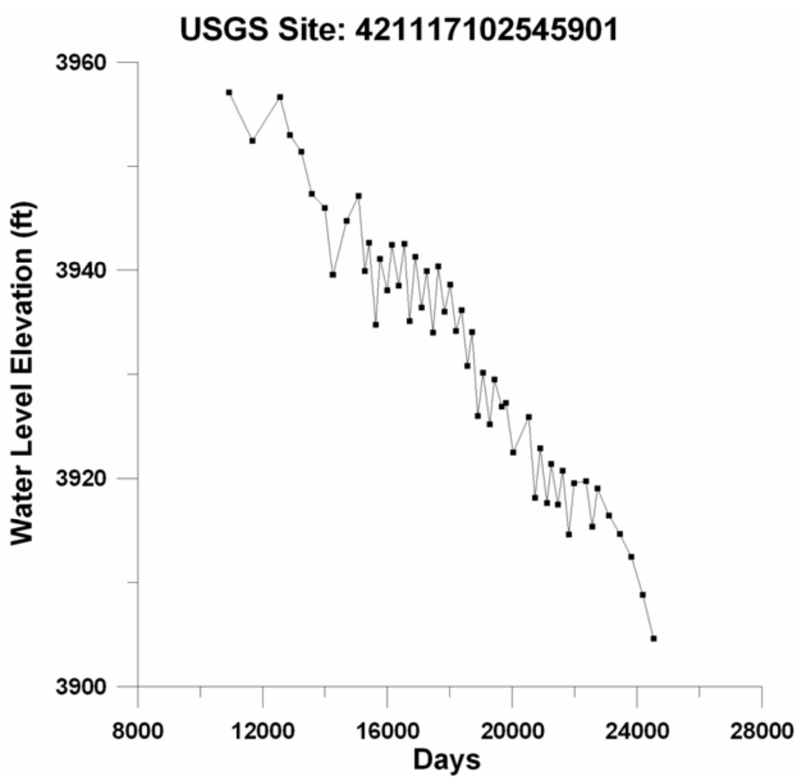


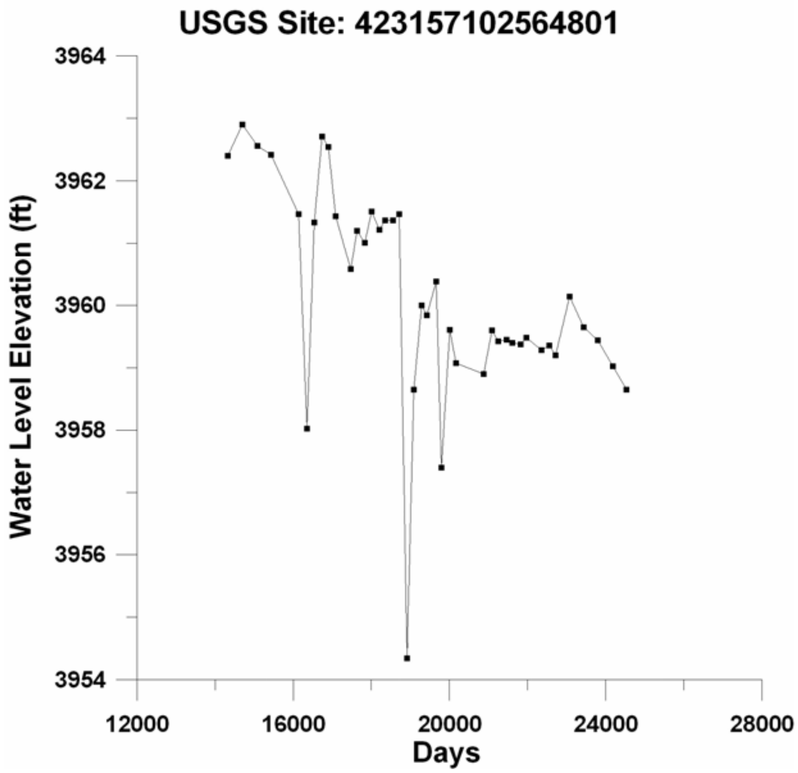
USGS Site: 420029102514301
Water Level Elevation (ft)
3950
3948
3946
3944
3942
3940
3938
18000
20000
22000
24000
26000
Days

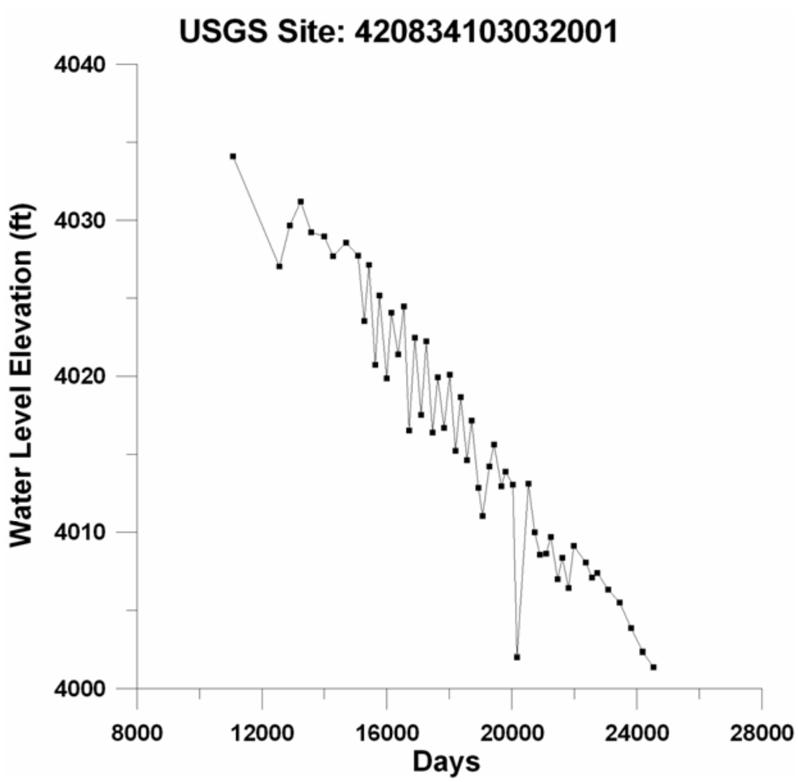

USGS Site: 421433103230001
Water Level Elevation (ft)
4345
4340
4335
4330
4325
4320
4315
0
5000
10000
15000
20000
25000
Days

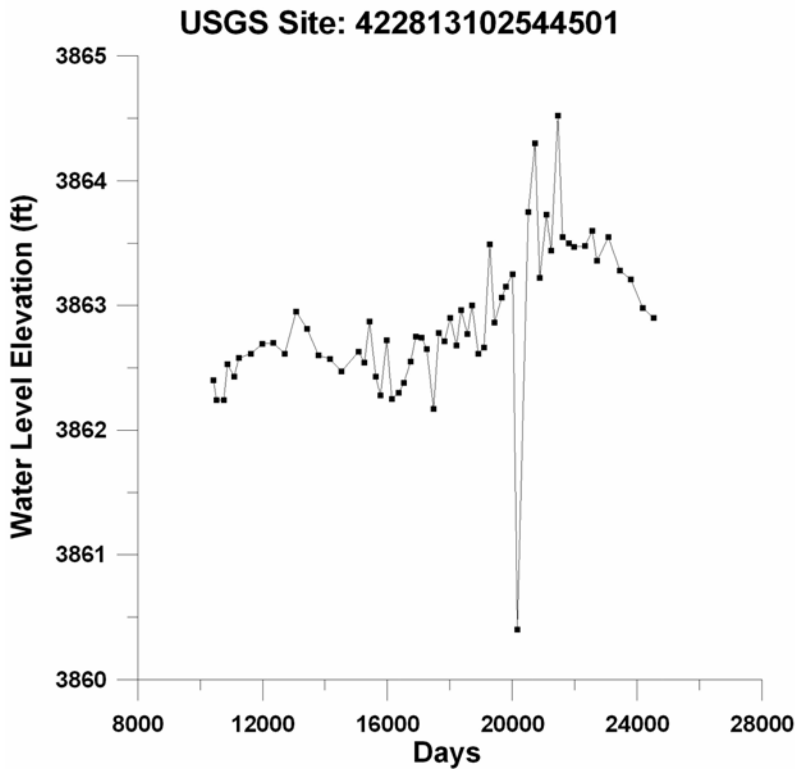

USGS Site: 420501102512101
Water Level Elevation (ft)
3915
3910
3905
3900
3895
3890
12000
14000
16000
18000
20000
22000
24000
Days


USGS Site: 421113103000001
Water Level Elevation (ft)
4040
4030
4020
4010
4000
8000
12000
16000
20000
24000
28000
Days

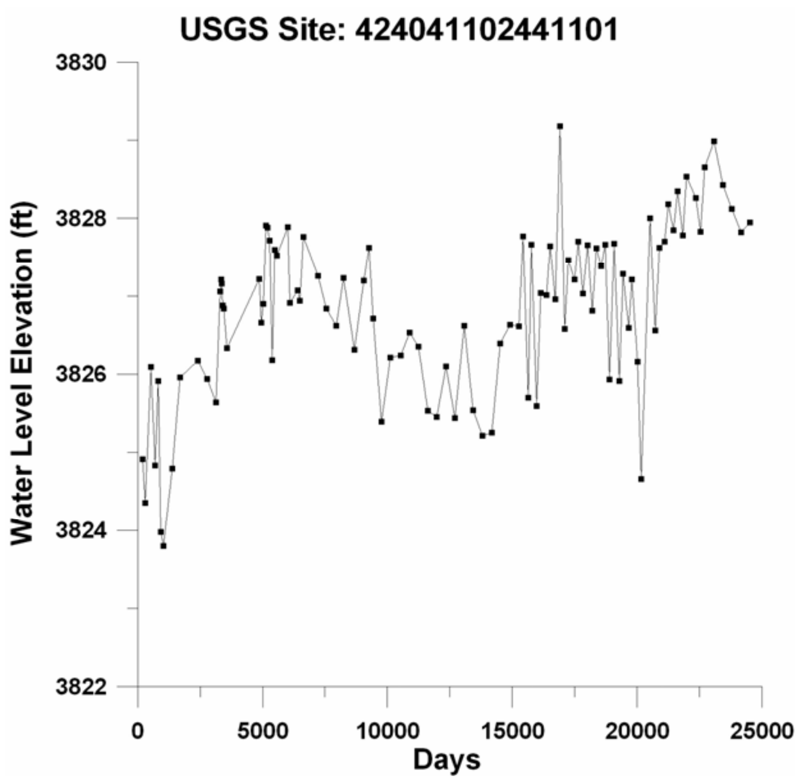

USGS Site: 421117102545901
Water Level Elevation (ft)
3960
3940
3920
3900
8000
12000
16000
20000
24000
28000
Days


USGS Site: 423157102564801
Water Level Elevation (ft)
3964
3962
3960
3958
3956
3954
12000
16000
20000
24000
28000
Days

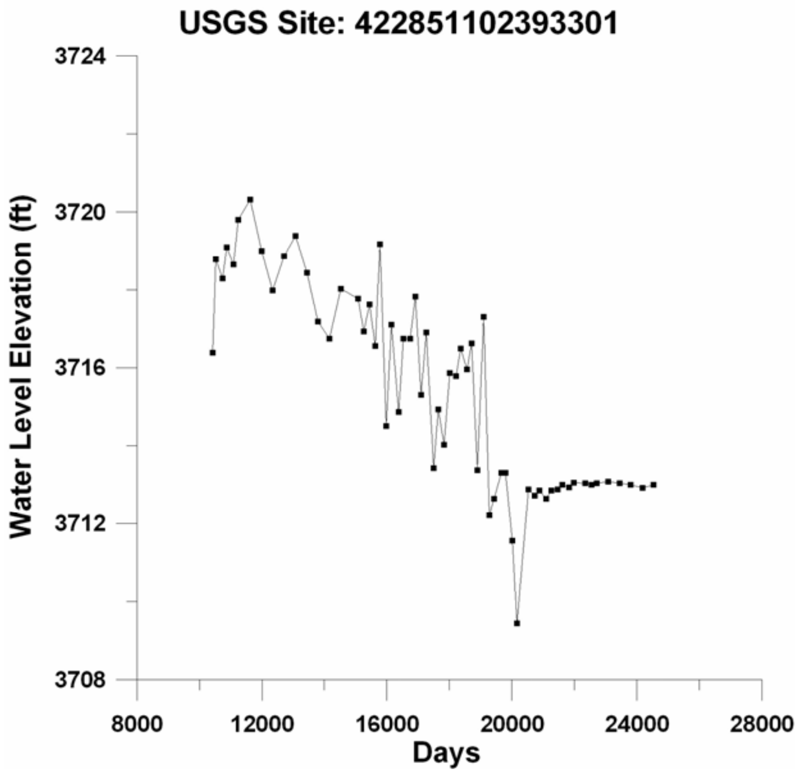

USGS Site: 420834103032001
Water Level Elevation (ft)
4040
4030
4020
4010
4000
8000
12000
16000
20000
24000
28000
Days

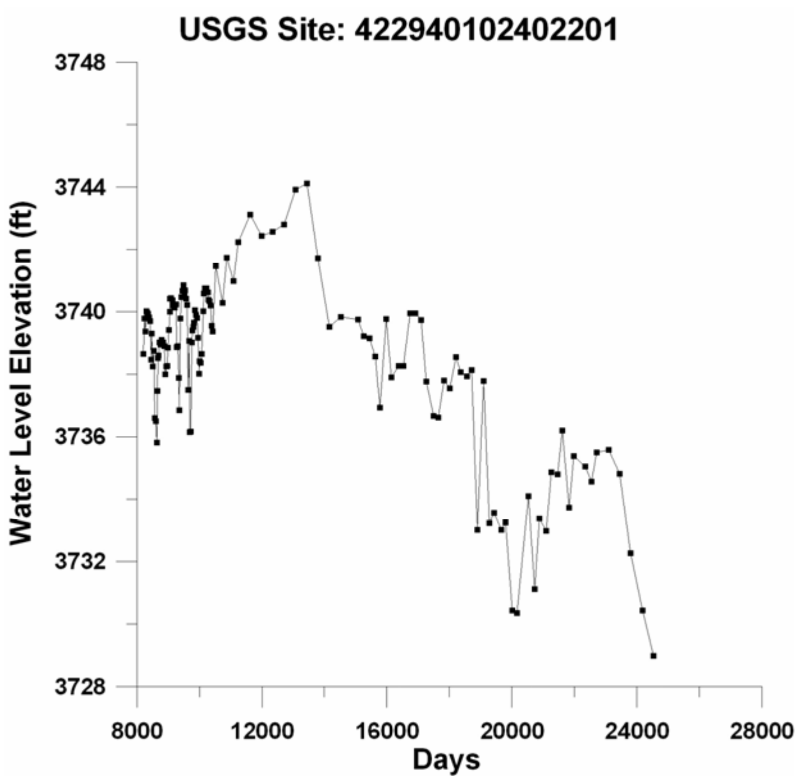


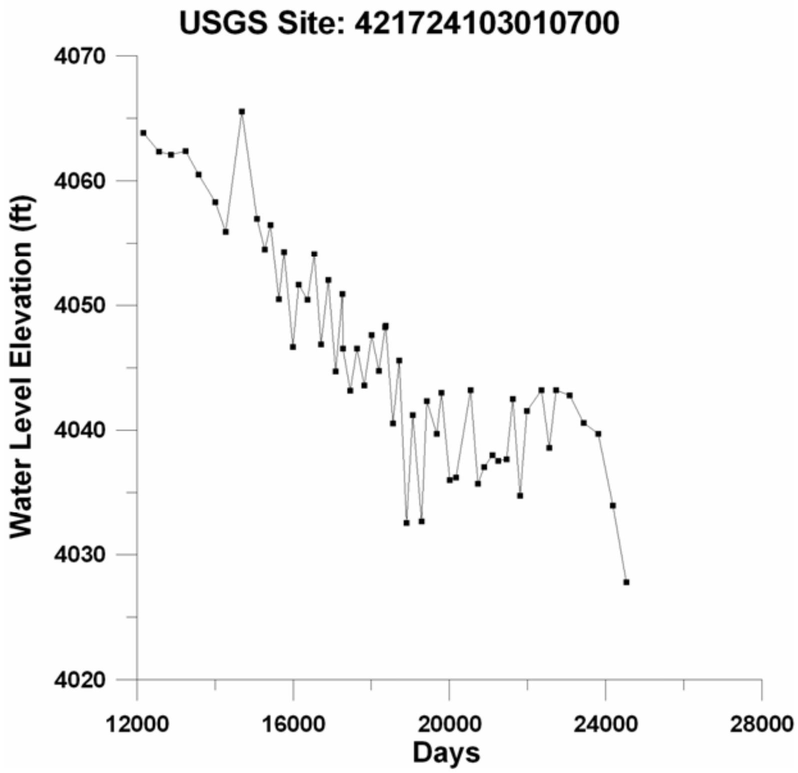
USGS Site: 422813102544501
Water Level Elevation (ft)
3865
3864
3863
3862
3861
3860
8000
12000
16000
20000
24000
28000
Days

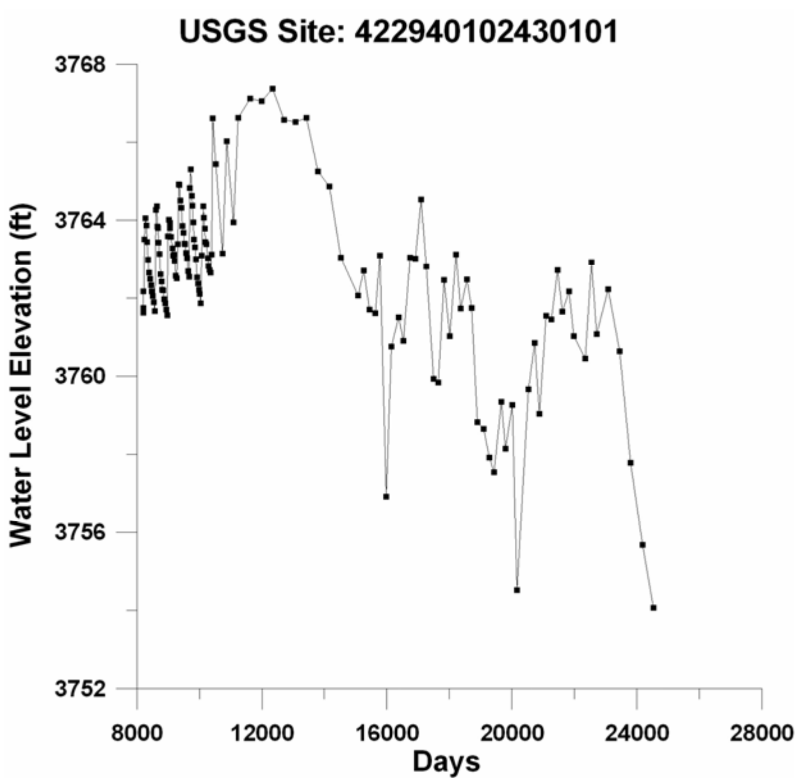


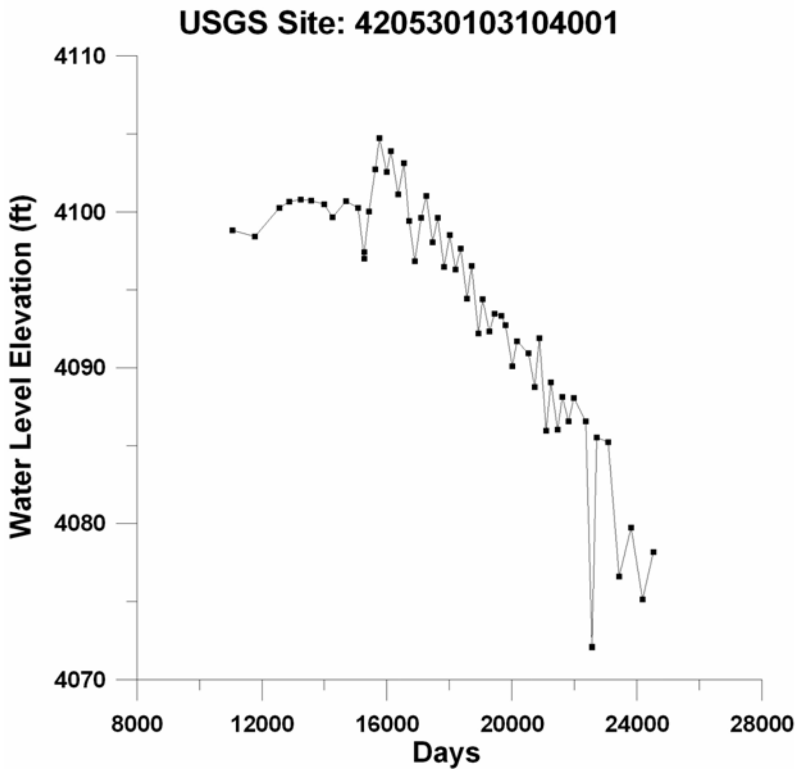
USGS Site: 424041102441101
Water Level Elevation (ft)
3830
3828
3826
3824
3822
0
5000
10000
15000
20000
25000
Days

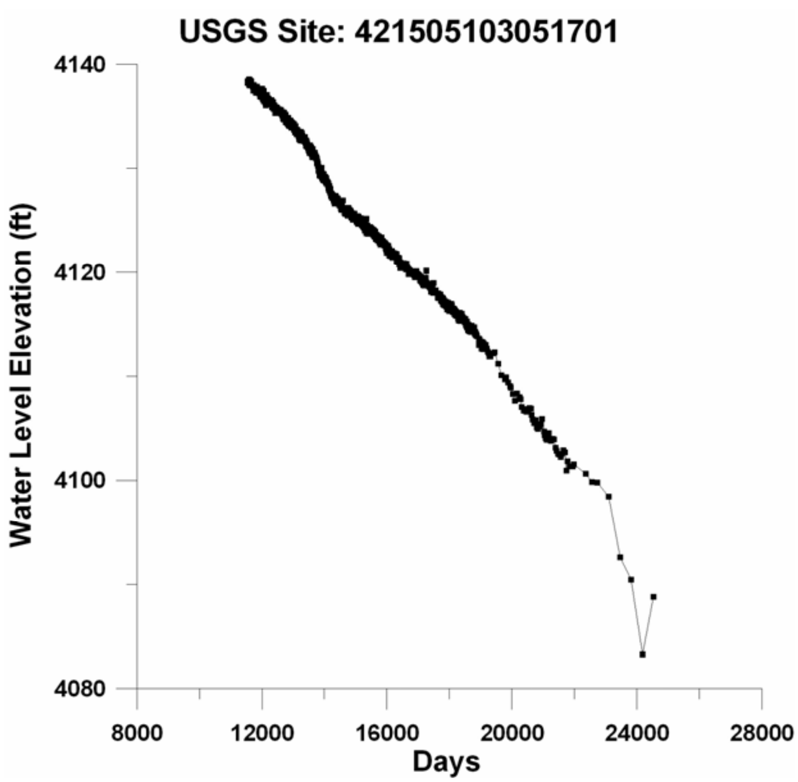

USGS Site: 422851102393301
Water Level Elevation (ft)
3724
3720
3716
3712
3708
8000
12000
16000
20000
24000
28000
Days

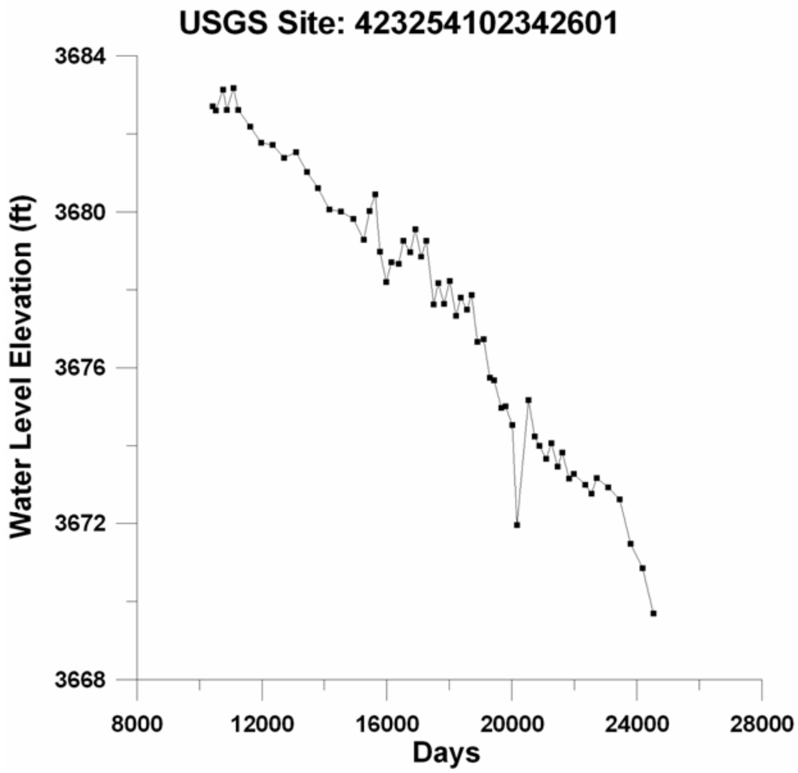

USGS Site: 422940102402201
Water Level Elevation (ft)
3748
3744
3740
3736
3732
3728
8000
12000
16000
20000
24000
28000
Days

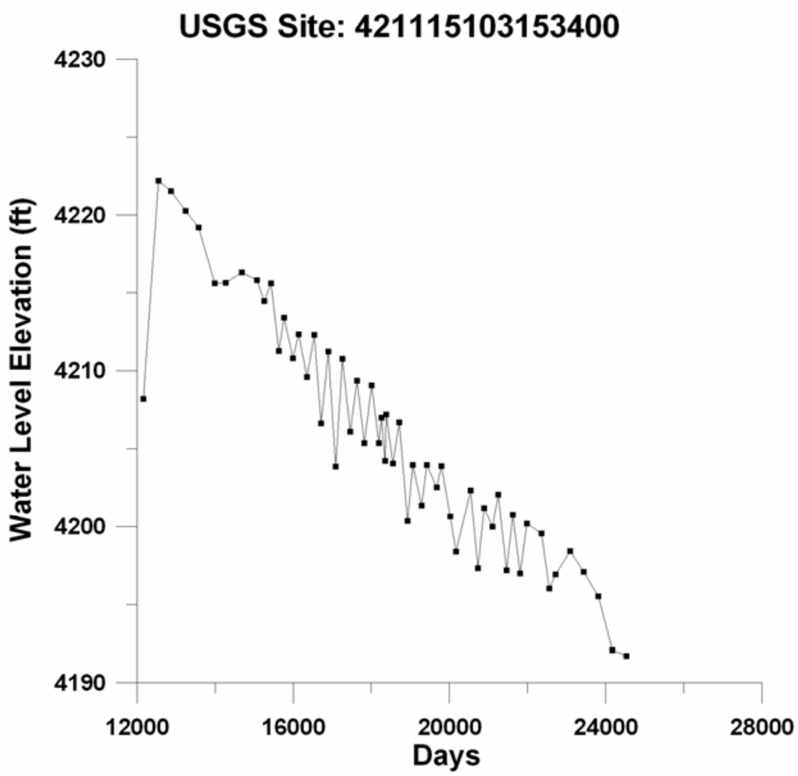

USGS Site: 421724103010700
Water Level Elevation (ft)
4070
4060
4050
4040
4030
4020
12000
16000
20000
24000
28000
Days

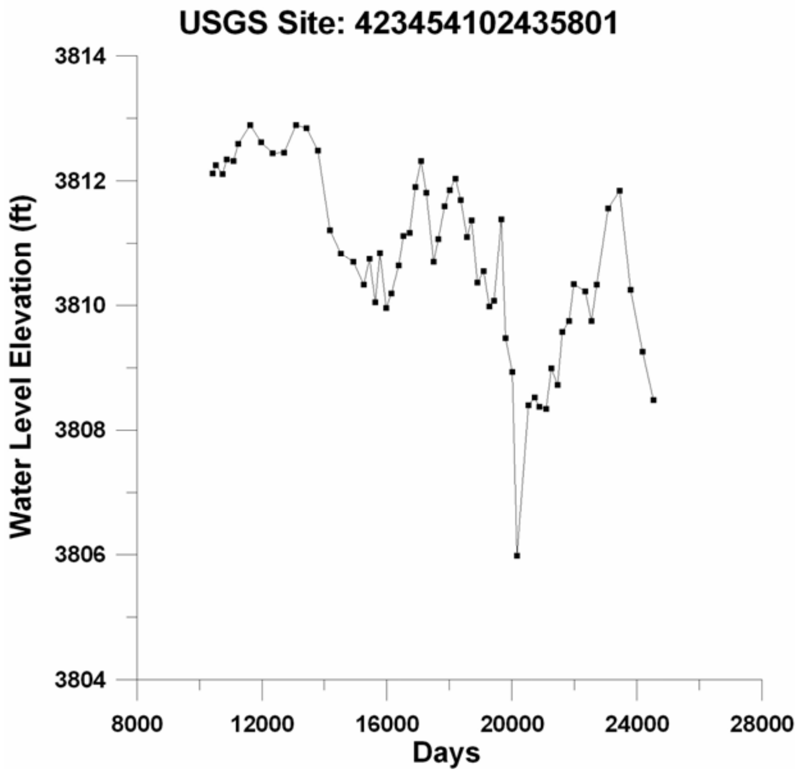

USGS Site: 422940102430101
Water Level Elevation (ft)
3768
3764
3760
3756
3752
8000
12000
16000
20000
24000
28000
Days

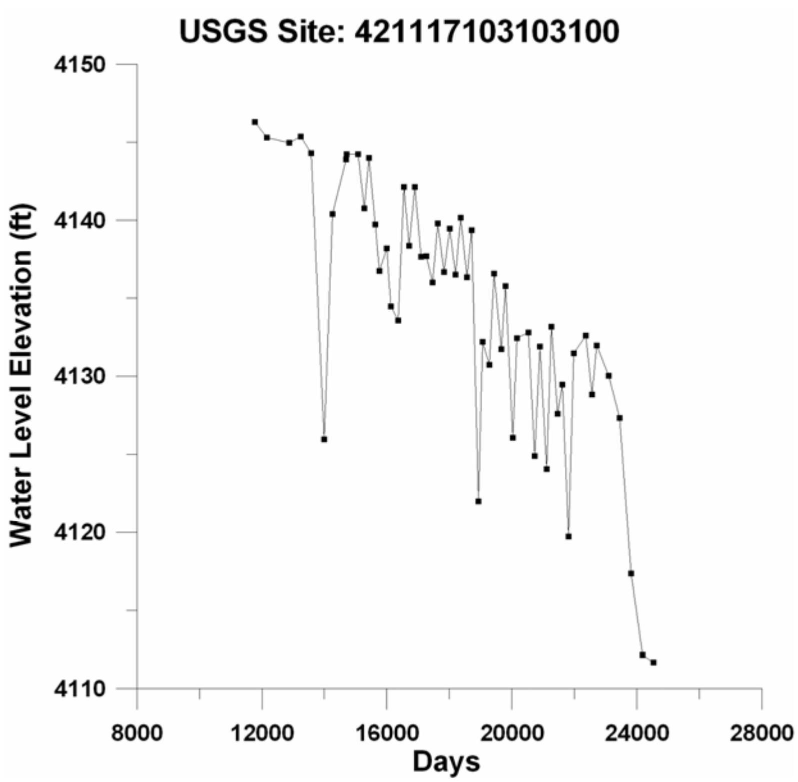

USGS Site: 420530103104001
Water Level Elevation (ft)
4070
4080
4090
4100
4110
8000
12000
16000
20000
24000
28000
Days

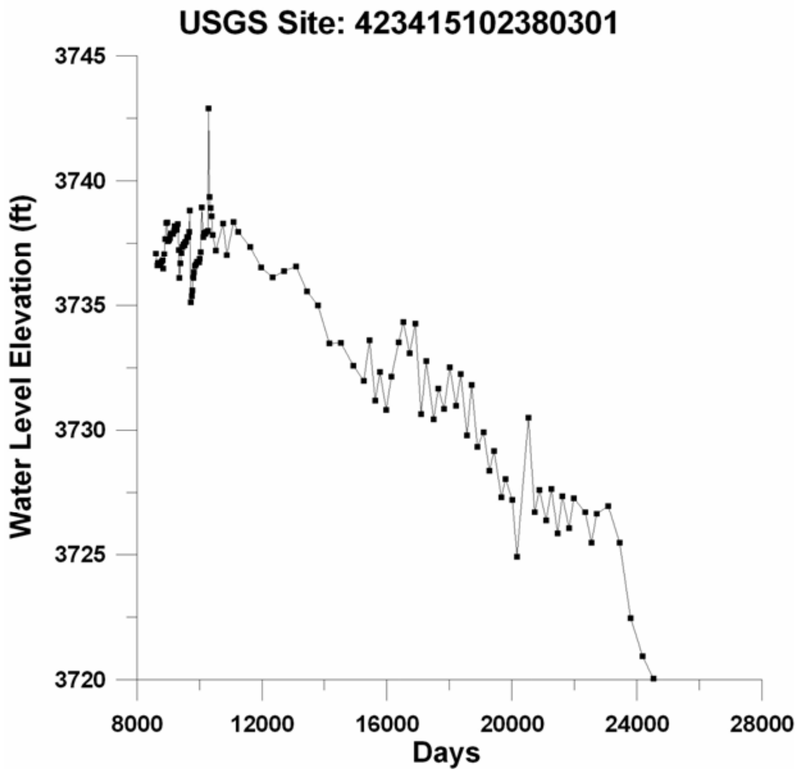

USGS Site: 421505103051701
Water Level Elevation (ft)
4080
4100
4120
4140
8000
12000
16000
20000
24000
28000
Days

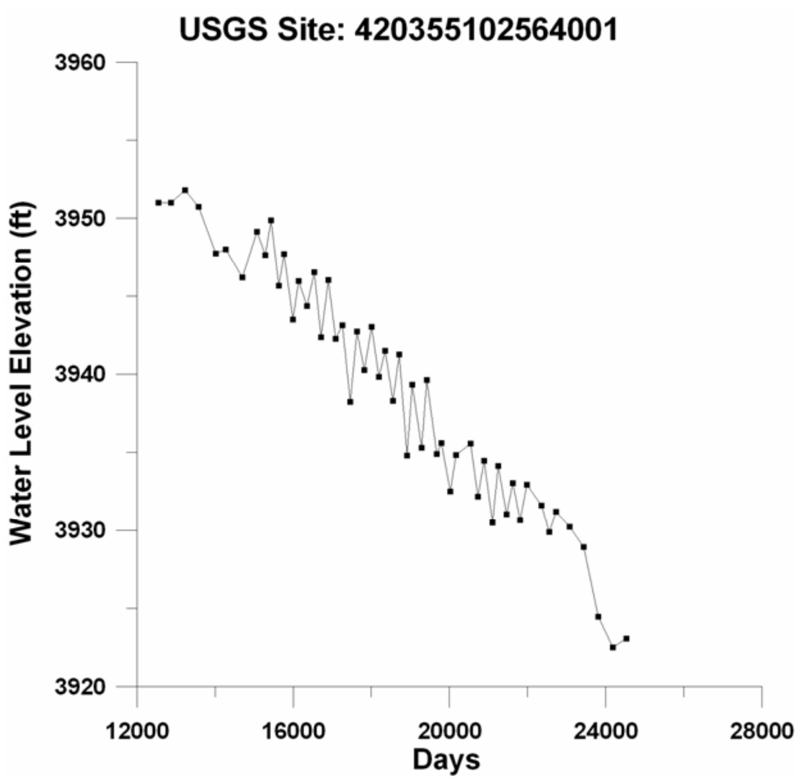

USGS Site: 423254102342601
Water Level Elevation (ft)
3684
3680
3676
3672
3668
8000
12000
16000
20000
24000
28000
Days

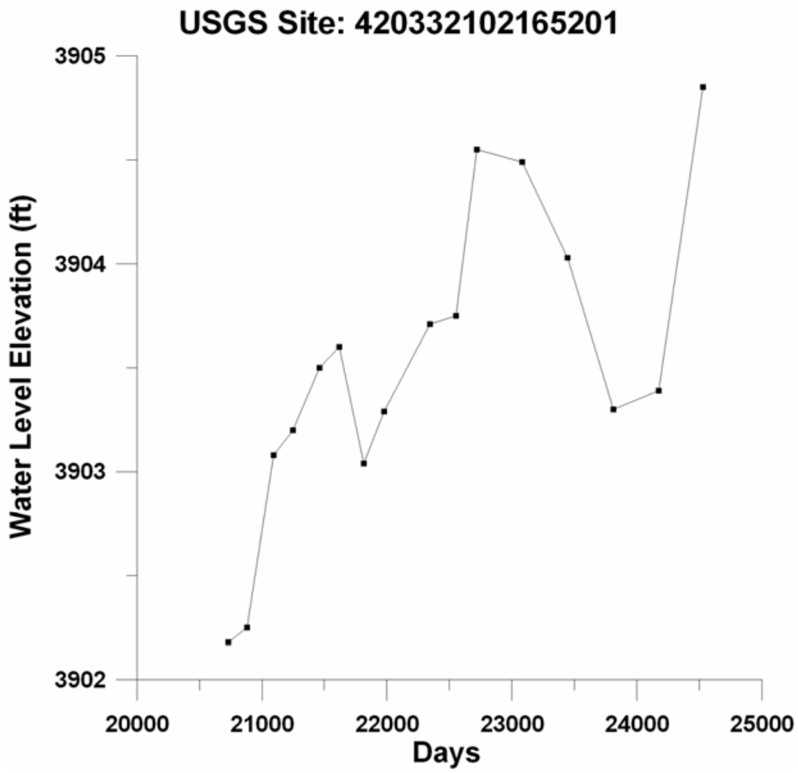

USGS Site: 421115103153400
Water Level Elevation (ft)
4230
4220
4210
4200
4190
12000
16000
20000
24000
28000
Days

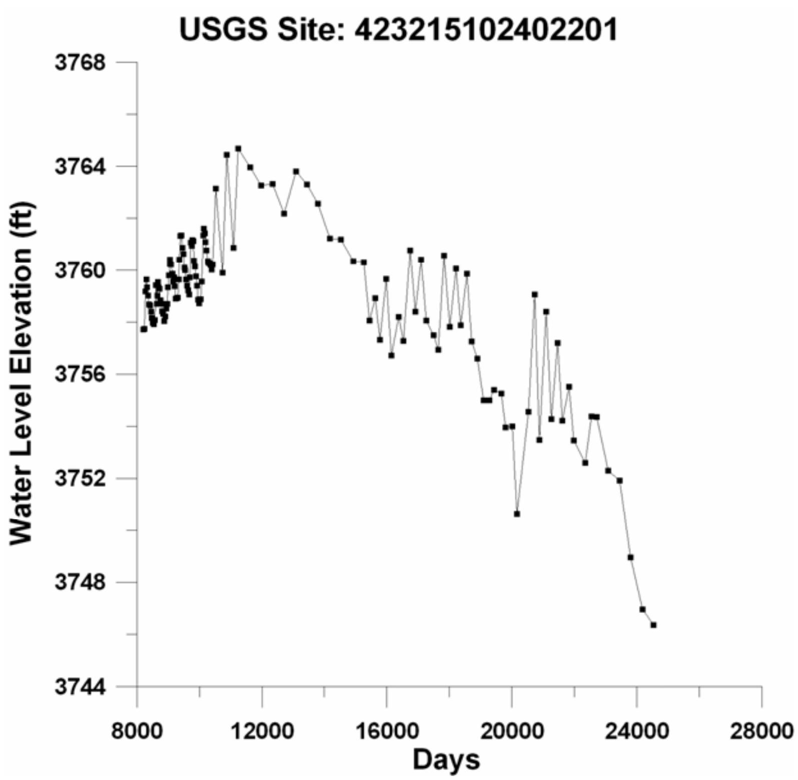

USGS Site: 423454102435801
Water Level Elevation (ft)
3814
3812
3810
3808
3806
3804
8000
12000
16000
20000
24000
28000
Days


USGS Site: 421117103103100
Water Level Elevation (ft)
4150
4140
4130
4120
4110
8000
12000
16000
20000
24000
28000
Days


USGS Site: 423415102380301
3745
3740
3735
3730
3725
3720
Water Level Elevation (ft)
8000
12000
16000
20000
24000
28000
Days


USGS Site: 420355102564001
3960
3950
3940
3930
3920
Water Level Elevation (ft)
12000
16000
20000
24000
28000
Days


USGS Site: 420332102165201
Water Level Elevation (ft)
3905
3904
3903
3902
20000
21000
22000
23000
24000
25000
Days


USGS Site: 423215102402201
Water Level Elevation (ft)
3768
3764
3760
3756
3752
3748
3744
8000
12000
16000
20000
24000
28000
Days